e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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D3.2	**Technology innovation needs**		

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document information

General purpose

Deliverable 3.2 (D3.2) deals with the identification of the technology research, development and demonstration and standardization needs over the **period 2015-2030** for a set of key critical technology components retained for implementing the concepts issued from e-Highway2050 project at the **2050 time horizon**.

Its main goal is to provide the electricity system stakeholders with these two types of information according to the reinforcement strategies considered in the e-Highway2050 project.

Key contributors

The results displayed in D3.2 result from a collective work performed within Work Package 3 under the management of TECHNOFI.

Construction of the deliverable

- Technofi, Europacable, T&D Europe, Transelectrica, Brunel, RTE

Quality review:

- At the work package level: KUL
- At the e-Highway2050 level according to the quality rules set by the project (Quality Management Plan).

Confidentiality

D3.2 is a public deliverable.

Title

D3.2 was renamed “Technology innovation needs” (“Standardization and innovation needs” in the Description of Work), the new title being more suitable to the project expectations and scope of the present study.

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Glossary and acronyms

Database The comprehensive set of data for each decade (from today to 2050) characterizing power system technologies (organized per technology and data type) and developed by e-Highway2050

Technology Area

The scope of power system technologies is organized according per function: generation, storage, transmission and demand. Seven technology areas have been considered in the e-Highway2050 project.

Technology family and variant

Classes and sub-classes respectively of a technology area. Example: for the transmission technology area, FACTS is a technology family and STATCOM represent a variant.

TR

Transmission Requirements (resulting from the project).

Transmission technology area: lines

OHL **Overhead Lines.** Conductors caring electric power (with their associated technologies: towers, isolators, etc.) under given operating conditions (voltage, current, climatic conditions such as temperature).

HTC **High Temperature Conductor**. Conductors capable to withstand high operating temperatures, and allowing higher current density than conventional conductors at equal cross section resulting in a higher power transfer on a line. Several types of high temperature conductors can be considered such as ACSS, ACSS/TW, ACCR, ACCC, GZTACSR, KTACSR, ZTACSR, ZTACIR.

HVAC High Voltage Alternating Current

AAAC All Aluminum Alloy Conductor

ACSS Aluminum Conductor Steel Supported

ACSS/TW Aluminum conductor Steel Supported, Trapezoidal shaped Wire strands

ACCR Aluminum Conductor Composite Reinforced

ACCC Aluminum Conductor Composite Core

MMC Metal Composite Conductor

PMC High Performance Organic Composite Core conductor

TACSR Thermal resistant Aluminum alloy Steel reinforced

KTAl High Strength Thermal Resistant Aluminum Alloy

KTACSR High strength thermal resistant Aluminum alloy Steel reinforced

GTACSR Ultra thermal resistant Aluminum alloy Steel reinforced

GZTACZR Gap type Ultra thermal resistant Aluminum alloy Steel reinforced

TACIR Thermal Resistant Aluminum Alloy Conductor, Invar Reinforced

TACSR Thermal Resistant Aluminum Alloy Conductor, Steel Reinforced

TAl Thermal-resistant Aluminum (aluminum zirconium alloy)

ZTACSR Aluminum Clad Steel Reinforced

ZTACIR Aluminum Clad Invar Reinforced

Transmission technology area: cables

AC	Alternate Current
CIGRE	International Council on Large Electric Systems
DC	Direct Current
DTS	Distributed Temperature Sensing
EHV	Extra High Voltage
GIL	Gas Insulated Line
GW	Giga Watt – power unit
HTSC	High Temperature Superconductor Cable
HV	High Voltage
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
IEC	International Electric Commission
IGBT	Insulated Gate Bipolar Transistors
LCC	Line Commutated Converters
MI	Mass Impregnated
MVA	Mega Volt Ampere – Apparent power unit
MVAR	Mega Var – Reactive power unit
MW	Mega Watt – active power unit
N_2	Nitrogen
PD	Partial discharges
SCFF	Self Contained Fluid Filled
SCFF-PPL	Self Contained Fluid Filled - Paper Polypropylene Laminated
SF_6	Sulfur Hexafluorid
U	AC Rated Voltage Phase to Phase
Uo	AC Rated Voltage Phase to Ground
Um	Maximum AC Rated Voltage Phase to Phase
XLPE	Cross Linked Polyethylene Insulation
YBCO	Yttrium Barium Copper Oxide

Transmission technology area: active equipment

HVDC Converters Components (CSC and VSC) used to convert electrical current from Alternating Current (AC) to Direct Current (DC) mode and vice-versa.

CSC Current Source Converters. Conventional, mature and well established HVDC converter. CSC require a synchronous voltage source. CSC is also known as LCC (Line Commutated Converters).

VSC Voltage Source Converters are self-commutated converters using devices[1] suitable for high power electronics applications. The VSC technology can rapidly control both active and reactive power independently from each other.

[1] Gate Turn-Off (GTO) thyristors, Integrated Gate Commutated Thyristor (IGCT) and Insulated Gate Bipolar Transistor (IGBT)

FACTS Flexible Alternating Current Transmission System. A power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability (IEEE). The main FACTS technologies can be classified in shunt controllers, able to provide reactive power compensation and voltage control, series controllers suitable for a more effective control of active power flow rather than shunt device and hybrid type controllers.

Combined type devices is a category of FACTS combining several devices and inherit the features (and benefits) of both shunt and series types simultaneously. This category includes devices such as the thyristor-controlled phase shifting transformer (TCPST), dynamic flow controller (DFC), unified power flow controller (UPFC), interline power flow controller (IPFC) which is a combination of several series devices.

PST Phase Shifting Transformer

RTTE Radio and Telecommunications Terminal Equipment refers to different solutions for line measurement in the system. These technologies are the information transmission media that is used to transport data between different nodes in the transmission system and the protection and controls centers that is built up in the systems.

RTTR Real Time Thermal Rating

PMU Phasor Measurement Unit. Measures the voltage and current simultaneously in a node and time stamps this measurements by a GPS clock signal.

SVC Static VAR Compensator

STATCOM STATic Synchronous COMpensator

WAM Wide Area Monitoring. Data concentrator components that receive the information from all connected PMUs and then transform the data to a ‘real-time’ view of all power flow and voltage and phase angles in the system.

The five eHighway2050 scenarios

Scenario title	Scenario short description	Challenges for the grid
Large scale RES	**Large scale RES (X5)**: focus on the deployment of large-scale RES technologies. A high priority is given to centralized storage solutions accompanying large-scale RES deployment.	High level of electricity demand. High variability due to renewable generation to be balanced.
Big and market	**Big & market (X10)**: High GDP growth and market-based energy policies. Internal EU market, EU wide security of supply and coordinated use of interconnectors for cross-border flows exchanges in EU. CCS technology is assumed mature.	Increase of electricity demand. Variability in generation to be balanced.
Large fossil fuel	**Fossil & Nuclear (X13):** Large fossil fuel deployment with CCS and nuclear electricity. Electrification of transport, heating and industry is considered to occur mainly at centralized (large scale) level. No flexibility is needed since variable generation from PV and wind is low.	Increase of electricity demand.
100% RES el.	**100% RES electricity (X7)**: 100% renewable electricity with both large scale and small-scale generation units, as well as links with North Africa. Both large-scale and small-scale storage technologies are needed to balance the variability in renewable generation.	High level of electricity demand. High variability in generation to be balanced.
Small and local	**Small and local (X16)**: the focus is on local solutions dealing with de-centralized generation and storage, as well as smart grid solutions mainly at distribution level.	Lower electricity demand but high level of renewables.

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EXECUTIVE SUMMARY

An analysis of the technology innovation needs has been performed on the basis of the transmission requirements (new links and reinforcements) identified in the system simulations carried out in WP2 and on the technology assessment performed during the first two years of the project (WP3, cf. the technology database of Deliverable 3.1).

For each e-Highway2050 scenario, the transmission requirements have been mapped in a two-dimensional space (transmission capacity, inter-cluster distance) so as to identify areas with the highest occurrences. These areas have been filled-in with matching technologies in the database [65].

For **terrestrial applications**, in addition to the available technologies for 400 kV overhead lines, the following options are of interest:

- HVAC overhead lines with different designs (number of circuits), various conductor types (high temperature low sag) and more bundles so as to reach higher power over short distances,
- standardized solution for HVAC XLPE underground cables, in order to provide partial undergrounding solutions which will complement overhead lines in sensitive areas (public consent),
- HVAC OHL consisting of several lines for very high power and short to medium distances (interest for such solutions strongly relies upon the maximum capacity of one line which is acceptable from the TSO point of view in case of a contingency).

In the longer term, other options might be considered:

- higher voltage AC lines -typically 550 kV- when addressing longer distances at medium power (where several 400 kV lines could also provide an acceptable solution),
- with high power VSC converters, and more specifically switchgear equipment becoming mature and gaining market experience, meshed HVDC networks could become possible in Europe, such HVDC meshed networks could be implemented with OHL technologies but also with HVDC cables over long distances.

For **submarine transmission** network development, there are today available technologies for all distances up to medium power. The challenge is to improve the efficiency of these technologies, both in technical (decrease of losses and failure rates, increase of possible depths) and economic (investment and O&M costs) terms. For higher power submarine liaisons over all distances, the main goals are to reach higher voltages and intensities, as well as to increase the installation depths so as to exceed 2500 meters in the coming decades with lighter cables. Like for terrestrial applications, the development of HVDC meshed networks is expected (in the North Sea for instance for the interconnections of offshore windfarms) with multi-terminal HVDC systems at sea.

Overall, a limited set of modular solutions for terrestrial and submarine liaisons could, when combined meet most of the new line and reinforcement needs identified by the project. In such a case, a balance should be found between the economies of scale and the wide range of possible links at the pan-European scale.

Technologies such as Gas Insulated Lines (GIL) and superconducting cables might be of interest in the long run, probably in densely-populated areas where huge amount of power have to be transmitted underground. High power transmission over longer distances will however require further RD&D studies on two complementary routes, the first one consisting in increasing the transfer capacity of conventional cables (such as XLPE), the second one aiming at developing solutions with high transfer capacity, such as superconducting cables, and improving their economic efficiency for long distance applications.

Detailed R&D agenda identifying key technological milestones (both in terms of R&D and standard) over the next decades are then proposed for several transmission technologies, from the manufacturers' and transmission system operators' points of view. These agenda provide possible roadmaps over the 2015-2030 period so as to be able to implement the grid architecture proposed by WP2 in 2050.

1 Introduction

1.1 Purpose

This document aims at identifying research, development and demonstration (RD&D) and standardization needs over the **period 2015-2030** for a set of key critical technology components retained for implementing the concepts issued from e-Highway2050 project at the **2050 time horizon**. It consists therefore in two main components:

- The formulation of RD&D needs under the form of technology roadmap for the **next 15 years**
- The standardization needs of the critical technology components **over the same period**.

The main goal of this public deliverable is thus to provide the electricity system stakeholders with two types of information according to the reinforcement strategies on electricity highways as resulting from the project and according to the conditions inherent to the degree of public acceptance on new transmission infrastructures and corridors (including refurbishment).

The report which concludes the work of the task T3.3 of e-Highway2050 project is based on two main inputs from the project and on external sources, the e-Highway2050 sources being:

- A database characterizing most evolution of cost and performance of technologies relevant for the power system at a mid/long-term time horizon (over the next four decades) that are the most *likely to play a significant role in the next decades for the power system (from generation to demand including storage and transmission)*
- The results of the system simulations on grid architectures performed by the project at the 2050 time horizon which are based on assumptions on the set of transmission technologies that are most likely to be implemented within that time horizon.

Another output of WP3 is also related to this deliverable : “Impacts of ICT on the pan-European Power System up to the 2050 Time Horizon” by Brunel University. It constitutes the synthesis report of the T3.2.8 aiming at identifying, qualifying and quantifying the impact of the major changes in ICT for the power system in Europe at the 2050 time horizon.

This study details a methodology designed to assess the impact of Information and Communications Technology (ICT) on the future development of pan-European power systems up to the 2050 time horizon. It addresses a highly challenging goal which is the prediction of the development and utilization of ICT in future power systems up to 2050.

1.2 General organisation of the deliverable

The present deliverable is organized in a main document in eight main sections, Annexes and a related document.

- A main document focusing on the RD&D and standardization needs
    - Section 1 introduces the approach
    - Section 2 proposes a cross-check of the predefined technology scope with the actual requirement needs as issued by the e-Highway2050 project at the 2050 time horizon. It constitutes the core part of the analysis leading to the identification of the future RD&D needs.
    - Section 3 provides an overview on requirements for new standards on technologies as well as the needs for improvements of existing ones
    - Section 4 to 6 detail each technology family both the RD&D and standardization needs, three main technology families are considered:
        - Section 4 on lines and cables (and AC transformers)
        - Section 5 on components for active transmission systems
        - Section 6 on other technologies enhancing observability, protection and control at system level

- Section 7 synthesizes the key findings according to different points of view.
- Section 8 details the sources used.

Annexes in Section 9

- Section 9.1 is overview of current standards
- Section 9.2 lists the references on technology background & roadmap and on standards.

Related document to the deliverable:

- "Impacts of ICT on the pan-European Power System up to the 2050 Time Horizon". Synthesis report of the T3.2.8. 2014. A. H. Alikhanzadeh, P. M. Ashton, I. Pisica, C. S. Saunders, and G. A. Taylor. 4th November 2014.

Key contributors are described in the Table 1. In the table "L" means leader, "c" contributor and "r" reviewer. The general organization of the task was carried out by Technofi.

Table 1 – Key providers and role in the data construction process

SECTION | | PARTNER	TECHNOFI	EUROPA CABLE	T&D EUROPE	TRANSELECTRICA	BRUNEL	EURELECTRIC	EWEA	KUL	RTE
SECTION 1	**L**								r
SECTION 2 (TR NEEDS)	**L**								c
SECTION 3 (SOA)	**r**				**L**	r	r	r	r
SECTION 4 (PASSIVE)	c	**L** (cables)		**L** (OHL)		r	r	r	r
SECTION 5 (ACTIVE)	r		**L**			r	r	r	r
SECTION 6 (SYSTEM)	**L**		c	c		r	r	r	r
SECTION 7 (CONCLUSIONS)	**L**	r	r	r	r	r	r	r	r
SECTION 8 (SOURCES)	**L**	c	c	c	c	r	r	r	r
RELATED DOCUMENT (IMPACTS OF ICT TO THE POWER SYSTEM AT 2050)	r				**L**				

1.3 Approach

It should be reminded that the technology assessment performed preliminary to that work reflects the common views of the e-Highway2050 experts about the main evolutions of the selected technologies in terms of technical performances, maturity, and costs. In particular, the construction of the database was a collective process involving the key stakeholders of the electricity value chain (manufacturers, TSOs, academia) and available scientific and technical literature.

The resulting database on cost and technologies is described in deliverable D3.1 (restricted access until project end [65]).

An overview of the successive stages to build the RD&D and standardization needs is given in Figure 1: the workflow is fully consistent with the successive sections of the present report. The section 3 details the matrix-relation between the three reinforcement strategies explored by e-Highway2050 and the required technologies. Then the three parallel flows further detail particular aspects in a traditional presentation by technologies comprising the two perspectives of the RD&D needs at a mid-term time horizon and the standardization needs for the next decade (and possibly 15 years according to the nature and time constant of evolution of the considered technologies[2]).

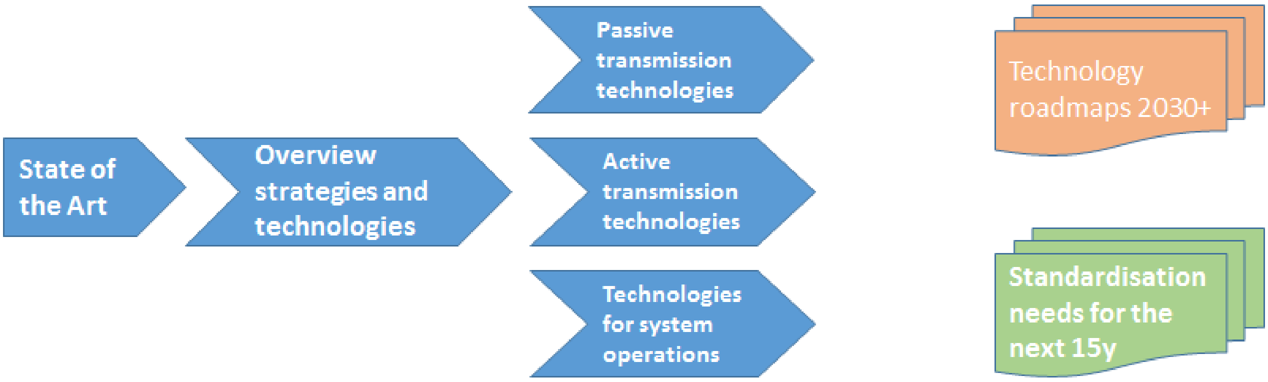


Figure 1: Overall approach to identify the RD&D and standardisation needs

Two main assumptions have to be adopted to be consistent with the work performed in the simulations of grid architectures at 2050. They deal with the technological scope of D3.2 and on a suitable time horizon to consider for each aspect (RD&D on one side and standardization needs on the other side). They are discussed in the next subsections 1.3.1 and 1.3.2 before addressing the methodology itself in 1.3.3, 1.3.4.

It should also be kept in mind that natural limitations of the study result from the e-Highway2050 assumptions related to the simplification of the grid and the related geographical clustering of Europe which naturally impacts the analysis of the distribution of reinforcement needs.

1.3.1 Time horizons

As mentioned in the main goal of the report two components with their own rationale are under scrutiny:

- Standardization issues result from manufacturers and TSO discussions with a short- to mid-term time horizon;
- Technology research, development and demonstration needs can be formulated through roadmaps for longer-term time horizons: they result from complementary inputs from manufacturers and TSOs.

The general time horizon of all the project research tasks is 2050: it is proposed to examine the RD&D conditions to enable an efficient implementation of the concept of electricity highways at the **2050 time horizon**.

Due to the sequence of adoption of an innovative technology by TSOs which foresees successive validation at the manufacturer level (R&D), at an integration stage (demonstration) by the TSO over its own control area and then possibly at the pan-European level, it makes sense to differentiate the manufacturer perspective (R&D) from the integration tests (demonstration) at the TSO or at the inter-TSO level. This is why it is proposed to formulate the technology research, development and demonstration needs for a set of key critical technology components over the **period 2015-2030**, the period 2030 to 2050 (renamed 2030+ in the following) consisting in the effective adoption by the European TSOs of the considered technology[3].

The RD&D time scale could then be split into three main periods to sequence the technology developments of critical components and of architectures in terms of research, development, demonstration and integration.

[2] Life time and constant of time of information technologies being shorter than the ones used classically in power systems.
[3] See also Realisegrid D1.4.2 [1]

- 2015-2022 timeframe, where the roadmap is bounded by the existing EU energy policy and by the already decided transmission infrastructure reinforcements;
- 2022-2030 timeframe, where technology providers and manufacturers could design the “next generation” of technology developments and implementation;
- 2030+ timeframe, which is the appropriate timeframe for early changes in network architectures, despite the higher uncertainty on technology developments.

The time horizon for standards could be of shorter range, for consistency purposes we will retain also the same 2030 time horizon as a common perspective for manufacturers and TSOs.

1.3.2 Technology scope

In the simulations of grid architectures at 2050, the set of transmission technologies that have been considered includes the following technology families:

- Overhead lines operated in AC and DC at several levels of voltage, in single or double circuits
- XLPE underground cables operated in AC and DC at several levels of voltage
- MI underground cable operated in DC at several levels of voltage
- HVDC converters (VSC and CSC), and
- AC transformers.

These technology families constitute a subset of the whole transmission technology area considered in the technology work package of e-Highway2050 (WP3). Indeed only the ones that have been considered as the most likely to be developed, tested and integrated by TSOs have been retained.

One should remark the gap between the large portfolio of transmission technologies considered in the cost and performance technology database and the subset retained for the reinforcement simulations. The gap includes in particular technologies that are regularly discussed such as: gas insulated lines, high temperature superconducting cables, etc.

It is thus proposed in the present work to extend the scope of technology for which RD&D needs and/or standardization needs could be formalized. The extended scope is close to the structure of the technology database of e-Highway2050 and includes the following technologies.

Table 2: Active transmission technologies detailed in the technology work package of e-Highway2050 (WP3) and in task T3.3

Technologies	Candidate technologies	RD&D needs at 2030+	Standardisation needs at 2030
HVDC technologies	CSC : Current Source Converters for HVDC	Y	Y
	VSC : Voltage Source Converters for HVDC	Y	Y
	DC breakers	Y	Y
	Tapping	Y	Y
	DC/DC Converters	Y	Y
FACTS	Shunt: SVC, STATCOM	Y	Y
	Series: TCSC, SSSC, TSSC	Y	Y
	Combined devices: DFC, UPFC/IPFC, TCPST	N	N
Transformers, AC breakers, PST	Phase Shift transformers and Transformers with tap changer	Y	Y
Protection and control at substations	HVDC - DC breaker	Y	Y
	AC breaker ; FCL (High Temperature Superconducting FCL; Solid state FCL; Hybrid)	N	N
Protection and control at system level	RTTR; WAMS/PMUs	Y	Y

Table 3: Passive transmission technologies detailed in the technology work package of e-Highway2050 (WP3) and in task T3.3

Technologies	Candidate technologies	RD&D needs at 2030+	Standardisation needs at 2030
Cable technologies (underground and submarine)	XLPE HVDC cables (underground and submarine)	Y	Y
	XLPE HVAC 380-420 kV cables (underground and submarine)	Y	Y
	Mass Impregnated HVDC cables (underground and submarine)	N	Y
	Self-Contained Fluid Field (underground and submarine)	N	N
Other type of cables or of design	Gas Insulated Lines	Y	N
	Superconducting conductor (high temperature or low temperature)	Y	N
	Partial undergrounding	Y	Y
	Hybrid HVAC-HVDC solutions	Y	Y
Overhead lines: classic conductors	AAAC Aero Z (400 kV ; 550 kV ; 750 kV)	Y	Y
Overhead lines: high temperature conductors	ACSS (400 kV)	Y	Y

The technological scope has to be considered with respect to the identified transmission requirement (TR) identified by the project in work package 2. This analysis is made in chapter 2 and will be used as an input for a better targeting of the technologies to be considered in the following chapters.

1.3.3 Methodology to build the RD&D needs for the critical technology components

The RD&D needs as seen by the various actors of the electricity value chain are expected to be formulated according to a nine-cell format (see Figure 2) capturing two complementary dimensions developed in a recent EC funded project [1].

- Vertically, the degree of maturity of the technology in three main steps (from the lab to the test and effective network integration over the vertical axis) and,
- Horizontally, the time line split in three time periods.

Typically the nine-cell template was built to reflect the life time of an innovation: the first line is dedicated to manufacturers while the 2nd and 3rd line are more in the domain of competence of TSOs.

The resulting RD&D statements for one technology organized by tentative period (columns) and maturity (lines) are called Action Agendas [1] and provide a tentative integration trajectory for the next decades as seen respectively by manufacturers and TSOs.

They include “by construction” the likely evolution (see arrows in diagonal in Figure 2) towards an increased industrial maturity of each technology along its life cycle curve. They were built based on an update of the Action Agendas produced in [1] and adjustments from e-Highway2050 partners. Some new tables have been added (e.g. RD&D agenda for DC breakers – see Figure 35).

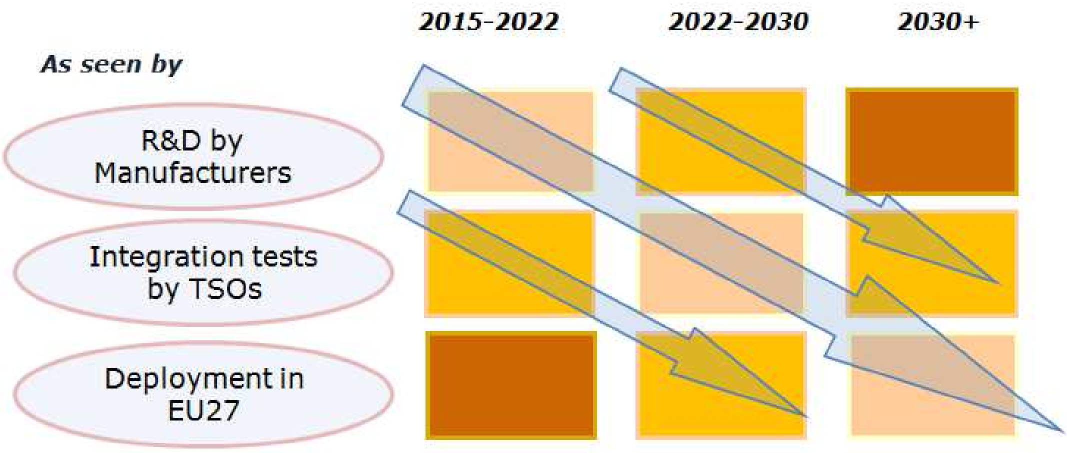


Figure 2: The nine-cell template of a RD&D agenda for a given technology

The following legend is used in all RD&D Agendas for each technology:

N/C No clear view in the development due to uncertainty at that the time horizon
No evidence of consensus between the manufacturers

N/D No Development are expected to occur due to the maturity stage of the technology

1.3.4 Methodology to build the standardization needs for the critical technology components

The professional associations and TSOs involved in that task have documented the section they have in charge based on their own respective expertise specifically for each family of technology.

2 The Transmission Requirements (TR) identified by the project

This chapter aims at cross-checking the predefined technology scope with the actual requirement needs as issued by the e-Highway2050 project at the 2050 time horizon from the simulations performed in the work package 2, the objective being to fine tune the technology portfolio indicated in Table 2 and Table 3.

To that purpose, the starting point was the distribution of all inter-cluster links candidate for transmission capacity reinforcement. The following approach was followed:

- Analysis of the inter-cluster links candidates. The inter-cluster links are reviewed and split in two subsets: the first one grouping all inter-cluster links with no needs for further reinforcement (with respect to the starting grid), the second one with identified additional capacity, which capacity could take the form of a new line or a reinforcement of existing capacity. See section 2.1.
- Focus on the 2nd subset and further analysis of the distribution of the links in a 2-dimension space identified transmission capacity X distance[4]. This analysis depend on each energy scenario and is thus repeated 5 times. See section 2.2.
- Identification of areas in that 2-dimension space delimitating min-max distance and min-max identified transmission capacity with suitable technologies. This analysis takes into account the nature of the liaison between the two considered clusters that could be either terrestrial or submarine. See section 2.3.
- Conclusion on technology needs stemming out the transmission capacity X distance needs. See section 2.4.

The following example allows to illustrate such analysis (for the scenario X5)

Table 4: Characteristics of a particular inter-cluster link (example, for one scenario)

Link	Dist. (km)	Nature	GTC (MW)	TR (MW)	Type in Starting Grid
17_fr - 22_fr	248	terrestrial	250	3000	AC

This link between two predefined clusters in France (respectively nb. 17 and 22) distant of 248 km is considered. The starting grid is an AC terrestrial line of 250 MW and for the scenario "Large scale RES (X5)" a level of 3000 MW would be necessary to ensure system adequacy in 2050.

Several technology options either in AC or DC could then be envisaged for such level of reinforcement and distance, for instance:
- AC OHL ACSS – 400 kV (single circuit)
- AC XLPE cable – 420 kV (3 circuits)
- DC OHL 4 X 265/35 -320 kV (double circuits)
- DC XLPE cable - 320 kV (3 circuits)

These particular technology options could also fit to any terrestrial link "close" to that particular liaison between clusters 17 and 22. The degree of proximity is assessed based on the geographic distance and the power capacity to be transmitted. One could also cluster in a same group all liaisons with the following characteristics
- Terrestrial
- Between 100 and 300 km of inter-cluster distance
- Identified transmission requirements of 3000 MW (±1000MW).

[4] Defined as the reference distance between two clusters, as used in WP2 [66]

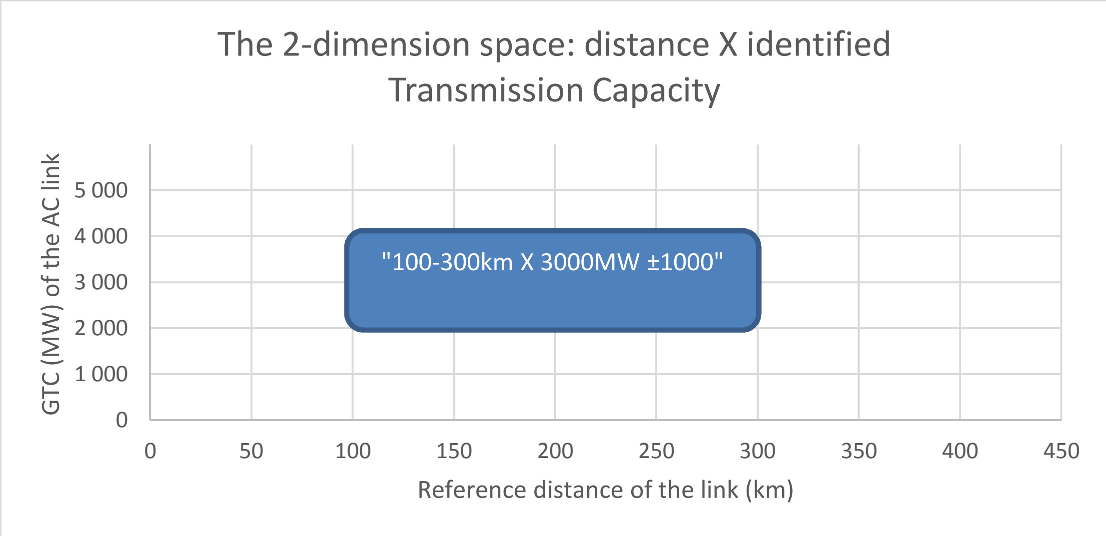


Figure 3: the 2-dimension space for analysis of the inter-cluster links to be reinforced

A discussion on an appropriate clustering of this 2-dimension space is proposed in section C in 25 categories (5 for each dimension).

2.1 Analysis of the inter-cluster links candidates

The pan-European map of e-Highway2050 clusters is reminded in the figure below.

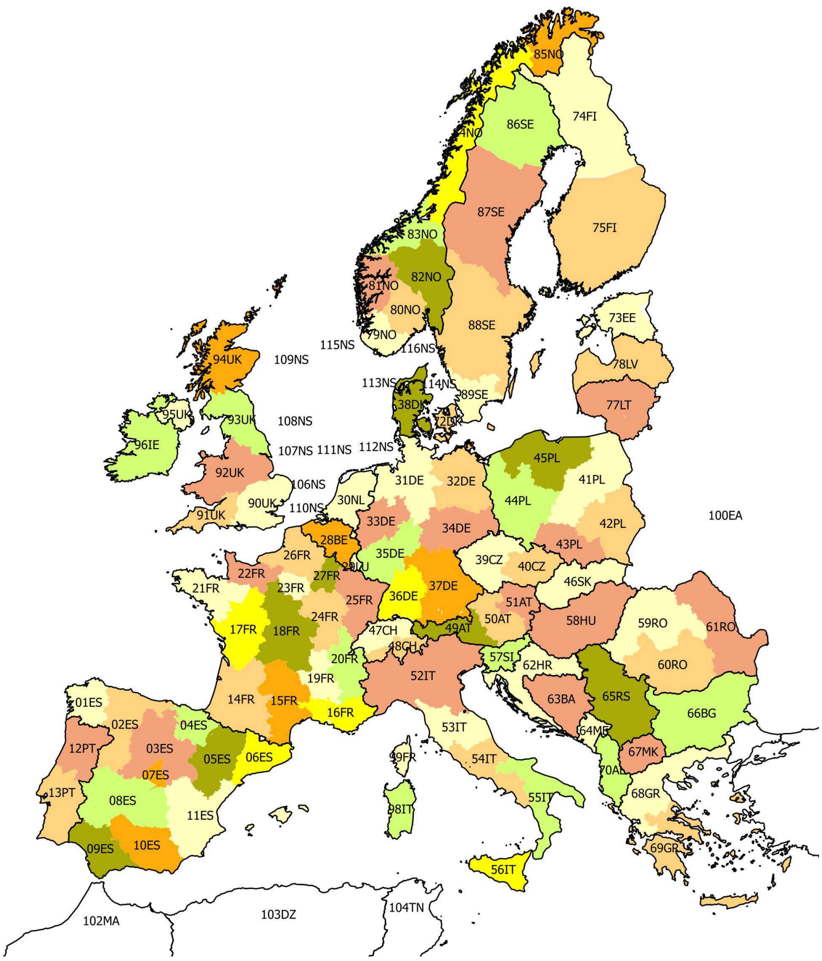


Figure 4: the 100+ clusters of e-Highway2050 including continental, marine and "rest of the world" clusters

This results in a list of 247 inter-cluster links, candidate for reinforcements: 56 submarine and 191 terrestrial. Out of the simulations performed by the project only a fraction of them would require either a reinforcement of a new liaison:

- Submarine liaisons: 34 for reinforcement (for at least one scenario), 10 new (since not existing in the starting grid) and 12 would not need any reinforcement (total 56)
- Terrestrial liaisons: 98 for reinforcement (for at least one scenario), 8 new (since not existing in the starting grid) and 85 would not need any reinforcement (total 191).

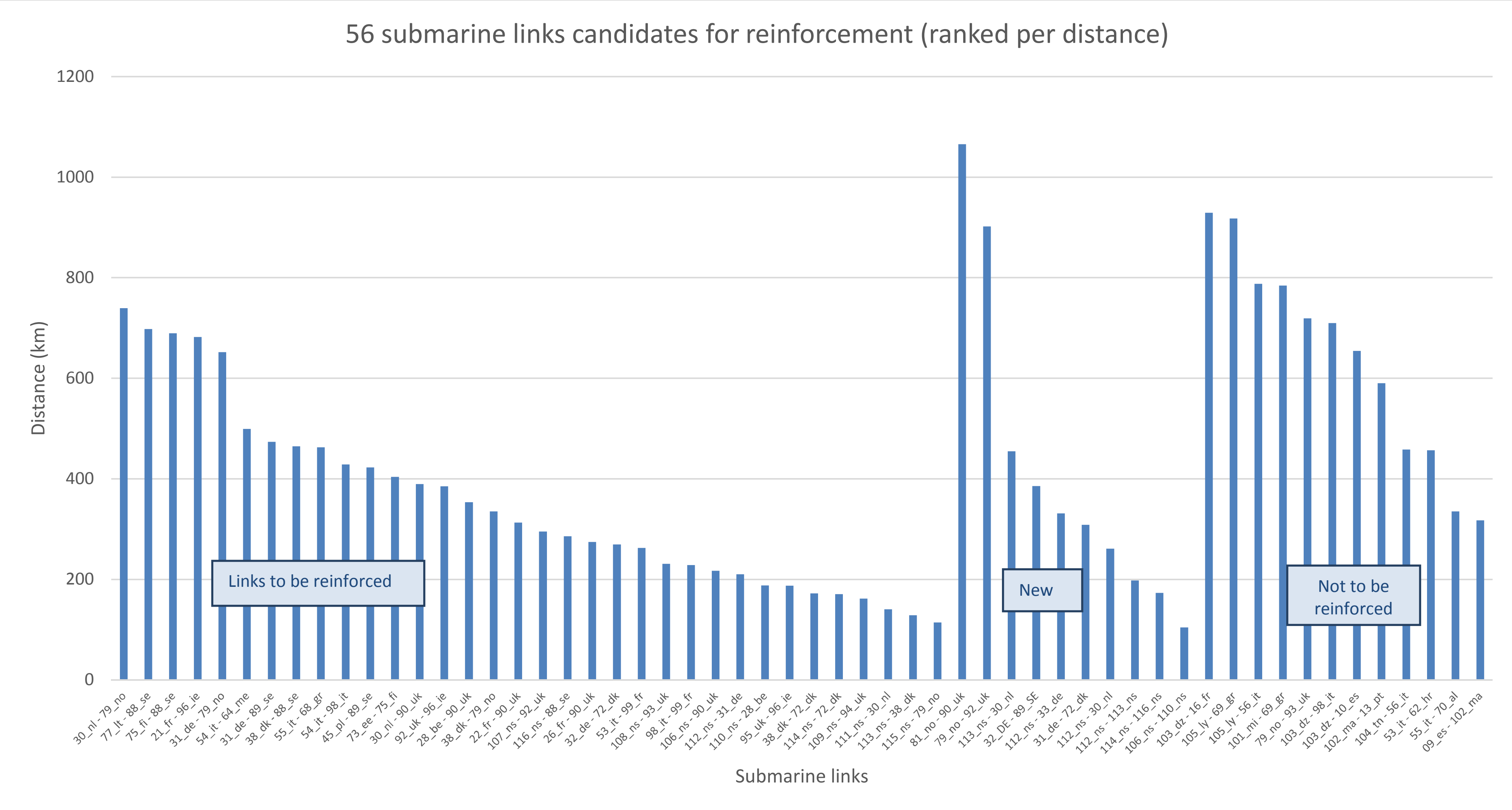


Figure 5: Submarine links candidates for reinforcement ranked per distance (km)

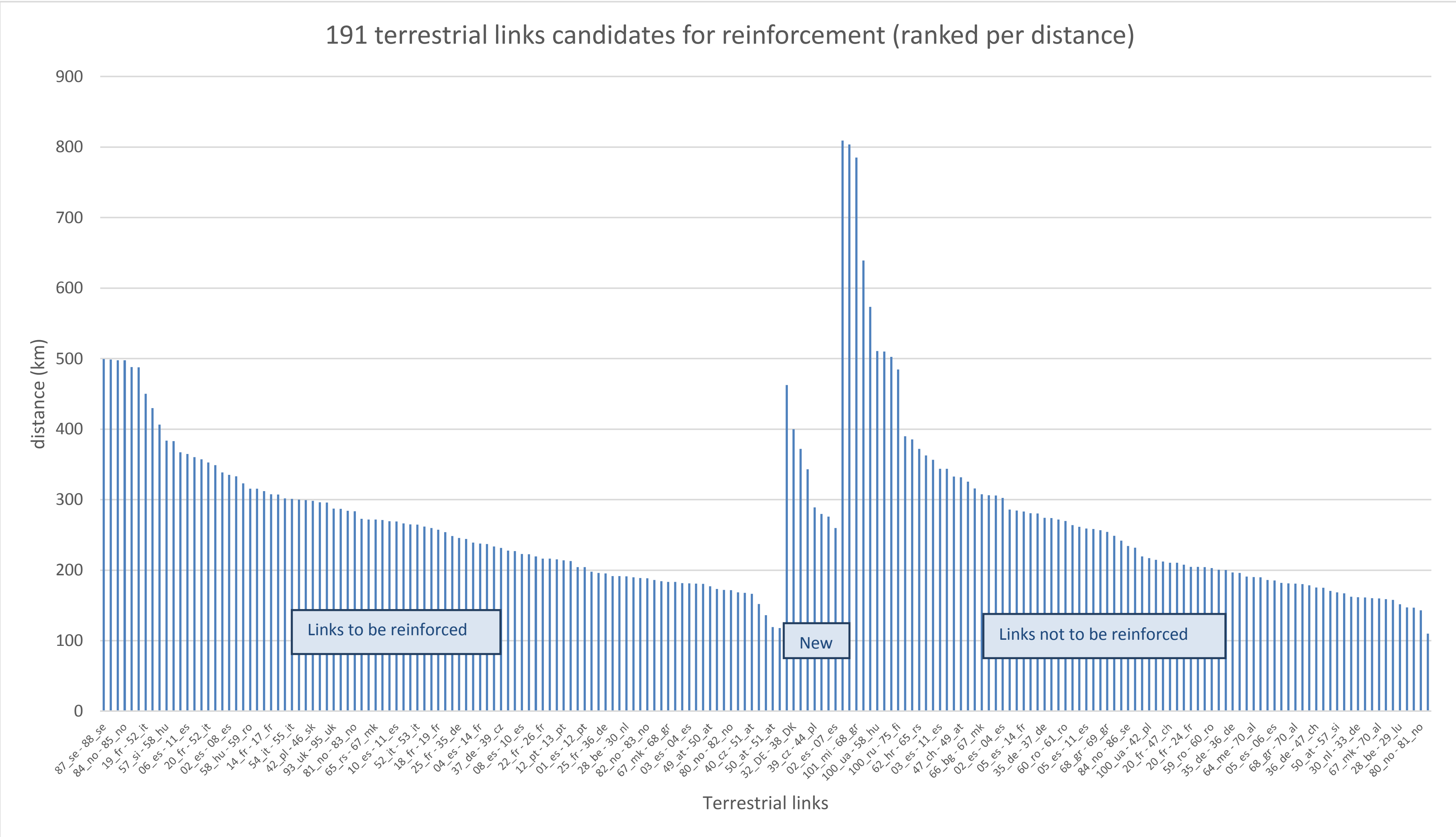


Figure 6: Terrestrial links candidates for reinforcement ranked per distance (km)

When considering the distribution of distances in the above Figure 5 and Figure 6, it should be noted that the range of 100-500 km for the 98 terrestrial links to be reinforced (and respectively the range of circa 100-750km for the 34 submarine liaisons to be reinforced)[5] are highly dependent on the granularity of the clustering made by the project. This should be kept in mind when proposing typical technologies for a given level of transmission capacity.

2.2 Focus on the 2nd subset and further analysis of the distribution of the links for each energy scenario

To proceed with the second step, the scenario-dependency should be taken into account. Therefore five successive analyses follow but focusing only on the 98+34 reinforcements and the 8+10 new liaisons (the first figure corresponding to the terrestrial links, the second one to the submarine). All in all 150 links out of the 247 possibly are concerned with at least one reinforcement/new line.

Table 5: Breakdown of the 150 links (2nd subset) on identified non-zero transmission reinforcements

Number of links with identified non-zero transmission reinforcement	Reinforcements	New liaisons	Total number of identified TR
Ground	98	8	106
Submarine	34	10	44
	132	**18**	**150**

It should be noted that for each scenario the actual number of identified TR is strictly less than 150. For the scenario X5 for instance only 95 links with TR >0 have been determined. An overview of number of links for each scenario is provided in the table below.

Table 6: Overview of the number of links with non-zero transmission reinforcement, per scenario

Number of links with identified non-zero transmission reinforcement	Large scale RES (X5)	100% RES (X7)	Big & market (X10)	Fossil & nuclear (X13)	Small & local (X16)
Ground	76	50	32	44	36
Submarine	34	25	21	27	14
	110	**75**	**53**	**71**	**50**

The above numbers are absolute whatever consideration of the distance or of the transmission capacity. A metric that could better capture the order of magnitude of the investment could be proposed as the scalar product of distances (in km) and transmission capacity (in MW) summing all links. The result given in GW*000'km reflects the intensity of a theoretical investment if all liaisons are decided. The proposed metrics is named "TR index".

Table 7: Overview of the Transmission Requirements index, per scenario

TR index (GW X 000' km)	Large scale RES (X5)	100% RES (X7)	Big & market (X10)	Fossil & nuclear (X13)	Small & local (X16)
Ground	81,6	62,2	41,9	46,0	36,7
Submarine	53,6	53,1	29,2	22,7	27
	135,2	**115,3**	**71,1**	**68,6**	**63,7**

In the following a focus on the distribution of the TR per scenario is proposed.

[5] This observation is still valid for the distribution in distance for the new links.

Large scale RES (X5)

As here above mentioned in Table 6, 110 links have been identified with non-zero transmission requirements. They are distributed as follow in terms of distance (horizontal axis expressed in km) and level of transmission requirements (vertical axis expressed in MW which represents the maximum transmission capacity identified in the system simulations carried out by the project for a given scenario)

In the next graphs per scenario, the blue dots correspond to the terrestrial links, the red dots to the submarine ones.

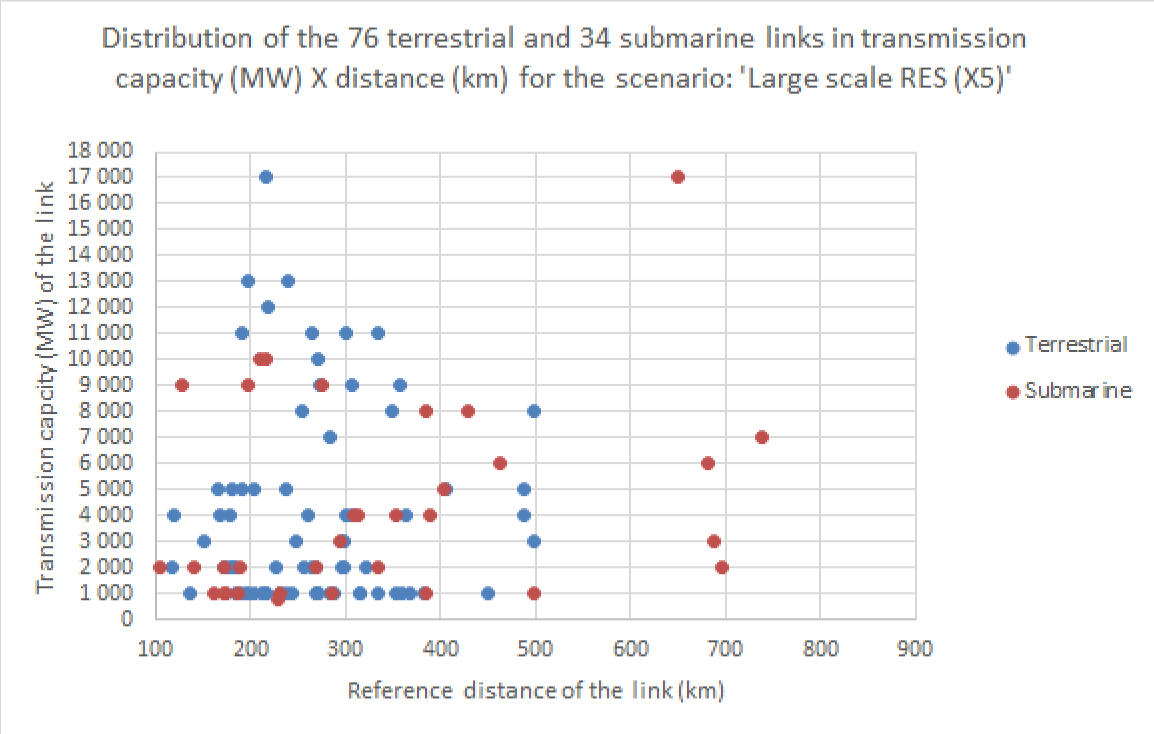


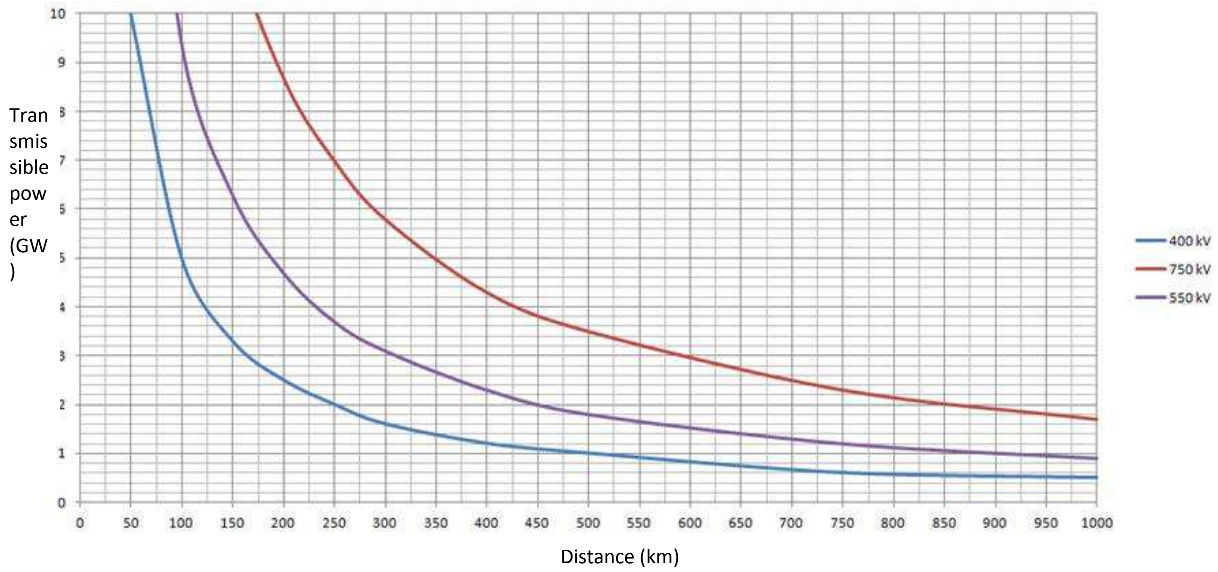
Figure 7: Distribution of the 110 links with non-zero TR for "Large scale RES" scenario

The following direct observations are formulated for the **terrestrial links**:

- ***In terms of distance:***
  - o all of the identified terrestrial links are below the 500 km threshold (among which only five are in the range 400-500 km)
  - o AC OHL solutions at 400 kV are the first options that could consider a grid planner for distances shorter than 300 km since for short distance the limitation on the maximum transmissible power is not a constraint (see
  - o Figure 8)
  - o For the range 300-500 km one should consider AC OHL solutions at an increased level of voltage (e.g. 550 kV); alternative solutions would consist of joining several consecutive shorter AC OHL solutions at 400 kV and including reactive compensation or intermediate generation to comply with the decreasing maximum transmissible power (see
  - o Figure **8**)
  - o We report below the figure describing the range of maximum transmissible power for typical OHL[6]. The figure shall be understood as reflecting the decreasing law of maximum transmissible

[6] See also technology Assessment Report of HVAC OHL (D3.1[65])

power at various level of voltages: it does not mean that operations at 750 kV (red curves) and possibly 550 kV (purple curves) will be implemented in the temporal scope of e-Highway2050 in Europe.



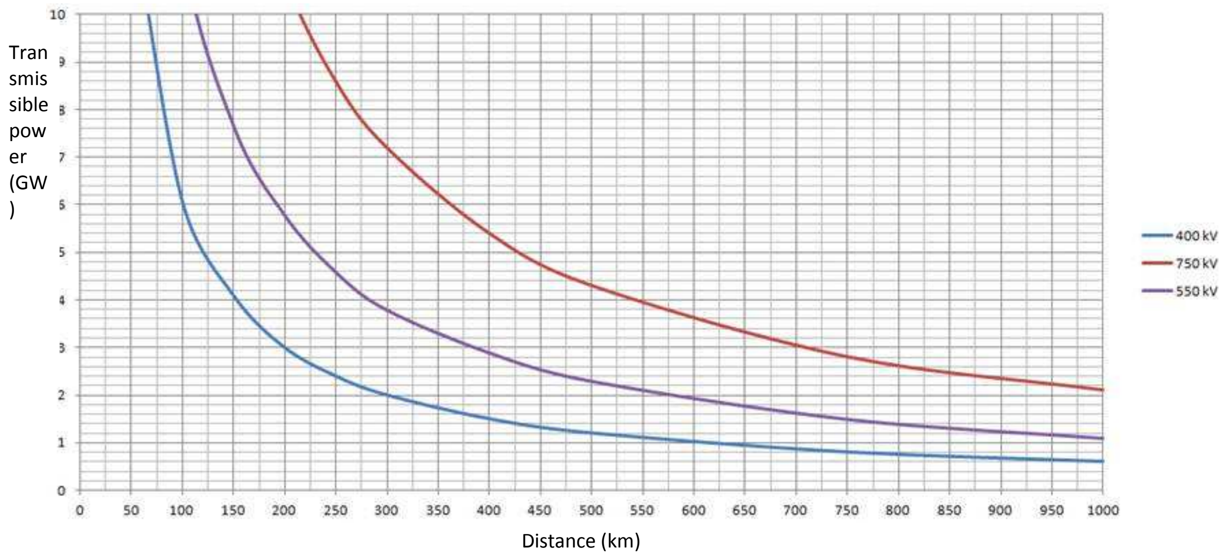


Figure 8 : Influence on maximum transmissible power over distance for different configurations of AC OHL (upper figure: two bundles per circuit; lower figure: four bundles per circuit)

- ***In terms of level of transmission capacity***, the variability in the Figure 7 is much higher ranging from 1 to 17 GW (on one specific case of a connection in Western Norway).
    - Technological options should include change in the structure[7] or the enlargement of corridor.
    - The challenge is less on technology than on public acceptance and environmental impact.
    - Partial undergrounding could also be envisaged in urban or semi-urban environments with specific cable solutions.

[7] geometric structure especially linked with the number of conductor per bundle, number of circuit and of course the operating voltage

- ***Some extreme situations*** with high transmission requirements over a long distance exist such as the link in Sweden '87_se - 88_se' requiring a major the North-South reinforcement (whatever the scenario).

For the submarine links we could formulate the following comments:

- The dispersion of the red bullet points is high covering the whole spectrum of distance and power.
- The extreme link between Norway and Germany "31_de - 79_no" is located in the upper right corner while four other long distance submarine links appear in the bottom right corner (long distance, with relatively lower transmission capacities)
- For submarine cables we would need to distinguish operations in DC or in AC considering the power break-even point due to the converters[8]
    - In AC: Submarine cables are XLPE for distances up to 100 km depending on the transmissible power
        - The technology database describes the technical characteristics and costs until 2050 of the HVAC 380-420 kV XLPE cables.
        - Some typical configurations for submarine XLPE cables are detailed in D3.1[65]: For the HVAC XLPE single core (three parallel cables for a 3-phase AC connection): see the recently announced project by Nexans in Norway (3X30 km, 420 kV, 390 m max depth) while the HVAC XLPE 3-core could be either in two or three circuits[9].
    - In DC: submarine cables could be XLPE or MI for much higher distances (>1000km)
        - Data of table 48 of D3.1 on recent realisations of HVDC submarine cables suggests that most interconnections between transmission networks are made with MI insulated cables, while connections with offshore platforms are mostly performed with XLPE insulation but this may be changed in the near future.
        - The technology variant retained in D3.1 for HVDC submarine solutions is a XLPE cable bipolar 300 kV, 2000mm2, 1031 MW.
        - It should also be noted that HVDC Mass Impregnated Cables are expected to continue to be used for many years but no major development is foreseen for this technology[10]
        - Typical solutions of XLPE Cables in DC for various levels of voltage (320kV, 450 kV, 500 kV, 550 kV, 600 kV) over distance above 1000 km can be envisaged (allowing respectively transportation of 1200, 1700, 1900, 2100, 2300 MW)

The TR index[11] for that scenario is the highest, at 135 for the pan-European continent.

[8] See D3.1 chapter 5.5 on HVDC systems: cables, lines and converter station [65]

[9] See D3.1 recent realisations on Submarine HVDC cables: cf. Prysmian project on the connection to the BorWin cluster at 155 kV (2X31 km and the related budget of 50M€, announced in 2013), or in three circuits as the connection by Nexans through the Gulf of Evia (Greece) operated at 150 kV over a sea route of 21 km and 3km underground (announced in 2010) [65]

[10] See for example the HVDC MI cable in bipolar configuration (2X600 MW) as implemented in the HVDC link between Italy and Montenegro -announced budget of 300 M€ for 393 km subsea and 22 km underground for the onshore connection.

[11] Unit is in GW X 000' km

100% RES (X7)

For that scenario, 75 links are active (i.e. with a non-zero transmission requirements). They are distributed as follow in terms of distance and level of transmission requirements.

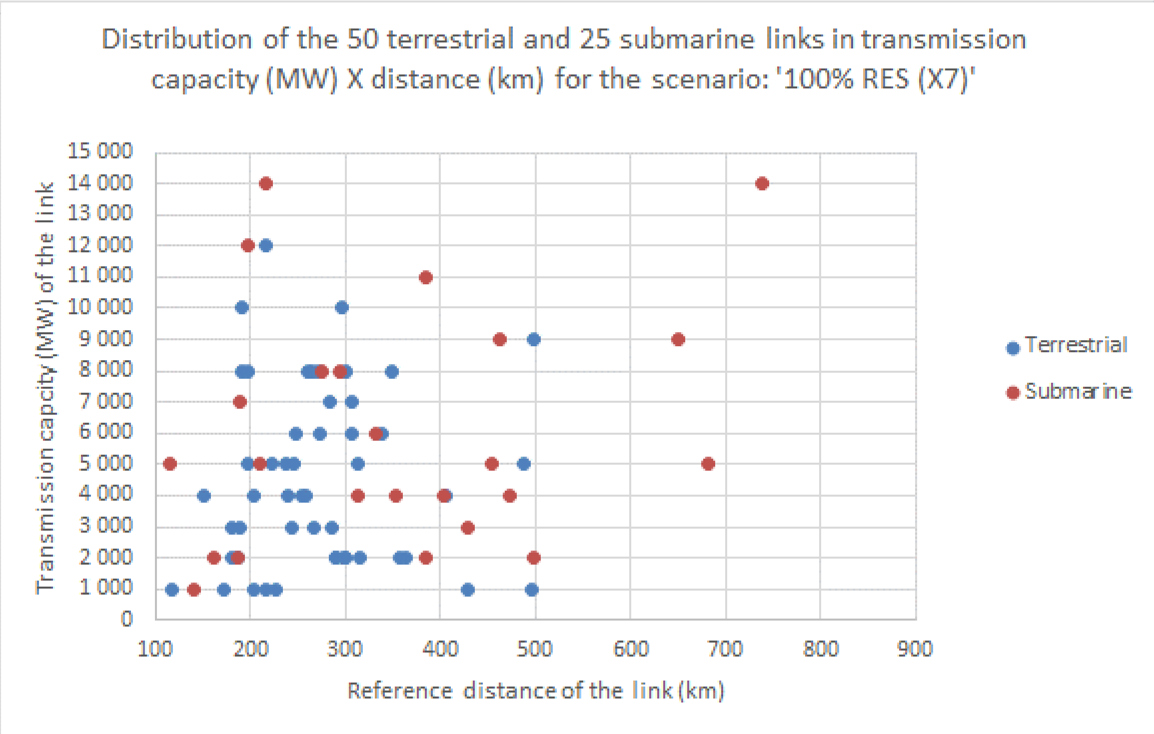


Figure 9: Distribution of the 75 links with non-zero TR for "100% RES" scenario

Most of the observations formulated for the horizontal dispersion (distance) and the vertical dispersion (power) remain valid for that scenario.

The TR index for that scenario is the second highest, at 115 (GW X 000' km) for the pan-European continent.

Big & market (X10)

For that scenario, only 53 links are active (i.e. with a non-zero transmission requirements) which are distributed as follows in terms of distance and level of transmission requirements. Again the technology considerations are still valid.

However the TR index for that scenario is almost half of the highest, at about 71 (GW X 000' km) for the pan-European continent (fully consistent with a number of links of 53 when compared with the 110 links for the 'large scale RES' scenario).

This is most likely due to the important number (more than half) of terrestrial links at low transmission capacity (1000 or 2000 MW).

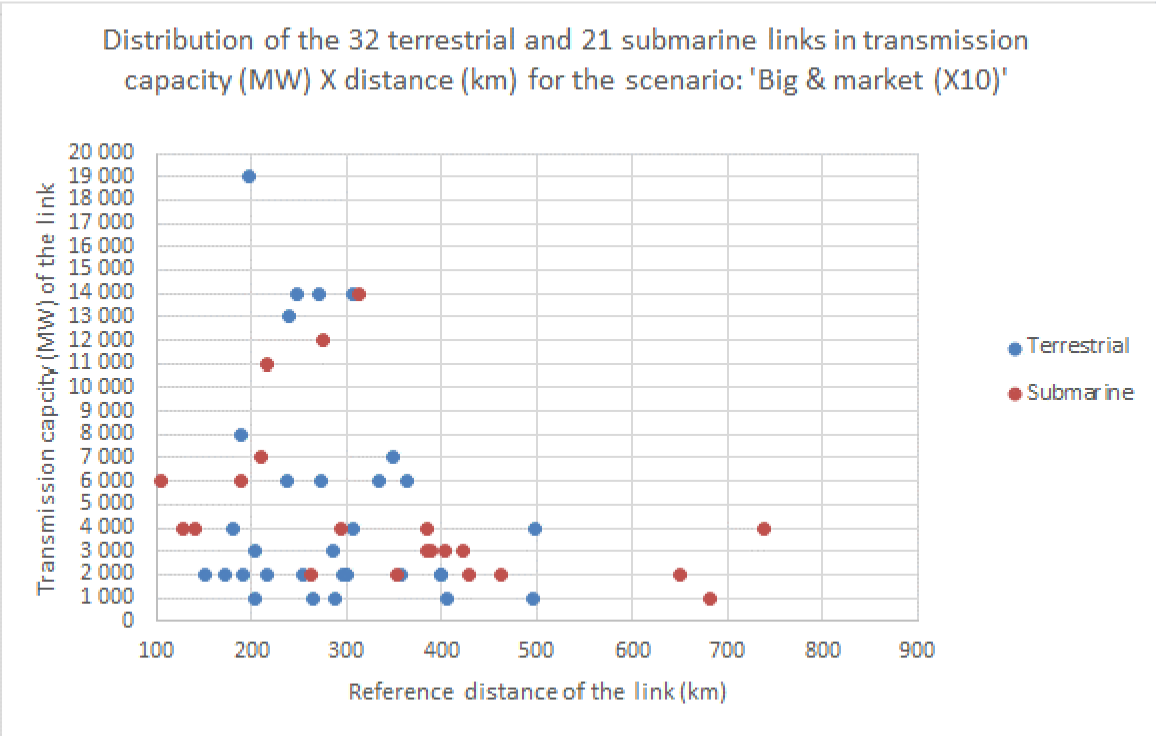


Figure 10: Distribution of the 53 links with non-zero TR for "Big & market" scenario

Fossil & nuclear (X13)

For that scenario, 71 links are active (i.e. with a non-zero transmission requirements) which are distributed as follow in terms of distance and level of transmission requirements. Again the technology considerations made for the first scenario are still valid (e.g., no long distance terrestrial link is needed).
The TR index for that scenario is also at 69, roughly half of the highest one. This means that even more links are at levels of 1000 / 2000 MW of TR.

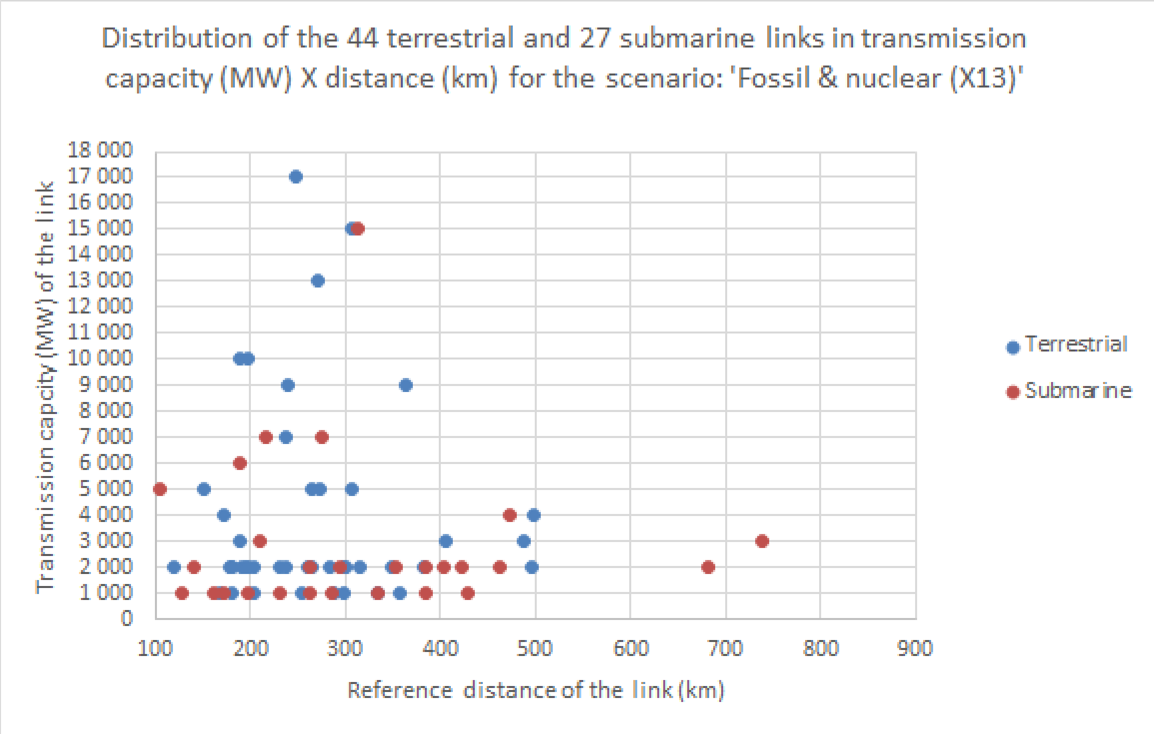


Figure 11: Distribution of the 71 links with non-zero TR for “Fossil & nuclear” scenario

Small & local (X16)

For that scenario, only 50 links are active (i.e. with a non-zero transmission requirements) which are distributed as follow in terms of distance and level of transmission requirements.

Again the technology considerations made for the first scenario are still valid (e.g., no long distance terrestrial link is needed, importance of the acceptance issue to increase the level of transmission capacity). The TR index for that scenario is at 64 (close to the TR index of scenarios x10 and x13) but with the lowest number of links. This is consistent with the wide dispersion along the vertical axis.

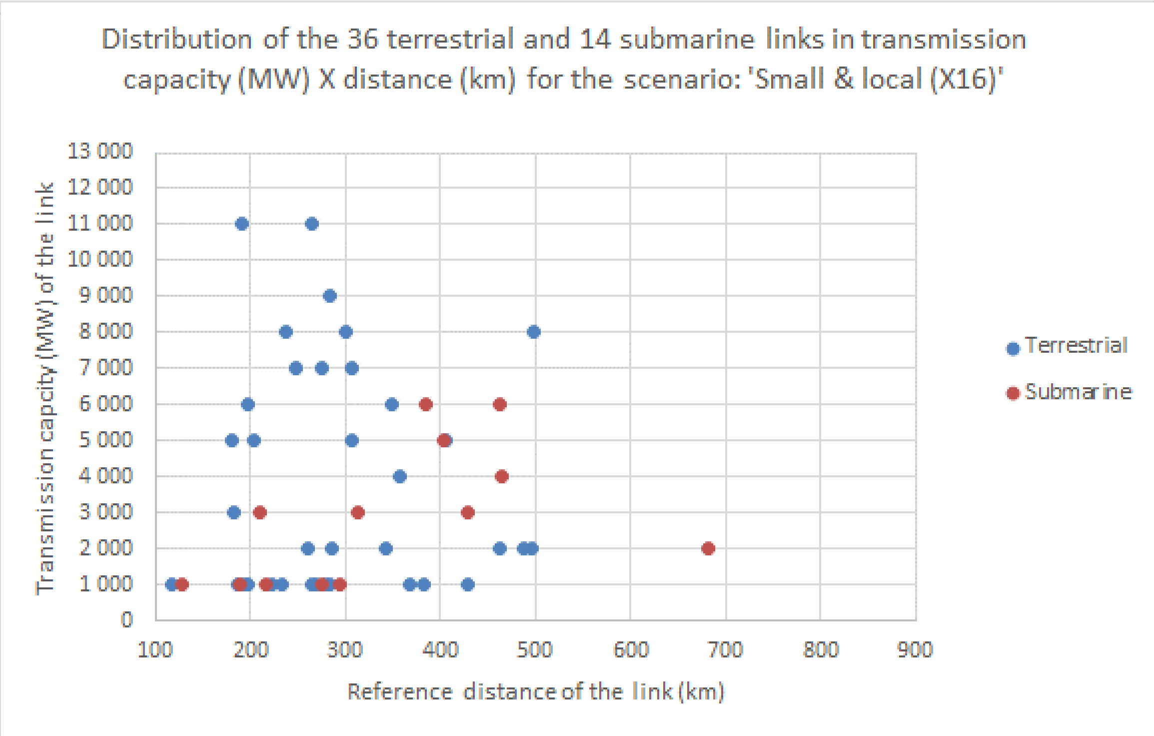


Figure 12: Distribution of the 50 links with non-zero TR for “Small and local” scenario

2.3 Identification of areas clustering the transmission requirements (TR)

In order to simplify the distribution, a clustering is proposed on that same 2-dimension space delimitating min-max distance and min-max identified transmission capacity with suitable terrestrial / submarine technologies.

Five classes of segmentation are proposed for each axis based on technological and safety of operations considerations.

Assumption (A1): maximum amount of (N-1) loss
Links above a certain threshold cannot meet a safe operation of the grid. A defect occurring in such a capacity might jeopardize the stability of the whole transmission system. Based on empirical knowledge of TSOs, such threshold was fixed at about **5 GW**. This gives an upper limit above which it is not worth investing any research or development effort on such high levels of transmission.

Assumption (A2): maximum transmissible power in HVAC
Reinforcements at **1-2 GW** can already be realized with various High Voltage technologies: either in AC or DC according to the specifications. For example overhead lines operated in HVAC for distance **up to 150 km** meet the maximum transmissible power law of Figure 8.

As a consequence the above assumptions help identifying some appropriate sampling steps for each of the two dimensions:

- Distance axis: This granularity of 150 km has been used to sample the distance axis with limits at 150, 300, 450 and 600 km, the final category being not bounded;

- Transmission capacity axis: a 1 GW step is proposed for the three first categories: "Low 1", "Low 2" and "Medium". The fourth category has a 2 GW step, while the last one has no upper boundary.

The 25 categories result directly.

Table 8: The 25 categories clustering the space distance X transmission capacity needs

Sampling of each axis		Category of distance of the link				
		Short (<150 km)	**Medium 1 (150-300 km)**	**Medium 2 (300-450 km)**	**Long (450-600 km)**	**Very long distance (>600 km)**
Category of Transmission capacity needs	**Low 1 (0.5-1.5 GW)**					
	Low 2 (1.5-2.5 GW)					
	Medium (2.5-3.5 GW)					
	High (3.5-5.5 GW)					
	Huge (>5.5GW)					

A distribution of all the active links is now possible according to the 25 sampled areas. This will allow to identify where the proposed reinforcement links outputs of the e-Highway2050 project are located.

To that purpose a list of combination of the 150 links that are potentially active (non-zero TR for a scenario) for the considered scenario is built. The whole list includes 754 entries of the form (distance, power) whose occurrences are counted according to the above 25 classes. The results are presented in the next figures:

the first one includes all terrestrial and submarine occurrences, the 2nd and the 3rd view presenting respectively the terrestrial and the submarine connections.

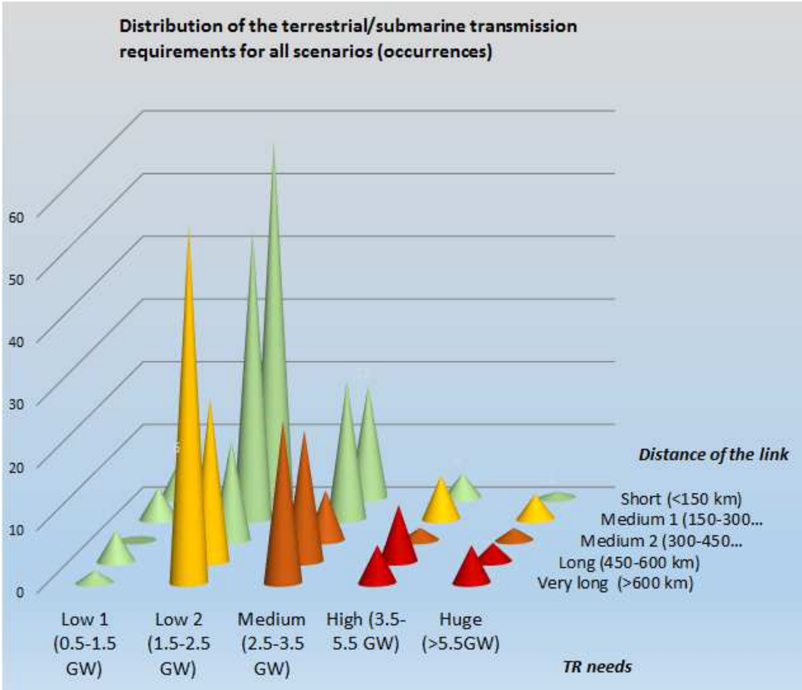


Figure 13: Distribution of the transmission requirements for all scenarios (terrestrial and submarine)

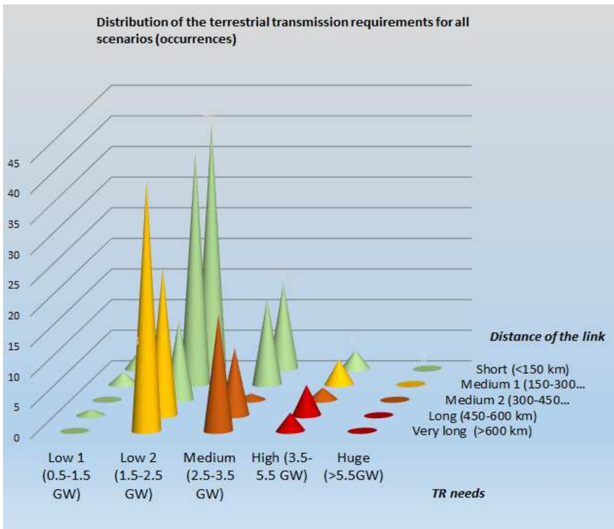


Figure 14: Distribution of the transmission requirements for all scenarios (terrestrial)

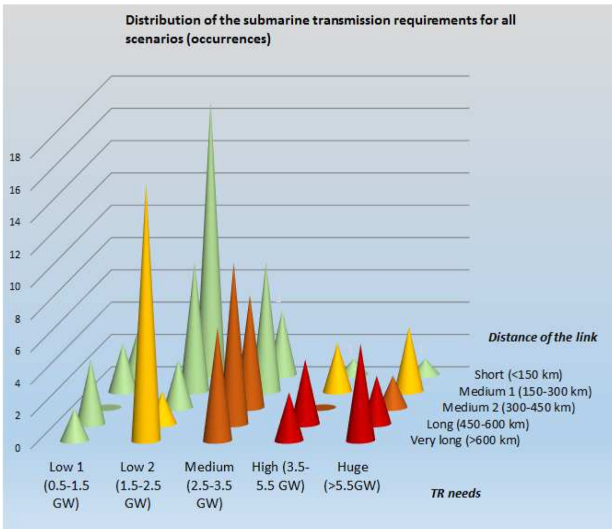


Figure 15: Distribution of the transmission requirements for all scenarios (submarine)

This occurrence analysis leads to the following observations on the transmission requirements. They are specific to the nature of the liaison (terrestrial / submarine).

Terrestrial:

Distance of the liaison

Nb of occurrences for all scenarios	Short (<150 km)	Medium 1 (150-300 km)	Medium 2 (300-450 km)	Long (450-600 km)	Very long (>600 km)		
Low 1 (0.5-1.5 GW)	3	2	0	1	0	6	2,5%
Low 2 (1.5-2.5 GW)	40	38	13	24	41	156	65,5%
Medium (2.5-3.5 GW)	14	14	1	11	19	59	24,8%
High (3.5-5.5 GW)	3	4	2	5	3	17	7,1%
Huge (>5.5GW)	0	0	0	0	0	0	0,0%
	60	58	16	41	63	**238**	
	25,2%	24,4%	6,7%	17,2%	26,5%		

- 238 terrestrial configurations are considered
- Most of the terrestrial reinforcement needs are located in the “Low 2” (1.5-2.5 GW) or “Medium” (2.5-3.5 GW) categories in terms of power: respectively 65% and 25% of occurrences, all other categories representing 10% all together
- For the “Low 2” category, a tri-modal distribution appears with two peaks at each extremity of the distance axis (short and very long distance connections) and a third one for the medium 1 distance
- For the “Medium” category the same bimodal distribution observed for the “Low 2” is confirmed
- When considering vertically the number of terrestrial liaisons it appears that the “Medium 2” (300-450 km) is the less observed with less than 7% of terrestrial occurrences. Three distance categories (“Short” <150 km; “Medium 1” (150-300 km) and “Very long” (>600km) represent each about ¼ of occurrences which reflects well the bimodal distribution in distance.

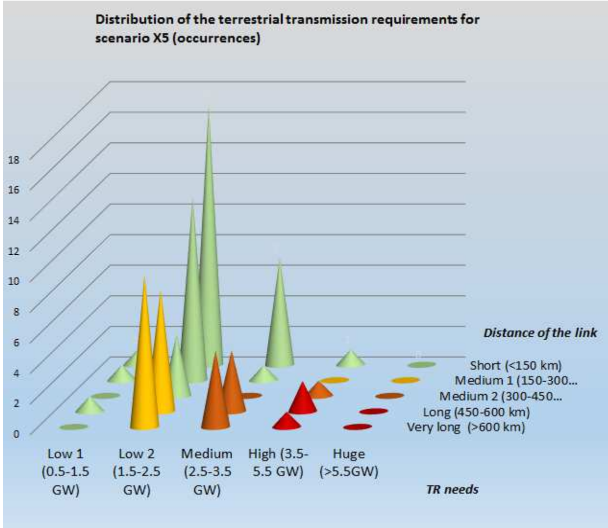
Submarine:

Distance of the liaison

Nb of occurrences for all scenarios	Short (<150 km)	Medium 1 (150-300 km)	Medium 2 (300-450 km)	Long (450-600 km)	Very long (>600 km)		
Low 1 (0.5-1.5 GW)	3	3	0	4	2	12	9,9%
Low 2 (1.5-2.5 GW)	17	8	3	2	16	46	38,0%
Medium (2.5-3.5 GW)	4	8	7	10	7	36	29,8%
High (3.5-5.5 GW)	1	3	0	4	3	11	9,1%
Huge (>5.5GW)	1	4	2	3	6	16	13,2%
	26	26	12	23	34	**121**	
	21,5%	21,5%	9,9%	19,0%	28,1%		

- 121 submarine configurations are considered
- Most of the submarine reinforcement needs are located in the “Low 2” (1.5-2.5 GW) or “Medium” (2.5-3.5 GW) categories in terms of power: respectively 38% and 30% of occurrences, the three other categories being quite equally represented (from 9% to 13%)
- For the “Low 2” category, the already mentioned bimodal distribution appears with two peaks at each extremity of the distance axis (short and very long distance connections).
- But this bimodal distribution is not confirmed for the “Medium” category for which an homogeneous repartition per distance is observed
- The vertical analysis per distance delivers a different message for submarine liaisons: they are quite homogeneously distributed from 19% to 28% for four of them, the fifth one (again “Medium 2” -300-450km- presenting a lower value at 10%.

This quick analysis could be complemented by a detailed analysis for each scenario. Active links are represented in the next views per scenario (on the left: the terrestrial active links; on the right the submarine ones).



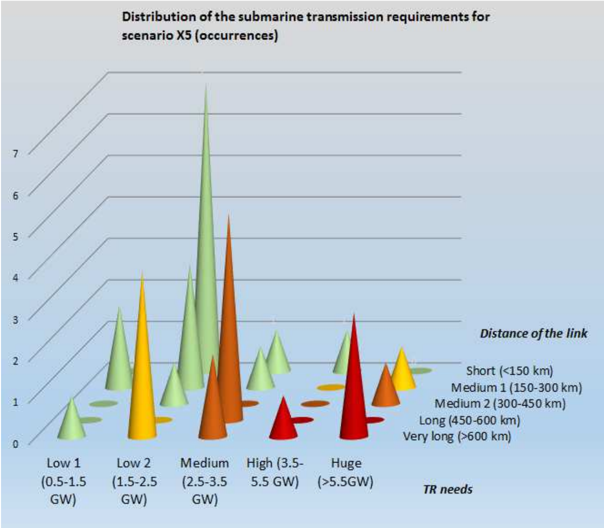
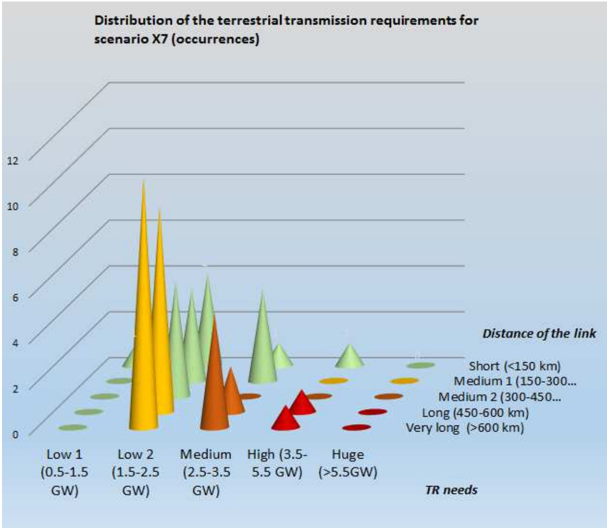


Figure 16: Distribution of the terrestrial and submarine requirements for the scenario “Large scale RES” (X5)



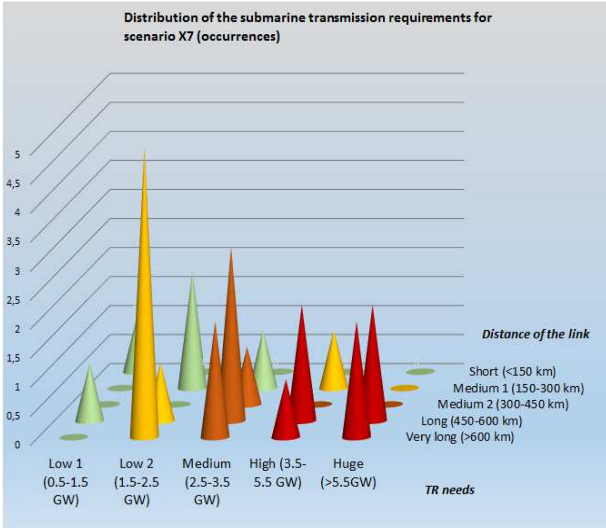
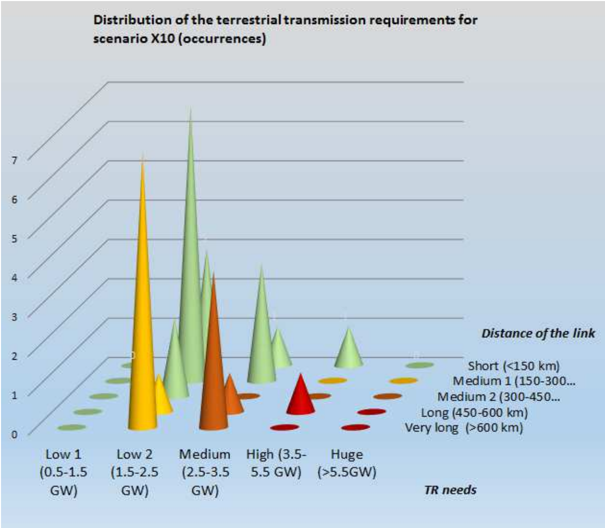


Figure 17: Distribution of the terrestrial and submarine requirements for the scenario “100% RES” (X7)



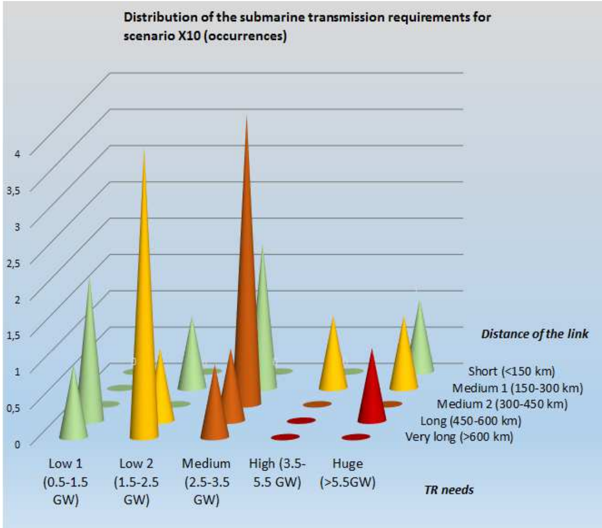
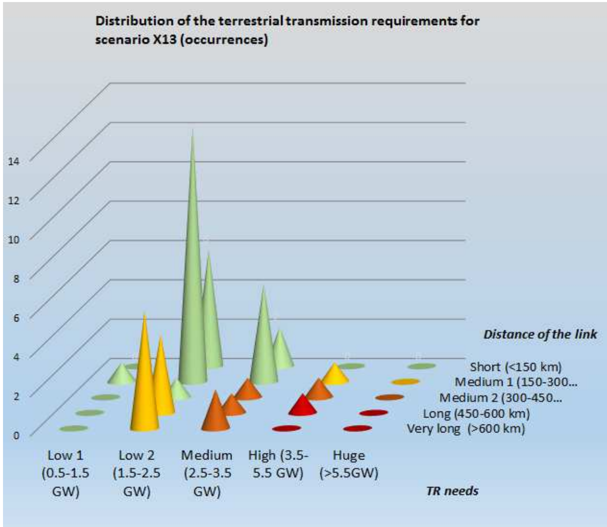


Figure 18: Distribution of the terrestrial and submarine requirements for the scenario “Big & market” (X10)



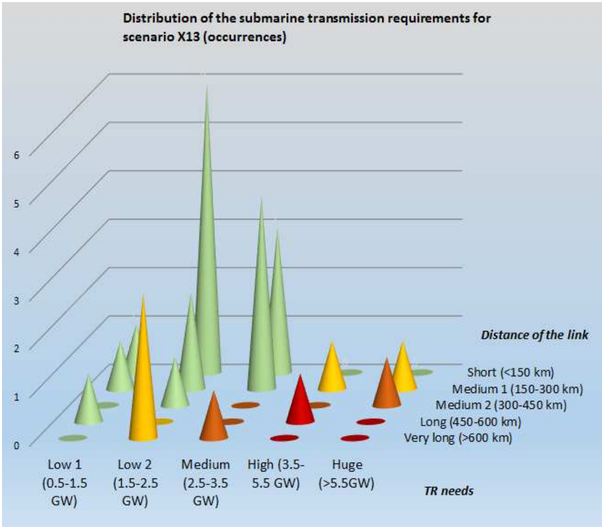
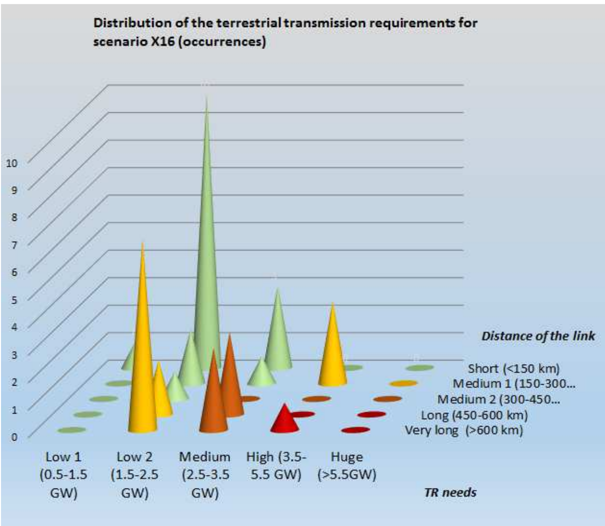


Figure 19: Distribution of the terrestrial and submarine requirements for the scenario “Fossil & nuclear” (X13)



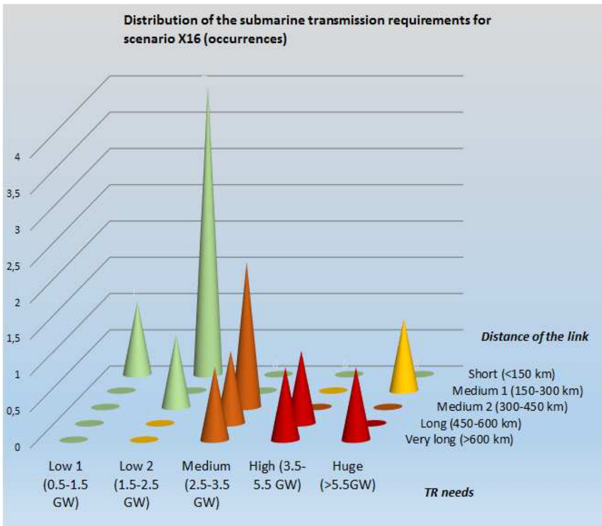


Figure 20: Distribution of the terrestrial and submarine requirements for the scenario “Small & local” (X16)

Despite some variations in the distribution for some scenarios, the observations on the distribution made when summing occurrences for all scenarios are still valid. We are now in position to identify typical needs according to the preselected categories of couples “capacity” X “distance”.

Terrestrial:

8 typical classes are retained with a threshold of selection fixed at 5% of terrestrial occurrences summed over all scenarios. They are highlighted in orange colour in the figure below.

	Distance of the liaison						
Nb of occurrences for all scenarios	Short (<150 km)	Medium 1 (150-300 km)	Medium 2 (300-450 km)	Long (450-600 km)	Very long (>600 km)		
Low 1 (0.5-1.5 GW)	3	2	0	1	0	6	2,5%
Low 2 (1.5-2.5 GW)	40	38	13	24	41	156	65,5%
Medium (2.5-3.5 GW)	14	14	1	11	19	59	24,8%
High (3.5-5.5 GW)	3	4	2	5	3	17	7,1%
Huge (>5.5GW)	0	0	0	0	0	0	0,0%
	60	58	16	41	63	**238**	
	25,2%	24,4%	6,7%	17,2%	26,5%		

Figure 21: the 8 identified classes for terrestrial liaisons (in orange colour)

Submarine:

Again 8 typical classes are retained when fixing the threshold of selection at 5% of submarine occurrences summed over all scenarios).

	Distance of the liaison						
Nb of occurrences for all scenarios	Short (<150 km)	Medium 1 (150-300 km)	Medium 2 (300-450 km)	Long (450-600 km)	Very long (>600 km)		
Low 1 (0.5-1.5 GW)	3	3	0	4	2	12	9,9%
Low 2 (1.5-2.5 GW)	17	8	3	2	16	46	38,0%
Medium (2.5-3.5 GW)	4	8	7	10	7	36	29,8%
High (3.5-5.5 GW)	1	3	0	4	3	11	9,1%
Huge (>5.5GW)	1	4	2	3	6	16	13,2%
	26	26	12	23	34	**121**	
	21,5%	21,5%	9,9%	19,0%	28,1%		

Figure 22: the 8 identified classes for submarine liaisons (in orange colour)

The above figures clearly show that the rating range of 2.5-3.5 GW appears as the most interesting independent of the distance and location (submarine, terrestrial). Next section 2.4 will provide possible technological solutions to address each of the identified classes.

It should however be noted that for each situation a wide variety of technological options are possible for the grid planner which have to be assessed and ranked according based on cost benefit approach including public acceptance and other regulatory issues. In this work the current scope is less ambitious by providing catalogue-type options and considering only technology features (performance and technology maturity), irrespectively from any public acceptance or regulatory issues.

The following tables detail typical configurations for a range of distance and transmission requirements that have been used for grid simulations (in Work package 2). It is observed that all options of distance X capacity per technology are not always possible.

Table 9: Terrestrial technological options based on HVAC OHL[12]

Technological options in OHL HVAC (terrestrial) used in grid simulations	**100-300 km**	**300-500 km**	**500-800 km**	**>800 km**
2-4 GW	- **2100 MW** of TR thanks to a OHL AC AAAC Aero-Z 400 kV 1 tower 1 circuit, - **2900 MW** of TR thanks to a OHL AC ACSS Aero-Z 400 kV 1 tower 1 circuit	- **2900 MW** of TR thanks to a OHL AC AAAC Aero-Z 550 kV 1 tower 1 circuit	**-3900 MW** of TR thanks to a OHL AC AAAC Aero-Z 750 kV 1 tower 1 circuit	
>4 GW	- **4200 MW** of TR thanks to a OHL AC AAAC Aero-Z 400 kV 1 tower 2 circuits, - **5800 MW** of TR thanks to a OHL AC ACSS Aero-Z 400 kV 1 tower 2 circuits	- **5800 MW** of TR thanks to a OHL AC AAAC Aero-Z 550 kV 1 tower 2 circuits	**-7800 MW** of TR thanks to a OHL AC AAAC Aero-Z 750 kV 1 tower 2 circuits	

Table 10: Terrestrial technological options based on HVDC OHL

Technological options in HVDC OHL (terrestrial) used in grid simulations	**100-300 km**	**300-500 km**	**500 km-800 km**	**>800 km**
1-2GW	In the area of liaisons with distance up to 500-800km, the converter costs drastically impact the cost benefit analysis of the option. Thus, the option is feasible on a technical standpoint but does not make sense on the economic perspective. The trade-off for HVDC terrestrial applications is rather an area than a precise line. This issue will be discussed in the next sections.			- **1700MW** with OHL DC 4X265/35 – 320 kV – 1 tower 1 circuit
2-4 GW				- **4000MW** with OHL DC 4X550/70 – 500 kV – 1 tower 1 circuit - **3400MW** with OHL DC 4X265/35 –

[12] The matrix was built on a collective work made between WP3 and WP2 work packages on a technology matrix synthesizing technology features to be used for grid simulations

		320 kV – 1 tower 1 circuit
>4 GW		- **8000MW** with OHL DC 4X550/70 – 500 kV – 1 tower 2 circuits[13]

Table 11: Technological options based on cables technologies in AC and DC

Technological options in cables [14]	**100 km**	**100-1000 km**	**>1000 km**
1-2GW	- **1300 MW:** HVAC XLPE cable 420kV	- **1200MW:** HVDC XLPE Cables 320kV - **1700MW:** HVDC XLPE Cables 450kV - **1900MW:** HVDC XLPE Cables 500kV	
2-4 GW		- **2100MW:** HVDC XLPE Cables 550kV - **2300MW:** HVDC XLPE Cables 600kV For submarine applications : - **2300 MW:** MI Cable 600 kV	

Controllability features brought by active type equipment such as FACTS or by phase shifting transformers are not included in the list of above technologies. Such equipment - by adding flexibility to the transmission grid- could be used to optimize operations of a given grid: they contribute to marginally enhance the transmission capacity of a passive system but cannot implement *per se* some technological options to achieve some transmission requirements between two points of the system.

When positioning the above solutions on the 2-dimensional space with the identified needs, the following type of figure is obtained. One should however be prudent on their interpretation: they can only provide some possible realistic technological options among others.

[13] some limitation factors have however to be considered for HVDC OHL in particular the voltage drop and the computation of losses
[14] Terrestrial, underground, submarine in AC or DC and used in grid simulations

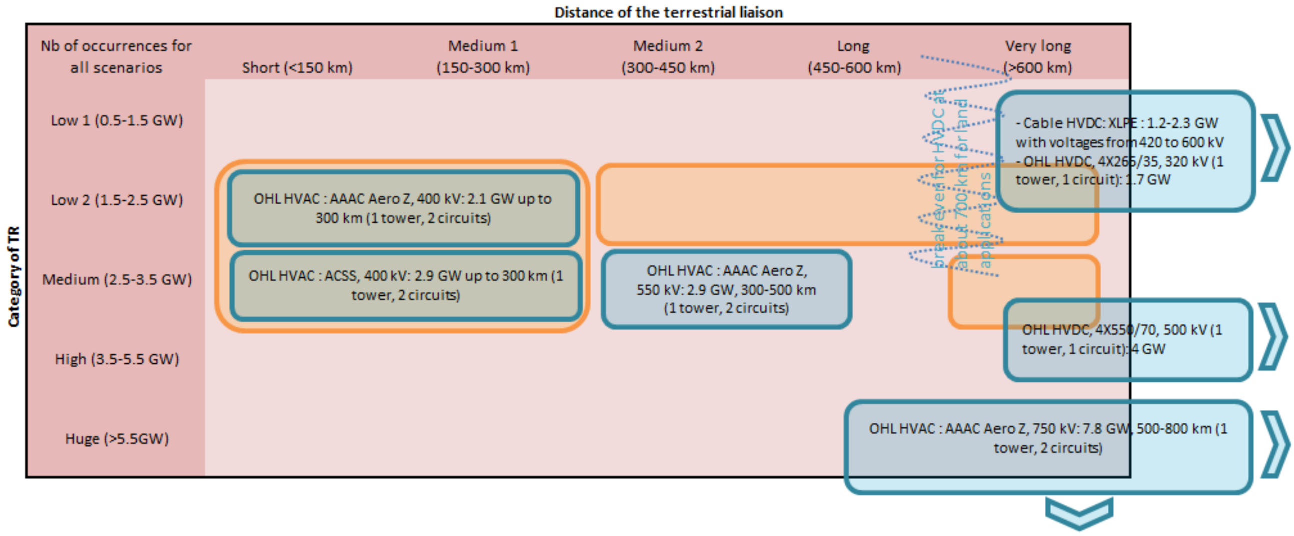


Figure 23: The technological options used in WP2 (in blue colour) compared to the needs (in orange colour) – terrestrial liaisons only

In order to formulate some useful indications for further RD&D needs based on a gap analysis between existing options and the identified reinforcement needs, a larger perspective is required. Rather than positioning particular solutions (e.g. in HVAC a particular conductor, a particular voltage, a particular design), a wider positioning of families of technologies would be sufficient (e.g. conventional conductor vs HTLS; HV vs extra high voltage; HVAC vs HVDC). This is the aim of objective of next section.

2.4 Conclusion on technology needs

It is proposed in this section to compare the identified technology needs with some "available" technological options. The question of "availability" is challenging since it includes technical and not technical considerations. Within the technical considerations, by available technological option it is meant:

- Either an already implemented solution in a transmission system
- Or an under development solution within a short-term time horizon.

As a consequence, technology options of low maturity (such as superconducting cables) are not considered as "available" technological options.

In the following, the granularity of the perspective on the technology standpoint is reduced to the level of the main technology families (and not to specific technologies whose implementation will naturally depend on detailed studies).

<u>For terrestrial solutions:</u>

- Conventional HVAC overhead lines (typically 400 kV, one line) including various options of designs (2 or 4 bundles) and of conductors (HTLS or conventional conductor);
- Alternative HVAC overhead lines: either one line at higher voltage – typically 550 kV or requiring several lines at 400 kV);
- Extra high voltage configurations in AC;
- HVDC solutions (lines, cables and converters).

<u>For submarine solutions:</u>

- HVAC solutions for short distance;
- XLPE and MI cables at various level of voltages in HVDC for longer distances;
- Converters VSC up to 1.5 GW;
- Converters CSC type up to 6 GW.

Figure 24 and Figure 25 depict the various gaps between the not yet covered areas by available technological options and the new lines and reinforcement needs (orange cells) in a two-dimensional space, i.e. power and distance under the following assumptions:

- The orange cells in both figures pinpoint the new lines and reinforcement needs coming out from the grid architectures identified by the project and thus the related RD&D efforts that they would imply.
- The various intensities of blue correspond to the "availability" of technology solutions. The light blue areas cover mature OHL technologies, whereas the dark blue ones stand for solutions under development.
- The purple colour in Figure 24 is dedicated to terrestrial cable solutions (underground). The performances for UGC refer to **unit performances** corresponding to a single circuit[15].
- The available technologies and the ones under development have been mapped with the list of technologies available in the project's database [65].

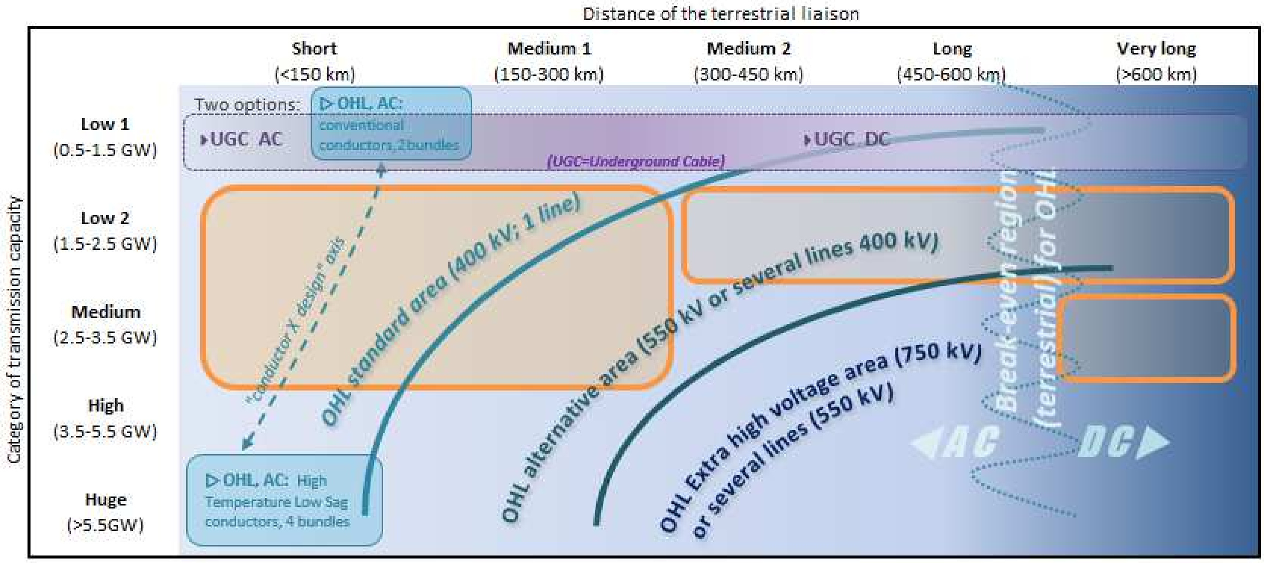


Figure 24: RD&D gap analysis: terrestrial needs (cells in orange colour) compared to available technology options (various grades of blue, from the more conventional to the less conventional)

[15] For example the France-Spain electrical underground interconnection of two 1000 MW links (64.5 km long) is located in the Figure 24 in the purple colour box in the "Low 1" category of transmission (0.5-1.5 GW) and not in the Low 2 (1.5-2.5 GW)

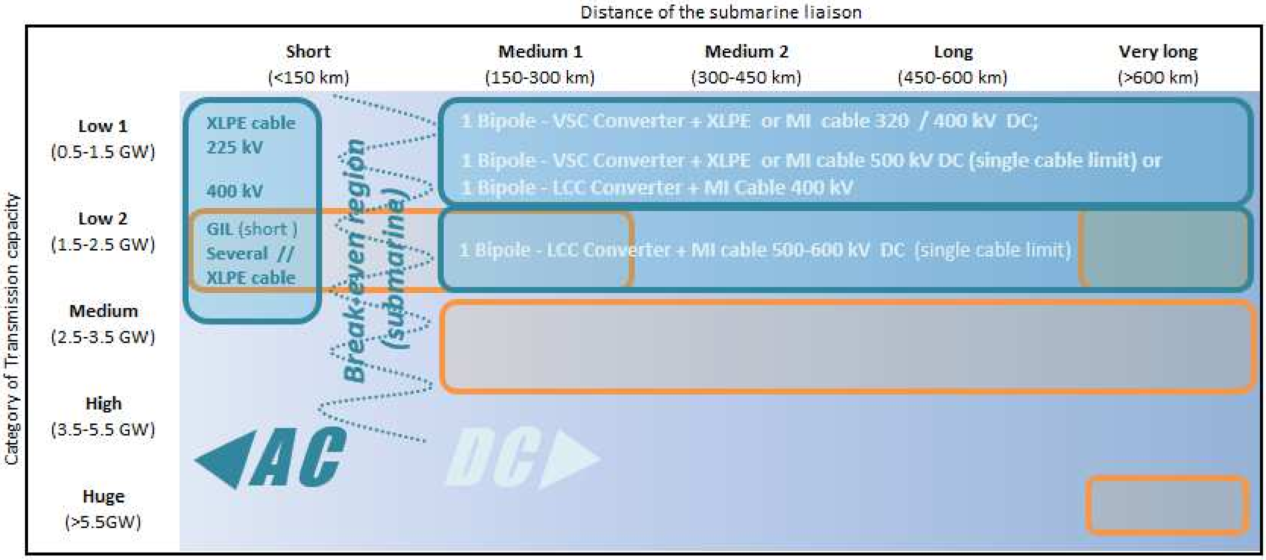


Figure 25: RD&D gap analysis: submarine needs (orange cells) compared to available technology options (blue cells)

From the above figures, the following observations can be formulated.

- <u>For terrestrial applications,</u>
    - if one considers only the HVAC OHL standard area, there is a first gap in the spectrum of transmission capacities for the “Low 2” and medium levels of transmission capacity (respectively 1.5-2.5 and 2.5 to 3.5 GW) for long and very long distance liaisons. The area “Medium 2” distances (300-450 km) though not the most needed (in terms of identified links between clusters) are poorly covered by technological options at the range of 1.5-2.5 GW. This gap is extended to shorter distances (150-300 km) for transmission capacities above 2.5 GW;
    - there is a domain called “OHL standard area” in which the tuning of architecture or the selection of a conductor may be sufficient to fulfil some high power needs: for example High temperature low sag (HTLS) lines with several bundles per conductor;
    - the necessity of an area beyond the “OHL standard area” emerges naturally from the Figure **24**. It is called “OHL alternative area” with higher level of voltages and the possibility to combine several lines
    - If one considers both OHL options that are either in the “standard area” or in the “alternative area” (with higher level of voltage up to 550 kV or the possibility to combine several lines instead of a unique one), most of the orange zones are covered. Only one limited gap in the area of 2.5 to 3.5 GW for long distance liaisons remains uncovered;
    - HVDC solutions for long distance fulfil the needs located in the upper right corner (up to 2.5 GW, above 600 km) but with some limitations on the power of the VSC HVDC converter (about 1.5 GW as of today) while CSC can reach transmission capacities up to around 6 GW (see also dedicated section 4.2.2 for more details).

- <u>For submarine applications,</u> there are some gap in the medium range of transmission capacity (2.5-3.5 GW), and above, for all identified distances
    - HVAC solutions can fulfil only short distance needs (threshold fixed by the break-even of 80-120 km to compensate the extra cost for converters)
    - In HVDC distance (above the indicated threshold) is not critical but one should distinguish various types of technological limitations regarding the transmitted power: on XLPE and MI cables for submarine allowing transmission up to 2.5 GW; on HVDC converters (1.5 GW for the VSC while CSC can reach transmission capacities up to around 6 GW)

- o Increasing the transmission power in submarine applications would then require either the possibility to increase the current or to combine cables in parallel
- o Addressing even higher levels of power would require even more alternative solutions such as gas insulated lines or superconducting solutions (High temperature superconductors at 77K or MgB_2 solutions[16] at 20K).

The above analysis has allowed the identification of the main technology families covering the TR domains. This identification process highlights the needs for further RD&D to better cover the TR domains, with the following observations:

- the possible R&D needs depend on several parameters going beyond the two dimensional (distance, transmitted power) TR domains. For example, voltage levels, the number of circuits and the number of bundles per conductor have to be considered. This complex multi-variable problem has to be solved with the foreseen costs since when implementing or refurbishing an existing OHL or cable link, different options are available: for instance, for a given distance, higher voltage levels extend the range of transmitted power but lead to higher towers (one could also have multi-circuit links at lower voltages with several bundles per circuit and lower towers);
- active transmission equipment combined with an increased observability of the network could be used to improve (marginally) the transmission capacity in a line by operating it closer to the physical limits. Such equipment do not provide any additional capacity but they contribute trough their flexible use to increase the overall transmission capacity of the grid;
- modular building blocks could naturally emerge and fulfil a large domain of TR needs. Indeed, a limited set of modular solutions for terrestrial and submarine liaisons may, when combined[17], meet most of the transmission requirements resulting from e-Highway2050;
- a debate on the relevance of having standardized solutions of technological options of the type "one-size-fits all" (in fact a limited number of sizes would be more exact) is still open. On the one hand, a consensus of European TSOs on a limited number of standardized needs would greatly facilitate the RD&D work of manufacturers. It will also be beneficial for TSOs in terms of costs. On the other hand, some TSOs could claim the need to keep more variety in the selection of reinforcement solutions (at least for short-term grid planning) and to have a full control on the specifications/development/installation process. This position relies upon the "local feature" statement: each liaison is unique due to the multiple local constraints (technical and non-technical). Such debate overcomes the technical issues but the value of the present work is to identify on a technical standpoint a limited set of archetypal solutions.
- An overview of technological options per degree of maturity and identified gap is presented in Table 12.

Table 12: Overview of the technological options per degree of maturity

TR needs X distance	Technological options (high maturity)	Technological options requiring further development	Other less mature technological options	Identified gap
Terrestrial <300 km	- OHL HVAC: 2GW AAAC Aero Z 400 kV - OHL HVAC: 3 GW ACSS 400 kV	GIL for short liaisons, high power	High Temperature Superconductivity or MGB_2 technology (likely to be used for	N

[16] see Bestpaths demonstration 5 Superconductor cables power up for DC grids at http://www.bestpaths-project.eu/en/demonstration/demo-5

[17] In this analysis no consideration of public acceptance or rights-of-way is made. Considerations are made only on the technological standpoint and focus mainly on the availability / maturity of the technology

	- Underground Cables 400 kV 1 GW/circuit		short links in densely populated areas[18])	
Terrestrial 300-500 km	N/A	- OHL HVAC: 3GW AAAC Aero Z 550 kV	N/A	N
Terrestrial 500-700 km	N/A	N/A	HVDC solutions dependant to the reduction of the break-even point (cost of converters)	Y
Terrestrial >700 km	- HVDC XLPE Cables at 320, 450, 500 kV: 1.2 to 1.9 GW - OHL HVDC at 320 kV: 1.7 GW (single), 3.4 GW (double circuit)	- HVDC XLPE at 550 or 600 kV: 2.1 to 2.3 GW - OHL HVDC at 500 kV: 4 GW (single), 8 GW (double circuit)	- OHL HVDC at 800 kV: 11.2 GW (single)	For medium capacities and higher (>2.5 GW)
Submarine <100 km, low to medium capacity	- HVAC XLPE Cable, single core or 3-core	N/A	N/A	N
Submarine >100 km, low to medium capacity	- HVDC XLPE Cable - HVDC MI Cable	N/A	Increase voltage	N
Submarine, medium capacity (2.5-3.W GW), all distances	N/A	Combination of several cables	Increase current in HVDC converters	Y
Submarine, high capacity and above (3.5 GW+)	N/A	GIL for short liaisons, high power	Exploration of alternative solutions (superconducting cables for DC)	Y

In conclusion, for terrestrial applications, in addition to the available technologies for 400 kV OHL[19], the following options are of interest:

- HVAC overhead lines with different designs (number of circuits), various conductor types (high temperature low sag) and more bundles so as to reach higher power over short distances,
- standardized solution for HVAC XLPE underground cables[20], in order to provide partial undergrounding solutions which will complement overhead lines in sensitive areas (public consent),
- HVAC OHL consisting of several lines for very high power and short to medium distances (interest for such solutions strongly relies upon the maximum capacity of one line which is acceptable from the TSO point of view, cf. N-1 security criteria in case of a contingency).

In the longer term, other options might be considered:

[18] See Best paths project: demonstration 5
[19] OHL (overhead lines) with conventional conductors and a reduced number of bundles.
[20] The capacity of HVAC XLPE underground cables is likely to stay in the range of 380 – 420 kV with an increase above 1,8 kA and transmitted power exceeding 1250 MW.

- higher voltage AC lines -typically 550 kV- when addressing longer distances at medium power (where several 400 kV lines could also provide an acceptable solution),
- with high power VSC converters, and more specifically switchgear equipment becoming mature and gaining market experience, meshed HVDC networks could become possible, thus creating local meshed HVDC networks that Europe. HVDC meshed networks could be implemented with OHL technologies but also with HVDC cables over long distances[21].

For submarine transmission network development, there are today available technologies for all distances up to medium power. The challenge is to improve the efficiency of these technologies, both in technical (decrease of losses and failure rates, increase of possible depths) and economic (investment and O&M costs) terms.

For higher power submarine liaisons over all distances, the main challenges are to reach higher voltages and intensities, as well as to increase the installation depths so as to exceed 2500 meters in the coming decades with lighter cables. Like for terrestrial applications, the development of HVDC meshed networks is expected (in the North Sea for instance for the interconnections of offshore windfarms) with multi-terminal HVDC systems at sea[22].

A limited set of modular solutions for terrestrial and submarine liaisons could, when combined[23], meet most of the new line and reinforcement needs identified by the project. In such a case, a balance should be found between the economies of scale and the wide range of possible links at the pan-European scale.

Technologies such as Gas Insulated Lines (GIL) and superconducting cables might be of interest in the long run, probably in densely-populated areas where huge amount of power have to be transmitted underground[24].

For the gap identified on high power to be transmitted over long distances two different paths are open for further RD&D studies both routes deserving to be explored by the stakeholders of the electricity value chain:

- to increase the transfer capacity of conventional cables (such as XLPE);
- to keep on developing solutions with high transfer capacity, such as superconducting cables, and improve their economic efficiency for long distance applications.

[21] HVDC underground cables could be installed over very long distances: it would improve public acceptance but permitting issues for large corridors would remain.
[22] Interoperability of the HVDC systems (VSC converters for instance) will be a key issue.
[23] No consideration of public acceptance or rights-of-way is made. Considerations are made only on the technological standpoint and focus mainly on the availability / maturity of the technology.
[24] These options have not been considered since suited for intra-cluster applications.

3 Overview of requirements for improvements and new standards

Transmission systems of today have already been equipped with intelligent systems, and these will continue to be developed and implemented in time. In this regard, development of new standards is crucial in order to accommodate emerging technologies. This will help to ensure that the transformation is achieved as simply, cost-effective and efficiently as possible.

Given the high voltages and ratings of the future power systems, stringent standards in test levels and test procedures are necessary for verifying for instance transformer performance under various operational conditions. In transformer technologies, innovations are occurring in developing units that perform multiple functions. For example, combining phase shifting and voltage transformation, combining transformers or phase shifters and reactors, combining transformers and the UPFC concept. If the demand for these applications becomes sufficient, the transformer standards will need updates or extensions, especially with regard to testing.

New and revised standards are required to cover the expanding range of applications and requirements, particularly those relating to renewable energy generation, the increasing use of power electronics in the networks, the drive for higher transmission voltages and lower losses. Furthermore, new materials, testing and assessment technology as well as requirements for enhanced safety and environmental capability drive the need for new and revised standards. For example, the increasing demand for reliable low-maintenance transformers alongside the satisfactory asset management information leads to the integration of monitoring and remote control systems into transformer designs. As a consequence, the coordination of monitoring and control interface with the substation systems is also required. In this regard, specific provisions need to be anticipated in updated standards [19].

In the case of HVDC transmission systems, based on the evolution of the technology, new standards need to be established. These standards should reflect the state-of-the-art technical trends in order to fulfil the requirements regarding planning, design, construction, operation and maintenance of HVDC transmission projects. The development of VSC-based HVDC transmission systems is mainly addressing multi-terminal technologies with higher voltage levels and larger capacity. This trend in technology needs the existing standards to be updated, and alternatively, new standards and technical reports which are not covered by the scopes of existing ones to be established. As this technology is still in the process of being developed, it might be challenging to define a common standard. The standard should be perspective enough to enable future interoperability of developments, while being flexible enough to allow for further innovation while it is observed that building standard covering both equipment and systems under development remains challenging to achieve [20]. Based on the new situations, standards for HVDC equipment, including converter transformer, converter valves, wall bushings, smoothing reactors, DC side switchgears and various types of surge arresters should be considered. Furthermore, standard for insulation coordination including altitude correction for HVDC system in high altitude areas is required [21].

Currently, most HVDC connections are point-to point and there is a higher freedom in designing this kind of HVDC schemes. However, for the future concept of HVDC grids, different parts can be provided separately by different suppliers. Given this situation, standards play a greater role in configuration and harmonization of HVDC grids. One important requirement is that all station connected to the grid should be designed for the same DC voltage level [22], [23].

In the case of FACTS devices, they have many common design features with the converters used in HVDC transmission systems. Therefore, the same developments and standardization requirements should be considered for FACTS devices. Furthermore, if the deployment of FACTS devices such as combined technologies becomes considerable in the future, new standards need to be established for their applications.

4 Lines and cables (in AC and DC) and AC transformers

4.1 Overhead lines: classic / high temperature conductors operated in HVAC

4.1.1 Overview

Overhead lines are commonly used for the transmission of large amounts of power. The largest part of the transmission lines (exceeding 220kV) on land are HVAC overhead lines and despite the new expected development to be realized using HVDC technology and /or underground cables, this relative share will be nearly unchanged for the next ten years in Europe.

The main components of an overhead line are towers, conductors, and insulators. These components will be required for whichever voltage level, type of current (AC or DC). But their design will be different depending on their use.

Towers

As OHL insulation is done by air, the global geometry of the line is an important parameter in the technical line design. This means that the selected geometry of a line will impact current capacity calculation, with a strong link with electric losses, electric and magnetic fields generation, and will have some influence on reliability.

Over the last decades of commercial deployment of OHL systems, typical standard tower configurations have been developed, which are optimized in terms of material, transportation, erection, maintenance, costs, lifetime, and appearance. But during the last decade, as reaching public acceptance is more difficult, alternative designs of towers are coming up which in turn impact the reference costs known for standards overhead lines.

Innovative towers: the development of new designs of towers is progressively encouraged by some TSOs in order to reduce the environmental footprint of overhead lines (e.g. in terms of visual impact and electromagnetic field level). Some common RD&D (Research, Development and Demonstration) challenges could be mutualized by TSOs at EU level, such as the eco-design of towers. Demonstration of new interfaces between lines and towers are needed. The cost differential is expected to be partially compensated, *inter alia*, by the advantages in terms of maintenance, since such structures are less prone to structural damages [1].

The main technical improvements in overhead lines during the last decade lies in the development of different technologies to reduce the sag caused by temperature elevation (and induced conductor extension). The main benefit of operating low sag conductors is that higher temperatures can be reached which allows the transmission of higher power flows.[25]

Conductors:

The type of conductor used is the main variable that can affect HVAC OHL performance characteristics in the future. Indeed, one could consider that all the other parameters like voltage level, number of circuits or type of bundle have already been optimized in the European context.

[25] To avoid repetition, a description of High Temperature Conductors has been included in next section on OHL HVDC (see section 4.2.1).

High Temperature Low Sag Conductors (HTLS) are able to withstand higher operating temperatures, thus carrying higher amount of power than conventional conductors. They can enhance transmission capacity without impacting the negotiated right-of-way and, in general, without modifications of transmission towers. They are increasingly adopted by European TSOs. HTLS comprises a wide spectrum of very different technologies in terms of potential for transmission capacity and investment costs (see Table 13). This explains the diverging viewpoints observed between equipment manufacturers and TSOs: the appropriate selection of a conductor will follow an in-depth analysis of the power system including operational and climatic conditions, fatigue and safety issues as well as the overall investment costs. Gains in transfer capacity can reach 30% for the most used HT Conductors, while transfer capacity could be more than doubled with composite type conductors. HTC costs are generally higher (in some cases much higher) than conventional ACSR (Aluminum Conductor, Steel Reinforced) conductors. Investment cost figures need to be tuned by considering electrical losses, potential structure reinforcement, installation and maintenance costs. The assessment of performances over the whole life-time through a better understanding of refurbished lines (models, endurance testing and level of electrical losses) is essential to further extend HTC uses [1].

In the longer term, other technologies based on metal composite (MMC) or organic composite (PMC) could develop. In particular PMC is expected to become a mature technology but, as far as it can be foreseen, it will probably have equivalent performances compared with the current ACCR conductors. Reduction of costs are likely to occur.

Nanotechnology could also provide breakthrough conductor performances (ampacity, weight, mechanical behaviour, etc.) but predictions remain difficult at that low level of technology maturity.

For preselecting the type of conductor in e-Highway2050, a three-step approach was adopted, discarding not relevant technologies and focusing on the most promising ones based on their performance and maturity (see next box).

As a result, the e-Highway2050 technology portfolio for HVAC OHL includes three HVAC overhead line reference cases, two with two types of conductors (AAAC Aero-Z and ACSS) at 400 kV, the third one being AAAC Aero-Z at 750 kV, all of them in double circuit applications.

The advantages and disadvantages of the two technologies are clearly stated in Table 13.

Rationale for selecting the type of conductor for an HVAC OHL for the European transmission grid:

a) Discarding a number of technologies too old or not relevant for the scope of the project:

- Copper: even if its electrical properties are very good, they do not compensate the counterpart of its weight and its cost.
- Pure Aluminum conductors (AAC): their mechanical performances are not adapted to 400 kV.
- A(A)CSR - Aluminum (Alloy) Conductor Steel Reinforced: there are few installations in Europe on 400kV lines. They have been used on specific occasions (only when high mechanical strength is needed, for instance in mountain areas). Compared to ACSS, it provides no better performances.

b) Technologies of interest for e-Highway2050

- **A Standard conductor - AAAC** (All Aluminum Alloy Conductor) which appears to be a good compromise between technical and economic aspects; it is a well-known technology (over 50 years of field experience). The Aero-Z AAAC, described in deliverable D3.1 [65], is considered as the best technical optimization technique with AL4 Aluminum Alloy.
- **A High Temperature Low Sag (HTLS) conductor - ACSS** (Aluminum Conductor Steel Supported): the high operation temperature (more than 200 °C) requires the use of Annealed Aluminum; this conductor presents a very good mechanical strength but is heavy compared to AAAC. The installation needs a pre-stressing operation, and a careful handling of the conductor (about ten years of field experience).

c) Other technologies not retained in e-Highway2050

- **ACCR** (Aluminum Conductor Composite Reinforced) – HTLS: Metallic Matrix Composite Core + Aluminum Zirconium (Thermal Aluminum AT3) – Similar performance compare to ACSS; the weight is lower but the cost is very high (field experience does not exceed 5 years).
- **PMC** (Polymer Matrix Composite) conductors – HTLS: it has a good mechanical strength despite its low weight, but the electrical performances are far lower than those of ACSS or ACCR (such technology is not mature as of today).
- **(G)TACSR** (Thermal Aluminum Conductor Steel Reinforced): better than ACSR regarding current capacity because of high temperature but high sag is observed when operating at high temperature. The Gap Type version allows better sag performance but it has not been chosen due to complex interactions with line implementation.
- **TACIR** (Thermal Aluminum Clad Invar Reinforced) - Invar (steel + Nickel Alloy) + Aluminum Zirconium: equivalent capacity as ACSS conductors, but this option presents lower mechanical performances with higher costs.

Table 13: Advantages and limitations of the selected technologies for HVAC OHL

	Advantages and limitations	
HVAC OHL technology	**Advantages**	**Limitations**
AAAC (Aero-Z)	- Cost - Lifetime	- Power flow Performance
ACSS	- Power flow Performance - Conductor Cost	- Weight ; particular pre-stressing operation

A common opinion view is that the AAAC conductor will be used in the next 15 years for the newest High Voltage Overhead Lines. As for the ACSS, in the same period, it will be most used for reconductoring existing installations for increased transport capacity and minimum investments. After this period of 15 years, it is thought that the trend might slowly switch.

The success of the HTLS conductor implementation will also be dependent on the degree of penetration of the HVDC technology for applications including high power flow corridors within and between European countries.

Other parameters:

Optimization of the other parameters (except conductors) for an HVAC OHL for the European transmission grid:

- **Type of bundle:** the number of conductors per phase will greatly impact the performance of the line. The higher the number of conductors, the higher the transmitted power, but mechanical constraints are increased on the towers which induces additional costs. For the present study, a four-conductor bundle for each phase appears to be a good compromise.
- **Number of circuits:** the performance of the line is also affected by the number of circuits installed per tower. The optimum commonly used is two circuits per tower. Increasing the number of circuits per tower could have a good effect on land use because it increases the transmission line capacity. However, a safe grid operation requires that a single failure (N-1) has to be of limited and controllable effect. More than 2 circuits on a single tower would lead to great risks of high electrical constraints in case of failure. Moreover, the shape of the tower would be very massive with such a visual impact that public acceptance specifications would not be met any longer.
- **Voltage level:** an increase of the voltage level seems to be hardly acceptable by the public: increasing the voltage level results in higher towers, higher level of electric fields, possibly specific insulators design and more noise disturbance issues. Though, it could be useful to examine the increased performances than can be reached with a higher voltage level (especially on losses), for long transmission corridors (over 500 km) and huge power flows (several GW), and to compare them with the standard solutions.

4.1.2 Outlook 2050

When considering the above selection for e-Highway2050 among the wide spectrum of conductor options for HVAC overhead lines, more information is provided hereafter for the long-term perspective of some less conventional ones such as organic composite core or metal composite.

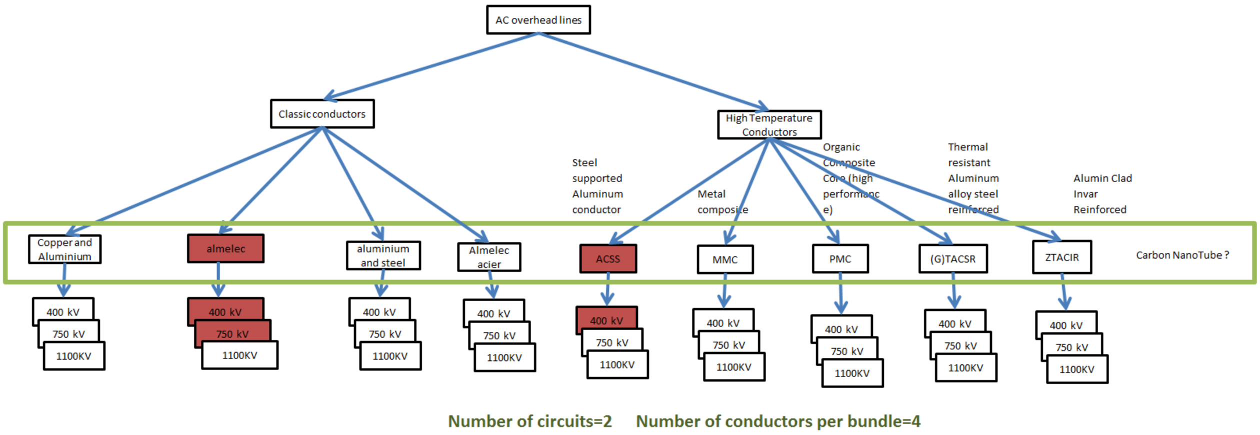


Figure 26: The e-Highway2050 selection among all conductor options for HVAC OHL

In the longer term, some low maturity technologies could enter the list of options:

- PMC is expected to become a mature technology but, as far as it can be foreseen, it will probably have equivalent performances compared with the current ACCR conductors. Reduction of costs are likely to occur. It could be observed that the field of experience of such technology is really narrow and the proof of its maturity (especially repairing, testing and ageing issues) remains to be done;
- Nanotechnology-based technologies could also emerge providing a great increase in conductor performances (ampacity, weight, mechanical behaviour, etc.). This field is under early investigation, and it is risky to formulate reasonable projections for the time horizon of the commercial exploitation stage.

4.1.3 RD&D agenda at the 2030+ time horizon

The next three figures detail the RD&D agenda for three families of technologies: towers, high temperature conductors and conventional conductors for HVAC.

Innovative Towers			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	***Eco-design of Towers*** ❑ Exploration of new tools to improve the design of towers in order to increase transmission capacity on a given "right-of-way" based on composite materials ❑ Corrosion ❑ Eco-friendly paintings ❑ Durability of components ❑ Modelling of towers resistance against storms ❑ New assembling/installation techniques, and new operating and maintenance procedures ❑ Anti Vandalism / anti terrorism solutions for HV towers	❑ Tower upgrading using composite material solutions are made available	N/C
Integration tests as seen by TSOs	❑ Demonstrations about technical interface problems between lines and towers ***Validation of composite materials solutions to :*** ❑ Reducing maintenance costs with the new technologies deployed ❑ Ageing ❑ Simulation and impact analysis of 400 kV (eg EMF) ❑ Tests and indutrialisation of composite materials	❑ N/C	N/C
Full scale use within the EU27 interconnected transmission system	❑ Common TSOs RD&D laboratory on modellisation issues ❑ More environment friendly designs deployed in several Member States	❑ Deployment of innovative towers allowing increased transmission capacity in Europe	N/C

Figure 27: RD&D agenda for innovative towers (adapted from [1])

HTC (High Temperature conductors)			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	*Research on Materials* ❑ Exploration of new materials, alloys and composites (Aluminium, Copper, polymers, Carbon, magnets, …) for conductors *System/Components Performance* ❑ Development of advanced conductor designs for high-current carrying capacity, reduced weight and line sags ❑ Estimation of corona effect and develoment of optimal design to reduce it (if needed) ❑ Estimation of variability of resistance as a function of temperature and development of designs to reduce it (if needed) ❑ Development of components (conductors, insulators, …) with higher durability and increased corrosion resistance ❑ Reduced manufacturing and installation costs ❑ For underground HTC applications, reduction of the number of cables junctions ❑ Development of lower cost re-conductoring techniques for existing OHL and underground cables ❑ Improved manufacturability of components meeting industry standards *Models and simulations* ❑ Development of tools to evaluate the long-term performance of different HTC conductors and ensure reliability of transmission lines with proper maintenance procedures	❑ Exploration of new materials (nanomaterials) for conductors ❑ Development of organic composite conductors with higher transit capacity (more than 100%) at lower cost	❑ Development of nanomaterials for conductors
Integration tests as seen by TSOs	*Models and simulations* ❑ Advanced HTC field tested and demonstrated ("corona effect" of HTC ; impact on numerical TV; effects on birds; reliability) ❑ Ability to validate cables/lines performance with HTC (at the end of the cable) ❑ Development of TSO tools for wide assessment of transmission lines/cables candidates for reconductoring ❑ Inspection techniques for maintenance and ageing analysis (aerial inspections) ❑ Definition of protocols for efficient replacement based on in-depth understanding of ageing coupling environment and loading conditions	❑ New reconductoring techniques demonstrated by several TSOs in Europe ❑ Expansion of the application field: from urban areas and wind farm connection to long-distance applications	❑ Nanomaterials type conductors field tested by TSO
Full scale use within the EU27 interconnected transmission system	❑ Implementation of high performances cables/lines in inter-TSO congested corridors (e.g. France-Italy interconnection)	❑ Reconductoring assessment tools (ageing, performances) are operational ❑ New inspection techniques made available ❑ Deployment in environmentally constrained or congested areas	N/C

Figure 28: RD&D agenda for High Temperature Conductors (adapted from [1])

HVAC conductors (conventional)			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	***Research on Materials*** ❑ Exploration of new materials for conductors ***System/Components Performance*** ❑ Estimation of corona effect and develoment of optimal design to reduce it (if needed) ❑ Development of components (conductors, insulators, …) with higher durability and increased corrosion resistance ❑ Reduced manufacturing and installation costs ❑ Lower cost monitoring systems ❑ Improved manufacturability of components meeting industry standards	❑ N/C	N/C
Integration tests as seen by TSOs	*Models and simulations* ❑ Ability to validate new cables/lines performance ❑ Development of TSO tools for wide assessment of transmission lines/cables candidates for reconductoring	N/C	N/C
Full scale use within the EU27 interconnected transmission system	N/C	N/C	N/C

Figure 29: RD&D agenda for conventional conductors for HVAC (adapted from [1])

4.1.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):
  - Standardization on monitoring systems for OHL;
  - Standardization of security systems for OHL.
- Mid-term standardization needs (2022-2030):
  - Standardization of the new technology for HTLS conductors;
  - Standardization of the new innovative towers for OHL.

4.2 Overhead lines operated in HVDC

4.2.1 Overview

DC overhead lines are commonly used for the transmission of large amounts of power over long distances. Today, the state-of-the-art DC transmission lines reach voltage levels up to 800 kV over a distance of more than 2000 km (ABB Ltd., 2014).

As already mentioned in the HVAC OHL section above, the main components of such systems (towers, conductors, and insulators) are designed for the required voltage level, transmission capacity and type of current (here DC). This means that the selected geometry of the line and conductor will impact the maximum voltage level (in relation to the EMF properties), the current capacity and the electric losses. For DC OHL technologies, the insulation of the conductor is performed by air.

Over the last decades of OHL deployment, typical lattice tower configurations have been developed, which are optimized in terms of material, transportation, erection, maintenance, costs, lifetime and appearance. But during the last decade, as the public acceptance has deteriorated, alternative design of towers has been coming up, changing the costs known for standard overhead lines.

In addition, technologies to reduce the sag caused by temperature elevation (and induced conductor extension) on existing lines include the development of new conductors with a higher fill factor[26].

The main variable that can affect HVDC OHL performance characteristics is the voltage level. The voltage level defines the diameter of conductor, the type of bundle and the tower design. **In contrast to the classical AC systems, the voltage level is defined by the converter.** Furthermore, unlike the classical model AC system there is **no direct limitation to the length of the transmission corridor**. Thus, the maximum length of a HVDC OHL is given by economic constraints.

With regard to conductors, the standard conductor ACSR (Aluminum-conductor steel-reinforced) is a good compromise between technical and economic aspects. It is a well-known technology (over 80 years of field experience). The number of conductors per phase greatly impacts the performance of the line. Capacity (and efficiency) directly depends on the number of conductors which has to be adapted to the applied voltage. The number of circuits installed per tower impacts also the performance of the line. Typically 1-2 circuits are foreseen per tower. Increasing the number of circuits per tower is favorable on land use but increases the risk for a safe grid operation (n-1 rule) and has also a negative visual impact (public acceptance of massive towers).

In the long term it is expected that AAAC (All Aluminum Alloy Conductors) will become a mature technology. It will probably have better performances compared with the current ACSR technology. The resistance should be lower and therefore the efficiency should increase. However, the selection of a conductor depends on the aggregated diameter. The higher the aggregated diameter the lower is the electric field gradient (linked with corona effect).

In the future, the emergence of nanotechnologies might offer a great improvement in conductor performances (ampacity, weight, mechanical behavior, etc.) but maturity is still low, making any projection difficult for the development into an industrial product.

The following configurations have been retained in the e-Highway2050 studies for overhead lines in HVDC:

- Two configurations in single circuits: 4X265/35 320 kV – 1 tower – 1 circuit ; 4X550/70[27] 500 kV – 1 tower – 1 circuit;

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[26] The description of High Temperature Conductors of section 4.1.1 is not repeated here but is fully valid also for OHL operated in HVDC.

[27] The identification code is as follow: the number "550" correlates to the area of the conductor and the number "70" corresponds to the area of the steel soul. The number "4" indicates the number of conductors for one bundle.

- Two configurations in double circuits: 4X265/35 320 kV – 1 tower – 2 circuits; 4X550/70 500 kV – 1 tower – 2 circuits.

4.2.2 Outlook 2050 and RD&D agenda[28]

Operations in DC allow to overcome the limitations in maximum transmissible power inherent to AC liaisons, which in turn extends the domain of transmission capacity. The new limits are therefore mainly conditioned by the performances of converters, typically 1.5 GW for VSC and much more in LCC can be reached:

- Ranges of operations for LCC in Europe: 3 to 5 GW for overhead lines in DC in 500 kV[29];
- Outside Europe (and beyond the scope of analysis of the e-Highway2050 project):
    - current performances could reach voltage levels up to 800 kV for transmission capacities ranging from 5 to 8 GW, and for distances from 1000 to 1500 km, provided that an economic optimization is made[30];
    - for longer liaisons (3000 km) and for higher transmission capacities (10 GW), ultrahigh voltage at 1100 kV would be needed.

The deployment of HVDC overhead lines could however face some limitation factors with regard to the voltage drop and the computation of losses: these topics are clearly mentioned in the RD&D agenda for the coming decade.

Apart from the technological and economic improvements of overhead lines operated in DC, a recurrent issue, which emerged recently mainly through TSOs and academics in Germany, is the better use of existing OHL through the conversion of existing AC circuits into bipolar DC circuits with metallic return. Recent articles have been published on studies dealing with the coupling between adjacent AC and DC circuits [67]. Design and layout of AC-DC hybrid lines is discussed in particular by C. Neumann et al. [68]. The authors discuss theoretical and experimental investigations of a conversion of 420 kV AC transmission circuits on existing HV lines into 400 or 500 kV DC circuits.

4.3 Extruded insulation HVAC Cables (underground and submarine)

4.3.1 Overview

Underground and submarine XLPE cables are fully available for extra high voltage power transmission. Such cables for HVDC and HVAC applications are more and more used, including partially undergrounded solutions complementing overhead lines. For HVAC XLPE cables, however, notwithstanding the recent technological progress, the further deployment and consequent cost reduction, the cost barrier (when compared with conventional solutions) is still high and expected to remain so due to the intrinsic higher complexity and installation constraints of this technology. Yet, the cost barrier might be reduced when all types of benefits stemming from this technology are considered, such as lower losses during the whole life-time, authorization procedures duration, visual impacts, etc. [1]. In addition improvements of technical performances for submarine cables is still expected in higher power and in the installation depths which can reach 2500 meters in the coming decades with lighter cables.

This category includes the following HVAC XLPE cable operated at 420 kV.

[28] See section 5.2 for more detailed information. A short summary is provided here.
[29] Manufacturers: ABB, Siemens, Alstom Grid
[30] Manufacturer: ABB

4.3.2 Outlook 2050

Looking at the decades ahead, the upgrade and expansion of Europe´s meshed high voltage AC networks will be a core necessity. At the same time, already today, the lack of public acceptance is often referred to as the key factor for delay in project implementation.

In the light of this background, Europacable strongly believes that the concept of partial undergrounding of high voltage AC power lines will be one of the most preeminent evolutions of Europe´s AC networks up-to 2050. Just as distribution networks across Europe are increasingly installed underground, parts of the EHV network (380 kV / 400 kV) will be put underground more frequently, thereby facilitating public acceptance and as a consequence more rapid planning consent. This overall evolution will be enabled by the maturity of EHV XLPE AC underground cables and accessories.

Given that EHV XLPE AC underground cables at 420 kV were introduced to the European market in the mid-1980s, Europacable expects that, looking to the 2050 horizon, the focus of the technical evolution will be orientated towards further increases in reliability and the rationalization of future applications, including:

- The capacity of EHV XLPE underground cables is likely to stay in a similar voltage range of 380 – 420 kV;
- The current rating for a typical partial undergrounding solution (400 kV, 2500 mm^2 copper) is expected to increase above 1,8 kA;
- The maximum power of such a system as described above is expected to exceed 1250 MW.

The key challenges for underground and submarine (HVAC and HVDC) XLPE technologies for the current and future decades include:

- Further development of insulation materials, innovative cable materials and novel cable architectures for improved performances;
- Advanced/automated installation techniques for cost reductions (including design of accessories);
- Multifunctional cables with communication capabilities;
- Development and validation of environment and ageing models;
- Improved commissioning thanks to fast qualification methods based on field applications;
- Automated remote sensing system for O&M for optimal use of capacity.

<u>Technical outlook 2050 (submarine cables)</u>

For extruded XLPE AC subsea cables, Europacable expects a similar technical evolution looking at the 2050 horizon as for XLPE AC underground cables. In addition, Europacable expects the possible depth for submarine HVAC installations to increase from 200 metres today to depths over 2,500 metres in the coming decades.

It should be noted that, in order to reach deeper water depths, a strong R&D activity shall be carried-out to improve the cable design and materials selection that will be necessary to make the cable lighter. Suitable laying facilities and vessels will also be needed to install the cable.

4.3.3 RD&D agenda at the 2030+ time horizon

Underground and submarine XLPE cables			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	*Performance and domain of applications* ❑ Development of higher voltage HVDC extruded insulation cables ❑ Development of AC and DC cables for deep water applications in excess of 2000m and for the transmission of high power in excess of 1000 MW *Diagnostics and testing* ❑ Development of equipment embedded sensors for real time monitoring of loading and operation closer to the limit (underground/submarine applications) ❑ Thermal monitoring systems and partial discharges measurement systems for operation and diagnostic tasks ❑ Monitoring of "digger effect" based on vibration sensors *Installation* ❑ Advanced installation techniques for installation costs reduction (incl. design of accessories) ❑ Optimization of the AC and DC land cable route for the simplification of the right of way procedures *Materials* ❑ Development of new insulation materials for extruded HVDC cables *Cable architecture* ❑ Reduction of thickness of cable section in order to reduce the numbers of cables junctions (including development of related tooling) ❑ Multifunctional cables with communication capabilities ❑ Increase of reliability and cable length ❑ Design of XLPE for retrofitting of uderground oil-filled cables (ongoing demonstrations) *Environment & ageing* ❑ Investigate low cost measures to reduce EMF levels in new underground designs ❑ Reduce the impact on biodiversity due to thermal elevation in soil	❑ Automated remote sensing systems for operation and maintenance for optimal use of capacity ❑ Automated underground XLPE cables installation ❑ ❑	N/C ❑ Carbon nano tubes protypes field-tested in transmission systems
Integration tests as seen by TSOs	❑ Validate improved performance of XLPE HV cables (monitoring of experiences world wide) ❑ Demonstrate the use of XLPE for HVDC power transmission (incl ageing/environmental testing) ❑ Demonstrate the performance of XLPE at higher voltage levels (from 225 kV to 400 kV) ❑ Enhanced confidence in XLPE cable material for use in critical area of the system (commissioning and post installation testing ; risk assessment analysis) ❑ Improved commissioning thanks to fast qualification methods based on field applications	❑ Integration of dynamic limits into system operation procedures and tools	N/C
Full scale use within the EU27 interconnected	❑ Cables (combined with other technical options) contribute to the expansion of the European network	❑ XLPE installation costs are reduced	N/C

Figure 30: RD&D agenda for all extruded insulation cables (underground & submarine) in HVAC and HVDC (adapted from [1])

4.3.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):

    - HVAC transmission cable systems up to the voltage of 550 kV are covered by the IEC international standards and are considered to be state of art and a viable solution for the realization of large power transmission systems.
    - Large underground projects have been realized and are in progress around the world without relevant technical difficulties. Today the adoption of underground cable systems at voltages up to 500 kV is driven mainly by cost and political decisions rather than technical limitations.
    - Submarine cable system is today the only solution for the realization of connections across the sea. Due to the inability to compensate the reactive power these connections have some limitation in length that depends on the voltage and power. (i.e. lengths of more than 150 km at 150 kV with power of 200 MVA to lengths of the order of 60 km at 420 kV and power of 1000 MVA. For longer lengths and higher power ratings, HVDC transmission is recommended.

- Mid-term standardization needs (2022-2030):

In the mid-term period, a larger use of underground and submarine AC extruded cables is expected. Based on the installation and operating experience gained in the past decades, some additional improvements and benefits will be achieved, such as:

- Due to the anticipated increase in project applications, a cost reduction can be expected
- Installation methodologies will be improved and optimized
- On the base of experience gained from operational projects an even higher reliability of the cable systems will be expected
- Cable accessories will be improved in terms of performances and rapidity of installation
- Application of real time thermal rating (RTTR) systems will make the cable systems more flexible
- Further application of the monitoring systems.

4.4 Extruded insulation HVDC Cables (underground and submarine)

4.4.1 Overview

See 4.3.1 which is still valid also for XLPE cables operated in HVDC.

This category includes the extruded insulation HVDC cable operated at various voltages: 320 kV, 450 kV, 500 kV, 550 kV, 600 kV. The extruded insulation of the HVDC cables is constituted by polymeric materials, today the most common insulation is based on XLPE compounds but other innovative materials are under development and may be used for the insulation of the HVDC cables of the future.

4.4.2 Outlook 2050

Looking at the coming decades up to 2050, Europacable expects the following evolution of extruded insulation HVDC subsea and underground cables:

- Increase in voltages up to 600 kV[31];
- Increase in conductor size from 2500 to 3000 mm^2, which is expected to result in capacity exceeding 2 GW per bipole;
- Due to the increased voltage, the typical losses per circuit (2500 mm^2 conductor rated at 1 GW per bipole) are expected to drop from 42 W/m (today) to 14 (by 2050);
- For subsea cables, the laying depth should reach more than 2.5 km at 2050.

For further information, including on the timing of these expected developments, please see the datasheet of HVDC XLPE underground and submarine cables submitted by Europacable to the e-Highway2050 project.

4.4.3 RD&D agenda at the 2030+ time horizon

See

Figure **30** the statements relative to XLPE cables in HVDC (underground and submarine)

4.4.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):

[31] The 525 kV HVDC extruded cable insulation system is currently developed by one manufacturer and it is expected that in less than 5 years some other manufacturers will develop the technology and this voltage level will be commercially available.

- There has been a rapid development of extruded HVDC cable systems following the exponential demand both for land and submarine cable applications in recent years. Today, extruded DC cables at 320 kV with VSC converters may be considered state of art and more than one cable system at this voltage level has been put in service during 2015. Several projects at this voltage are also in progress and will enter into service soon. In order to understand the progress of this technology, it should be noted that one manufacture qualified a cable system at 400 kV LCC and another manufacturer obtained the qualification of the cable system at 500 kV VSC. Although no cable systems are yet operational at these voltages, it is expected that in a period of 5 years some other cable manufacturers will obtain the qualification for these HVDC voltages and that some projects will be realized.
- Today the typical power that can be transmitted at 320 kV VSC is around 1000 MW per bipole, by increasing the voltage up to 500 kV and the conductor size, the transmittable power will be of the order of 2000 MVA per bipole.

- Mid-term standardization needs (2022-2030):

Due to the advantages represented by HVDC transmission and the expected large demand for future applications, major R&D efforts by the manufacturers in this field are under way. The major developments and targets that will be reasonably reached in the mid-term can be summarized as follows:

- The voltage and the transmittable power will be increased and it is expected that voltages of 600 kV will be reached;
- Conductor sizes will also be increased and transmittable power of 2500 MW per bipole could be reached;
- New extruded insulation materials for HVDC cable different from XLPE will be developed that may have an influence on the cable system global costs.

4.5 MI HVDC Cables (underground and submarine)

This category includes the HVDC Mass Impregnated (MI) Cable operated at 600 kV.

4.5.1 Outlook 2050

Looking at the 2050 horizon, Europacable expects the following evolution for Mass Impregnated HVDC subsea cables:

- Increasing capacity up to 2200 MW of the voltage level from 500 to 600 kV;
- As a result of this increase, it will be possible to transmit a power of 1000 MW with a reduction in the range of 30% of losses per bipole;
- An increase in power from 1560 to 2340 MW per bipole;
- An increase in water depth for submarine installations from around 1000 m to over 2500 m by 2050;
- Increase of world market volumes reaching about 2500 km of total MI HVDC underground cables by 2050 and about 4500 km of total MI HVDC subsea cables installed by 2050.

Further information, including on the timing of these expected developments is included in the datasheet of MI cables submitted by Europacable to the e-Highway2050 project[32].

4.5.2 RD&D agenda at the 2030+ time horizon and related standardization needs

At a short-term time horizon (2015-2022):

- MI HVDC cable systems have been used for more than 50 years and have to be considered a very consolidated technology for the HVDC transmission up to voltages of 500 kV and power of

[32] Attached to e-Highway2050 deliverable D3.1 [65]

1700 MW. Many thousands of kilometres of cables are in service at this voltage level both for submarine and land applications. The maximum transmissible power of this technology is currently around 1700 MW per bipole at 500 kV. One project is in progress at the moment at the voltage of 600 kV and for the transmissible power of 2200 MW per bipole. This cable is insulated with a special laminated paper and PPL foil sandwich that is then impregnated with a similar compound as for MI cables but has better performances in terms of temperature and electric stress.

- At a mid-term time horizon (2022-2030):

  - It could be considered that MI cables have reached a peak of development and that additional future improvements will be extremely difficult.
  - Due to the adoption of special impregnated laminated PPL paper, it may be possible that voltages in excess of 600 kV will be reached.
  - In terms of standards, the MI cables do not need any additional action since standardized by the previous service experience.

4.6 Other types of cables or of design

4.6.1 Overview

This category includes technologies such as High Temperature Superconducting Conductors, Gas Insulated Lines.

- *Gas Insulated Line (GIL)* is a proven, yet not widespread, technology mostly used in short length installations (exploiting tunnels, bridges, or other existing infrastructures). It allows carrying a much higher amount of power through a single line than conventional solutions and XLPE cables. Yet, it faces strong environmental concerns in terms of SF_6 emissions, which are much more harmful than CO_2 emissions, with a cost ratio over conventional solutions that remains high. However recent progress on substitution gas opens promising perspectives for the GIL technology GIL, deployment is likely to continue within niche applications valorizing existing non-electrical infrastructures: much will also depend on the successful implementation of GILs in planned projects at European level (Brenner tunnel) [1].
- Among the studied technologies, *High Temperature Superconducting (HTS) cables* are the ones which are the farthest away from commercial applications. Some optimistic experts consider first applications of HTS by 2020 thanks to a second generation of materials (Yttrium Barium Copper Oxide, YBCO) and advanced deposition techniques, starting at distribution system level. Recent EC funded projects focus precisely on demonstration of super conductor cables power for DC grids. However, the majority of manufacturers are much more prudent with regards to their use in transmission systems and do not consider any significant application at least before 2030. Costs and size of the cryogenic refrigeration units will remain a major obstacle. Field tests experimentations within very specific situations (short distance, dense urban area, DC applications) will contribute to the further development of the HTS technology models [1].

In addition, one could also consider particular designs or architectures combining several transmission systems such as partial undergrounding or hybrid HVAC-HVDC solutions.

4.6.2 Outlook 2050

Technologies such as Gas Insulated Lines (GIL) and superconducting cables might be of interest in the long run, probably in densely-populated areas where huge amount of power have to be transmitted underground. They appear as suitable solutions for the identified needs on “High power transmission over longer distances”. This challenge at a future time horizon will however require further RD&D studies for improving their economic efficiency for long distance applications.

Technical outlook 2050 for GIL

Europacable does not consider Gas Insulated Lines (GIL) to be a relevant technology for future electricity highways involving transmission over long distances. The following considerations need to be accounted for:

- While GIL transmission technology can transmit very high AC power over long distances, the impact of such high power in one individual line may require a careful evaluation on the safety of supply and the (n-1) consequences on the network in case of failure. Also, there may be some concern for the application or insertion of GIL in existing transmission grids in order not to imbalance load flows and possibly increase fault current due to the low impedance of the GIL;
- GIL insulation medium is composed by a gas mixture that contains a significant volume of SF_6. GIL applications may be subject to any EU restrictions relative to SF_6 gases.

However, a recent innovation communicated by 3M on the development of a new generation of gas substitute to SF_6 opens new perspectives for GIL (this technology is currently used to replace the SF_6 in substations) at that time horizon.

The main R&D challenges facing GIL focus on safety and environmental impacts and include the following topics:

- Use of the new generation of gas substitute to SF_6 for GIL applications
- Reduced corrosion for long distance underground applications;
- Enhanced safety of installations;
- Reduced material costs by optimization of design and materials for a given rating which will lead to a reduction in the number of components.

Technical outlook 2050 for HTS

HTS cable technology has recently seen some major technical breakthroughs allowing its implementation in the grid. In particular, HTS cable system accessories, such as joints, are now available up to 138 kV. Technical solutions to repair the cryogenic envelope on site have been validated. In parallel, with the advent of long length HTS cable manufacturing, these technical progresses allow multi-kilometre HTS cable links. However, the technical feasibility and viability have yet to be proven for HTS cable systems. Multi-kilometre installations are expected in the next few years. However, industrial viability, especially for the cooling system, should be studied further, as superconducting cable systems are more complex than conventional cable systems.

Operating experience will be crucial to switch from technical matureness to industrial implementation. The experience of existing and upcoming superconducting cable systems in the next years will establish reliability track record, releasing restrictions to commercial implementation and overcoming concerns regarding possible unbalanced load flows in existing meshed transmission grids.

The following major evolutions are expected in the coming decades, in the materials and the learning process of the manufacturing industry:

- Development of new superconducting materials working at higher temperatures;
- Development of electric insulation materials for High Voltage superconducting applications;
- Increase of HTS material performance: in the past five years, HTS tapes capability has been already increased by 30 to 50% of average current density (2nd generation YBCO[33] and advanced deposition techniques);
- Cost decrease due to volume increase and manufacturing processes improvement;

[33] YBCO : Yttrium Barium Copper Oxide

- Cooling system: decrease of cost and of moving parts combined with efficiency increase;
- Validation of models on low temperature phenomena and components ageing based on assessment of performances and losses in operation;
- Demonstration of combined use of HTS with storage and with Fault Current Limiters (to mitigate post-fault cable recovery).

The main achievements expected in terms of power capability by 2050 are:
- Increase of power capability in medium voltage systems up to 500 MVA;
- Increase of power capability for AC transmission higher than 4000 MVA (500 kV class or higher);
- Integration of HVDC HTS cable system into the grid and increase of power transmission capability up to the 500 kV class or higher, and 10 kA (or higher), i.e. 5 GW.

4.6.3 RD&D agenda at the 2030+ time horizon

GILs			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	*Components and system* ❑ Development of 2nd generation of GIL based on N2/SF6 gas mixtures with low SF6 contents (below today's value : 10%-20%) ❑ Enhanced safety of GIL installations (using the substitute to SF6) ❑ Reduced corrosion for long distance underground applications *Costs* ❑ Reduced material costs of GILs by the optimisation of the design and materials for a given rating ❑ Reduction of manufacturing costs by simplification and reduction in the number of components ❑ Reduction of installation costs by designing components for simple assembly so that large numbers of joints maybe made onsite in a reasonable timescale ❑ Simple laying and burial techniques to reduce civil engineering costs *Performances* ❑ Assessment of performance of GILs based on conditions of use (temperature, use of assets , etc) and of electrical characteristics (inductance, capacitance, resistance, impedance) compared to OHL and XLPE *Models Validation* ❑ Validation of thermal models of GILs based on collection of historical thermal and load data and variability of electrical parameters versus temperature ❑ Validation of protocols of operations : analysis of correlations between use of assets and transmission capacity (thermal hysterisis in closed environment) *Applications* ❑ Development of longer distance applications suitable for offshore wind power and hydro power conection	❑ Develop substitute solutions to SF6 for use in GIL applications	N/C
	Field tests ❑ Field tests of GIL applications in densely populated areas	❑ Field tests of longer distance or 2nd generation applications based on N2/SF6 mixtures	N/C
Full scale use within the EU27 interconnected transmission system	❑ GILs are used in a few locations in Europe	❑ Implementation of GIL based solutions as underground technologies to enter densely populated areas	N/C: no development seem to be expected beyond niches applications

Figure 31: RD&D agenda for GILs (adapted from [1])

High Temperature Superconducting (HTS) cables			
Techno-economic challenges	2015-2022	2022-2030	2030+
RD&D as seen by manufacturers	*HTS materials* ❑ Basic research to identify higher temperature superconducting materials ❑ R&D on electrical insulating materials for high voltage superconducting applications *HTS components and system* ❑ Assessment of reliable performance and losses in operation ❑ Pilot testing of 2nd generation of (lower costs down to 50…20…10 €/kAm2) HTS tapes (YBCO based) ❑ Development of more efficient and affordable (in terms of costs and size) cryogenic refrigeration system ❑ Simulation and tests to validate models on low temperature phenomena and components ageing (long term durability of HT superconductors properties)	❑ Continuation of the research on higher temperature superconducting materials ❑ Continuation of the research and development on HTS components (cryogenic system, HTS tapes,…) for improved performances /costs	N/C
Integration tests as seen by TSOs	❑ Demonstration of superconducting cables for novel network architecture (ENTSOE project 2012-2018) ❑ Demonstration of combined use of high temperature superconductivity and storage devices, including SMES ❑ Demonstration of combined use of superconducting cables with FCL to mitigate post-fault cable recovery time for 110 kV application ❑ Standards for testing and integration of HTS cables	❑ Demonstration of HTS cables performrmances for niche applications (short distances in dense urban areas ; generation units connection; DC applications) -	❑ Scaling up and replication rules to develop niche applications in Europe ❑ First implementation of underground superconducting solutions to enter densely populated areas
Full scale use within the EU27 interconnected transmission system	N/D	N/D	N/D

Figure 32: RD&D agenda for HTS cables (adapted from [1])

4.6.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):

GIL and HTS systems have been used for limited applications the choice of these technologies is today often chosen for trial reasons rather than real need. Due to the limited service experience and the few available information is not possible to evaluate the performances of these technologies when used in the extended transmission grid systems.

- Mid-term standardization needs (2022-2030):

It is believed that these technologies will remain still for some special and limited applications, if superconductor at higher temperature that the present should become available, it will be possible a wider extend of this technology.

4.7 Transformers

4.7.1 Overview

Transformers are essential pieces of power systems that help to transmit and distribute electricity efficiently. The design of transformers is highly dependent on the scope of their application, voltage level, and rated power. The transmission of electricity can be divided into two parts: firstly, transmission over long distances at high voltages; the transformers employed in this part are traditionally called power transformers. Secondly, distribution from substations to the consumers; the transformers employed in this part are traditionally called distribution transformers. Since the scope of this deliverable is limited to the transmission system, only the power transformers are considered in this section.

Power transformers can be also divided into different categories according to their applications including: generator step-up (GSU) transformers, step-down transformers, converter transformers, Phase Shifting

Transformers (PSTs), system interconnecting transformers, etc. Currently, an increasing interest can be observed for the application of system intertie transformers, such as converter transformers and PSTs [2].

The power rating of system intertie transformers is usually high. Such transformers can be also designed in the form of auto-connected (auto-transformer) instead of separate windings. This design facilitates the transportation by the lower weight and physical dimensions as well as reducing the manufacturing cost. The turn ratio of such transformers might be fixed. However, tappings[34] can be also provided, if required. The different tappings may not noticeably change the voltage on either side of the transformer. However, it can provide the ability to influence the exchange of reactive power between the systems [2].

The basic physical principle of transformers is still the same as it was 130 years ago. However, the efficiency, rating, weight, dimensions, and costs have been significantly improved over time. Nowadays, larger amounts of electricity need to be transported from generating sites located in further away areas. Therefore, higher power ratings and voltages are required for transmission systems and, in turn, for transformers. In this regard, the highest DC transmission voltage has been approximately doubled during the last decade. For example, ABB has recently developed a 1100 kV Ultra-High Voltage Direct Current (UHVDC) converter transformer that enables up to 10000 MW of power to be transmitted over distances as long as 3000 km. This moving towards Ultra-High Voltage Alternating Current (UHVAC) and UHVDC (observed at a worldwide perspective, therefore out of Europe) necessitates new levels of transformers technologies. In addition, mechanical rigidity of the transformers in such sizes is a critical performance factor, especially to withstand short-circuit stresses. The mechanical forces caused by short-circuit can reach millions of kN in milliseconds. Overall, transformer manufacturers encounter number of challenges for the design of large power transformers including: insulation, transient over-voltages, the magnetic leakage field, mechanical forces, power rating limitations, and cooling requirements.

Therefore further improvements on the mechanical, thermal and dielectric integrity of transformers should be considered in order to deal with the greater stresses that will affect future networks. In these developments, the priority is on cost-effective approaches. For example, the new ways of designing transformers through better control of the thermal capability can reduce the use of expensive materials [2] [4].

Another factor that should be considered in operation of transformers is their losses. It is an important factor as transformers operate continuously in the power networks. Since transformers cause a substantial part of the network losses, for energy efficiency approaches, transformers require designs and technologies with lower losses. Reaching the transformer efficiency of up to 99.85 percent is possible by using special materials for their construction and optimized design. The low-loss transformers are initially more expensive, but their additional costs can be recovered by saving energy in a few years [3] [4].

Furthermore, the concept of smart transformer should be further developed. The advanced monitoring of transformers not only improves their reliability but also the reliability of the other assets. By obtaining real-time information from transformer’s critical components, their status can be evaluated on-line, remotely, and without de-energizing the transformer. In this way, the asset owners and operators are able to monitor the behaviour of core, windings, oil, bushings etc. and plan to prevent faults from occurring [4][6].

This category includes AC transformers operated at 400 kV, 550 kV, 750 kV.

4.7.2 Outlook 2050

The transformer development has developed in terms of efficiency and material choices a lot during the last 50 year prior to 2015. The level reached in power and efficiency has approached level where T&D Europe does not expect further significant advances. The major points will consist in further optimizing production from delivery time and production cost in addition to the main trends described in the above overview.

[34] For PST and tappings see also chapter 5 on components for active transmission systems

4.7.3 RD&D agenda at the 2030+ time horizon

No RD&D agenda is proposed due to the high maturity of the technology.

4.7.4 Standardisation needs at short and mid-term horizons

Current standards of transformers are described in section 9.2.1.

- Short-term standardization needs (2015-2022):

  Transformer standards for large power transformers exist through IEC and is widely used in the industry: no further work needed.

- Mid-term standardization needs (2022-2030):

  Transformer standards for large power transformers exist through IEC and is widely used in the industry: no further work needed.

5 Components for active transmission systems

This section includes the critical technology components allowing to control power flow: PST, HVDC converters, FACTS as well as protection and control equipment al local level.

5.1 PST

5.1.1 Overview

Phase Shifting Transformers (PSTs) are a mature technology, implemented by TSOs in Europe to control active power through preventive or curative strategies.

On the technological standpoint, a PST is a special type of transformer usually with a 1:1 ratio that enables to apply a voltage with an arbitrary phase angle and change the effective phase displacement. This feature can be used for controlling the power flow in specific transmission lines as well as balancing the loading between parallel lines. Currently, PSTs are generally three-phase and have two-terminal pair design with the power ratings of up to 1600 MVA. The symmetric and asymmetric PSTs are the most common designs for power systems applications. In symmetric design the no-load voltage ratio is constant during the phase shifting operation and in asymmetric design this voltage changes with the phase angle variation tap position. PSTs need to provide desirable steps for changing the displacement angle within a certain range. One issue that should be considered for the differential relay protection of PSTs is that the current difference is higher than conventional power transformers due to the phase angle difference between the source and the load current. Therefore, a special differential scheme needs to be adopted [2][4].

5.1.2 Outlook 2050

During the last 50 years, significant progress has been made in transformers in terms of efficiency and a large spectrum of material choices is available. Power and efficiency levels have however reached their asymptotes according to T&D Europe. The major challenges consist now to further optimize production from delivery time and production cost.

Enabling issues might also be investigated through for example the development of shared PST models by TSOs and standards should facilitate PST integration in transmission systems. Increase needs of power flow controllability is expected to lead to more equipment integrated by TSOs, possibly operated by power electronics and enhanced by coordinated control protocols implemented within inter-TSO coordination centers [1].

5.1.3 RD&D agenda at the 2030+ time horizon

PST			
As seen by	2015-2022	2022-2030	2030+
RD&D by manufacturers	❑ Improve response time at an acceptable cost, thanks to power electronics	N/C	N/C
Integration tests by TSOs	❑ Inter-TSO standardisation of PST modelling despite huge diversity of PST designs based on shared trial tests	❑ Large scale experiments for TCPST are performed in Europe to improve response time	N/C
Deployment in EU27	❑ Coordinated control of PST (coordination centers in Europe)	❑ PST models are implemented in operations to carry out security analysis at European level	❑ Fast response time PST are implemented in Europe to better manage congested areas

Figure 33: RD&D agenda for PST (adapted from [1])

5.1.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022) and mid-term standardization needs (2022-2030):

    - Since transformer standards for large power transformers exist through IEC and is widely used in the industry no further work is needed.

5.2 HVDC converters (VSC, CSC)

5.2.1 Overview

The *High Voltage Direct Current (HVDC)* technology has proven its reliability and attractiveness for long distance power transmission, long submarine cable links and interconnection of asynchronous systems. Converters to convert current from AC to DC and DC to AC are critical. The most recent technology, self-commutated Voltage Source Converter (VSC), is more flexible than the more conventional line-commutated Current Source Converter (CSC) since it allows controlling active and reactive power independently. HVDC key benefits are in terms of increased transmission capacity when compared to conventional HVAC, and power flow controllability, which in turn can enhance the stability of the link and of its surrounding environment. Although the investment costs of a VSC-HVDC converter station are higher than those of an AC substation, the overall investment costs of a DC transmission link can be lower than those ones of a corresponding AC interconnection if a certain transmission distance is reached (i.e. “break-even” distance). This break-even distance strongly depends on the specific project parameters: it is typically between 80 and 120 km for offshore submarine cable connections; while for onshore applications, the break-even distance between an AC and DC OHL is in the order of 700 km [6]. Typical applications of VSC-HVDC include the active control of flows, interconnection of offshore wind farms, black start functionalities and multi-terminal DC applications. This technology is a key component of future European grid architectures. Meshed DC systems will appear with the advent of commercial DC breakers.

Converter transformer or HVDC transformer is one of the key components in converter stations installed at each end of the HVDC transmission system. This type of transformer provides the required interface between AC grid and high power converters. Apart from adapting the AC grid voltage to a suitable level for the valve system of converter, this type of transformers is also used to control the load flow over HVDC transmission system. The design concept of HVDC transformers depends on the rated power, rated voltage, and transportation requirements, such as mode of transportation, dimensions and weight. Typically, converter transformers are single phase units containing 2 winding limbs. This concept can include either two parallel valve windings (two for delta or two for wye system) or two different valve windings (one for delta and one for wye) [3]. For controlling the voltage, converter transformers need to be equipped with a fairly large tapping range on the line side [2]. One of the transformer windings is connected to the AC side, which is called the line-side winding. The other winding is connected to the converter valves, which is called the valve-side winding.

In conventional converter stations, the transformer acts as a barrier to prevent DC voltage from entering the AC network. Therefore, compared with a conventional power transformer in the AC network, a converter transformer must be tested for the ability of valve-side windings to withstand DC voltages. As the valve windings are exposed to AC and DC dielectric stress and therefore a special insulation assembly is necessary. DC voltage causes additional demands on the insulation structure in comparison to AC voltages [4]. The voltage distribution between solid and fluid transformer insulation is capacitive when exposed to AC. This means that the voltage distribution and dielectric stresses are determined by the permittivity of the materials. On the other hand, in the case of exposing to DC, the voltage distribution and dielectric stresses are determined by the resistivity of the materials. Since the resistivity of the solid insulation materials is considerably higher than the resistivity of the transformer oil, almost all the DC voltage will be on the solid insulation. Therefore, converter transformers require a much higher share of solid insulation than in conventional AC transformers. Additionally, the load currents contain certain harmonics of considerable energy, which causes higher converter transformers losses and noise. The harmonics magnitudes depend on the parameters of the converter stations [2] [3].

As the voltage and power ratings of HVDC systems are steadily increasing, there is an ever-increasing requirement to raise the ratings of individual converter transformers accordingly. However, the size and weight of UHVDC converter transformers can reach to the point that they face transport constraints. Therefore, special modular designs may become necessary for the UHVDC converter transformers. As there is a limited space for the active part of UHVDC converter transformers, this can cause challenges with regard to design and optimisation of the dielectric system [5].

In HVDC systems, the high-voltage AC needs to be converted to the high-voltage DC when transmitting power, and needs to be converted back to AC at the receiving point. In this regard, converters are a key technology and their operation has significant influence on the power system performance. Power electronics is playing an important role in the development of converter technologies and a continuous progress has been observed in high-voltage high-power switching devices over the last decades [6] [7]. Furthermore, **the continuous development of power electronics presents more cost-effective opportunities for the utilities to exploit HVDC transmission systems**. The invention of Mercury-arc valves in the 1930s made the design of Line-Commutated Current Source Converters (LCC/CSC) possible. Afterwards, the replacement of Mercury-arc valves by thyristor valves was the next major development. The line-commutated thyristor valves were initially introduced in 1967 and they are still used for bulk power transmission systems up to 1100 kV. The so called turn off capability which did not exist in the normal thyristors was later implemented in the Gate Turn-Off (GTO) thyristor, followed by the hard driven GTO, and the Integrated Gate-Commutated Thyristor (IGCT). Later, the metal oxide semiconductor technology became available in the 1970s, and provided a new field of semiconductor switching devices including the Insulated-Gate Bipolar Transistor (IGBT) invented in the 1980s and widely accepted in the 1990s. The high power IGBT makes smaller HVDC systems economical. With the development of the IGBT, the Self-Commutated Voltage Source Converters (SCC/VSC) have been developed. This type is called Self-Commutated, as they do not rely on the AC system to operate [5][6].

Basically, **the HVDC converters can be designed either as CSC or VSC**. The CSC-based HVDC system, which is also known as classic HVDC, is mature technology today. It is particularly well-stablished for high power, typically around 500 - 8000 MW. The Jinping-Sunan 800 kV UHVDC project with the rated capacity of 7200 MW, completed in 2013, and the Southern Hami-Zhengzhou 800 kV UHVDC project with the rated capacity of 8000 MW, completed in 2014 are currently the most powerful transmission lines in the world. The CSC is a current stiff converter at the DC side, which is achieved by the connection of a large series reactor. The CSC requires the inductor as its energy storage device and DC filters that provide appropriate fault current limiting features. The CSC blocks voltages of both polarities and conduct current in one direction. Using switching control strategies, it is possible to control the phase angle and magnitude of the ac current directly. Furthermore, power reversal in CSC-based HVDC can be performed by reversing the polarity of the DC voltage. A shunt capacitor is required at the CSC converter AC side terminals for the interface. The deployed capacitance normally operates as passive filters, which for the frequencies below the tuned value will be capacitive. However, additional capacitor banks may be required to provide reactive power compensation [6] [8].

On the other hand, VSC has been a well-stablished technology for low and medium power levels, ranging around 100 - 1000 MW. The VSC power conversion implies the presence of a voltage source on the DC side. A capacitor should be added to the DC side in order to provide the required storage of the energy for controlling the power flow and offer filtering for the DC harmonics. The voltage source maintains a determined voltage across its terminals and by controlling the phase angle and magnitude of the AC voltage through the switching method, the converter operates with lagging or leading reactive power. **In contrast to the CSC-based HVDC system, the switches in VSCs can have bidirectional current conducting**. Therefore, power reversal in VSC-based HVDC can be performed by controlling the DC Current direction while the DC voltage has a fixed polarity. It should be also noted that a VSC cannot be directly connected to a strong AC system. In such a case, a coupling reactance is needed between the converter terminal and the ac system [5] [8]. The CSCs have the natural ability to withstand short-circuits as the DC inductors are effective in limiting the currents during fault conditions and to restart shortly after fugitive defaults (which is not the case for VSC since the clearance of the defaults would need the opening of AC breakers) [9].

Advantages of VSC in comparison to CSC [9]:

- Disturbances in the AC network do not cause commutation failures.
- Higher flexibility, as the active and reactive power of the converter can be controlled independently.
- It can be connected to a weak AC power networks.
- The Pulse Width Modulated (PWM) based VSC operates at frequencies higher than the CSC and line frequency, which provides faster dynamic response as well as reducing filtering requirements.
- The conventional AC transformers can be used, while CSC-based HVDC needs special designed and more expensive transformers (so called converter transformers) to cope with both AC and DC stress for the DC or valve winding.
- No assistance required by transformers for the commutation process
- It does not require a synchronous voltage source in order to operate (as in the case of CSC). In addition, it offers the black start capability; black start is the procedure to recover from a total or partial shutdown of the transmission system which has caused an extensive loss of supply [10].
- Usage of extruded polymer cables; for CSC-based HVDC, Mass Impregnated (MI) cables have to be used because these cables can cope with the power reversal by reversing the polarity of the DC. For VSC-based HVDC, apart from MI, the cheaper extruded XLPE cables can be used because power reversal in a VSC-based HVDC scheme is achieved by current reversal, and the DC voltage has a fixed polarity. The polymeric HVDC insulation materials were developed in the 1990's in parallel with the development of VSC technology. The solid dielectric cable like XLPE provides more environmental benefits compared to the cable with an oil impregnated dielectric [7].
- Smaller station footprint.

In the case of bulk-power transmission, exceeding 1000 MW, the CSC-based HVDC is today the main option. However, VSC-based HVDC addresses a number of shortcomings in the classic line-commutated thyristor HVDC converters, and therefore, the demand for fully controllable VSC topology is increasing in medium and high-power applications. **The future technological development of VSC-based HVDC will provide another option for bulk-power transmission. This technology is a key component of future European grid architectures and will continue to drive down costs and increase performance** [11].

The series connection of IGBTs provides a higher blocking voltage capability for the converter and enables to reach the required high DC transmission voltage. A basic conventional two-level VSC (CSC) has only one V_{DC} (I_{DC}) level when providing an average value equal to the reference voltage or current in each switching cycle. In such a condition, the quality of the output waveform depends on the sampling frequency and the higher sampling frequency provides waveform closer to the sinusoidal reference. However, increasing the switching frequency results in higher switching loss and Total Harmonic Distortion (THD) as well as Electro-Magnetic Compatibility (EMC) problems. In order to solve these problems, the **concept of multilevel converters** has been introduced. Multilevel converter is designed in a way to synthesize a staircase waveform. It can be optimized such that the THD of the output voltage or current becomes minimum, which results in a significant reduction of the filter size in comparison with a two-level converter. Furthermore, the switching losses are significantly reduced due to lower switching frequency and voltage stress [6] [12]. Various high-voltage multilevel converter topologies have been developed for high-power applications. Among the various multilevel converters, **Modular Multilevel Converters (MMCs) have recently drawn considerable interest in the high-power applications of HVDC and Flexible AC Transmission Systems (FACTS)**. Over the last few years, significant research has been performed to address the technical challenges associated with the operation and control of the MMC as well as extending its applications [12] [13]. Generally, modularity refers to a technique to develop comparably large systems by combining smaller subsystems, which in the case of converters is an effective solution to reach high-voltage and high-quality waveforms. MMC's modular and scalable structure of the MMC offer various technical advantages. It enables to meet any voltage level requirements, higher efficiency, improved harmonic performance, etc. Furthermore, the improved ability to optimise the valve to the insulation coordination requirements,, simpler mechanical design, and service are other advantages of the MMCs in comparison to monolithic converters. From the economic point of view, the modular structure offers more economic life-cycle maintenance and lower operating costs. Therefore, **the deployment of MMCs for high-power applications becomes more desirable as the long-term operational cost reduction justifies the higher initial costs**. Nevertheless, the price trends show that semiconductors are becoming cheaper while energy is becoming more expensive [6][13].

This category includes the following converters for HVDC: VSC operated at 320 kV, 500 kV, 800 kV, 1100 kV and CSC that could be operated at 800 kV, 1100 kV.

5.2.2 Outlook 2050

The HVDC converter CSC technology has existed for many years and its development potential appears as rather limited. In parallel the more recent VSC technology is expected to have a promising and significant development. The following areas are examples where the development teams should concentrate their efforts:

- Reduced losses (VSC)
- Increased power transmission capacity (VSC)
- VSC in meshed DC networks
- Improved security of supply (both VSC and CSC).

5.2.3 RD&D agenda at the 2030+ time horizon

HVDC (VSC ; CSC)			
As seen by	**2015-2022**	**2022-2030**	**2030+**
RD&D by manufacturers	*Perfomance and costs* ❑ Higher power ratings in operation ❑ Improved efficiency and security of supply of HVDC -VSC converter ❑ Development of transformerless VSC converters ❑ Decreased investment costs of HVDC VSC and CSC terminals *New swiching topologies for VSC* ❑ Development of novel multilevel switching topologies to enhance ❑ Quantification of technical benefits of new topologies (e.g. efficiency, AC filter requirement, space requirement, reliability, fault response,...) *Fault detection and isolation in DC* ❑ Understanding of the propagation and the impact of a fault on DC network and related corrective actions ❑ Development of DC circuit breakers and selective fault clearance processes *Controllable MTDC (Multiterminal HVDC) ;* ❑ Development of transformerless VSC ❑ Development of multiterminal VSC transmission ❑ Development of multiterminals with more than 3 converter stations on a DC line *Interoperability and eco-conception* ❑ Coherent technological evolution of HV cables and VSC /CSC convertors for HVDC ❑ Interoperability of HVDC converters manufactured by different vendors ❑ Interoperability between VSC and CSC converters ❑ Defined of standards required to realise a large HVDC grid ❑ Eco-conception of VSC/CSC converters (assessment of CO_2 impact, noise, lifetime etc)	❑ New cost efficient solutions for tappings ❑ Breakthroughs in semiconductors materials technology to replace ❑ Development of high voltage DC/DC converters	❑ N/C
Integration tests by TSOs	*Extended domains of use* ❑ Testing far-offshore connections with DC links *Embedding HVDC in an AC network* ❑ Testing HVDC in highly meshed networks : coordination and control; harmonised use with WAMS ❑ Impact of combined HVAC and HVDC in terms of reliability for planners and *Commissioning* ❑ Commissioning tests based on real time simulators *Training* ❑ Coordination center for system operations, including HVDC ❑ Specialized training development for operation and maintenance	❑ Test selected options of HVDC backbone for supergrid, offshore and onshore highways ❑ Test systems components of MTDC ❑ Increase the social acceptance of HVDC taking account improved design and reduced envorinmental	
Deployment in EU27	*Pan-European architecture* ❑ Validation of options for pan-European backbone architecture: e.g. CSC (point-to-point) converters used for North-South long distance bulk transmission and VSC used for transversal links between North-South HVDC -CSC cables allowing increased controllability ❑ Techno-economic feasibility of VSC/CSC HVDC for wind power connections in the pan-European context	❑ Combined AC/HVDC grids become a reality with network safety issues addressed properly at acceptable costs	*MTDC (Multiterminal HVDC)* ❑ Deployment of an MTDC backbone in Europe

Figure 34: RD&D agenda for HVDC Converters (VSC, CSC) (adapted from [1] by T&D Europe)

5.2.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):
  - Standards for both CSC and VSC technologies exist but it is expected to be a continuous development for new application (e.g. DC grid issues for small grids)
- Mid-term standardization needs (2022-2030):
  - The standardization process will continue to also include larger DC grids.

5.3 Other critical components for HVDC (DC breakers)

5.3.1 Outlook 2050

The DC fault current breaking functionality will be needed for larger HVDC grids to separate faulty parts of the grid during earth faults. DC breakers for HVDC grids need to handle fault currents with very fast rising times and operate without a natural zero crossing current as in AC applications. Different concepts have been developed and tested. It is foreseen that this development process will continue and result in new improved designs.

5.3.2 RD&D agenda at the 2030+ time horizon

DC Breakers			
As seen by	2015-2022	2022-2030	2030+
RD&D by manufacturers	*Fast breaking DC-breakers* ❑ Develop DC-Breakers systems solutions ❑ Perform type test and show capabilties *Cost-effectiveness* ❑ Cost-effective development of DC Breaker systems solutions	❑ Upgrade the voltage rating, current rating	❑ Integrate next generation semiconductor
Integration tests by TSOs	❑ Indentify pilot installation ❑ Perform system intergation test	❑ Install and evaluate pilot installations	N/C
Deployment in EU27	❑ Start pushing for the integration plan of meshed multi-terminal systems ❑ Push for common testing and validation of DC-breakers	❑ Facilitate the regulatory framework for large scale meshed DC-grids that need DC-breakers.	❑ Start implement in DC-grids

Figure 35: RD&D agenda for DC breakers (T&D Europe)

5.3.3 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):
  - Standards for the first generations HVDC breakers will be developed.
- Mid-term standardization needs (2022-2030):
  - Development will result following the continuous need in developing new standards.

5.4 Other critical components for HVDC (tapping, DC/DC converters)

This category includes the following critical technology components: tapping, DC/DC converters.

5.4.1 Outlook 2050

For the tapping functionality the main challenge consists in finding a cost effective solution.

Indeed, the tapping is a special case of the multi-terminal system, where the power rating of the station is much smaller than the main converter station in the scheme. The initial cost for the 'first' MW is very high for an HVDC station and this makes the tapping solution a challenge mainly from a cost perspective.

5.4.2 RD&D agenda at the 2030+ time horizon

DC/DC converters			
As seen by	**2015-2022**	**2022-2030**	**2030+**
RD&D by manufacturers	*Topolgy evaluation* ❑ Develop and decide on the most cost effective converter design to offer the market	❑ Develop the first large scale pilot installations	❑ Start delivering the first DC/DC converters to the market
Integration tests by TSOs	❑ No hardware implementation but planning work identify possible pilot installations	❑ Install the first pilot installations together with the manufactures	❑ Start implementing the DC/DC converter solution in commerical projects
Deployment in EU27	❑ Adapt the grid code so that the DC/DC aspects is covered	❑ Facilitate the neccessary technical standards to enable the first commerical contracts	❑ Start implementing DC/DC converters to integrate point-to-point solutions with different

Figure 36: RD&D agenda for DC/DC converters (T&D Europe)

One should also mention two related topics that are included in Figure 34 (in the first column the items on " Fault detection and isolation in DC"):

- Understanding of the propagation and the impact of a fault on DC network and related corrective actions (DC breakers; controllable pyrotechnique fuses; ..)
- Development of DC circuit breakers and selective fault clearance processes.

5.4.3 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):
    - o Many of the standards used for HVDC converters are also applicable for tapings. But there may be a need for new standards pending the technology development.
- Mid-term standardization needs (2022-2030):
    - o There may be a need for new standards pending the technology development.

5.5 FACTS

5.5.1 Overview

Flexible Alternating Current Transmission System (FACTS) equipment is a family of power electronics-based devices able to enhance AC system controllability and stability and to increase power transfer capability. FACTS are naturally compared by TSOs with mechanical driven equipment providing controllability features, such as PST (a simpler, more robust, reliable and generally less costly solution, but with limited dynamic capabilities).

FACTS devices can be classified according to their shunt, series or combined types of connection.

Classification of FACTS

- **Shunt type devices** present relevant features for reactive power compensation and voltage control; the main devices in this category are the static VAR compensator (SVC) and static synchronous compensator (STATCOM).
- **Series devices** offer key advantages for active power flow control and transient stability enhancement; this category includes devices such as the thyristor-controlled series capacitor (TCSC) and static synchronous series compensator (SSSC).
- **Combined type devices**, as the name implies, combine several devices and they can benefit from the features of both shunt and series types simultaneously; this category includes devices such as the thyristor-controlled phase shifting transformer (TCPST), dynamic flow controller (DFC), unified power flow controller (UPFC), interline power flow controller (IPFC). It should be noted that IPFC is only a combination of several series devices.

SVC, TCSC, TCPST and DFC are based on thyristors, while STATCOM, SSSC, UPFC and IPFC are based on voltage source controllers using GTO, IGCT and IGBT power electronics technologies [14]. Up to present, shunt devices have been the most widespread and mature FACTS technologies, especially the SVC technology. SVCs are generally connected to the medium and high voltage grids. The thyristor valves nearly always require a voltage rating greater than the level that can be provided with a single thyristor. In order to reach higher voltage ratings, multiple thyristors have to be connected in series similar to CSC converters in HVDC transmission systems. Therefore, thyristor valves in SVCs have many common design features with thyristor valves in CSCs. In the case of STATCOM, the same range of converter topologies as the VSC used in HVDC is available. The advent of high-power IGBTs makes this type of FACTS devices more economically attractive. For lower ratings, 2 and 3-level converters can be used, and for higher ratings, the MMC topology is more suitable. **The STATCOM technology could experience significant improvements with regard to achieving higher rated voltages and powers in the future** [15].

The deployment of other FACTS technologies may also become considerable in the future. TCSCs use an arrangement similar to an SVC to provide greater controllability. In fact, the TCSC technology is a fixed series capacitor with the addition of a thyristor-controlled reactor. SSSCs are essentially a STATCOM inserted in series with a transmission line. TCPSTs are basically a phase shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle [16]. DFCs are hybrid devices combining traditional PST and switched series compensation. Structurally, a DFC is comprised of a mechanically-switched PST, a mechanically switched shunt capacitor, a multi-module thyristor switched series capacitor and thyristor switched series reactors [17]. The UPFC is a combination of a STATCOM and SSSC coupled via a common DC link. Finally, IPFCs consist of two (or more) SSSCs connected at their DC terminals; these to SCCCs are installed on different AC lines in series and they allow power to be transferred between lines [15].

Costs, complexity and reliability issues represent nowadays the main barriers to the integration of these promising technologies from the TSOs' perspective. Further FACTS penetration will depend on the technology providers' ability to overcome these barriers, thanks to more standardization, interoperability and economies of scale. Key technology challenges are in terms of power electronic topologies and exploration of new types of semiconductors replacing silicon. New power electronics advances are necessary in order to lower the costs of these systems, and accelerate their applications [18]. More user-friendly interfaces and proof of performance through field testing will contribute to improve TSOs' confidence in these new technologies. Like other active equipments (HVDC VSC and PST), FACTS will be crucial for the future integration of RES into the European system, while delivering full benefits when subject to a coordinated control, in combination with Wide Area Measurement Systems.

In e-Highway2050 technology portfolio the retained FACTS are the following:

- Shunt: This category includes the following critical technology components: SVC, STATCOM.
- Series: This category includes the following critical technology components: TCSC, SSSC, and TSSC.

5.5.2 Outlook 2050

Shunt:

The technology for SVC technology has existed for many years and the development potential is limited. Since the base key technologies of the valves and the control and protection as well as main circuit components are sharing solutions for HVDC the outlook is very similar between the SVC and CSC here above described.

The technologies for STATCOM are similar to the HVDC VSC technology. Since they are recent technologies, they are expected to have a significant development, for example in the following areas:

- Reduced losses (VSC)
- Increased reactive power rating (STATCOM)
- Reduced footprint
- Improved security of supply due improved performance.

Series:

The technology for series FACTS devices are very mature and T&D Europe foresees very limited development in this technology. The technology is very well positioned for long unmeshed AC-line and will be used and maintained in these applications.

5.5.3 RD&D agenda at the 2030+ time horizon

FACTS			
As seen by	**2015-2022**	**2022-2030**	**2030+**
RD&D by manufacturers	*Semiconductor Materials and components* ❑ New power electronics converter topologies and controls ❑ Research, measurements, mitigation of power quality impacts of large scale power electronics applications (e.g. harmonics) *Performance* ❑ Increased ratings ❑ Improved efficiency and security of supply ❑ Development of transformerless VSC converters *Standards* ❑ Standardisation of equipment specifications, maintenance and operational requirements	❑ Breakthroughs in semiconductors materials technology to replace silicon	N/C
Integration tests by TSOs	*Performance validation* ❑ Validation of coordinated control of multiple FACTS devices in transmission system ❑ Evaluation of cost and benefits of FACTS through demonstrations ❑ Performance, reliability evaluation through field tests *Applications* ❑ Combined Use of FCL with FACTS ❑ Validation of STATCOMs for wind power plants type integration into the transmission system ❑ Deployment of FACTS (shunt) in areas where voltage control becomes critical ❑ Field tests of relocatable FACTS *Environmental impacts* ❑ Reduce environmental impact (surface occupation, noise, EMF) *Virtual interfaces for operators* ❑ Simplified Man-machine Interface for grid operators ❑ Use of adaptative mesh techniques to anticipate the system behaviour with FACTS in critical areas of the network *Training* ❑ Specialized training development for operation and maintenance ❑ Improved knowldge on the levels of reliability and availability	❑ Large scale validation of FACTS solutions to voltage control (FACTS - shunt) ❑ Large scale validation of FACTS solutions to control line reactance control (FACTS -series)	N/C
Deployment in EU27	❑ Evaluation of cost and benefits of utility-scale FACTS in real world applications	❑ Significant deployment of FACTS (shunt) in areas where voltage control becomes critical ❑ Combined use of FACTS and WAMS ❑ Decreased investment costs thanks to economies of scale	❑ FACTS (series, combined) implemented in areas where fast response line reactance control

Figure 37: RD&D agenda for FACTS (shunt and series) (adapted from [1] by T&D Europe)

5.5.4 Standardisation needs at short and mid-term horizons

- Short-term standardization needs (2015-2022):
    - Standards for both SVC and STATCOM technologies exist but there will be a continuous adjustment to apply with new application and grid codes (Shunt)
    - Continuous adjustment to future grid codes
- Mid-term standardization needs (2022-2030):
    - Continuous adjustment to future grid codes.

6 Other technologies enhancing observability, protection and control at system level

This section includes all technology components or systems that enhancing observability, protection and control at the system level.

6.1 WAMS/PMUs

Wide Area Monitoring System (WAMS) is an enabling technology based on an information facility with monitoring purposes. Based on *Phasor Measurements Units (PMUs)*, WAMS allow monitoring transmission system conditions over large areas in view of detecting and further counteracting grid instabilities. This early warning system contributes to increase system reliability by avoiding the spreading of large area disturbances, and optimizing the use of assets. Yet, **some critical R&D challenges lie in signal accuracy and reliability, communication architectures and data processing**. Standards for data processing, large scale demonstrations, possibly in combination with other active equipment, will be needed to estimate benefits brought by WAMS.

6.1.1 Outlook 2050

Power systems are operating in a more complicated condition than they used to, and therefore encounter more challenges. From the generation viewpoint, power industries have been deregulated and more independent power generators contribute as suppliers. In addition, there is a wider penetration of renewable and variable sources of generation. On the other hand, by the presence of less predictable load patterns and more power electronics driven sensitive loads, there is a higher requirements in providing reliability and power quality. Meanwhile, difficulties also exist in upgrading the transmission system proportional to the growing generations and loads. Reliability is one of the prominent factors in operation of power systems that has notable economic impact and influence on society. Historically, power systems have been remarkably reliable. Although minor outages have been common, large-scale and wide-spread outages rarely happened and interruptions have occurred over relatively limited area. However, changes in the wholesale electricity market alongside the difficulties in upgrading the transmission systems have caused power systems to face more challenging network wide issues. In this condition, a minor disturbance can be intensified by a series of events leading to network wide effect. Subsequently, system may completely collapse, if timely actions are not adopted. In this regard, **we need to use advanced and smart monitoring tools to quickly and reliably observe the changing state of the key electrical parameters in real time, take appropriate corrective measures, and isolate faults** [28].

Traditionally, Supervisory Control And Data Acquisition (SCADA) systems were designed for monitoring of the power systems by polling the Remote Terminal Units (RTUs) at all the substations. They have been the essential component for monitoring in power system for years. However, the current SCADA systems collect data and observe grid conditions every few seconds. Thus they are incapable of providing information about the dynamic state of the power system and the monitoring is relatively static and infrequent. In addition, SCADA data are not consistently time-synchronized and shared widely across the network. Therefore, SCADA does not provide operators with real-time and wide-area visibility. Consequently, it is not effective for the real-time wide-area monitoring applications. The emergence of the new generation of measurement technology, known as Phasor Measurement Units (PMUs), provides a significant improvement in reliability. **PMUs offer unprecedented time-synchronized and high resolution information over a wide-area, in real-time**. PMU data can be provided in higher rates, commonly once every cycle, and with higher accuracy. Many advanced smart grid applications can take advantage of the measurement capabilities of PMUs. These applications enable utilities to react promptly to the contingencies and prevent large-scale blackouts [29].

As shown in Figure 38 [30], **a PMU-based WAMS is a system in which PMUs measure power system parameters including frequency, voltage and current phasors with a high degree of accuracy**. Meanwhile, the phasors are time-stamped using signals from Global Positioning System (GPS) so that the microsecond when the measurement taken is permanently attached to it. This feature enables simultaneous measurement of system parameters from different locations in the power system, making the comparison of measured parameters simple. Afterwards, the time-critical phasor data are collected from various locations in the electrical grid and will be transmitted to a central location known as Phasor Data Concentrator (PDC). A PDC receives and time-synchronizes phasor data from geographically distributed PMUs and produces a real-time, synchronized output data stream. This information can be exploited by many smart grid applications, ranging from visualization and alarms for situational awareness, to ones that provide sophisticated analytical, control, or protection functionality. The collected data can be also stored for future offline analysis. PMUs have a significant role to play in the successful transition of today's huge amount of power delivery into a "Smart Transmission Grid" since the number of PMUs is growing in Europe and around the world [31].

WAMS consists of three layers, similar to the traditional SCADA system. The first layer is the section that WAMS interfaces with power system to measure required parameters. This layer is called the **Data**. Acquisition Layer and PMUs are located in this section. Layer 2 is where the PMUs measured data are collected and time-aligned. This layer is known as the **Data Management Layer** and PDC is placed at this layer. Finally, layer 3 is the **Application Layer** where the sorted PMUs measurements are used by the different kind of functions for the monitoring, control and protection applications. These three layers are **connected through communication networks**. Therefore, WAMS comprises of four main parts: PMUs, PDCs, application software, and communication networks. A successful implementation of WAMS needs an elaborate planning and designation of equipment and methods to fulfil these four parts requirements [32]. In most cases, PMU installation is for a permanent operation so all aspects should be considered in order to have a well-established measurement system. PMUs can be different in the matter of algorithm selection, timing input, number of voltage and current inputs, communication interface, accuracy, etc. [33]. However, they have number of common requirements, including: access to signals to be measured, a timing signal to synchronize the measurements, a power supply, etc. [34].

Phasor representation of sinusoidal signals is commonly used in AC power system concept. A phasor is a mathematical representation of an electrical waveform based on the amplitude and phase angle. Using the phasor notation considerably simplifies not only the mathematics but also the electronics and processing requirement [35]. The most common technique for determining phasor representation of AC waveforms in PMUs is to take data samples from the waveform using an analog to digital (A/D) converter and apply the Discrete Fourier Transform (DFT) [36]. There is a wide variety of phasor measurement equipment available. Many PMUs are produced as dedicated devices, while there are also vendors that offer PMU functionality as a supplementary feature on their other products, such as relays and Digital Fault Recorders (DFRs) [37]. In order to assure that the measurements from all PMUs are comparable under various power system operations and for the advancement of the connectivity and interoperability, standardization is an important requirement. The Synchrophasor and frequency values must meet the general definition as well as minimum accuracy requirements given in the standard [38].

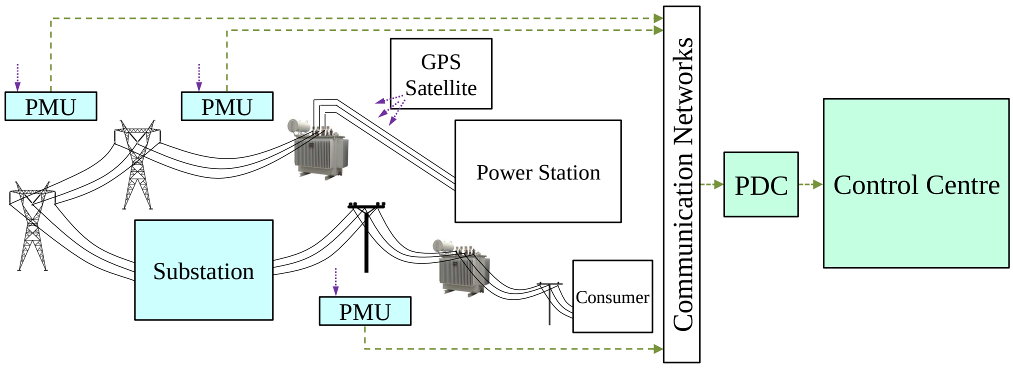

Figure 38: The deployment of PMUs in Wide Area Monitoring Systems

Having more PMUs installed across the power system, provides better view of the event propagation in the network. Therefore, more PMUs are required to be employed in future. The number of PMUs installed in the whole power system depend on the number of PDCs to process and store their data. Therefore, each

PDC needs to deal with huge amount of data and the required data storage capacity should be considered. As more PMUs are deployed in the system, the number of measurement samples increases and the storage requirement accelerates [39]. Storing and processing a huge volume of PMU data and scanning through terabytes of information to find the particular event will be a big challenge for WAMS. Currently available storage and processing systems, such as Storage Area Network (SAN) and Relational DataBase Management System (RDBMS), have low read rates and do not work well with high resolution time-series data of WAMS. Thus an efficient platform is required to interact with huge amounts of high-resolution data, such as **Hadoop** [40][41]. Hadoop is a framework provided by the Apache Software Foundation [42] as an open source project for running applications on large clusters built of commodity hardware. By running parallel processes, analysis can be conducted in less time. In fact, Hadoop transfers the processing to the data instead of the conventional procedure of transferring the data to the processing [43]. In addition, **more advanced applications that can analyse data efficiently** and recognize potential problems quickly need to be developed and implemented. These applications can provide useful information for operators in order to **identify sequence of events and their causes during a power system disturbance** [44].

Furthermore, in order to achieve real-time monitoring, **a high-speed and reliable communications infrastructure is required** to transfer PMUs time-critical synchrophasor data from remote locations to the PDC and application software. The excess delay in the communication network is a challenging factor that affects the data transmission and could make the applications at best inefficient and at worse ineffective. Therefore, communication infrastructure can represent potential bottlenecks in the architecture of such systems and the performance evaluation of latency exhibited in a WAMS is a very important aspect that should be also considered [45] [46].

6.1.2 RD&D agenda at the 2030+ time horizon

WAMS			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	*Signal accuracy* ❑ Methodologies to estimate PMU data accuracy (standardisation) ❑ Improved accuracy and reliability of the Synchronized Data Acquisition processes (supercalibrator) *Communication or architectures and processing* ❑ Optimal PMUs placement with respect to system operation ❑ Improved performances of Communication infrastructure ❑ Overcoming time lags inherent in long-distance information transmission ❑ WACS development: distributed control architectures based on intelligent device (smart sensors) ❑ Scalable processing systems supporting the intense WAMS data computation requirements allowing full use of collected data *Algorithms* ❑ Development of standards for oscillation detection algorithms to exploit dynamic capabilities of PMU and ❑ Understandable link for operators between operational conditions and inter-area power oscillation damping thanks to correlations of synthetic measurements data	❑ WACS/WAPS: Development of reliable turn-key systems combining data monitoring, control and protection	N/C
Integration tests as seen by TSOs	❑ Full scale demonstrations to be performed to value the real system benefits of WAMS (first results expected by 2015) ❑ Development of standards on accuracy of data and deployment recommendations involving manufacturers and TSOs ❑ Integration and processing of accurate data at local level and tranmission of syntethic information at central level ❑ Integration test of non conventional sensors based on optical fibers	❑ Full integration of PMUs information into SCADA systems including special protection schemes and automation ❑ Opening a transparent data exchange in an inter-TSOs context	N/C
Full scale use within the EU27 interconnected transmission system	❑ A few EU contries have implemented country -wide WAMS: Italy; Austria; France, Sweden, Denmark, Hungary (2010)	❑ All European TSO are using WAMS in order to monitor/control inter-area power oscillations, ..	❑ WACS /WAPS : use of WAMS data for control and protection issues

Figure 39: RD&D agenda for WAMS [1]

6.2 RTTR

Real-Time Thermal Rating (RTTR)-monitored cables/lines are a rather mature technology based on the real time control of thermal rating of a line or a cable. It aims at maximizing the capability of a transmission line/cable while respecting design margins, thus reducing potential congestion problems. Its further development will be facilitated by solving some practical integration challenges: integration with other tools, interoperability with protection equipment settings, coordination of RTTR monitored links, communication with SCADA and use of RTTR output values at a dispatch level.

Combined uses of RTTR measurements with weather forecast might significantly increase the value of RTTR for network operations: it could become an interesting option for TSOs to achieve higher transmission capacity ratings safely and reliably for existing systems, at relatively low investment costs (with respect to the investment needed for new transmission links).

6.2.1 Outlook 2050

An important parameter that should be taken into account in the design of transmission systems is the temperature. Power lines have **a maximum operational temperature** that should not be exceeded. This maximum temperature is used to determine the maximum current that can be transmitted by the line. There are three **widely used models** for calculating line capacity, provided by CIGRE, IEC, and the IEEE. **Conventionally, a constant rating is considered** for power lines in accordance with a conservative set of weather conditions. However, in reality a conductor's rating is continually fluctuating. Since the obtained rating is calculated based on a low probability of exceeding a certain design temperature, the power lines capacities are not exploited efficiently majority of the time. In fact, **observing the local weather conditions dynamically in real-time can reveal additional transmission capacity**. In this regard, RTTR is an emerging technology used for calculating the dynamic rating of electrical conductors. It allows electrical conductors to operate at an enhanced rating based on information from local, real-time weather conditions[35] and in accordance with the IEC 60287 and IEC 60853 standards [61][62].

The benefits that RTTR provides include: deferring costly network reinforcement, increasing the yield of distributed generators, planning scheduled outages by considering the potential higher line ratings, and reducing the number of disconnected customers for supporting the network during unscheduled outages. The **deployment of RTTR** not only leads to save money but also provides **a faster solution to increase the network capacity in comparison with building new infrastructures**. Furthermore, a properly planned and analysed RTTR deployment could even reduce power systems operating risk. By increasing the thermal observability of network, system operators are able to see when the line rating is below the determined static rating and hence perform the required corrective actions. Overhead lines can take higher advantage of the RTTR technology; since in the case of cables the thermal time constant is higher and they can operate at an elevated rating on a cyclic basis. It should be noted that the RTTR technology is currently in the prototype phase and active use of RTTR is imminent [61] [63].

[35] It should be noted that local weather forecasts can also be used for day ahead capacity forecasts.

6.2.2 RD&D agenda at the 2030+ time horizon

RTTR (Real Time Thermal Rating) -based cables/lines			
Techno-economic challenges	**2015-2022**	**2022-2030**	**2030+**
RD&D as seen by manufacturers	*RTTR-based Underground/ submarine cables* ❑ Refinement of dynamic models for predictive rating of submarine cables and of underground cable circuits ❑ Industrialisation of RTTR systems for underground /submarine applications *RTTR-based OHL (direct & indirect)* ❑ Technical characteristics of sensors for installation: safety in installation, reduced outage time of line during installation and calibration process ❑ Design of sensors to facilitate interoperability ❑ Interoperability between RTTR scheme and protection equipment settings ❑ Novel ICT distributed, interoperable architectures to process locally monitored data ❑ New mathematical modelling for OHL rating predictions (3 hour-ahead): fuzzy logic, data mining, autoregression,… (indirect methods based on weather data) *Innovative monitoring systems* ❑ Assess reliability, life-cycle, costs of innovative monitoring sensors (Optical or laser based sensors ; Ultrasonic type sensors target tracking type sensors)	N/C	N/C
Integration tests as seen by TSOs	❑ Solve communication with SCADA problems ❑ Large scale experiments involving the coupling with PST ❑ Coordination between RTTR monitored thermally limited lines ❑ Demonstration of the beneficial impact of integrating RTTR into EMS in terms of improved system reliability and efficiency	❑ Grid optimization using RTTR technologies (at TSO level)	N/C
Full scale use within the EU27 interconnected transmission system	❑ Revision of standards (IEC, CENELEC) explicitely allowing interoperable dynamic rating ❑ Interconnection with other countries : inter-TSO agreements needed on RTTR operation modes which are based on common criteria	❑ Combined use of RTTR, PST and WAMS to better manage highly congested areas (generated by wind power	❑ Grid optimization using RTTR technologies (at EU level)

Figure 40: RD&D agenda for RTTR [1]

6.3 RTTE

6.3.1 Outlook 2050

Radio and Telecommunications Terminal Equipment refers to different solutions for line measurement in the system. These technologies are the information transmission media that is used to transport data between different nodes in the transmission system and the protection and controls centers that is built up in the systems

6.3.2 RD&D agenda at the 2030+ time horizon

RD&D agenda refers to ICT technologies strictly beyond the core business of transmission system operators and power transmission manufacturers. It is thus beyond the scope of this present report.

However, a study has been performed in relation to the current deliverable: "Impacts of ICT on the pan-European Power System up to the 2050 Time Horizon" performed by Brunel University. It constitutes the synthesis report of the T3.2.8 aiming at identifying, qualifying and quantifying the impact of the major changes in ICT for the power system in Europe at the 2050 time horizon.

6.3.3 Standardisation needs at short and mid-term horizons

The RTTE Regulations aim to ensure that relevant products in this scope meet certain minimum essential requirements concerning health and safety, electromagnetic interference and radio spectrum matters. In this regard, manufacturers must ensure their products comply with these regulations [57]. Directive 1999/5/EC on radio and telecommunications terminal specifies in detail the requirements that products must meet. This directive is known as "Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on Radio Equipment and Telecommunications Terminal Equipment and the mutual recognition of their conformity". It establishes a regulatory framework for placing and putting into service the radio and telecommunications terminal equipment on the free market.

Harmonised standards play an important role in the operation of the directive. The easiest route to demonstrate compliance of equipment with the directive is to have the equipment comply with the related harmonized standards. A harmonised standard is a European standard developed by a recognised European standards organisation: CEN, CENELEC, or ETSI. It is created following a request from the European Commission to one of these organisations and enters to force when the reference is published in the Official Journal of the European Union (OJEU). The harmonized standards are developed mostly by ETSI alongside number of safety and health standards that are developed by CENELEC. A summary list of the references of harmonised standards under Directive 1999/5/EC for RTTE is available in [58]. Manufacturers, other economic operators, or conformity assessment bodies can use harmonised standards to demonstrate that products, services, or processes comply with relevant EU legislation. Products, which conform to harmonised standards, are presumed to comply with the directive. Where manufacturers don't use harmonised standards, they should demonstrate in extension how the essential requirements of the directive are met [58], [59].

The European Parliament and Council Directive on Radio and Telecommunication Terminal Equipment (1999/5/EC) was revised in 2014 to become the Radio Equipment Directive 2014/53/EU. This new radio equipment directive is called "Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC". This new directive will be applicable from 13 June 2016 and aligns the previous directive with the new legislative framework for the marketing of products. The revision considers the need for improved market surveillance, in particular for the traceability obligations of manufacturers, importers and distributors. It provides improved instruments for market surveillance, such as the possibility to require prior registration of radio equipment, within those categories affected by low levels of compliance [60].

7 The technological landscape required to implement the e-Highway2050 architectures

7.1 The technological landscape at 2050 as seen by manufacturers

The expected major technical evolutions for each technology option are outlined below.

Cables in terrestrial and submarine applications

For high and extra high voltage underground and submarine cable technologies, the most significant progress in the coming 20 years will come from the HVDC XLPE technology. Whereas R&D in Mass Impregnated (MI) HVDC cables has reached an asymptote, voltage levels of XLPE DC underground and subsea cables will increase considerably and with switchgear equipment gaining market experience, meshed HVDC networks will become available.

- XLPE AC High and Extra High Voltage Cables: a further increase in transmission capacity above today´s 500kV limit is expected. This will help partial undergrounding complement overhead lines in more and more sensitive areas thus strengthening Europe´s meshed AC transmission networks.
- XLPE HVDC cable: voltage levels of DC underground and subsea cables will increase considerably. With switchgear equipment gaining market experience, meshed HVDC networks will become available.
- HTS and GIL: High Temperature Superconducting (HTS) and MGB_2 cables will eventually become available for wider scale deployment and Gas Insulated Lines (GIL) may be deployed in specific projects ensuring safe use. Today, the currently deployed GIL technologies (mostly for substations) meets all applicable environmental standards and the foreseen substitution of SF_6 by non-greenhouse gases should further facilitate the deployment of that technology.
- Partial undergrounding solutions will be a competitive alternative for faster project implementations and accelerated permitting procedures: the higher investment costs may be compensated through overall societal benefits.

Overhead lines

The design problem of a line is a challenging optimization exercise.

- Each reinforcement project is specific and aims at minimizing costs taking into account the electrical performances of conductors and the mechanical performances of towers under normal and severe climatic conditions, as well as environmental issues (visual impact of the line, electric and magnetic fields in the vicinity of the line, noise).
- Minimizing costs is a challenging problem since costs depend on many parameters such as conductor technology, i.e. electrical performances and behavior (thermal dilatation) versus mechanical features (weight, maximum temperature, etc.) and the overall line design including tower design and civil works (depending on the mechanical constraints induced by the towers).
- Standard overhead lines to be used in future reinforcements in Europe were put forward by the partners when studying possible grid architectures at 2050. In particular,
  - candidate conductors were defined, as well as the voltage level (400 kV, with a possible extension at higher voltages in case of high performance conductors),
  - for the overall design a «reasonable» architecture was assumed composed of 2 three-phase circuits on one tower and of 4 bundled conductors for each phase.

Active power technologies

The portfolio of active power technologies is presented in the e-Highway2050 database [65]: HVDC CSC (current source converter) and VSC (voltage source converter) technology; HVDC breaker technology; FACTS (shunt and series compensation) technology; Transformers (phase shifting transformers -PST-, transformers with tap changers); Protection at substation and system levels.

The following evolution foreseen by the manufacturers until 2050 are listed hereafter.

- HVDC converters: an increase of the existing rated voltage and power to adapt to market requirements is expected to be realistic. Incremental improvements of CSC (Current Source Converter) technologies are foreseen from today's levels. In parallel, the VSC technology (Voltage Source Converter) will increase its transmission capacity and losses will be reduced close to the conventional CSC technology. In a time horizon of 10-15 years, manufacturers will be in position to offer solutions of 2 or 3 GW for the VSC technology. As a consequence, VSC could be the predominant HVDC technology in Europe. However manufacturers are not in position today to determine whether this innovation will be market pull or push: if TSO needs do not evolve, the offer on converters will stay the same as today.
- HVDC architectures: the evolution from the HVDC point-to-point applications to multi-terminal systems could be seen as a journey which will raise economic and regulatory issues and will require a close cooperation between TSOs and manufactures in the coming years. Recent studies illustrate the respective advantages of point to point and meshed HVDC architectures.
- FACTS: SVC technology, as a mature technology, will be subject to incremental improvements, as well as the STATCOM technology as today's rated voltage and power will increase while losses will decrease. FACTS deployment is increasing both in Europe and worldwide with a constant growing penetration of shunt FACTS, while series FACTS may become also an option for TSOs in the future.
- Transformers: both PSTs and tap changers are conventional and mature technologies. The foreseen incremental improvements will be driven by the evolutions of market requirements.
- Protection (both at substation level and at system level): there will be a need to adapt protection components and systems to new technical (high penetration of power electronics) and market requirements. New material could emerge, which could open the possibility to commercialize new solutions, such as Fault Current Limiters with superconductive materials.
- Real-time observability: monitoring the conductor temperature appears as an interesting solution to increase efficiency of operations provided that the information is communicated to the dispatcher with a forecast (wind, temperature) at day-ahead. In the case of wind power production, there is an interesting conjunction, i.e. when there is wind the temperatures of the conductors are lower (forced convection), which should allow to increase the load. Significant progress are expected for the so-called dynamic line rating technologies.

7.2 The point of view of TSOs on the technological landscape

From the point of view of TSOs key issues concentrate on grid planning and on operation in safe conditions. Typical questions include the level of voltage, the way to combine and operate safely AC and DC components in a system and acceptance issues.

- Operating in the future the system at higher levels of voltage in Europe (e.g. 750 kV)

  The increased transmitted power would be the main benefit for operating at higher voltages. When transporting huge amounts of electricity over a long distance in AC, reactance problems emerge. Practically, FACTS or service capacitors would be then needed above 3 or 4 GW in order to reduce the reactance, which would increase the complexity of the grid.

This benefit faces directly the question of public acceptance. In a very densely populated Europe, the EMF issue and the visual aspects of a new line are of prime importance as high voltages above 400 kV lead to increase the height of tower and the difficulties to operate the system (reactance problems are easier to be addressed than public acceptance issues).

- Operating the transmission system (or part of it) in DC

  The competition between AC with DC in transmission systems has some particularities in Europe (when compared to other larger continents) due to the shorter geographical space and to shorter interconnection lines which may limit the possible DC applications.

- Operating the transmission system combining HVAC and HVDC

  There are challenging questions on the coupling of active transmission technologies which will require detailed studies (e.g. studying the integration of some HVDC links in a meshed transmission AC system).

- Expanding the grid with overhead lines vs underground cables

  The perspective of TSOs has to be compared with the one of cable manufacturers which claim that underground cables will continue to help overcome public acceptance constraints. TSOs from their side estimate that development of high-power underground cables will have some system implications to be looked at carefully and that over the next decades, the balance between lines and underground cables in future grid expansion will greatly depend on the degree of deployment of the HVDC grid in Europe.

- Increasing the controllability of the grid thanks to active components

  Adding more active components (FACTS, HVDC) combined with enhanced observability of the grid, should increase the controllability of the transmission system and allow some transmission capacity deferral and the investment in new transmission capacities. But the increased flexibility is not expected to absorb the full amount of new transmission capacity which might be necessary in a case of massive penetration of renewables. The reliability of some real-time observability equipment (WAMS/PMUS and the communication links), especially in emergency situation will be an issue.

7.3 The identified transmission reinforcement needs resulting from the project and the gap for further RD&D

The performed analysis has allowed the identification of the main technology families covering the transmission reinforcement domains. This identification process highlights the needs for further RD&D to better cover the transmission reinforcement domains, with the following observations:

- the possible R&D needs depend on several parameters going beyond the two dimensional (distance, transmitted power) TR domains. For example, voltages levels, the number of circuits and the number of bundle per conductor have to be considered. This complex multi-variable problem has to be solved with the foreseen costs since when implementing or refurbishing an existing OHL or cable link, different options are available: for instance, for a given distance, higher voltage levels extend the range of transmitted power but lead to higher towers (one could also have multi-circuit links at lower voltages with several bundles per circuit and lower towers);
- active transmission equipment combined with an increased observability of the network could be used to improve (marginally) the transmission capacity in a line by operating it closer to the physical limits. Such equipment do not provide any additional capacity but they contribute trough their flexible use to increase the overall transmission capacity of the grid;

- modular building blocks could naturally emerge and fulfil a large domain of TR needs. Indeed, a limited set of modular solutions for terrestrial and submarine liaisons may, when combined[36], meet most of the Transmission Requirements resulting from e-Highway2050;
- a debate on the relevance of having standardized solutions of technological options of the type "one-size-fits all" (in fact a limited number of sizes would be more exact) is still open. On the one hand, a consensus of European TSOs on a limited number of standardized needs would greatly facilitate the RD&D work of manufacturers. It will also be beneficial for TSOs in terms of costs. On the other hand, some TSOs could claim the need to keep more variety in the selection of reinforcement solutions (at least for short-term grid planning) and to have a full control on the specifications/development/installation process. This position relies upon the "local feature" statement: each liaison is unique due to the multiple local constraints (technical and non-technical). Such debate overcomes the technical issues but the value of the present work is to identify on a technical standpoint a limited set of archetypal solutions.

[36] In this analysis no consideration of public acceptance or rights-of-way is made. Considerations are made only on the technological standpoint and focus mainly on the availability / maturity of the technology

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9 Annexes

9.1 Identified references on technology background & roadmap and on standards[37]

The references have been divided into two main categories: (1) General references (2) References related to each of the considered technologies. The technology references have also been divided into two parts: (2.1) Technology background & roadmap (2.2) Standards. This section provides an overview of the considered references. The detailed list of references are available in Annex 2).

9.1.1 General References

The references in this category are the ones that provide information that can be used for all the considered technologies. For example, the documents that are prepared by the Smart Grid Coordination Group in order to address the M/490 mandate.

– Standardization Mandate to European Standardisation Organisations (ESOs) to support European Smart Grid deployment, EUROPEAN COMMISSION-M/490, Brussels 1st March 2011;
– CEN-CENELEC-ETSI Smart Grid Coordination Group Smart Grid Reference Architecture, CEN-CENELEC-ETSI Smart Grid Coordination Group, November 2012;
– SGCG/M490/G_Smart Grid Set of Standards 24 Version 3.1, CEN-CENELEC-ETSI Smart Grid Coordination Group, Oct 31th 2014.

9.1.2 Technology References

Such references provide information about a specific technology or a family of technology. They are of two kinds:

- references on the general background and tentative roadmap of the considered technology;
- references dealing with the current standardization for the considered technology (or family of technology).

For example, the section on “Technology Background & Roadmap” on transformers is based upon the following references:

- Siemens Energy Sector, Power Engineering Guide Edition 7.1, Chapter 5: Transformers;
- ABB Transformer Handbook;
- ABB Review Special Report Transformers.

The section on standards is based on a series of sources that are further detailed in green boxes:

– EN 50216: Power transformer and reactor fittings
– EN 50299: Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV
– EN 60076: Power transformers
– EN 60214: Tap-changers
– EN 61378: Convertor transformers

Usually the references on standards consist of several parts. These parts will be only considered when consistent with the scope of deliverable.

[37] Source Brunel

9.2 Annex 1: Overview of current standards

This section is organized by technology component, starting with the transformers. For each technology, a description of current standards is proposed.

9.2.1 Current standards on Transformers

9.2.1.1 EN 50216: Power transformer and reactor fittings

The European standard 50216 deals with the accessories for oil immersed and dry-type transformers and reactors. Generally, IEC standards do not distinguish between power transformers and distribution transformers. They are all power transformers in the sense that their purpose is to convert power from one voltage level to another. EN 50216 is divided into several parts. The first part provides general features and the remaining parts address different accessories. This European Standard was prepared by the Technical Committee CENELEC TC 14, Power transformers.

The text of the first part was submitted to the formal vote and was approved by CENELEC as EN 50216-1 on 2001-07-01. So far it has only one version, which has been published on 2002. Based on this standard EN 50216 standard consists of the following 7 parts, under the general title of “Power transformer and reactor fittings”.

Part 1: General – latest version 2002
Provides details regarding general conditions of service, electrical characteristics of contacts, dynamic characteristics, and mechanical construction.
Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator – latest version 2002
Provides details regarding the gas and oil actuated relay (Buchholz relay) for liquid immersed power transformers and reactors with conservator for indoor or outdoor installation. The device is responsible for detecting: gas release from the unit to be protected, oil surge from the tank to the conservator, and complete loss of oil in the conservator.
The standard provides specifications for the operating limits, dimensions, operational performance, electrical characteristics, and dynamic characteristics. It should be noted that the standard is only applicable to relays with dry contacts and is not used for flameproof relays.
Part 3: Protective relay for hermetically sealed liquid-immersed transformers and reactors without gaseous cushion – latest version 2002
Provides details regarding the protective relays for hermetically liquid-immersed transformers, complying with the EN 60076 series and reactors, complying with EN 60289, without gaseous cushions for indoor or outdoor installations.
The standard provides specifications for the operating limits, outline and mounting details, operational performance, electrical characteristics, and dynamic characteristics.
Part 4: Basic accessories (earthing terminal, drain and filling devices, thermometer pocket, wheel assembly) – latest version 2015
This standard supersedes EN 50216-4:2002, which will be withdrawn on 15 December 2017. In fact, this is the deadline fixed for any national standards conflicting with the EN 50216-4:2015 to be withdrawn by that time.
The standard defines basic accessories of transformers and reactors including: thermometer, earth terminals, draining plugs, filling openings, and rollers.
Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers – latest version 2002
As the title of the standard shows, EN 50216-5 defines the liquid level, pressure and flow indicators as well as pressure relief devices and dehydrating breathers for power transformer and reactor fittings.
Part 6: Cooling equipment – Removable radiators for oil-immersed transformers – latest version 2002
Provides details regarding radiators for cooling oil-immersed transformers. It specifies the overall dimensions and criteria to ensure interchangeability between radiators of different manufacturers.
Part 7: Electric pumps for transformer oil – latest version 2002
Specifies requirements for electric pumps used in transformers and reactors conforming to the EN 60076 series and their associated cooling systems. Electric pumps circulate the insulating oil in transformers and reactors. The pumps considered in this standard are rotodynamic pumps driven by a squirrel cage induction motor which is immersed in the insulating oil. Also the insulating oils considered to comply with subclause 2.5 of IEC 60296-1.
This standard specifies requirements for the electrical and hydraulic performance, mechanical design, routine testing and type testing. Furthermore, it provides performance and dimensions of preferred sizes of pump sets.

However, in later years after the publication of the first part, other parts have been also added to EN 50216 standard. These additional parts include:

Part 8: Butterfly valves for insulating liquid circuits – latest version 2005
Provides details regarding butterfly valves mounted on the pipelines, where the insulating liquid of power transformers or reactors flows. It is used to enable the replacement of components, without removing the whole or a large amount of the insulating liquid from the conservator and the tank.
This standard specifies the general overall dimensions as well as number of functional and manufacturing characteristics to ensure interchangeability.
Part 9: Oil-to-water heat exchangers – latest version 2009
Provides details regarding oil-to-water heat exchangers. This type of heat exchanger uses a forced oil circuit and a forced water circuit for the cooling of the transformer oil. They are more common on industrial units and it reduces the size of the active oil cooling part by using water as the cooling medium.
This standard specifies dimensions and the requirements to provide interchangeability.
Part 10: Oil-to-air heat exchangers – latest version 2009
Provides details regarding oil-to-air heat exchangers. This type of heat exchanger uses a forced oil circuit and a forced air circuit for the cooling of the transformer oil.
This standard specifies dimensions and the requirements to provide interchangeability.
Part 11: Oil and winding temperature indicators – latest version 2008
Provides details regarding oil and winding temperature indicators of the mechanical type with contacts for using with liquid immersed power transformers and reactors.
This standard specifies instruments characteristics in order to provide interchangeability.
Part 12: Fans – latest version 2011
Provides details regarding fans that are used for oil-to-air coolers in transformers. The standard specifications are only applied to fans operating axially.
This standard specifies dimensions and the requirements to provide interchangeability as well as uniform fan assembly.

9.2.1.2 EN 50299: Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV

This European Standard was prepared by the Technical Committee CENELEC TC 14, Power transformers. It deals with the oil-immersed connection assembly of cables for transformers and reactors conforming to the EN 60076 series. It provides details regarding the electrical and mechanical requirements (including interchangeability), the limits of supply, and the respective tests. The latest version of the standard was approved by CENELEC on 2014-10-13 and is divided into two parts.

Part 1: EN 50299-1 describes requirements for fluid-filled cable terminations, and
Part 2: EN 50299-2 describes requirements for dry-type cable terminations. These two parts supersede the previous version EN 50299:2002, which will be withdrawn on 13 October 2017

9.2.1.3 EN 60076: Power transformers

This European Standard applies to three-phase and single phase power transformers. It does not cover small transformer categories, such as single-phase transformers with rated power less than 1 kVA, three-phase transformers with rated power less than 5 kVA, instrument transformers etc. Furthermore, it does not cover special purpose transformers, such as traction transformers, testing transformers, welding transformers etc. It should be noted that this standard does not consider the specifications that a transformer may require to be suitable for mounting in a position accessible to the general public.

This European Standard was prepared by the IEC TC 14, Power transformers and is divided into different parts. The latest version of the first part (EN60076-1) was approved by CENELEC on 2011-05-25. Here, each part of the standard which is more relevant to this deliverable is briefly described.

Part 1: General – latest version 2011
Provides details regarding the requirements for transformers operation, rating, safety, environmental etc.
Part 2: Temperature rise for liquid-immersed transformers – latest version 2011
This standard covers the liquid-immersed transformers and provides details regarding the cooling methods employed by transformers. It also specifies limits for temperature rise and provides methods for temperature rise tests. The temperature rise is the temperature difference between the considered part of transformer, such as winding, and the external cooling medium.

Part 3: Insulation levels, dielectric tests and external clearances in air – latest version 2013
EN 60076-3:2013 supersedes EN 60076-3:2001, which will be withdrawn on 4 September 2016. This part provides details regarding the insulation requirements and the corresponding insulation tests according to specific windings and their terminals. It also recommends the minimum external clearances requirements in air. Clearance in air is defined as the shortest distance between any metallic part of the bushing terminal and any part of the transformer

Part 4: Guide to the lightning impulse and switching impulse testing – power transformers and reactors – latest version 2002
Provides guidance and explanatory information on the existing procedures for lightning and switching impulse testing of power transformers to supplement the requirements of IEC 60076-3. Details are provided regarding waveshapes, test circuits including test connections, earthing practices, failure detection methods, test procedures, measuring techniques and interpretation of results.

Part 5: Ability to withstand short circuit – latest version 2006
The ability to withstand short circuits is considered as a very crucial function of power transformers in the network. This standard specifies the requirements for power transformers to withstand the overcurrent caused by external short circuits. It provides calculation procedures for determining thermal ability as well as special tests and theoretical methods to evaluate the relevant dynamic effects.

Part 7: Loading guide for oil-immersed power transformers – latest version 2015
Recently, a draft version of EN 60076-7 Ed 2.0 has been published on 28 January 2015. There is a high probability that this document could be adopted by CENELEC as a reference standard. It is based on the previous version of the standard EN 60076-7 Ed 1.0 published on 2005. This standard provides detail regarding the effect of ambient temperatures and load condition on oil-immersed power transformer life.

Part 8: Application guide – latest version 1997
This standard provides information about fundamental service characteristics of different transformer connections and magnetic circuit designs, fault currents, parallel operation of transformers, calculation of voltage drop or rise under load, selection of rated and tapping quantities based on prospective loading cases, measuring technique and accuracy in loss measurement, etc.

Part 10: Determination of sound levels – latest version 2011
A draft version of EN 60076-10 Ed 2.0 has been published on 13 September 2011. If this document is published as a standard, it will supersede the previous version EN 60076-10:2001, which was approved by CENELEC on 2001-06-01. This standard provides methods for determining sound power levels of transformers and their associated cooling auxiliaries.

Part 10-1: Determination of sound levels – Application guide – latest version 2013
A draft version of EN 60076-10-1 has been published on 12 November 2013. There is a high probability that this document could be adopted by CENELEC as a reference standard. This standard provides supporting information for applying the measurement techniques presented in IEC 60076-10. The sources and characteristics of transformer sound as well as basic acoustics are described.

Part 14: Liquid-immersed power transformers using high-temperature insulation materials – latest version 2013
EN 60076-14:2013 supersedes EN 60076-14:2009, which will be withdrawn on 21 October 2016. This standard covers liquid-immersed transformers that use high-temperature insulation. It can be applied to power transformers consistent with EN 60076-1, converter transformers consistent with IEC 61378 series, etc. The insulation materials in normal liquid-immersed transformers, such as kraft paper, pressboard, wood, mineral oil, which operate within temperature limits provided in EN 60076-2, are considered as normal or conventional insulation. All other insulation materials that have a higher thermal capability are considered as high-temperature insulation.

Part 15: Gas-filled power transformers – latest version 2015
IEC 60076-15 standard applies to three-phase and single phase gas-filled power transformers. This part has not been considered by CENELEC yet.

Part 18: Measurement of frequency response – latest version 2013
Provides details regarding the measurement technique and measuring equipment for frequency response measurement. Frequency response analysis can be used to detect changes to the active part of the test object, such as windings, leads, and core. Interpretation of the result is not part of the normative text but some details has been provided in Annex B of the standard. This standard can be used for power transformers, reactors, phase shifting transformers and similar equipment.

Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors – latest version 2013
The losses of the transformers need to be considered in the evaluation of the total (service) costs and therefore play an important role in the investments. IEC 60076-19 is a Technical Specification and provides the procedures that should be applied to evaluate the uncertainty affecting the measurements of no-load and load losses during the routine tests on power transformers. This part has not been considered by CENELEC yet.

Part 20: Energy efficiency – latest version 2013
A draft version of EN 60076-20 has been published on 23 December 2013. There is a high probability that this document could be adopted by CENELEC as a reference standard. EN 60076-20 provides information for selecting a transformer with an appropriate level of energy efficiency based on the loading and operating conditions applicable. It should be noted that Energy efficiency is not the only criteria for selecting a transformer. The total capital and estimated lifetime operating and maintenance costs are also important factors that should be considered in selecting a transformer for the specific application.

Part 57-1202: Liquid immersed phase-shifting transformers – latest version 2014
A draft version of EN 60076-57-1202 has been published on 19 May 2014. This standard provides details regarding the requirements for phase-shifting transformers of all types. However, the scope excludes transformers with a fixed unregulated phase shift. It should be noted that this standard is particularly limited to phase-shifting transformers and does not cover general requirements for power transformers considered in the IEC 60076 series or IEEE C57.12.00.

9.2.1.4 EN 60214-1: Tap-changers. Performance requirements and test methods – latest version 2014

EN 60214-Part 1 applies to power and distribution transformers of all types. This standard is used for on-load tap-changers of both resistor and reactor types, de-energized tap-changers, and their motor-drive mechanisms. It is mainly used for tap-changers immersed in mineral insulating oil but may also be used for tap-changers with air or gas insulation or immersed in other insulating liquids insofar as conditions are applicable. Furthermore, it is mainly used for tap-changers with arcing contacts but may also be used for arcing-free on-load tap-changers (such as electronic switching) insofar as conditions are applicable.

9.2.1.5 EN 61378: Convertor transformers

In addition to the standard parameters of power transformers, special performance requirements have to be considered for the design of converter transformers. Currently, this standard is divided into three parts.

Except **Part 1,** which applies to **transformers associated with general "Industrial" converter uses**, in this deliverable the two remaining parts are considered.

Part 2: Transformers for HVDC applications – latest version 2001

There are two types of HVDC power transmission systems known as "back to back" and "transmission" schemes. The operation and evaluation of transformers operating within these two systems are considered in this standard. EN 61378-2 applies to oil-immersed three-phase and single-phase convertor transformers. It can be used for transformers that have two, three or multiple windings.

Part 3: Application guide – latest version 2015

This part has not been considered by CENELEC yet. EN 61378-3 provides information regarding specific topics related HVDC converter transformers with design, construction, testing and operating conditions differing from conventional transformers. In addition, it provides manufacturers with the technical background that forms the basis for the principles used within EN 61378-2.

It is intended that EN 61378-3 is used to supplement and not replace or supersede IEC 60076-8, the application guide for power transformers. Therefore, many of the general principles within IEC 60076-8 are equally applicable to converter transformers. Furthermore, EN 61378-2 does not explicitly cover transformers connected to Voltage Source Converters (VSC). As VSC applications are becoming more common, this standard also provides some details in this regard.

9.2.2 Current standards on Converters

9.2.2.1 EN 60071: Insulation co-ordination

IEC 60071 provides guidance on the procedures for insulation co-ordination. The insulation co-ordination is defined as the selection of the dielectric strength of equipment in relation to the operating voltages and over-voltages and considering the service environment as well as the characteristics of the available preventing and protective devices.

Part 5: Procedures for high-voltage direct current (HVDC) converter stations – latest version 2015

This part of IEC 60071 provides guidance on the procedures for insulation co-ordination of HVDC converter stations, without prescribing standardized insulation levels. It should be noted that this standard discusses insulation co-ordination related to CSC stations and the insulation coordination of VSC is not part of this standard. The basic principles and design objectives of insulation co-ordination of converter stations, in so far as they differ from normal AC system practice, are presented. This standard outlines the procedures for evaluating the overvoltage stresses on the converter station equipment subjected to combined DC, AC power frequency, harmonic and impulse voltages. The criteria for defining the protective levels of series and/or parallel combinations of surge arresters used to ensure optimal protection are also described.

9.2.2.2 EN 60099: Surge arresters

Part 9: Metal-oxide surge arresters without gaps for HVDC converter stations – latest version 2014

This part of IEC 60099 applies to non-linear metal-oxide resistor type surge arresters without spark gaps designed to limit over-voltages in HVDC converter stations of two terminal, multi-terminal and back-to-back type up to and including an operating voltage of 1100 kV. It should be noted that the arresters for VSCs are not covered. Furthermore, arresters applied on the AC systems at the converter station and subjected to power-frequency voltage of 50 or 60 Hz principally without harmonics are tested as per IEC 60099 - part 4. However, the arresters on AC filters are tested according to this standard.

9.2.2.3 EN 60146: Semiconductor converters

Part 1: General requirements and line commutated converters
Part 1-1: Specification of basic requirements – latest version 2010
This standard defines the performance requirements of all semiconductor power converters and semiconductor power switches using controllable and/or non-controllable electronic valve devices. The electronic valve devices mainly comprise semiconductor devices, either not controllable (i.e. rectifier diodes) or controllable (i.e. thyristors, triacs, turn-off thyristors and power transistors). This standard is primarily intended to specify the basic requirements for converters in general and the requirements applicable to line commutated converters for conversion of AC power to DC power or vice versa. Parts of this standard can be also used for other types of electronic power converter provided that they do not have their own product standards. These specific equipment requirements are applicable to semiconductor power converters that either implement power conversion or use commutation (for example semiconductor self-commutated converters).
Part 1-2: Application guide – latest version 2011
This part provides guidance on variations to the specifications given in IEC 60146-1-1 to enable the specification to be extended in a controlled form for special cases. Background information is also provided on technical points which should facilitate the use of IEC 60146-1-1.
Part 2: Self-commutated semiconductor converters including direct DC converters – latest version 2000
This part is used for all types of semiconductor converters of the self-commutated type including power converters. As mentioned in part 1-1 of the standard, the requirements of IEC 60146-1-1 can be also used for self-commutated converters as far as they are not in contradiction to this part.

9.2.2.4 IEC/TR 60919: Performance of high-voltage direct current (HVDC) systems with line-commutated converters

The document has not been fully considered by CENELEC yet and only part 2 of the technical report has been considered. The document can be applied to the two-terminal HVDC systems utilizing 12-pulse converter units comprised of three-phase bridge (double- way) connections. It should be noted that the document does not cover multi-terminal HVDC transmission systems. Both terminals are assumed to use thyristor valves as the main semiconductor valves and to have power flow capability in both directions. Line-commutated converters are covered in this document and VSCs are not considered.

Part 1: Steady-state conditions – latest version 2010 + amendment 1 2013
This part provides general guidance on the steady-state performance requirements of high-voltage HVDC systems. Basically, performance specifications are specified as a single package for the two HVDC substations in a particular system. Alternatively, some parts of the HVDC system can be separately specified and purchased. In such cases, coordination of each part with the overall HVDC system performance objectives needs to be considered and the interface of each with the system should be clearly defined.
Part 2: Faults and switching – latest version 2008
This part of the document provides guidance on the transient performance and fault protection requirements of HVDC systems.
Part 3: Dynamic conditions – latest version 2009
This part provides general guidance on the dynamic performance of HVDC systems. In the technical report the dynamic condition is described as those events and phenomena whose characteristic frequencies or time domain cover the range between transient conditions and steady state.

9.2.2.5 EN 61803: Determination of power losses in high-voltage direct current (HVDC) converter stations – Latest version 1999 + A1 2010 + A2 2014

There is a high probability that the latest version of this standard could be adopted by CENELEC as a reference standard. This standard provides a set of standard procedures for determining the total losses of an HVDC converter station. It addresses no-load operation and operating losses together with their methods of calculation. It should be noted that the standard applies to all line-commutated HVDC converter stations used for power exchange in utility systems. This standard presumes the use of 12-pulse thyristor converters but can, with due care, also be used for 6-pulse thyristor converters.

9.2.2.6 EN 62501: Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission. Electrical testing – latest version 2009 + A1 2014

This standard applies to self-commutated converter valves, for use in a three-phase bridge VSC for high voltage DC power transmission or as part of a back-to-back link. The tests specified in this standard are based on air insulated valves. For other types of valves, the test requirements and acceptance criteria must be agreed. This standard can be used as a guide for testing of STATCOM valves as well.

9.2.2.7 IEC/TR 62543: High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC) – latest version 2011 + A1 2013

This technical report has not been considered by CENELEC yet.

The report provides general guidance regarding self-commutated VSCs. The scope includes 2-level and 3-level converters with PWM, along with multi-level converters, modular multi-level converters and cascaded two-level converters, but excludes 2-level and 3-level converters operated without PWM, in square-wave output mode. The various types of circuit that can be used for VSC-based transmission are discussed, alongside their principal operational characteristics and typical applications. The overall aim is to help purchasers with the task of specifying a VSC transmission scheme. It should be noted that this technical report does not cover the CSCs.

9.2.2.8 IEC/TS 62672: Reliability and availability evaluation of HVDC systems

This a technical specification that has not been considered by CENELEC yet. In exceptional circumstances, an IEC technical committee may propose the publication of a technical specification when:

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

Part 1: HVDC systems with line commutated converters – latest version 2013
This part applies to all CSC-based HVDC systems and VSC-based HVDC systems are not covered.
Reliability and availability need to be evaluated in assessing the operational performance of HVDC systems. This technical specification defines a standardized reporting protocol so that data collected from different HVDC transmission systems can be compared on an equitable basis.

9.2.2.9 EN 62751: Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems

Part 1: General requirements – latest version 2014
This part provides general principles for calculating the power losses in the converter valves of a VSC-based HVDC substation, independent of the converter topology. This standard can be also used as a guidance for the power losses of the valves for a STATCOM installation. Apart from the converter valves, this standard does not cover the power loss calculations for other devices in HVDC substation. For calculation of power losses of equipment in a VSC-based substation, a similar procedure as provided for CSC-based substations in EN 61803 standard can be used.

9.2.3 Current standards at substation level

9.2.3.1 IEC 61850: Communication networks and systems for power utility automation

IEC 61850 is a communication standard released by the Technical Committee (TC) 57 of IEC. The goal of this standard is to provide interoperability between the IEDs from different suppliers or, more precisely, between functions to be performed for power utility automation. It was originally introduced for the design of Substation Automation Systems (SAS). It defines communication between IEDs in substations and related system requirements. As a consequence of employing advanced and fast devices, the efficient and high-speed communication infrastructure has become an important issue in the substations. The IEC 61850 standard has enabled IEDs and devices in a substation to be integrated on a high-speed peer-to-peer communication network as well as client/server. In this standard, the application is independent from the communication protocol by specifying a set of abstract services and objects. IEC 61850 applies Object Oriented (OO) data and service models to support all substation functions. This provides more flexibility to the developer and users as well as simplifying engineering tasks [14].

The IEC 61850 set of documents is comprised of 10 parts, which each part defines a specific aspect of the standard.

- **IEC 61850-1**: Introduction and overview
- **IEC 61850-2**: Glossary of specific terminology and definitions
- **IEC 61850-3**: General requirements of the communication network with regard to the quality requirements, environmental conditions, and auxiliary services
- **IEC 61850-4**: System and project management with respect to the engineering process, the life cycle of the SAS, and the quality assurance
- **IEC 61850-5**: Communication requirements for functions and device models
- **IEC 61850-6**: Configuration description language for communication in electrical substations related IEDs
- **IEC 61850-7**: Basic Communication structure:
    - **IEC 61850-7-1**: Principles and models
    - **IEC 61850-7-2**: Abstract Communication Service Interface (ACSI)
    - **IEC 61850-7-3**: Common Data Classes
    - **IEC 61850-7-4**: Compatible logical node classes and data classes
    - **IEC 61850-7-5**: Application guide and usage of information models
- **IEC 61850-8**: Specific communication service mapping (SCSM)
    - **IEC 61850-8-1**: Mappings to MMS and to ISO/IEC 8802-3
- **IEC 61850-9**: Specific communication service mapping (SCSM)
    - **IEC 61850-9-1**: Sampled values over serial unidirectional multi-drop point to point link
    - **IEC 61850-9-2**: Sampled values over ISO/IEC 8802-3
- **IEC 61850-l0**: Conformance testing

IEC 61850-5 defines the communication requirements for functions and device models for power utility automation systems. The power utility functions refer to tasks which have to be performed by the automation system. These are functions to monitor, protect, control and maintain the system for reliable and economic operation. For specifying the communication requirements, all the functions need to be identified. Each IED includes various simple and complex functions that can be different in terms of supplier. In IEC 61850, functions are split into indivisible pieces called Logical Nodes (LN), which are then used to communicate. In fact, these virtual units are the objects specified in the OO approach of the standard. For example, a virtual representation of a circuit breaker class as a LN with the standardised class name XCBR. This is one of the important advantages of the standard over legacy protocols. In other words, each individual function can be built up by integrating the required LN from the standard. This allows identification of all functions independently from IEDs and supporting future implementations. The LNs are modelled and their requirements are defined from the conceptual application point of view in IEC 61850-5 [25].

Part 7-1 of the IEC 61850 series provides an overview of the architecture for communication and interactions between systems for power utility automation. It introduces the modelling methods, communication principles, and information models that are used in the various parts of the IEC 61850-7-x series. In addition, it describes the relationships between different parts of the IEC 61850 series. The modelling and implementation approaches applied in the different parts of the standard and their relation are shown in [26]. IEC 61850 documentation is quite extensive. There are also normative and informative documents in the standard. Technical specifications provide guidelines for applying the standard for various applications areas and communication mapping. For example, using IEC 61850 between control centre and substations together with IEC 60870-5-101 or 104 (specified in IEC 61850-80-1). Technical reports provide recommendations about applying the standard and for further enhancements or extensions. For example, using IEC 61850 standard to transmit synchrophasor information according to IEEE C37.118 (specified in IEC 61850-90-5). The LNs, data, data attributes and service parameters are defined in order to provide the information required to perform an application as well as exchange of information between IEDs. A logical node groups number of data classes to build up a specific functionality. Over one hundred logical nodes covering the most common applications of substation and feeder equipment are defined in IEC 61850-7-4. The applications include various functions for measurement, monitoring, protection, control etc. The whole set of all the data attributes defined for the data is called Common Data Class (CDC). IEC 61850-7-3 defines CDCs for a wide range of applications.

The information exchange is defined by means of services and the categories of services are presented in IEC 61850-7-2. The provided services are called abstract services. Abstract means that only those aspects that are required to describe the relevant actions on the receiving and sending side of a service request are defined. The abstracting technique is the dominant architectural construct that IEC 61850 adopts. This feature provides the definition of objects that are independent of any underlying communication protocols. In other words, abstract means that the standard only determines what the services are intended to provide, rather than how they are built. Therefore, abstraction allows various mappings of services appropriate for different requirements. Furthermore, the system will be compatible with the future developments in the communication technology as there is no need to change models, databases, etc. Additional mappings to other communication stacks are possible. However, in order to maintain interoperability efficiently, the number of adopted mappings in the standard should be limited [27].

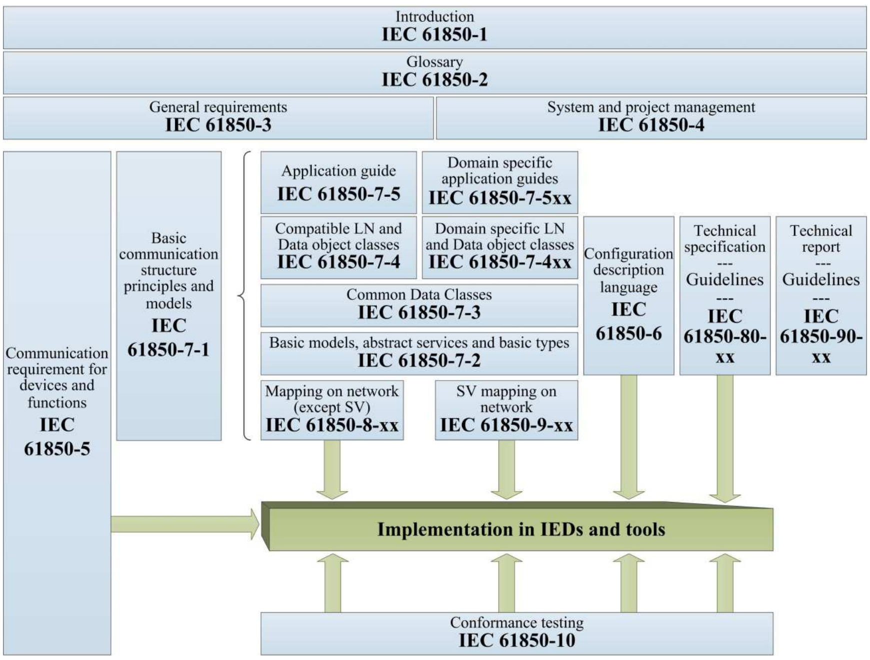

Figure 41: Relations between IEC 61850 parts

The semantic of the service models with their attributes are defined in IEC 61850-7-2 based on the functional requirements in IEC 61850-5. The communication services can be categorized into two groups. One group is based on client-server model and the other one uses peer-to-peer model. Overall, IEC 61850 standard provides five types of communication services. Among these services, Generic Object Oriented Substation Event (GOOSE) and Sampled Value (SV) are mapped directly to the data link layer. Therefore, they eliminate processing of any middle layers and increase the performance [27]. GOOSE service is used for time-critical purposes (such as fast transmission of data between protection IEDs), and SV service is used for transmission of data on a periodic basis (such as transmission of measured values from merging units). A GOOSE message should at least be generated each time when a value from members referenced by the data-set varies. The transmission of SVs also requires special consideration with regard to the time constraints.

9.2.4 Current standards on protection and control at system level: WAMS

9.2.4.1 IEEE Standard for Synchrophasors for Power Systems

The primary purpose of the synchrophasor standard is to ensure PMUs interoperability. The first standard for synchrophasors, IEEE 1344, was introduced in 1995 and was reaffirmed in 2001. It defined basic concepts for the measurement and method for data handling. However, technology is constantly evolving and standards should be updated in order to accommodate new requirements. Thus, the new standard IEEE C37.118 was published in 2005, which significantly improved the previous standard, while still maintained basic compatibility. The IEEE C37.118-2005 standard specified a set of fundamental characteristics including: Time Reference (UTC), Rate of Measurement, Phase Reference (cosine), Accuracy Metrics (Total Vector Error), and Communication Model (format of messages). By defining these specifications, the real-time and off-line processing of synchrophasor data from different measuring systems can be performed more easily. Although the publication of IEEE C37.118-2005 was an important step in standardizing phasor measurements, the standard does not cover all aspects. For example, it does not specify PMU performance requirements under dynamic conditions, which could lead to PMUs using the same standard to show different results under transient situations. Moreover, it does not address frequency measurement requirements, and does not specify communication protocol, as it only defines the data format with basic methods for data transfer [47], [48].

Due to the above issues, further work was done to revise the standard in 2008. In addition, IEC 61850 was proposed to be employed as a communication standard for transferring measured synchrophasors [49]. However, there were some problems in merging C37.118 into IEC 61850. As a solution to these issues, it was proposed to split the C37.118 standard into two parts. In fact, the revision separates the measurement and communication sub-clauses into individual standards. This facilitates widespread adoption and deployment of this standard by allowing freer use of other standards for synchrophasor communication. The two new revised standards were completed and published in December 2011. The first part, C37.118.1-2011, includes the synchrophasor measurement definitions and requirements, and the second part, C37.118.2-2011 includes a new standard for synchrophasor data transfer, which is designed to be compatible with the IEC 61850. Both standards have maintained features from the previous version, but with updates and additional provisions.

Part 1: IEEE Standard for Synchrophasor Measurements for Power Systems – latest version 2011 + amendment 1 2014
This standard defines synchronized phasor and frequency measurements across power system using PMUs. In addition, it specifies a set of performance requirements for evaluating these measurements and compliance of devices from different manufacturers. When the measurements taken from various substations in power grid are compliant with the standard, they are comparable and can be accurately combined for power system operation analysis. This standard has five clauses along with six informative annexes. The details regarding measurements accuracy and evaluation criteria as well as PMUs reporting times are provided in Clause 5. The values obtained from a PMU and the actual theoretical values of parameters may be show differences. In order to assess the accuracy of measurements, this standard defines the uncertainty requirements for the PMUs in terms of Total Vector Error (TVE). It defines the TVE as a vectorial difference between the measured and theoretical values of the phasor, expressed as a fraction of the magnitude of the theoretical phasor [50]. Apart from the TVE, the standard defines criteria for evaluating errors in frequency and rate of change of frequency (ROCOF) measurements. In addition, measurement response time and delay time as well as measurement reporting latency are also considered for the exact analysis of PMUs operations. This standard defines two classes of performance: P class and M class. P class is used for applications requiring fast response. The letter P is adopted since protection applications require fast response. M class is used for applications that do not require the high reporting speed. The letter M is adopted since analytic measurements often require greater precision rather than minimal reporting delay. Therefore, the standard evaluates the compliance with requirements in accordance with the PMU's class of performance.
Part 2: IEEE Standard for Synchrophasor Data Transfer for Power Systems – latest version 2011
This standard defines a method for real-time exchange of synchronized phasor measurement data in power systems. It specifies data transmission formats that can be used with any suitable communication protocol for real-time data transfer between PMUs, PDCs, and relevant smart grid applications. It does not impose any constraints on the communication system or media itself. In fact, any communication system that is able to support the provided message structure in the standard and has sufficient bandwidth can be deployed for PMUs data transmission. The required bandwidth depends on the reporting rate and message size. The message size in turn corresponds to the parameters included in the frame. This standard has six clauses along with six informative annexes. The Clause 6 is the main one that defines the real-time communication protocol and message formats. Informative annexes are provided to clarify the standard and give supporting information about communication options and requirements. Four message types are defined in this standard, which are: data, configuration, header, and command. The first three message types are transmitted from the data source, PMU or PDC, and the last one is received by the data source.

9.2.4.2 Modbus

The Modbus transmission protocol was developed by Gould Modicon (now Schneider) for process control systems. Basically, Modbus is a simple, inexpensive, robust, and easy to use serial communications protocol that has become a de facto standard communication protocol in the industry since 1979 [51], [52]. In fact, Modbus is an application layer protocol positioned at level 7 of the Open Systems Interconnection (OSI) model. It provides client/server communication for one server and up to 247 clients, which are connected to the different networks. Transactions are either a query/response type where only a single client is addressed, or a broadcast/no response type where all clients are addressed. In either case only the server initiates messages and in other words report by exception is not supported except for Modbus over Ethernet TCP/IP. Therefore, the server must routinely poll each client to identify changes in the data. Accordingly, this occupies bandwidth and takes much time that is more significant where bandwidth is limited and expensive, such as over a low-bit-rate radio link. Modbus is currently implemented using the following different transmission protocols [51], [53]:

- TCP/IP over Ethernet
- Asynchronous serial transmission over variety of media (wire RS-232, 422 or 485, fiber, radio, etc.)
- Modbus Plus, a high speed token passing network (which is currently proprietary to Modicon)

For Asynchronous Modbus and Modbus Plus the application Data Unit (ADU) is directly mapped to the physical layer, while in Modbus Ethernet TCP/IP it is first passed through the transport and the network layers.

9.2.4.3 IEC 60870: Telecontrol equipment and systems

In 1988, IEC started publishing a standard entitled 'IEC 870 telecontrol equipment and system'. The standard was developed and published progressively and was later renamed IEC 60870, by adding the prefix 60.There are six main parts in the standard of which part five is for transmission protocols. IEC 60870-5 was developed in a hierarchical manner in five core sections alongside four companion standards in order to define an open standard for SCADA communications and wide area processes. The IEC 60870 protocol is mainly used in the electrical industries of European countries, and has data objects that are specifically provided for such applications [54]. Primarily, the three-layer Enhanced Performance Architecture (EPA) was adopted as the basis for data transmission in the IEC 60870 standard. The EPA is the simplified three-layer sub-set of the OSI seven-layer model and consists of application, data link and physical layers. One layer is normally added to the top of the EPA model, which is defined as the "user process" layer. This extra layer represents the various functions or processes that must be specified to provide telecontrol system operations [55].

When it is discussed about IEC 60870 in the field of SCADA system, the IEC 60870-5-101 part of the protocol has the key role. This companion standard is called 'Companion Standard for Basic Telecontrol Tasks". It provides the application level data objects that are required for SCADA operations. IEC 60870-5 set of standards was initially published on the basis of IEC 60870-5-101 profile. It covered only transmission over relatively low bandwidth bit-serial communication circuits. But after increasing of network communication applications, the fourth companion standard IEC 60870-5-104, was introduced in order to define the transport of IEC 60870-5 applications messages over networks using the TCP/IP protocol. IEC60870-5-104, which is titled 'Network Access using Standard Transport Profiles' provides a different physical and data transport procedure compared to IEC 60870-5-101. In this protocol the lower levels of the protocol have been completely replaced by the TCP and IP transport and network protocols, respectively. However, it retained most of the higher application level functions and data objects as it was. TCP and IP protocols are applied for transport of the Application Service Data Units (ASDUs) over local area and wide area networks. IEC 60870-5-102 and IEC 60870-5-103 companion standards provide data types and functions to support electrical protection systems. However, here the main focus is on the T101 and T104 companion standards [51].

Whereas T101 provides full definition of the protocol stack right down to the physical level, this is not provided under T104 as existing and varied physical and link layer operations are employed. IEC 60870-5-101 supports point-to-point and multidrop communication links carrying bit-serial low-bandwidth data communications. It also provides the choice of using balanced or unbalanced communication at the link level. Under unbalanced communication, only the master can initiate communications by transmitting primary frames. As the slaves are not able to initiate a transaction, the collision avoidance process is not required. Under T101 profile the balanced communication can be used only for the point-to-point links. This means that T101 profile cannot support unsolicited messages from slaves, in order to send data directly to the master, for the multidrop topologies. Therefore, it must adopt a cyclic polling procedure to inquire about the secondary stations [51].

9.2.4.4 Distributed Network Protocol Version 3 (DNP3)

During the same period that IEC 60870-5 was gradually published, the DNP3 protocol was developed and introduced in North America. In fact, they originated from a common point provided by the early IEC 870 document [51]. Nevertheless, they differ in many aspects of physical, data link and application functions. Initially, Harris Control Division created DNP3 as a proprietary protocol for electrical industry applications in the early 1990s. However, in November 1993 the protocol ownership was transferred to the DNP3 User Group in order to use it as an open standard in industry. Both DNP3 and IEC 60870-5 were developed fundamentally for SCADA applications. These entail acquisition of information and sending of control commands between master stations, RTUs and other IEDs. They are designed in a way to transmit relatively small packets of data in a deterministic sequence and reliable manner. Therefore, they are distinct from more general purpose communication protocols, such as FTP. Whereas these kinds of protocols can send quite large files, they are not suitable for SCADA applications [49].

DNP3 supports multi-slave, peer-to-peer, and multiple master communications. It uses only balanced communications so it supports report by exception as well as polled operational mode. Report by exception capability enables the outstation devices to send unsolicited messages to the master station. This provides efficient use of the communication system capacity and greater flexibility. It should be noted that although the outstation devices can initiate the communication in DNP3, only the master station could initiate a request for data or send commands [51]. DNP3 same as IEC 60870-5 is based on EPA model. However, it adds some kind of transport functions, which are represented as a layer named “pseudo-transport”. This layer is located below the application layer and provides the transmission of larger data blocks than data link layer. Due to the need for operating over larger geographical areas, it has been also proposed to use Internet Protocol suite and Ethernet for DNP3. In this case the transport, network and data link layer related to the TCP/UDP, IP and Ethernet are added at the bottom of the pseudo-transport and data link layer of DNP3 [49].

9.2.4.5 IEC 61850: Communication networks and systems for power utility automation

Although the scope of IEC 61850 was initially limited to the inside of substations, it is believed that the capabilities of IEC 61850 can be used to improve wide area communication applications. The integration of IEC 61850 for PMU communications is one of the proposed applications [56].

Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118 – latest version 2012

This technical report provides a way of sending PMUs data to PDCs and control centre applications based on IEC 61850. As the PMUs generate data based on IEEE C37.118 standard, the data needs to be transmitted in such a way that is also compliant to the concept of IEC 61850. In addition, PMUs data are transmitted over wide area where they need a routable profile. Basically, IEC 61850 does not provide a network layer protocol. Therefore, this protocol does not inherently provide routing capability required for wide area applications. Accordingly, the IEEE 61850-90-5 standard has been proposed to provide routable profiles for IEC 61850-8-1 (GOOSE) and IEC 61850-9-2 (SV) services. These routable services are shortly called R-GOOSE and R-SV, respectively. The Internet Protocol (IP) is one of the options for communications over wide area. This is the protocol that IEEE C37.118.2 standard uses for transmission of data over network. Although IEEE C37.118.2 allows communication over IP using both the TCP and UDP transport protocols, IEC 61850-90-5 focuses on UDP. As described, IEEE C37.118.2 defines four message types of Data, Configuration, Header, and Command. Therefore, in order to be compliant with IEC 61850, the functions that are performed by these frame types need to be mapped to the existing services in IEC 61850. The control and configuration services are mapped to the conventional IEC 61850 MMS over TCP/IP; while data need to use the proposed R-GOOSE or R-SV services. According to the IEC 61850 standard services, the fast cyclic communications are typically based on SV and additional event data can be communicated using GOOSE.

9.3 Annex 2: list of references on technology background & roadmap and on standards

9.3.1 Transformers and PSTs

9.3.1.1 Technology background & roadmap

- Siemens Energy Sector, Power Engineering Guide Edition 7.1, Chapter 5: Transformers
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- ABB Transformer Handbook http://new.abb.com/products/transformers
- http://new.abb.com/products/transformers
- ABB Review Special Report Transformers
- http://new.abb.com/products/transformers
- Think Grid no.8, Alstom Grid, spring/summer 2011.

9.3.1.2 Standards

- Power Transformers, Strategic Business Plan, IEC/TC 14, October 2014.
- EN 50216: Power transformer and reactor fittings
- EN 50299: Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment Um from 72,5 kV to 550 kV
- EN 60076: Power transformers
- EN 60214-1: Tap-changers. Performance requirements and test methods
- EN 61378: Convertor transformers

9.3.2 Converters

9.3.2.1 Technology background & roadmap

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9.3.2.2 Standards

- EN 60071: Insulation co-ordination
- EN 60099: Surge arresters
- EN 60146: Semiconductor converters
- IEC/TR 60919: Performance of high-voltage direct current (HVDC) systems with line-commutated converters

- EN 61803: Determination of power losses in high-voltage direct current (HVDC) converter stations
- EN 62501: Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission
- IEC/TR 62543: High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)
- IEC/TS 62672: Reliability and availability evaluation of HVDC systems
- EN 62751: Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems

9.3.3 FACTS

9.3.3.1 Technology background & roadmap

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9.3.3.2 Standards

- EN 60143: Series capacitors for power systems
- EN 61954: Static VAR compensators (SVC) — Testing of thyristor valves
- EN 62823: Thyristor valves for thyristor controlled series capacitors (TCSC) - Electrical Testing
- EN 62927: Voltage sourced converter (VSC) valves for static synchronous compensator (STATCOM) - Electrical Testing

9.3.4 Protection & control at system and substation levels

9.3.4.1 Technology background & roadmap

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9.3.4.2 Standards

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