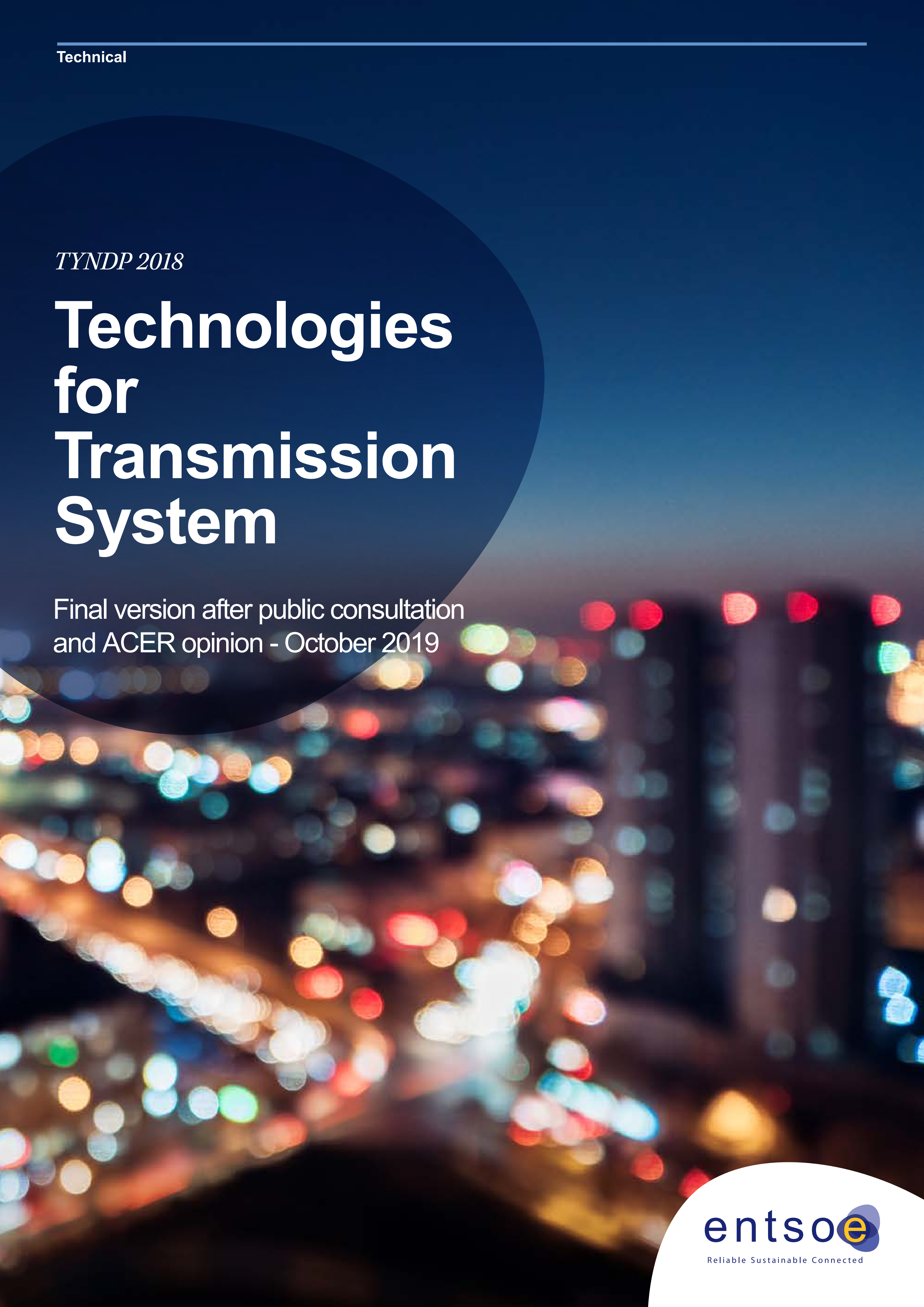
TYNDP 2018

Technologies for Transmission System

Final version after public consultation
and ACER opinion - October 2019



entsoe
Reliable Sustainable Connected

Contents

ENTSO-E Reports 2018

As an improvement to the TYNDP 2018 package, the Insight Reports have been categorised in order to help readers navigate through the document and focus on what readers might find of interest. The category of reports are:

— Executive Report – Contains the key insights of the whole TYNDP package through its two-year cycle.

— Regional Reports – Based on the four projects of common interest (PCI) regions, the reports focus on the regional challenges of the energy transition.

— Communication – These reports communicate how we have interacted with our stakeholders and improved the TYNDP package from 2016 to 2018.

— Technical – These reports give a deeper insight into the technical subjects, including how we use our data, and the technical challenges of energy transition.

We hope this guide is of benefit to all stakeholders.

Main Report

Regional Reports
- North-South Interconnections East
- North-South Interconnections West
- Northern Seas Offshore Grid
- Nordic & Baltics

Communication
- Stakeholder Engagement
- Improvements to TYNDP 2018

Technical
- Data and Expertise
- Technologies for
- Transmission
- Viability of the Energy Mix
- CBA Technical

Adequacy
- Mid-Term Adequacy Forecast

Foreword

Technology advancements offer project promoters many solutions for future network development, as defined in the TYNDP. Together with state of the art technologies, new technologies will be incorporated with the existing infrastructure. These technologies have their own learning curves and innovation cycles. Project promotors, regulators and policy makers need to understand each technology and their availability by the time of project development.

The projects in the TYNDP comprise of alternating and direct current technologies, overhead lines, onshore and offshore cables as well as technologies for optimisation of grid operation as for example dynamic line rating, FACT's, WAMS etc. Therefore, technologies for future network development can be grouped as follows:

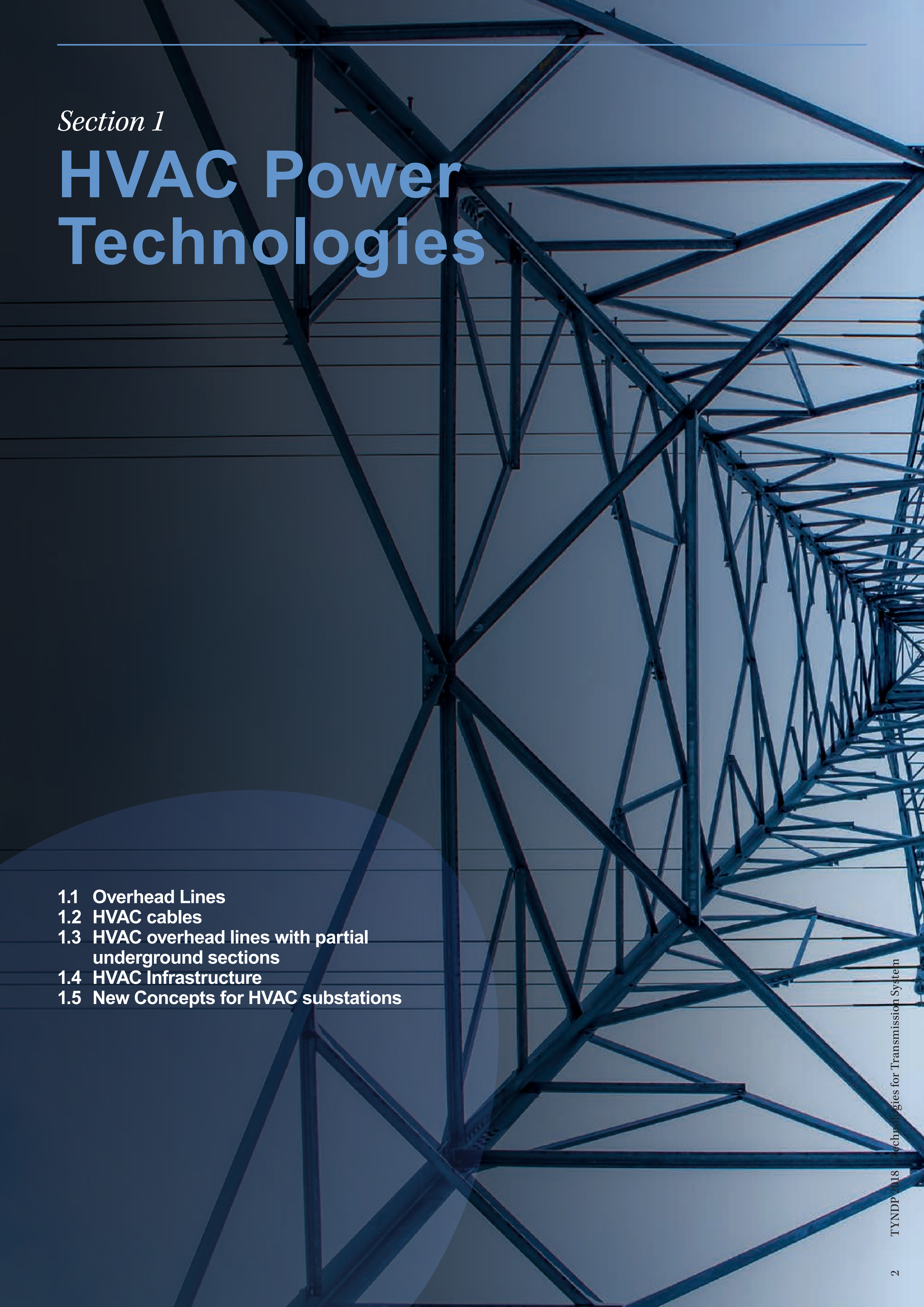
— High voltage alternating current (HVAC) power technologies
— High voltage direct current (HVDC) power technologies
— Hybrid HVAC/HVDC power technologies

This report aims at providing an assessment of transmission technologies available today and project their availabilities beyond the next ten years, to 2030. The report cross refers to the technology related deliverables of the e-Highway2050 project **(http://www.e-highway2050.eu/results/)** which readers are recommended to read for detailed information.

The present report focuses on the availability of technologies and the time by which they might be in service. It provides a high-level view of a technology spectrum for project promotors to select and investigate further technologies that could best suit their projects.

The application of the technologies that are included in this report to specific projects requires more thoughtful studies. The availability of the technology on the market does not mean it can be applied without any restrictions to any project. Such decisions are typically more complex and include technical, economic, environmental and system wide investigations. Hence TYNDP can only derive an overview of the technology maturity from this document. It is assumed that the TSOs who are going to apply any technology in their network, will carry out comprehensive studies before the projects are placed in TYNDP process. Last but not least, the list of the technologies should not be assumed as exhaustive.

This report is jointly drafted by experts from TSOs, ENTSO-E, T&D Europe, Europacable, Orgalime and Friends of the Super Grid.



Section 1

HVAC Power Technologies

1.1

Overhead Lines

The overhead line is the state of the art technology for a secure and efficient energy supply all over the world.

Current developments and research is on all the various components in the construction of overhead lines including conductors (e.g. see high-temperature conductors below), insulators and tower designs.

1.1.1 High-temperature conductors

Nowadays, many conductor types are available allowing higher currents to be carried at higher conductor temperatures. Those conductors, such as Aluminum Conductor Steel Supported (ACSS), Aluminum Conductor Composite Core (ACCC), Aluminum Conductor Composite Reinforced (ACCR) are made of materials with a broader range of arrangement possibilities than conventional Aluminum Conductor Steel Reinforced (ACSR).

The application of high-temperature conductors (HTC) allows the capacity of an existing line to be increased without large changes to existing support structures (Figure 1.1). Basically, there are two types of HTC:

- HTC with standard sag behavior – conductors which can be operated at higher temperatures (e.g. >80°C) which sag depends linearly on conductor temperature. Frequently, the present clearances limit the ampacity of the line and not the maximal conductor temperature.
- HTC with low sag behavior (so called HTLS high temperature low sag conductors) – conductors which can be operated at higher temperatures (e.g. >80°C) whose sag is strongly nonlinear. These conductors can be applied if there are restrictions concerning the clearances.

The cost and thermal losses of HTLS are typically higher than conventional conductors. However, HTLS can enhance security reserves (covering as a minimum for the loss of one item of plant and equipment) and transmission capacity without impacting the negotiated right-of-way, ideally with minor modifications of transmission towers (mostly clamps of the conductors and their mountings). Although existing lines are used, in some countries such projects have to go through authorization or impact assessment procedure again, especially when magnetic field levels are increased as the expected currents are higher.

HTLS conductors are different type of technologies according to Table 1.1 of TB Cigré 426 (see overleaf). Some solutions are already proven technologies in operational environmental (ZTACIR, GZTACSR, TACSR) with higher TRL (9), while other HTLS with Polymer matrix composites can be considered at lower TRL (7).

Figure 1.1: Sag comparison at 180°C

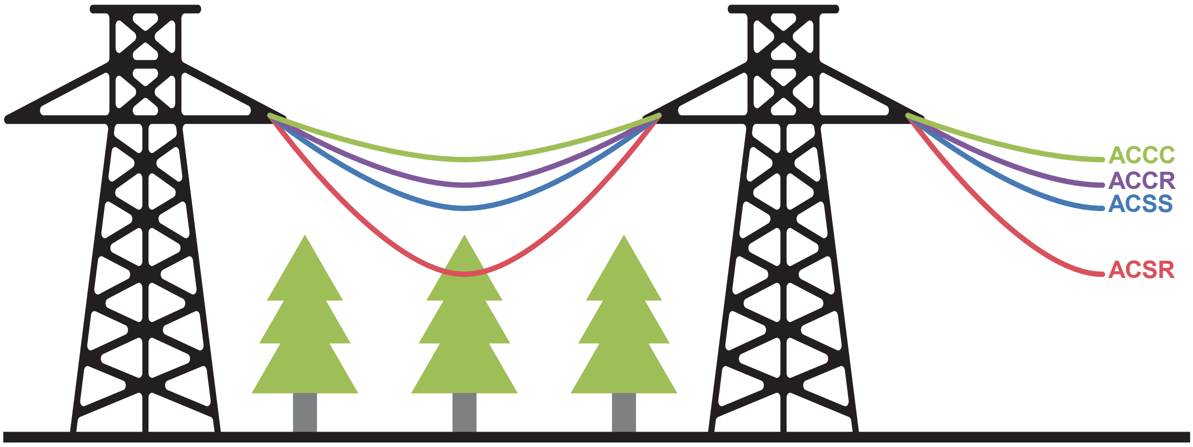


Table 1.1: Constituent Materials used in HTLS Conductors

Iron-based strands
Steel (regular-, high-, extra-high-, ultra-high- strength)
Coated steel (galvanized, aluminium-clad, aluminium-5%mischmetal clad)
Invar (typically Fe-Ni alloy – with coatings above)
Aluminium
Hard drawn pure aluminium
Annealed pure aluminium
Heat-resistant aluminium (aluminium-zirconium alloys). TAL (A1). ZTAL (A3)
High strength aluminium alloys (6201 etc) (aluminium-magnesium-silicon alloys)
Aluminium composite (aluminium reinforced with fibres)
Polymer
Polymer matrix composites (resin with carbon fibres)

There are many examples where the choice of HTC has been made for projects in the TYNDP: the 260 km long 400 kV overhead line between France and Italy, the 80 km 400 kV double circuit line between Belgium and France, the ongoing upgrade of a 220kV line in Poland, and in Belgium the Horta-Mercator and Gramme-Van Eyck lines.

1.1.2 Dynamic Line Rating

The rated ampacity of overhead lines is determined based on the worst case ambient weather conditions in the considered country. For example, in Europe the chosen ampacity should not lead to exceed of maximal operating temperature conductor (for conventional conductors 80°C) at following ambient conditions 35°C ambient temperature, 0,6m/s wind speed and 900W/m2 global solar radiation. It is obvious that these conditions occur very seldom in a year. For most of the time the ambient temperatures are lower and wind speeds higher. These conditions improve cooling of the overhead line conductors. Herewith, the ampacity of overhead line can by dynamically adapted to current or forecasted ambient conditions in order to increase the ampacity of the line. An increase of ampacity can be achieved from 15% up to 50% depending on the typical regional weather conditions. The higher rates can be achieved in regions where high wind generation have a strong transversal cooling effect on the line conductor. However, the DLR may also predict a necessary decrease of the load on the conductor, especially in some heavy sunny conditions with few adverse cooling effects.

Application of dynamic line rating requires the precise knowledge of ambient weather conditions and conductor sag along the considered OHL. In dispatching centres, the grid loading/operation is planned a day ahead. Hence there also exists a necessity to forecast the ampacity based on weather measurements and/or its forecasts.

In addition, the application of DLR may require:
- Extensive condition assessment of OHL and equipment in substations
- A reliable predictive computation model
- Adapting the settings of protection devices
- Extending the dispatching centre for processing dynamic line ratings in congestion calculation

Consequently, due to the need for accurate prediction of future operating conditions, dynamic line rating is typically applied in an operational timeframe where there is an appropriate level of accuracy in future weather predictions, as opposed to longer term network planning where future weather conditions cannot be predicted with any certainty.

1.1.3 New tower designs

In many countries (e.g. Germany, Netherland, Belgium) new tower designs have recently been introduced. The trend from the lattice towers towards steel or concrete pylons is observed. The main driving factor is improvement of the public acceptance by reduction of emission and visual impact of the towers. The new tower designs have been applied to date as pilot projects and do not have a status of a standard application yet. The lattice towers are used widely because of their proven record of good service experience and cost efficiency.

1.1.4 Voltage uprating

For bulk energy transmission, voltages above 145kV are typically used. By uprating the voltage of the line, the transmission capacity of existing corridors can be significantly increased.

The need for refurbishment of old 220kV lines frequently raises a question of whether to uprate the voltage to 380kV on the same right of way. Such uprating typically requires new and higher towers and new bundled conductors to maintain the same noise emission level. Many examples of such uprating can be found in literature.

The use of voltages above 420kV for example of 550kV or 750kV using overhead lines is not very common in Europe. There are currently only very few overhead lines in operation at these voltages. However numerous applications can be found worldwide. The main barrier for application of higher voltages is by permitting. Such voltage upgrade typically requires higher towers in order to remain on the same EML-Level brighter right of way because of larger conductor swing out and higher distances to public possessions due to potentially increased noise emissions.

1.2

HVAC cables

Typically, cables are used as an alternative when an overhead line is not appropriate, e.g. offshore, in densely populated areas and areas of Outstanding Natural Beauty or across a river. Around 2,000 km of underground HVAC cables exist in Europe and over 5,000 km worldwide today. In specific cases, gas insulated lines could be an alternative.

The application of a long AC cable has to be chosen carefully, because it leads to changes in the network impedance and/or shift of network resonance frequencies that in some cases lead to over voltages beyond todays limits. Depending on the system properties and length of the cable, the AC cable technology may not be feasible for specific projects. For the real applications, detailed studies are needed.

1.2.1 Land cable technology

From an underground cable perspective, HV AC cables are internationally widely used at voltage levels up to a maximum voltage of 550 kV. In Europe, currently the maximum voltage is 420 kV. Extruded XLPE insulated cables are the most common, with cables up to 300 kV being used for over 25 years and cables at 420 kV in use over the last 20 years. Depending on the specific requirements of the Transmission System Operator cables can either be directly buried, installed in pipes or be installed in tunnels.

The concept of partial undergrounding of HV AC transmission lines has become one of the solutions to overcome public acceptance and obtaining building permits, although it causes significantly higher costs. This overall evolution is enabled by the maturity of XLPE underground HV AC cables and accessories. However, long outage times after damage or failure are an issue still. Moreover, cable systems integration into networks has to be carefully analyzed case by case to ensure safe network operation (e.g. to determine the right level of shunt compensation).

The focus of the technical evolution will be oriented toward the further increase of reliability and the rationalization of future applications:

- The European transmission network voltage is likely to stay in a similar voltage range of 380 – 420 kV and consequently no increase of this voltage level is expected in the future;
- Current rating for a typical partial undergrounding solution at 420 kV is expected to increase up to 1,8 kA due to conductor cross sections exceeding 2,500 mm^2;
- Transmission power of such a system as described above can lay between 1000 MW and 1300 MW per circuit depending on the soil/tunnel properties.

Examples:

- National Grid 400 kV AC London tunnel project, UK: Total length 32 km, Transmission capacity 1600/1700MVA summer/winter, XLPE cable.

1.2.2 Submarine cable technology

HV AC extruded insulation cables are also commonly used for submarine connections. Their configuration may be single core or three cores. Today, HVAC cables with extruded XLPE insulation cover transmission system voltages up to 550 kV and the maximum power that can be transmitted is in the order of magnitude of 1.5 GVA per circuit, with a 2500 mm^2 copper conductor.

For extruded XLPE HV AC submarine cables, looking out at 2050 a similar technological evolution as for XLPE HV AC underground cables can be expected. In addition, the possible depth for submarine HV AC installations is expected to increase from several hundred meters to depths over 2500 m in the coming decades.

Examples:

- Submarine cable connecting Ormen Lange gas processing plant, 400 kV AC submarine, Norway: Total length 2.4 km, Transmission capacity 1000 MVA, Maximum water depth 210 m, XLPE cable
- Submarine cable crossing the Dardannelles Straight, 400 kV AC submarine, Turkey: Two circuits each with a total length of 4.5 km. Transmissible power of each circuit 1000 MW, Maximum water depth 90 m, XLPE cable.
- Submarine cable connecting Mallorca-Ibiza (Red Eléctrica): 118 km of 132 kV submarine cable. The aim of the project is to connect Ibiza to mainland through Mallorca. The maximum depth is 800 m and a power of 2x100 MW.
- Italy-Sicily 400 kV link: Two circuits, with a rated power of 2 x 1000 MW, SCOF submarine cables and XLPE land cables. Total length is about 42 km.
- Malta-Sicily 230 kV link: 100 km of 245 kV submarine 3-core XLPE cable and 20 km of XLPE underground cables, with a rated power of 225 MW.

1.2.3 Gas insulated lines

Gas insulated lines (GIL) are another alternative for high capacity transfer and in areas where governmental regulations or technological requirements limit the maximum electromagnetic field and thus where power cables or overhead lines are not possible.

Since the 1970s, more than 150 GIL projects have been installed worldwide, proving exceptional operation performance with an expected lifetime of considerably more than 60 years, which is largely given by the gaseous insulation. Due to the absence of flammable material, GIL is frequently applied in tunnel installations e.g. in hydro power plants or in tunnel applications beneath cities. The first installations realized with this technology (e.g. the 420 kV GIL for Schluchsee Hydro Power Pumping Storage plant in Germany, installed 1975) still operating at a high reliability.

In later GIL applications the insulation gas was shifted from 100% SF_6 to a gas-mixture of 80% N_2 and 20% SF_6. With latter gas mixture there is no risk of external impact even in case of an internal arc fault related to the large foot print (low temperature of the aluminium enclosure). Currently new dielectric gases with much lower global warming potential have been developed and first pilot projects are carried out. This could cover 90% of the new GIL's European needs in the next decades.

With increased restrictions concerning rights of way in densely populated areas, the use of GIL for HVAC solutions will increase. One of the longest GIL-applications in service today is approximately 3.3 km (Japan). The longest installed length in Europe is 1 km. GIL can be installed above ground, in trenches or tunnels as well as directly buried (Figure 1.2).

Figure 1.2 left side: view into a tunnel with two GIL systems and elastic bending, Paulaner Munich;
right side: directly buried GIL at Kelsterbach, close to Frankfurt Airport

1.2.4 Super-Conducting Cables

Super-Conducting Cables allow transmitting energy with marginal losses. For this purpose, special super-conducting materials are cooled down to very low temperatures (e.g. 92 K) using liquid nitrogen in order to lunch the superconductivity phenomenon (no resistance). These conductors are placed in a pipe with vacuum (cryogen) in order to thermally isolate the superconductor from the remaining environment. The energy losses came to being for keeping up low nitrogen temperatures and its circulation. The technology requires special cable joints and specific cable termination for extreme temperature differences. Moreover, a substation for cryogenic generation is needed.

These cable types are beneficial in an urban setting, high current capacity, strong reduction of the magnetic field and avoiding thermal interaction with other infrastructure.

Currently, there are few pilot projects at MV level (e.g. Supernet in Netherlands, JEJU in South Korea, LIPA in USA) and only one project in HV grid (275 kV M-PACC in Japan).

1.3

HVAC overhead lines with partial underground sections

At present some underground cable projects experience a higher public acceptance than overhead lines. Therefore, it may be beneficial to complement overhead lines with partial underground sections in sensitive areas. The decisions about the use of partial underground section should be taken in conjunction with the investment costs, obstacles (roads, water pipes etc.) in the cable route and different environmental impacts during the construction phase. Moreover, further specific system aspects like shift of the network resonance frequencies or dynamic stability have to be considered.

Examples:
- Amprion 380 kV AC Diele - Niederrhein, Germany: Total circuit length 181 km which consists of 4 underground sections. Total cable length is 15 km, 2x1800 MVA, XLPE cable. Project currently under construction/permitting. Full commissioning expected in 2021.
- Elia 380 kV AC Stevin project, Belgium: Total length 47 km, of which 10 km underground; Transmission capacity 3000 MW, XLPE cable
- TenneT 380 kV AC Randstad project, The Netherlands: Total length 85 km, of which 20 km underground (several sections, up to 10 km); Transmission capacity 2x2635 MVA, XLPE cable
- National Grid 400 kV AC London tunnel project, UK: Total length 32 km, Transmission capacity 1600/1700 MVA summer/winter, XLPE cable.

Figure 1.3 left side: view of a partial undergrounding section of the Diele-Niederrhein project; right side: view of a partial undergrounding section of the Randstad project.

1.4

HVAC Infrastructure

The increase of the transmission capacity of the existing system can be achieved by optimization of the loadings in a strongly meshed grid. This can be achieved by application of conventional technologies like Phase Shifting Transformer (PST) or technologies with use of power electronics (FACTS – Flexible AC Transmission system).

Frequently, an increase of the capacity of circuits requires also additional technologies for reactive power compensation. Here conventional technologies like Mechanically Switched Capacitors with Damping Networks (MSCDNs) or PSTs, or power electronic technologies like STATic synchronous COMpensators (STATCOMs) can be applied. Better utilization of the existing grid by load optimization and reactive power compensation reduces the degrees of freedom in its operation, than those which are present today. Operation of the grid at the edge of stability requires additional surveillance and control measures like WAMS or WACS.

1.4.1 Optimization of circuit loading

1.4.1.1 Phase Shifting Transformer

The Phase Shifting Transformer (PST) is a mature technology, implemented by TSOs in Europe to control active power through preventive or curative strategies. The PST system provides a means to control power flow between two grids. PSTs do not increase the capacity of the lines themselves, but if some lines are overloaded while capacity is still available on others parallel to them, optimizing the power flows with PSTs can increase the overall grid capacity

In the future, the focus will be on enabling issues: the development of shared PST models by TSOs and standards should facilitate PST integration in transmission systems. In parallel, the development of cross-border power trade and the integration of renewable generation will increase the need for such a technology to be in operation.

Examples: PST at the border between Germany and Poland, France and Spain, and Italy and France.

1.4.1.2 DSR – Distributed series reactors

Distributed series reactors inject or reduce the impedance of the overhead lines in order to increase respectively reduce the line loading. The general idea is to apply numerous power electronics devices along overhead lines, depending on the required load shedding. The technology is beneficial in meshed grids.

The technology has been applied mostly in low voltage networks with single conductor circuits. Several examples in networks up to 160kV can be found. Currently, the trend is seen towards high voltage applications and higher conductor bundles.

1.4.2 Reactive power compensation

1.4.2.1 Static VAR Compensators

A Static VAR Compensator (SVC) is a fast acting power electronic device used to dynamically control the voltage in a local area or at an interface point. It is a member of the family of equipment known as Flexible AC Transmission Systems (FACTS). Essentially SVCs and STATCOMs deliver a similar function using different power electronic technologies and methods. Regarding the use and the expected benefits, the SVC provides variable inductive and capacitive reactive power using a combination of Thyristor Controlled Reactors (TCR), Thyristor Switched Reactor (TSR), and Thyristor Switched Capacitors (TSC). These are connected to the AC network using a compensator transformer or via a transformer tertiary winding.

Examples:

- Cycladic Islands Interconnection with the Hellenic Power Transmission System (national TYNDP project): The project is on-going and aims to connect the Cycladic islands with the Greek mainland and phase-out some of the costly diesel units operating in the past. The phase A is comprised of the connection of Syros Island with Lavrion (mainland) as well as with the islands of Paros, Mykonos and Tinos. The phase B is comprised of the connection of Paros island with Naxos island and the connection of Naxos island with Mykonos island. The phase C is comprised of the second interconnection between Lavrion (mainland) and Syros island. On the islands GIS 150/20kV are/will be installed. All connections are submarine AC XLPE cables 150kV. Longest distance of all cables is 108km (Lavrio-Syros). On Syros island and SVC substation has already been commissioned in early 2018. Nominal voltage is 150kV (up to 170kV) and reactive power rating +/-100MVar.

Figure 1.4 The SVC substation on Syros island

1.4.2.2 STATCOM

A STATic synchronous COMpensator (STATCOM) is a fast-acting device which can produce or consume reactive power, more quickly than with AC capacitor banks, reactors or SVCs. It is a FACTS technology, which may be used for example at an onshore interface point to achieve System Operator/Transmission Owner Code (STC) dynamic compliance between 0.95 power factor lag and 0.95 power factor lead. The design and faster response enables it to be used to actively filter harmonics and flicker to improve power quality. STATCOMs are voltage source converters (VSC) using IGBTs (Insulated Gate Bipolar Transistor) or IGCTs (Integrated Gate Commutated Thyristors). They can also incorporate static capacitors and reactors into their design but these are typically smaller in comparison with those required by Static VAR Compensators (SVC), and therefore have an overall smaller physical footprint.

1.4.2.3 Synchronous condenser

Synchronous condenser is a DC-excited synchronous motor. It provides capacitive and inductive reactive power to the grid and also, contrary to a PST, inertia to the grid. HVAC synchronous condensers are available to a power range of +/- 300 MVA.
Their application is interesting especially in networks with high penetration of power electronic devices and in networks of high risk of becoming separated from the main network or 'islanded'.

Examples:

- Biblis, Germany: An old generator of decommissioned nuclear power plant is used for reactive power compensation.
- Oberrotmarhausen, Germany: Commissioning 2018.
- Codrongianos, Italy: 2 x 250 Mvar synchronous condensers for stabilizing the Sardinian grid

1.4.2.4 MSCDN – Mechanically Switched Capacitor with Damping Network

MSCDN allows increasing the voltage of highly loaded overhead lines.

Several examples worldwide are available.

1.4.2.5 VSR – Variable shunt reactor

In networks with high penetration of cables it is important to control the amount of the reactive power in a smooth way and in a wide range. The variable shunt reactors provide this functionality.

Several examples worldwide are available.

1.4.3 Synchrophasors, Wide Area Management Systems (WAMS) and Wide Area Control Systems (WACS)

Stronger environmental policies, lack of new generation close to load centres and the decommissioning of traditional thermal power plants in favor of new renewables generation sources (wind and solar prominently) are reducing the system inertia and forcing power transmission over longer distances. Early Wide Area Management Systems (WAMS) implementations initially provided increased grid visibility. This allows for visualization of energy oscillations and real-time stability assessment to be performed, increasing understanding of network operation and performance.

It later evolved to increase grid capacity while operating inside safe operational limits allowing greater transfer of energy between regions, avoiding the need for construction of new assets and unlocking the connection of additional new renewable energy into the transmission system. WAMS is now being coupled and integrated with the operational SCADA/EMS as a day to day tool for operators.

Hybrid applications based on EMS and WAMS concepts are increasing the accuracy of the power system solutions and the evaluation of grid operation based on network models, load forecast and generation dispatch. This has been especially helpful with dealing with the intermittency of renewable energy.

In the digital transformation of power system operation, WAMS will contribute to increase automation, not only releasing network operators from manual tasks but providing fast and optimal response particularly when the power system deviates from optimum point (due to renewable intermittency or unexpected power outages). Wide Area Control Schemes (WACS) based on synchro-phasors can identify in a few milliseconds the source of a disturbance, calculate corrective responses, and send associated controls. Fast frequency response service is one example where WACS has demonstrated optimal results.

Current WAMS implementation over the world varies from early R&D initiatives to fully deployed systems with thousands of PMUs (India, Brazil). Typically, the most advanced WAMS are found in places where the grid is mostly stressed due to large renewable penetration or due to constrained transmission capacity to transfer power. When complemented by big data analytics technology and Internet of Things (IoT), the association of WAMS data, asset performance monitoring and renewable predictive analytics will unleash new limits for power system operation.

1.5

New Concepts for HVAC substations

1.5.1 GIS – Gas Insulated Substations

The worldwide use of gas insulated switchgear (GIS) in substation applications has been around since the 1960s and is becoming an increasingly used asset for substation construction: the major structures are contained in a sealed environment with sulfur hexafluoride gas (SF6) as the insulating medium and the clearance required for phase to phase and phase to ground for all equipment is much lower than that required in an air insulated substation. The total space required for a GIS is 10% of that needed for a conventional substation.

Latest EU F-Gas Regulation No. 517/2014 came into force on 9 June 2014. It strengthens measures to contain emissions of fluorinated greenhouse gases such as SF6. Current technological advancements in the GIS alternatives include: (i) the deployment of new insulation gas mixture as an alternative to SF6 (i.e. pilot project in substation located in Oerlikon, Zürich and pilot project in Grimaud 63 kV in the south-east of France) so as to reduce carbon footprint, (ii) alternative compact design configurations that limit required space, cost and construction time (iii) fiber optics sensors and current measurement technologies that limit recalibration needs.

1.5.2 HIS – Hybrid Insulated Substations

Hybrid switchgear modules have been developed in the 1990's. They use two different technologies: one to extinguish the arc and the other to connect to the other equipment of the HV substation, with the goal of maximizing the advantages of both of these existing technologies. The hybrid module typically utilizes gas-insulated switchgear components and conventional air-insulated bushings for connecting to the busbar. This mixed-technology switchgear reduces substation footprint by up to 50 percent and offers a dependable and cost-efficient solution for new installations and extensions as well as rehabilitation (refurbishment) projects. Technology advancements in hybrid Insulated Substations follow the same trends of GIS and AIS installations. Hybrid Switchgear modules are commercially available for all voltage levels up to 420 kV.

1.5.3 Fully digitalized substations

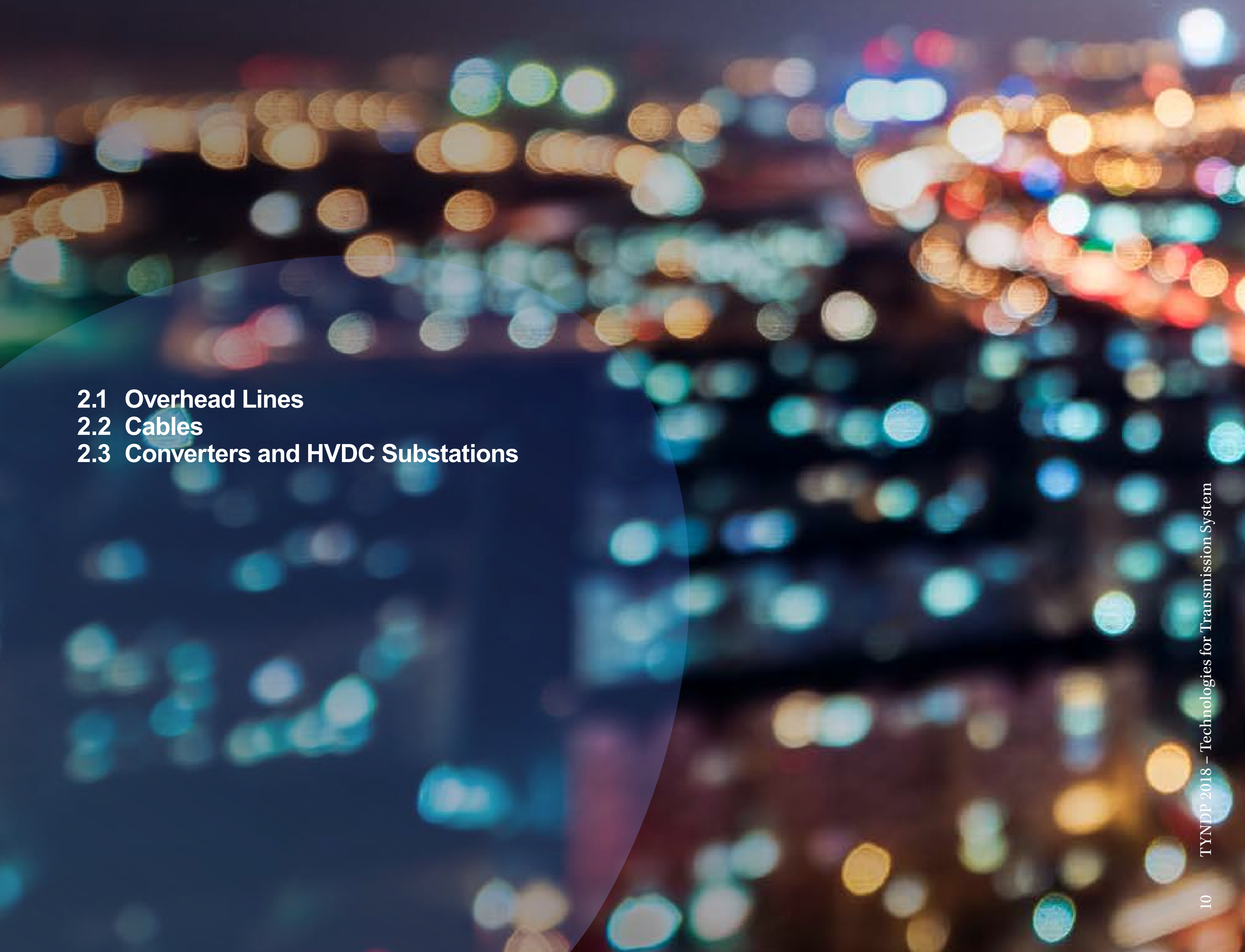
Worldwide several pilot projects of "full digital substations" have been built, although only a few have been built in Europe (e.g. the so-called "Postes nouvelle génération" project in BLOCAUX 225/90 kV and ALLEUX 90/20 kV in the north of France). However, as the application of IEC 61850 based communication bus technology in substations has developed, the use of process bus communication, in addition to station buses, will become more and more common. Safety issues with oil filled instrument transformers (IT) are one main driver for the breakthrough of full digital substations using non-conventional IT, in combination with the potential cost savings and reduced physical safety issues.

Users also are becoming more interested in condition monitoring and, especially, remote monitoring. These technologies should be implemented with careful consideration of cyber security issues, in order not to reduce the level of security of the grid.

A rise of digitized substations is expected as a substation will be considered equally as a data hub and a power hub.

Section 2

HVDC Power Transmission



2.1
Overhead Lines

The overhead lines are “state of the art” technology for a secure and efficient energy supply all over the world. Current developments and research focus on reduction of environmental impact and improvement of the insulators performance.

2.2
Cables

Europe has been and remains a pioneer and an innovator in the field of HVDC since its modern re-invention in the second half of the 20th century. Multiple HVDC schemes have been designed and installed, mostly point-to-point schemes using submarine cables to exploit the sea crossings in Scandinavia, the British Isles, the Baltic Sea, the North Sea and the Mediterranean Sea. In some land projects, HVDC cables have been used (e.g. Interconnector France-Spain, SouthWest Link Sweden, France-Italy interconnection). A limited number of back-to-back schemes have been built, the most recent being the 2 x 500MW link between Lithuania and Poland. There is only one working multi-terminal system in Europe, the Sardinia – Corsica – Italy (SACOI) link, although others are in construction (SouthWest Link, in Sweden and Caithness – Moray – Shetland, in the UK). Looking into the decade ahead, Germany’s planned HVDC land projects (A-Nord, SüdLink and SüdOstlink) which are required “to give priority to undergrounding”, will become the largest scale HVDC underground cable installations in Europe.

HVDC cable technology has been implemented for more than 60 years:

- Initially, Mass Impregnated (MI) cables were regarded as the preferred solution. Line Commutated Converters (LCC) were used, implying polarity reversal. Almost all of the schemes built in this period have used LCC technology
- In the 1990s, the development of Voltage Source Converter (VSC) technology was considered as an opportunity to introduce XLPE extruded insulation cables for HVDC applications in addition to MI cables. VSC has rapidly gained acceptance, such that it is now the predominant choice for HVDC schemes throughout Europe.

The differences between these two technologies and hence an explanation for the rapid change from LCC to VSC schemes are discussed in the following sections.

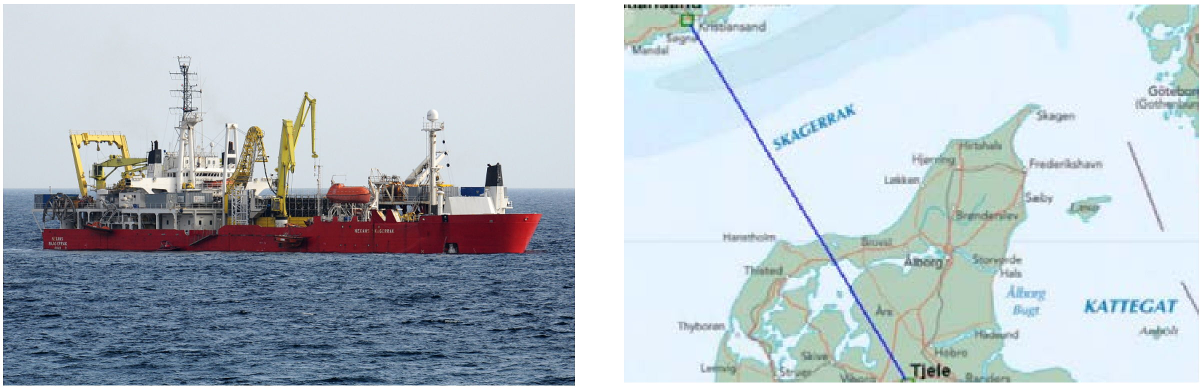
2.2.1 Mass Impregnated HV DC Cables

Mass Impregnated (MI) HV DC cables are currently the most used cables for HVDC applications. Benefiting from more than 45 years of experience in service, with a proven high reliability, they can be provided by European manufacturers at voltages up to ±600 kV and 1800 A, which makes 2200 MW per bi-pole. Currently, this technology is mainly deployed for HVDC subsea applications.

The main development of MI HV DC cables is increasing the power (from 2200 to 2340 MW per bi-pole). Thanks to that progress, particularly the upgrading of nominal service voltage, it will be possible to transmit a power of 1000 MW with a reduction of around 30% in the losses per bi-pole. Moreover, an increase in water depth for submarine installations from around 1600 m to over 2500 m by 2050 is expected. HVDC underground and submarine examples include:

- TenneT Nordlink, HVDC ±500 kV Interconnector Norway – Germany: Total length 623 km of which 516 km is submarine cable, 53 km HVDC overhead line (Norway) and 54 km HVDC underground cable (Germany), transmission capacity 1,4 GW, MI cable
- Western Link bi-pole scheme in the UK: Operating at a DC voltage of ±600kV using MI submarine and land cables is due to enter commercial service in 2018.
- Statnett and Energinet.dk Skagerrak 4, HVDC ±500 kV interconnector Norway – Denmark: Total length 237 km of which 137 km is submarine cable and 100 km underground cable, Transmission capacity 715 MW, water depth 550 m, MI cable, in service as of end of 2014.
- SAPEI, HVDC ±500 kV Italian domestic submarine intertie interconnecting Sardinia with the Italian Peninsula: Total length 440 km of which 424 km is submarine cable and 16 km underground cable, Transmission capacity 1000 MW, water depth 1640 m (the deepest in the world and the longest at 500 kV), MI cable, in service since 2009.

Figure 2.1 left side: view of a section of the TenneT Nordlink, HVDC ±500 kV Interconnector Norway – Germany project; right side: map of the Statnett and Energinet.dk Skagerrak 4 HVDC ±500 kV Interconnector Norway – Denmark project.



2.2.2 Extruded XLPE HV DC Cables

Polymeric HV DC cables are used mainly with VSC converters that enable power flow to reverse without polarity reversal. Today, this technology has been implemented up to ±320 kV with a capacity of 1000 MW for a symmetrical monopole. ±525 kV cable systems are now qualified and commercially available. The basics for HV DC submarine cables are the same as those of HV DC land cables except for mechanical features.

The following evolution of XLPE HV DC submarine and land cables can be expected:
- Increase in voltages up to ±600 kV; several suppliers have tested cables ±600 kV.
- Increase in conductor size from 2500 to 3000 mm^2, which is expected to result in a capacity exceeding 2 GW;
- Due to the increased voltage, the typical transmission power losses per circuit (2500 mm^2 conductor rated at 1 GW per bipole) are expected to drop from 42 W/m (today) to 14 W/m (by 2050);
- New extruded materials beside XLPE are under development
- For subsea cables, the laying depth should reach more than 2500 m by 2050.

HV DC land and submarine examples include:
- RTE / RED INELFE HVDC ±320kV Interconnector France-Spain: Total length 65 km land cable, of which 8.5 km is through a tunnel underneath the Pyrenees, transmission capacity 2 GW, XLPE cable
- TenneT Borwin 2, HVDC ±300 kV Connector, Germany: 75 km land cable, 125 km submarine cable, transmission capacity: 800 MW, XLPE cable
- National Grid/Elia NEMO HVDC ±400kV Interconnector UK – Belgium: Total length 140km of XLPE cable, of which 130km is submarine cable, 8km is land cable in Belgium and 2km is land cable in the UK. The scheme will be operational by 2019.
- Red Eléctrica, mainland-Balearic Islands +/- 250kV link: 3 cables spanning 237km with a maximum depth of 1485 m (second deepest in the world).

Figure 2.2 View of an undergrounding section of the RTE / RED INELFE HVDC ±320kV Interconnector France-Spain project.

2.2.3 DC Gas insulated lines (DC GIL)

DC gas-insulated technology was first established in the 1970s with several development projects in USA, Sweden and Germany. The focus of these developments was to reduce the space for HV DC converter stations and to provide powerful underground transmission systems. In parallel DC GIL for ±500 kV (Um,cov = ±550 kV) are under development and expected to be available from 2020. New dielectric gases with better environmental performances are under development as an alternative for SF6. The present developments are designed for the transmission of high power (up to 5000A DC / 5GW). The main benefits of technology are no additional fire load in tunnel installations, situations when low thermal losses are required, sharp angles). DC GIL can directly interface with DC GIS and with DC power cables as well as with OHLs via air bushings. Currently, DC GIL have not been realised in high voltage network yet.

2.2.4 DC Superconducting cables

The "BEST PATHS" European project, (BEyond State-of-the-art Technologies for repowering Ac corridors and multi-Terminal Hvdc Systems), focuses on the demonstrations of solutions to allow for transition from High Voltage Direct Current (HVDC) lines to HVDC grids, to upgrade and repower existing Alternating Current (AC) parts of the network, and to integrate superconducting high-power DC links within AC meshed network. This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 612748). DEMO #5 of the project will deliver in September 2018, a 30 m, 320 kV, 10 kA MgB2 – Superconducting DC cable, with a cooling system based on pressurized gaseous Helium (20 K, 20 bars) and liquid Nitrogen (70K, 5bars).

The TRL is still low. This pilot project will show further development needs towards a DC Supergrid.

2.3

Converters and HVDC Substations

2.3.1 Line Commutated Converter (LCC) technology

HVDC stations using LCC technology have been widely implemented throughout Europe and the world since the 1960's, for both OHL and cable applications. The technology is based on the use of high power thyristors, which provide the switching between the HVAC and HVDC systems. The technology is widely used for point-to-point, or back-to-back links between asynchronous networks. It can also be implemented as an embedded link within a synchronous network.

Following many years of development, thyristor devices are able to operate at blocking voltages up to 8.5kV and switch DC currents of up to 6250A. This has allowed LCC schemes to be installed up to 10000MW and ±800kV, although to date such ratings are only required in China, India and Brazil. In Europe the largest LCC scheme, currently under construction, is rated at 2200MW at ±600kV (Western Link in the UK). A key feature of this thyristor based technology is its short time overload capability, allowing schemes to have significant (1.3 – 1.5pu) levels for useful times (1 – 3s) to support the wider AC network.

LCC technology is highly efficient, with a total operating power loss in a converter station of typically 0.7 – 0.8% of the scheme rating.
Examples:
- Red Eléctrica, Santa ponsa and Morvedre: HVDC station (LCC) for the link between mainland and the Balearic Islands.
- TERNA, SAPEI HVDC stations ± 500 kV – 1000 MW interconnecting Sardinia with the Italian Peninsula.

2.3.2 Voltage-Sourced Converter (VSC) technology

HVDC stations using VSC technology have been in service since 1997. The technology is based on the use of Insulated Gate Bipolar Transistors (IGBT), which provide the switching between HVAC and HVDC systems. To date all applications, with one exception, use sub-sea or underground cables. In addition to point-to-point links and back-to-back links, the technology is also suitable for developing multi-terminal systems. The first of these are in operation (in China) and others are in construction (in Europe).

In comparison with LCC technology, VSC is a less mature technology and still in development, using IGBT devices rated up to 6.5kV and 2000A. The largest scheme in service is the 2 x 1000MW ±320kV INELFE project (France – Spain) and the highest voltage is on the 700MW Skagerrak Pole 4 project at 500kV (Norway – Denmark). The North Sea Link (NSL) project now under construction between the UK and Norway will operate as a bi-pole at 1400MW and ±525kV. Although power and voltage ratings have risen dramatically in recent years, the overload capability of VSC technology still remains low, limited by the capability of the IGBT devices. This technology is still limited to the so called "symmetric monopole", practically a "balanced" bipolar system without earth/sea/metallic return a not negligible limitation.

Future development involved the "full bridge" solution that will allow a more flexible operation of the VSC technology especially for overhead line links since the current technology, i.e. the "half bridge" solution was born for cable link. In fact, the half bridge solution can be used also for overhead line link but its performances for fugitive faults on the overhead lines are well far for the better performances of the LCC solution.

The operating losses of VSC technology have decreased dramatically in recent years to reach about 1% per converter station (half bridge solution). The losses are higher than LCC but the VSC technology provides technical improvements like resilience to commutation failure and ancillary services such as reactive power control (and consequently voltage control) and black start. It allows also to connecting of weak grids (e.g. offshore) and creating of multi terminal meshed DC grids.

Examples:

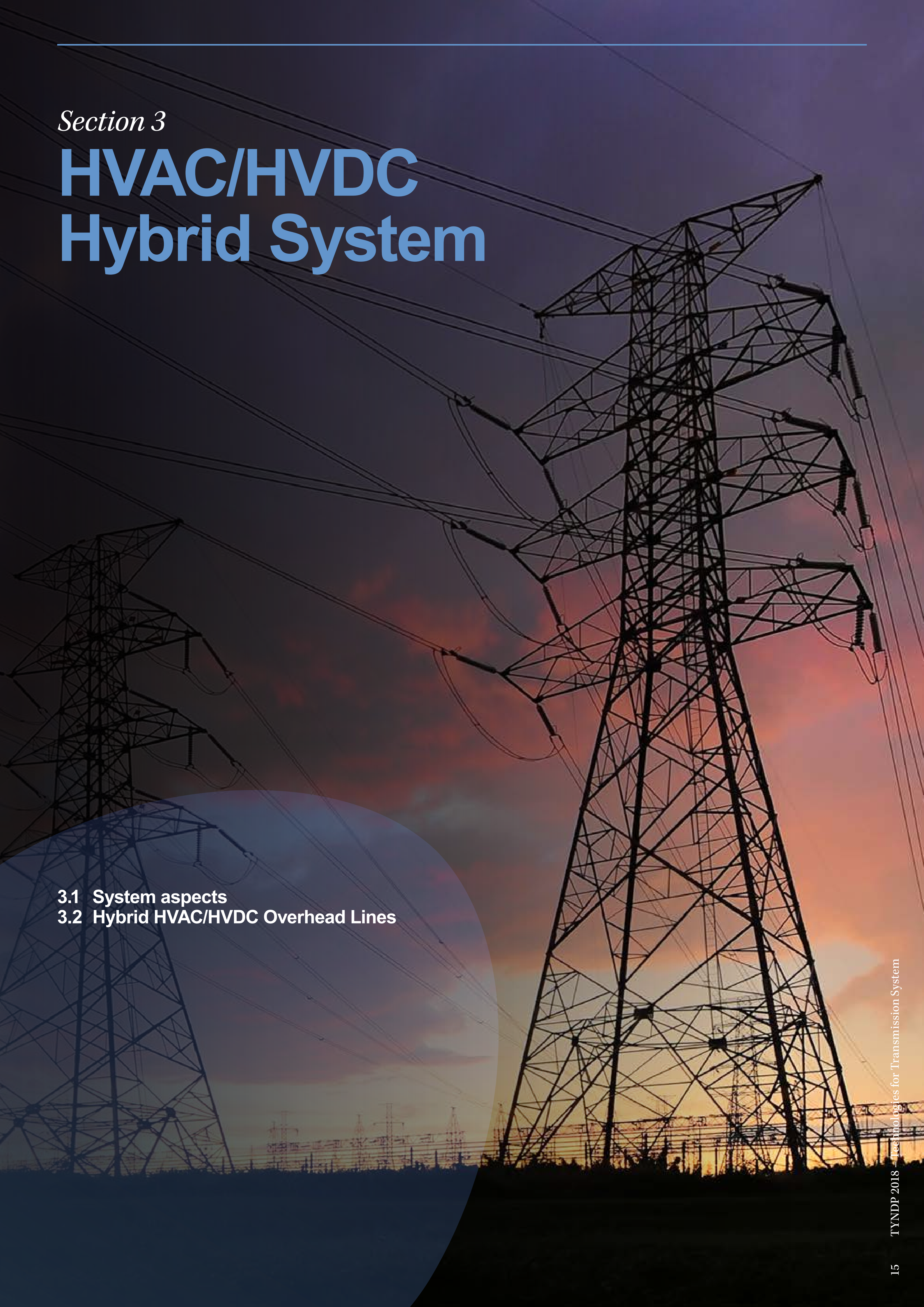
- Red Eléctrica & RTE, Santa Llogaia and Baixas: HVDC stations (VSC) for the interconnection between France and Spain through the Pyrenees, named INELFE.

2.3.3 DC gas-insulated switchgear (DC GIS)

Gas-insulated switchgear under DC operation has a modular design and provides new and space-saving layouts for converter and transition stations with a high density of functionality:

- Set up a safe separating distance with grounding on both sides
- Measurement of current and voltage
- Protection against overvoltage
- Connection of different transmission media, e.g. cable & overhead-line, cable & cable or cable and DC GIL
- Provision of interfaces for line-fault location (online and offline).

DC gas-insulated switchgear is having advantages over air-insulated solutions, where requirements exist concerning space-saving installations, aesthetic planning of converter stations or transition stations, independence of environmental conditions and the prevention of lightning stroke. It can be applied for both, VSC and LCC systems. The technology is available for ±320 kV (Um,cov = ±352 kV). Development for ±500 kV (Um,cov = ±550 kV) is currently ongoing and will be available by 2019.



Section 3

HVAC/HVDC Hybrid System

3.1 System aspects
3.2 Hybrid HVAC/HVDC Overhead Lines

3.1
System aspects

The HVDC technologies have been gradually integrated to the existing pan-European HVAC system. With the estimation of TYNDP, over 25,000 km of HVDC transmission lines will be built and operated in parallel with over 300,000 km HVAC transmission lines. HVAC / HVDC interaction will be a key feature in the coming years for system operation, development and maintenance. The HVAC network, which needs to be able to supply or import the power of the HVDC link, may require system reinforcement. Under certain contingency conditions on the HVAC network, automatic curtailment of the HVDC link power may be required due to thermal reasons or to maintain system stability. Issues related to the active control of reactive power interchange have made VSC technology the preferred and sometimes the only choice for many schemes. In networks with high levels of background harmonic distortion, the low levels of distortion achieved by VSC converters can make them an attractive solution.

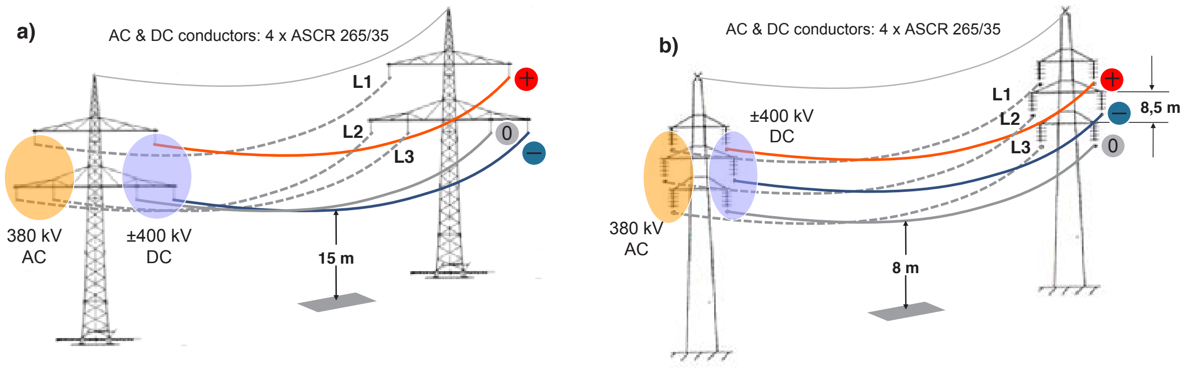
3.2
Hybrid HVAC/HVDC Overhead Lines

An upgrade of existing transmission lines from low voltages (110kV, 150 kV or 220 kV) to higher voltage level (e.g. 400 kV) can increase the capacity of existing infrastructure, efficiently damp wide area oscillations support the system with reactive power and reduce loading of existing HVAC grid by effectively creating a by-pass of it.

Due to the lack of new transmission line corridors and public concerns about the erection of new transmission lines, increasing transmission capacity by converting one of the existing HVAC lines to HVDC can be an interesting option.

Some examples of HVAC/HVDC hybrid lines are presented in Figure 3.1.

Figure 3.1 Double-circuit line, AC and DC system a) triangular; b) semi-vertical

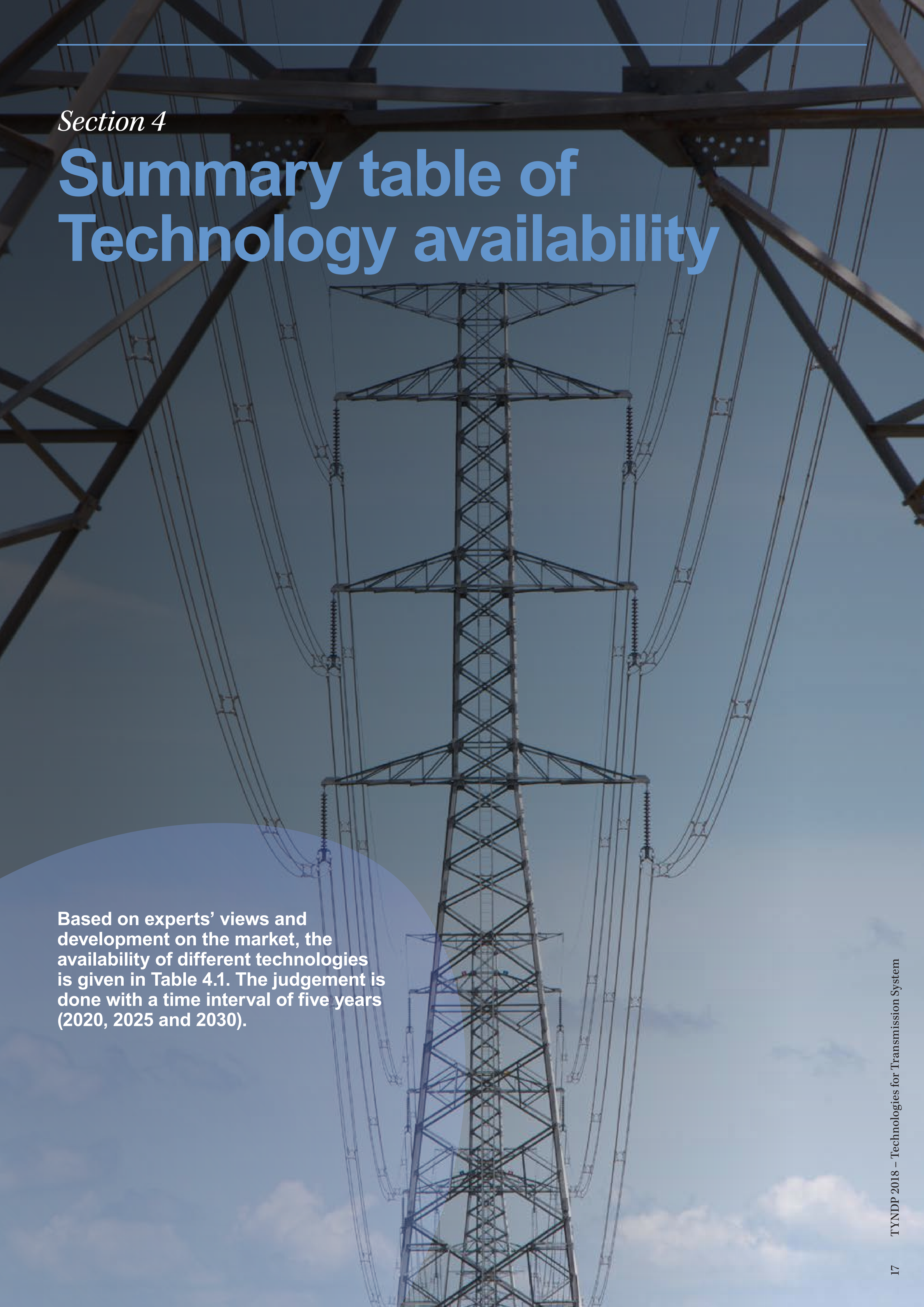


Operation of HVAC/HVDC hybrid lines requires intensive studies about electrical coupling (capacitive, inductive and resistive) between HVAC and HVDC circuits. The results of the studies have an impact on the specification of the converter and also on the protection schemes of HVAC and HVDC systems.

The conversion of existing overhead line can be simply done by replacement of insulators and leaving the conductors as they are. Thereby the towers remain as they are. However, one has to choose the maximum operating voltage properly, in order to avoid corona associated levels of noise and ionisation of air.

The probability of faults on the HVDC lines, e.g. due to lightning strikes or polluted insulators, will require solutions which can clear the fault and auto-reclose in a similar manner to HVAC systems. This requires application of full-bridge multi-level VSC converters.

Example:
— Germany, Ultranet HVDC ±380 kV: Total length ~ 340 km hybrid OHL (Commissioning in 2021).

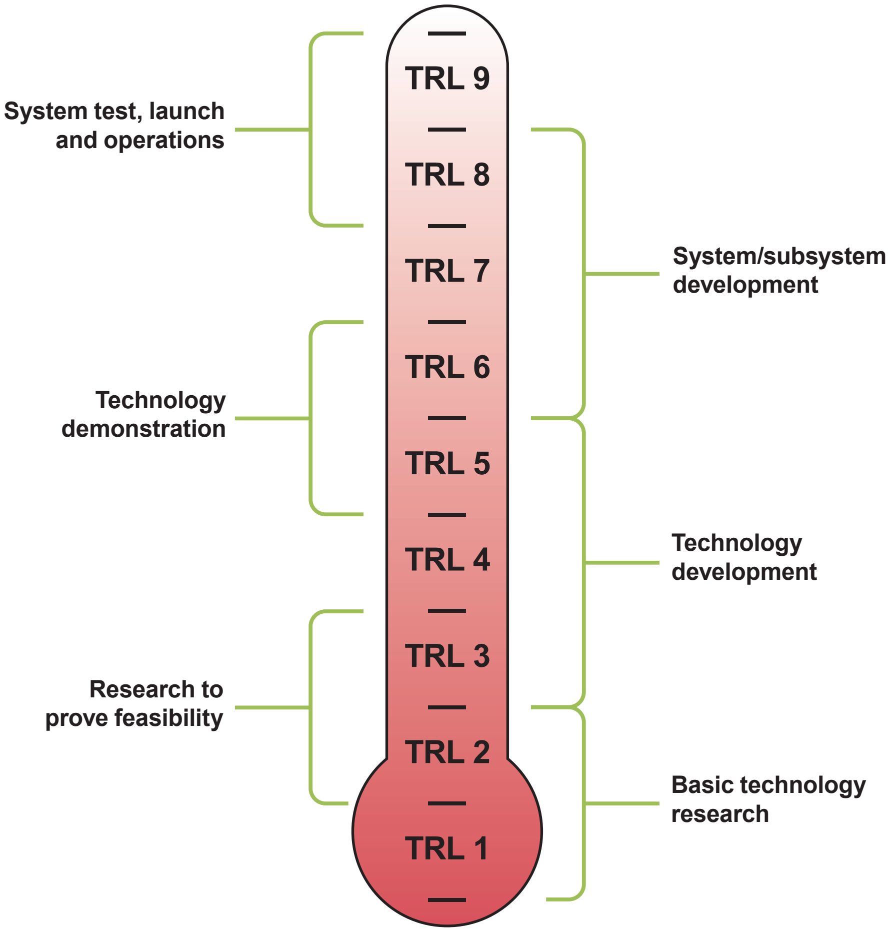


Section 4

Summary table of Technology availability

Based on experts' views and development on the market, the availability of different technologies is given in Table 4.1. The judgement is done with a time interval of five years (2020, 2025 and 2030).

Figure 4.1 Summary table of the technologies and the respective TRL levels



Technology Readiness Levels (TRL)

- — TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
- — TRL 8 – system complete and qualified (some smaller improvements need to be done still)
- — TRL 7 – system prototype demonstration in operational environment
- — TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- — TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- — TRL 4 – technology validated in lab
- — TRL 3 – experimental proof of concept
- — TRL 2 – technology concept formulated
- — TRL 1 – basic principles observed.

https://web.archive.org/web/20051206035043/http://as.nasa.gov/aboutus/trl-introduction.html

Table 4.1 Summary table of the technologies and the respective TRL levels

Technologies	Technology Availability		
	2020	2025	2030
HVAC and HVDC Overhead lines			
High Temperature Low Sag Conductors	7*	8	9
Dynamic Line Rating	8	8	8
HV AC cables			
Underground cable technology	7	9	9
Submarine cable technology	9	9	9
Superconducting cable (HV)	4	6	8
Gas insulated lines	4	6	8
Better utilisation of existing infrastructure			
Phase Shifting Transformer	9	9	9
Distributed Series Reactors	7	9	9
Reactive power compensation (STATCOM, Synchronous condenser, Static VAR Compensator, VAR, MSCDN)	9	9	9
WAMS/PMU	8	8	8
New concepts for HVAC Substations			
GIS (with alternative gas to SF6)	6**	9	9
HIS (with alternative gas to SF6)	5	7	9
Fully Digitized Substation	7	8	9
HVDC Power Transmission			
Mass Impregnated HV DC Cables, ±600 kV	9	9	9
Extruded HV DC Cables, ±320 kV	7	9	9
Extruded HV DC Cables, ±525 kV	5	7	9
Extruded HV DC Cables, ±600 kV	3	5	7
HV DC Gas insulated lines, 525kV	3	5	7
HV DC Superconducting cables	3	5	7
Converter/ HVDC Substations			
Line Commutated Converter (LCC)	9	9	9
Voltage Source Converter (VSC) – Half bridge	7	9	9
Voltage Source Converter (VSC) – Full bridge	4	7	9
DC gas insulated switchgear ±500 kV	5	7	9
HVAC/DC Hybrid System			
System aspects	7	9	9
HVAC/DC Hybrid overhead lines	7	9	9

*for lower voltage levels of around 63 kV higher TRL (e.g. TRL 7) can be assumed.
**depending on the type of the conductor as described in 2.1.1 subchapter

ENTSO-E AISBL
Avenue de
Cortenbergh 100,
1000 Brussels,
Belgium

Tel (+32) 2 741 09 50

info@entsoe.eu
www.entsoe.eu

entsoe
Reliable Sustainable Connected