Renewables Grid Initiative

Background Paper for the RGI Workshop on:

Transmission Technologies and Technical Developments: Cable vs. Overhead – AC vs. DC – Innovations

Summary

This background paper discusses High Voltage (HV) transmission technologies that are currently available commercially and highlights their future development. The objective of this document is twofold; to present an overview of HV transmission options within the context of a pan-European electricity grid largely penetrated by renewable energy sources, and to relate them to the main parameters, that developers of such a project need to consider (without focusing on environmental considerations[1]). This background paper is written as support to the RGI Transmission Technologies Workshop and aims at contributing to the workshop a broad but general overview on transmission technologies.

Electricity is transmitted at High Voltages (HV>110 kV), Extra High Voltages (EHV>220 kV) or Ultra High Voltages (UHV>500 kV)[2] to reduce the energy lost in long distance transmission. Transmission options can be categorized according to three defining characteristics; the type of current transmitted {AC vs. DC}, how it is transmitted {Overhead Line (OHL) vs. Underground / Submarine Cable (UGC)}, and what type of conversion is required for DC transmission {Line Commutated Converter (LCC) vs. Voltage Source Converter (VSC)}. The category types that arise from these characteristics are:

- HVAC Overhead Line
- HVDC Overhead Line (LCC or VSC)
- HVAC Underground / Submarine Cable
- HVDC Underground / Submarine Cable (LCC or VSC)

There is no clear winner that should be applied in all cases. When choosing a transmission option the decision should not be made between AC or DC transmission and Overhead Lines or Underground Cables, but it should be a decision that takes into account all parameters collectively. This constitutes the close collaboration of experts in the fields of high voltage cables, high voltage transmission system design, landscape architecture and civil engineering. The choice is based on a case-by-case basis where all factors are taken into consideration and evaluated according to the project's characteristics.

Integration of Renewables to the HV Transmission Network

The nature of electricity requires the continuous balancing of generation and demand in order to maintain system stability. Today the structure of the system consists of three layers; generation, transmission and distribution. This

[1] Workshops focusing on the environmental and health considerations of HV transmission technologies will follow this workshop in 2011

[2] For simplicity, HV will be used throughout this document for all voltage levels of of transmission, unless otherwise stated

implies the formation of a network connecting the three layers together and enabling the transferring of electricity from the point of generation to the point of consumption. Electricity is generated in bulk through large-scale power plants and transferred through the electricity network to demand centres. The transmission and distribution form what is termed the electricity grid. The generated electricity is transmitted in high voltages to local substations and subsequently distributed to numerous loads. To enhance system stability and ensure generation very closely matches demand at all times, transmission networks are interconnected nationally, regionally or even continentally. They typically consist of transmission circuits and substations. The transmission structure enables multiple alternate routes for power flow should a fault occur. A high voltage transmission network needs to take into account safety, reliability and operational constraints while preserving the efficient transmission of electricity.

The liberalisation of the electricity market on all levels and the emergence of renewable energy sources have created additional requirements for the operation of the system. Long distance high voltage transmission has become a necessity in order to allow (remote) energy sources to be utilized. For example, wind generation in Northern Europe can be complemented by PV generation in Southern Europe during different times of the day. This necessity has in effect brought the debate of high voltage transmission options at the forefront. A high voltage transmission link can carry Alternating Current (AC) or Direct Current (DC) and transmitted through Overhead Lines (OHL) or Underground / Submarine Cables (UGC). When designing the future architecture of the high voltage transmission network, the variability and diversity of renewable energy generation needs to be taken into account. Wind and photovoltaics (PV) are in principle the two core renewable sources that contribute to this fluctuating generation. Hydro, geothermal or thermal solar (CSP) have to a large extent the ability to address these issues.

The high voltage transmission network and its required grid expansion play a dual role. Firstly, it enables the connection of increased levels of (remote) renewable capacity and secondly, transfers bulk amounts of electricity from one region to another to account for the seasonal fluctuation of renewable generation from wind and/or solar. The current composition of the high voltage transmission network of AC overhead lines, needs to be expanded to allow the smooth and efficient integration of high shares of renewable energy generation required, to decarbonise the European power sector. Hence, when designing this grid expansion, the choice between AC vs. DC and Overhead vs. Underground needs to be re-defined to fulfil the needs of a grid highly penetrated by renewable generation.

Overhead Lines and Underground/Submarine Cables

Overhead Lines

The HV transmission architecture across Europe consists almost completely of overhead lines. It represents the most common solution that provides high performance levels at a low cost. Depending on whether AC or DC is transmitted, the components of an overhead line may vary. Common equipment typically found in an overhead line is the supporting structure, the metal conductor (typically aluminium), and insulation. Overhead lines are supported by a tower, which can be made from wood, steel, concrete, aluminium or reinforced plastics. The purpose of this structure is to keep the high voltage conductors away from their surroundings and from each other. Their design requires minimum safety clearances. Each structure's design is project-specific and depends on the weight of the conductor they have to support and other factors such as the usage of area under the line and its structure, level of rigidness, angle, terminating line, river / road crossings, sag of the conductor[3]. Also, adverse weather conditions of high wind and low temperatures (icing of lines) can lead to oscillatory motion of the line (galloping) and power outages[4]. Typically, failures arising from such conditions are easily located and quickly repaired.

[3] The sag of the conductor is the vertical distance between the highest and lowest point the wire is supposed to vary. It varies depending on the temperature

[4] Wind speeds of the order of 40 km/h can permit conductors to surpass operating limits resulting in loss of supply

Underground / Submarine Cables

Electricity can be also be transmitted through cables running underground or undersea (submarine). Currently, underground transmission represents a very small fraction of HV transmission across Europe and it has been utilized when overhead transmission is not deemed possible. Underground cables are insulated with a medium (e.g. oil, paper, XLPE) and the cable can be directly buried in the ground or installed in tunnels. When cables are buried in ducts, forced cooling can be facilitated by buried water pipes for oil-filled cables and XLPE, while tunnels are preferred due to the ease of access for the cable and space constraints in densely populated areas.

There are a number of cables that could be used, including:

- low-density polyethylene (LDPE)[5]
- cross-linked polyethylene (XLPE)[6]
- high-pressure fluid-filled paper insulated pipe-type cable (HPFF)[7]
- self-contained fluid-filled paper insulated cable (SCFF)[8]
- self-contained fluid-filled paper-polypropylene laminate (SCFF-PPL)[9]
- gas-insulated line (GIL)[10]
- mass-impregnated (MI)[11]

Application Considerations

Underground transmission is used in urban areas or sensitive locations but often has higher cost and greater operational limitations. Specifically, underground transmission can be used in a number of applications including:

- urban areas which are densely populated
- areas where planning consent is difficult
- rivers and natural obstacles
- land with natural or environmental heritage

Besides the above applications areas where underground transmission is preferred over overhead lines, there are a few other characteristics that best those of OHL:

- less prone to severe weather conditions (lightning, wind, ice and snow)
- narrower right-of-way[12]
- safer (no shock hazards or threat to wildlife through collision)
- less visual impact

On the other hand, there are a number of areas where underground cables have a disadvantage towards OHL:

- more expensive[13]
- worse maintainability and reparability[14] resulting to longer outage times and thus lower availability

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[5] LDPE: dry dielectric where the inner conductor is covered with polyethylene

[6] XLPE: same as LDPE except that it has been chemically cross-linked to raise its maximum operating temperature from 70 °C to 90 °C

[7] HPFF: three unsealthed, paper insulated cores pulled into a single steel pipe which is filled with an insulating fluid

[8] SCFF: same as HPFF with the exception of a flexible extruded metallic sheath applied to the cores enabling them to be laid separately directly into the ground

[9] SCFF-PPL: variation of SCFF using PPL tapes that effectively reduce the capacitance and dielectric losses

[10] GIL: conductors are placed in pipes with an insulative mixture of sulfur hexafluoride gas (SF_6) and nitrogen (N_2)

[11] MI: paper tape insulation impregnated with high viscosity dielectric fluid

[12] Right-of-way reflects the land needed to build, operate and maintain the overhead/underground line/cable. It provides a safety margin for surrounding structures and vegetation

[13] The life-cycle cost of an underground cable can be two to four times the cost of an overhead line for voltages up to 150kV. For higher voltages it can be significantly higher

[14] When repairing underground cables, they can not be maintained "live" and it takes weeks or months for the process while OHL maintanance can be performed in a significantly shorter period of time

- longer construction time
- lower power transfer per circuit
- complex operation[15]
- less flexible[16]
- significant impact due to construction (land use, natural and cultural heritage, heating underground soil)

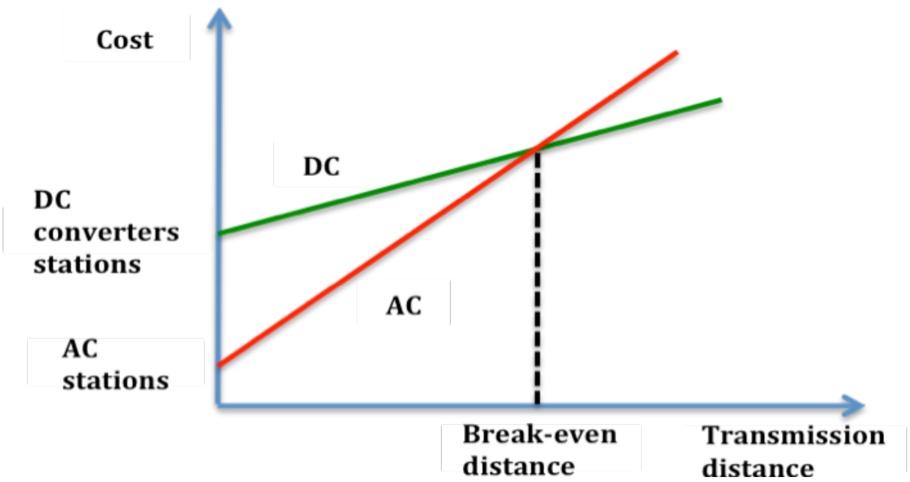
HVDC and HVAC

HVAC Transmission

The vast majority of EHV transmission in Europe consists of 3-phase HVAC transmission. It is the most common solution as it fulfils two important criteria; it represents the most cost effective technically feasible option for short to medium distances, and it can be easily transformed to comply with the required voltage levels of the transmission and distribution networks of the electricity grid. It is because of this ease of operation and efficiency that AC has prevailed over DC over the past decades.

HVDC Transmission

DC is more complex than AC transmission as it requires converter stations at both ends of the transmission line to convert AC to DC (and vice-versa) and transform voltage to the desired level of the rest of the AC network. These stations increase costs and losses. However, DC can be more economical over long distances as it can carry more power per conductor compared to AC. The station's costs and the transmission distance form the two variables that determine the break-even point between AC and DC as illustrated in the graph below:



The fundamental operation of a HVDC system is that the AC is rectified at the transmitting end and inverted at the receiving end. Most HVDC connections are point-to-point connections. However, in the future an increasing number of multi-terminal connections[17] could be used.

In more detail, the main components of HVDC system can be:

[15] The added equipment and their electrical properties required for UGC result to more complex control and modes of failure
[16] An overhead line is much easier to be adapted to system changes (reinforcing the network, modification to system topology, etc)
[17] In essence, a monopolar connection is the equivalent of a single AC circuit. A bipolar connection is used to provide redundancy and increase reliability that was worsened due to the added equipment and their complexity. Multi-terminal systems are more rare and difficult to design and control

- transformer (adjusting the voltage level of the AC source to the required entry voltage level of the converter)
- converter (conversion from AC to DC or from DC to AC)
- the smoothing reactor (prevention of intermittent current and resonance in the DC circuits, and limitation of DC fault currents)
- AC and DC side filters (absorb harmonic currents and supply reactive power)
- DC transmission circuit (lines, cables, etc)
- control and protection equipment (switchgear)

One of the most crucial parts in HVDC is the converter. DC transmission, based on Line Commutated Converters, also called Current Source Converters (LCC/CSC), has been employed for the past 50 years with intense development of such projects only over the last couple of decades. Voltage Source Converters (VSC) have come into use over the past few years and offer higher flexibility requiring less physical space in terms of bulk power transmission. However, LCC are still ahead of VSC systems.

Losses

Transmitting electricity at higher voltages reduces the energy lost due to resistance. A higher voltage reduces the current for a given power transfer and subsequently the resistive losses in the conductor[18]. Increasing the diameter of the conductor can also reduce losses and effectively reduce its resistance. However, larger conductors are heavier, more difficult to handle and more expensive.

In AC transmission, the inductance and capacitance of the cable or line can be substantial at large distances. The resulting reactive current flow causes extra voltage losses. Capacitor banks and other components (phase-shifting transformers, static VAR compensators, Flexible AC transmission systems[19]) are used to control reactive power flow to reduce voltage losses and stabilize system voltage.

Limitations

For AC transmission, the amount of electricity that can be transmitted at a certain voltage level depends on the length of the line.

For short AC lines (<100 km), the limit is thermal and is governed by the amount of current and the resulting line losses causing overheating. Overheating the line can cause an increase of its sag and reduce the mechanical strength and life of the line.

For intermediate length AC lines, the limit is set by the voltage drop or rise in the line. Large voltage drop or rise may damage equipment and affect the operation of the system.

For longer AC lines (>500 km), system stability sets the limit. Maximising the power transmitted through an AC line whilst maintaining line stability, reduces the length of the line. The allowable product of line length and maximum load is proportional to the square of the system voltage.

For DC transmission, the limit is not influenced by the length of the line. The limit is rather constant and is set by thermal and voltage drop limits.

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[18] An increase in voltage requires the same amount of current reduction. Hence, the losses (I^2R) are reduced proportionally to the square of the amount of current reduced

[19] A flexible AC transmission system (FACTS) is a combination of technical solutions that compensate reactive power in AC transmission with series and shunt compensation

Another source of losses present in both AC and DC overhead transmission is due to the corona discharge[20]. For EHV, bundle conductors are used to reduce corona losses, which in most systems are orders of magnitude smaller than resistive losses.

Application Considerations

So far, HVAC has been used in the vast majority of applications. However, HVDC is becoming increasingly attractive for cases where bulk electricity needs to be transmitted over long distances (>500 km) or for interconnections between asynchronous grids[21]. It is also used for long submarine cables (>50 km). Theoretically, HVDC can be used for all kinds of electricity transmission. However, the necessary converting stations are costly. In practice, long distance high power transmission favours HVDC against HVAC, while for shorter distances HVAC is preferred.

The main advantages of DC over AC transmission are:

- bulk electricity transmission from and to remote areas without any intermediate steps
- increasing the capacity of an existing transmission grid using existing rights-of-way
- connecting asynchronous AC systems and improve system stability[22]
- precise control of power flows on a circuit
- reduced line cost
- lower losses for long transmission lines
- synchronize and transfer AC generated by (remote) renewable energy sources[23]

The disadvantages of HVDC as compared with HVAC lie among the following areas:

- conversion (inverters are expensive and cause high loses)
- availability (lower availability than AC systems due to the extra conversion equipment)[24]
- operation & maintenance (DC equipment are system-specific and less standardized)
- more land required for the station[25]
- less flexible in terms of future system expansion
- lack of DC switchgear[26]

[20] Corona discharge occurs at EHV (>200 kV) from the creation of ions in the air when a strong electric field is present. This, in essence, can cause power losses and audible noise

[21] AC transmission between two regions would require continuous real-time adjustment of the relative phase of the two grids. When using HVDC, the AC flow from one region would be converted to HVDC and then transmitted over the distance between the regions before converted back to locally synchronized AC

[22] HVDC can prevent failures to propagate from one part of the transmission network to another. Additionally, the magnitude and direction of electricity flow can be regulated by the system operator as required for the further stabilization of the AC networks. Lastly, reactive power flow and AC voltage control can be achieved through a HVDC link

[23] This in effect mitigates the intermittent nature of renewable energy sources by averaging and smoothing the outputs of dispersed wind/solar power plants

[24] There is concern that if a more wide application of HVDC is applied across Europe's transmission network, the curent high availabi-lity provided by HVAC overhead lines could be compromised

[25] Transformers and filters are placed outdoors as it would be too expensive to place them along with the control equipment in a temperature controlled building

[26] Currently, no DC-breaker exists. Hence, this function is performed at AC converter station

Overview of Transmission Options

HVAC Overhead Line

HVAC overhead lines use air to provide most of the insulation. Aluminium alloy is used as the conductor material, composed of several strands. At high voltages that are commonly used for the transmission of electricity, suspension-type strain insulators[27] are used.

This option is most suitable for short to medium length transmission lines (≤500km) at a lower cost than other alternatives. It reflects a proven technology that provides voltages and power up to 500kV and 1000-3000MW per circuit. Installing a double circuit on the same tower can double their capacity. This approach increases slightly the wideness of the right-of-way and the height of the tower but cost-wise is cheaper than two single circuit lines.

Overall, HVAC overhead lines are an efficient and economic option for transmitting electricity over short and medium distances. Over longer distances they are less efficient and have higher losses that need to be compensated by the application of FACTS technologies and/or series capacitors.

Below is a summary of the advantages and disadvantages of HVAC overhead transmission:

Advantages	Disadvantages
• proven technology • long lifetime • lower cost compared to other options • increased capacity at low incremental cost by double circuit • ease of connection to the existing grid • high level of reliability • easy and quick to repair, operate, manage	• visual pollution • compensation may be needed over long distances (eg. FACTS) • health concerns about electromagnetic fields (EMF) • wider right-of-way • permitting obstacles

HVAC Underground / Submarine Cable

HVAC underground transmission can be categorized to installations of over 300kV and under 300kV. Currently, there is more operational experience for cables up to 300kV than for higher voltages where the technology has developed to a commercial phase only the past decade. Most cables for HVAC underground transmission are insulated by cross-linked polyethylene (XLPE) or by self-contained fluid-filled cable systems (SCFF).

The choice of cable technology depends on a range of factors including reliability, local manufacturing support, and cost. XLPE offers the best ratings (400-500 kV, 1300 MW per circuit) and the minimum charging current. Double cables can be installed for more power transfer capability but they significantly increase overall costs. The predominant cables used for these ratings were fluid-filled type (eg. SCFF oil-filled paper) but XLPE is displacing them as the dominant technology. A concern affecting both cable types is their limited world production capacity.

The transmission capacity of such cable types depends predominantly on the thermal properties and the type of the location. A double circuit of underground cable can be installed to increase the capacity to similar levels to a single overhead line circuit.

Due to the high capacitance of an underground cable, more reactive power is produced resulting in the need of shunt compensation at either end and perhaps at an intermediate point.

[27] Insulators are needed to provide electrical insulation and support both the full span of the conductors' load and additional weight due to ice or wind. They can be used as a set of multiple units made of porcelain, glass or glass-reinforced polymer. The number of units depends on a number of factors such as operating voltage and surges (due to switching or lightning), altitude and environmental factors (fog, pollution, etc)

Both SCFF and XLPE cable types are highly reliable. However, the overall reliability of the cable system is lowered due to the added equipment required. In case of a fault, the outage time can be significantly long. Because of this, a spare cable can be installed to provide redundancy.

Overall, HVAC underground transmission is commonly used for short distances (< 50km) in projects where overhead transmission is not possible (densely populated areas, limited right-of-way, etc). For longer undersea transmission, HVDC transmission is the only technical option.

Below is a summary of the advantages and disadvantages of HVAC underground transmission:

Advantages	Disadvantages

• low visual pollution
• applicable to:
  ○ intensively populated urban areas
  ○ areas where land is unavailable or planning consent is difficult
  ○ rivers and natural obstacles
  ○ land with natural or environmental heritage
• narrow right-of-way
	• lack of operational experience with extra high voltages (>300kV) and long distances (>50km)
	• low maintainability and reparability and thus low availability compared to overhead HVAC transmission
	• expensive
	• higher amounts of reactive power compensation required as compared to overhead AC transmission
	• complex cable routeing (difficult to dismantle, significant impact on environment)
	• specific corridor constraints

HVDC Line Commutated Converter (LCC) Overhead Line

The components of a HVDC overhead line are similar as with HVAC lines. The most significant difference lies in the design of the tower's structure. Both designs have a ground conductor but because of the nature of AC and DC transmission, 2 conductors are needed for DC instead of 3 for AC for each circuit. This results to a significant reduced tower size and right-of-way. In other words, more power transmission capacity is possible for a certain right-of-way. The configuration of one conductor on each side of the tower is termed bipolar. Typically, it is operating at voltage and power ratings of the order of 500kV[28] and 2000-3000MW per converter.

HVDC LCC is the conventional method of HVDC transmission (often quoted as HVDC Classic). The converter used is a thyristor[29] converter, which does the actual conversion from AC to DC current and inversion from DC to AC.

Many items of the system are duplicated in order to minimise loss of transmission in case of a fault. This along with the high converter cost results in higher overall costs as compared to an AC system. With increasing transmission distance, the two cost lines converge.

Overall, HVDC LCC overhead transmission is preferable for bulk power transmission over long distances (>500km). However, there are cases of shorter distances where HVDC may be preferred such as its ability to connect asynchronous systems, optimal power flow control or flexible increase in power capacity.

Below is a summary of the advantages and disadvantages of HVDC LCC overhead transmission:

Advantages	Disadvantages
• high capability of bulk power transfer • narrower right-of-way	• high converter station cost • lower availability

[28] For Ultra HVDC transmission of the order of 800kV and 6000MW, two different configurations are under development in China and India. These configurations are intended for bulk power transmission from remote locations with the lowest possible transmission losses and transmission width. This configuration would be applicable only for very large systems

[29] A thyristor functions like a diode (allowing current flow in one direction when voltage is applied) with an additional mode of operation; when it is in the conducting state it "holds" the current until "triggered" through a current threshold value

• less losses • less visual pollution compared to HVAC OHL • better power flow control • ability to link asynchronous grids	• permitting obstacles • system considerations (requires a strong system to connect to, generates harmonic distortion)

HVDC Line Commutated Converter (LCC) Underground Cable

The equipment used in underground HVDC LCC are essentially the same as with an overhead line with two cable types that can be used for underground HVDC; self-contained fluid-filled cables (SCFF) and Mass Impregnated (MI) cables.

Currently, mass impregnated cables have been designed to operate at ratings up to 500kV, 800MW (per cable) and can be found for submarine interconnectors for distances higher than 40km where the majority of such projects use DC transmission. Further applications have not been yet developed for two reasons. Firstly, replacing the overhead line with an underground cable incurs a substantial increase in overall costs. Secondly, there is no operational experience cable for higher voltage and power ratings.

HVDC Voltage Source Converter (VSC) Overhead Line

VSC technology has been in use for many years but has only recently been employed for HVDC due to the availability of high voltage, high power transistors.

HVDC VSC serves the same purpose as HVDC LCC; that is to rectify AC to DC current on the transmitting end and invert on the receiving end. The main difference in its converter structure is that instead of thyristors, transistor switches (IBGTs) are used. This implies that the converter can be self-commutating and that no synchronization to the network frequency is required.

HVDC VSC is not developed enough for bulk power. Due to self-commutation it is very useful to connect weaker networks and is preferable for island systems, offshore wind power and electrifying oilrigs.

Overall, HVDC VSC is a relatively new technology without a lot of operational experience. As with other HVDC configurations, its main application is to transmit bulk electricity. However, the added benefit of VSC over LCC is the capability of multi-terminal configurations that VSC can offer. Multi-terminal operation has not yet been fully applied but its benefits[30] position it as a suitable solution for the integration of diverse and intermittent renewable energy sources. HVDC VSC with the additional Modular Multilevel Converter (MCC) topology is often termed as HVDC Plus, whereas the basic converter topology is often termed as HVDC Light.

Currently, HVDC VSC is providing voltage and power ratings (200 kV and 600 MW) that are lower to the ones of LCC. It is expected that in the future VSC technologies will reach capacities equivalent to that of conventional LCC converters.

Below is a summary of the advantages and disadvantages of HVDC VSC overhead transmission:

Advantages	Disadvantages
• multi-terminal operation possible • less visual pollution • high capability of bulk power transfer • ability to link asynchronous grids • ability to connect to weaker grids • narrower right-of-way • no reactive power demand	• minimum commercial operational experience • high converter cost – suitable only for long distances • lower power ratings • higher converter losses • less standardized than AC systems • permitting obstacles

[30] A multi-terminal system can reduce the number of converter stations, lower investment and transmission losses, adapt easily to changing network conditions and increase network availability

• independent control of active and reactive power • less area required as compared to LCC • capable of providing continuous variable power in both directions • lower converter costs when compared to LCC	

HVDC Voltage Source Converter (VSC) Underground Cable

Both MI and XLPE cables could be used in HVDC VSC underground transmission for voltage and power ratings that could reach in the near future 500kV and 2000MW per converter. Currently, such VSC systems have been used for underground and submarine applications at voltage and power ratings up to 200kV and 400MW per converter.

Below is a summary of the advantages and disadvantages of HVDC VSC underground transmission:

Advantages	Disadvantages
• less visual pollution • capable of providing continuous variable power in both directions • no reactive power demand • safer (minimal weather-related outages) • advantages of underground transmission • narrow right-of-way • less converter costs than LCC	• higher losses as compared with LCC • low cable capacity • specific corridor constraints

HVAC Gas Insulated Line (GIL)

Gas insulated lines (GIL) consist of tubular aluminium conductors that are enclosed in a metallic pipe. The conductors are gas-insulated by sulfur hexafluoride (SF6). Second-generation gas mixtures are expected to have a composition of the order of 20% sulfur hexafluoride gas (SF6) and 80% nitrogen (N2). GIL is suitable for bulk transmission at EHV of the order 1000MVA–3800MVA and 230kV-550kV. It can be applied to distances up to 100km without the need for reactive compensation.

GIL's flexibility lies in the fact that it can be placed both over and under the ground. It can be installed in tunnels or buried directly in the soil.

Below is a summary of the advantages and disadvantages of HVAC GIL transmission:

Advantages	Disadvantages
• high transmission capacity • low transmission losses • low capacitance, reactive compensation • high reliability • long lifetime • flexible installation • high safety (minimal weather-related outages) • very low EMF • advantages of underground transmission	• expensive • greenhouse gas

Superconducting cables

High temperature superconducting (HTS) cables have the capability of transmitting bulk AC power at significantly lower conduction losses. In the case of DC, the transmission is loss free. HTS occurs in certain materials below a characteristic temperature.

Due to this superconducting state, the transmission capacity is not limited by the power transmitted. This constitutes HTS an ideal technology for interconnectors.

HTS is a new technology but currently it could only be applied to voltage and power ratings of the order of 150 kV and 570 MVA respectively.

Below is a summary of the advantages and disadvantages of superconducting cables:

Advantages	Disadvantages
• high power and voltage ratings • reduced or loss free transmission • suitable for interconnectors	• not mature technology • dependant on active secondary systems[31]

Choosing between the transmission options

In essence, the criteria for choosing a transmission technology remain the same. Trade-offs between economical factors, technical / operational features[32] and environmental considerations[33] remain at the forefront during the decision making process. However, the requirements of the transmission grid are changing. For example, bulk transmission of electricity is required over long distances and the capability to control it in a flexible manner, are deemed necessary in the future grid architecture. Hence, project developers are re-evaluating the aforementioned criteria according to the transmission's grid changing requirements.

This choice is not a straightforward one. The same features of a specific transmission technology could be identified as an advantage or disadvantage depending on the project and the system's architecture. For example, the fact that DC transmission acts independently of AC transmission system faults could be seen either as an advantage or disadvantage in post fault response depending upon the topography of the system.

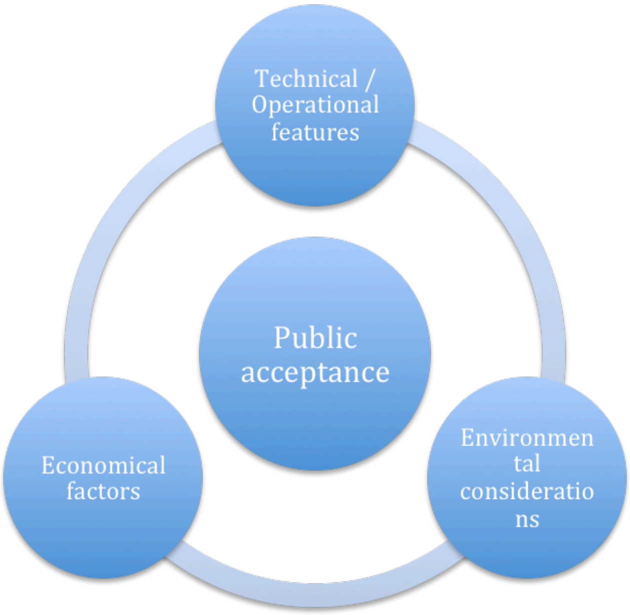
The choice between overhead and underground transmission is project-specific as elements of the project's location need to be taken into account and tested against the transmission options. For example, in some cases underground transmission could be preferred in locations where planning consent is difficult. On the contrary, overhead transmission could provide the cost effective and reliable option when permitting is possible.

The choice between AC and DC transmission is an operational one in terms of which option would be more appropriate from the system's perspective. For example, over long distances, DC transmission is the option that could provide the least costs, least losses option, while for shorter distances AC could prove to be the preferred option as it has low transformation costs.

At the heart of this process is public acceptance for grid expansion and transmission technologies. Public acceptance and lengthy permitting procedures have become a hurdle that has proven to be insurmountable in some cases. When project developers identify the most suitable choice, they often face opposition from individuals, local communities and/or municipalities. Public acceptance considerations have become part of the decision-making process. Therefore, methods and tools to overcome opposition are being developed for each project.

Selection of transmission technology

[31] Superconducting cables require cooling equipment that allow the cable to operate below a certain temperature
[32] eg. transmission capacity, losses, limitations, availability
[33] eg. land use, natural heritage



All of the aforementioned considerations constitute the selection of a transmission technology a highly complex and controversial process. RGI aims at increasing understanding of these issues through facilitating cooperation between TSOs, NGOs, technology suppliers, governments and policy makers. What remains clear is that it is premature to identify a 'winning' technology. However, what is required is a common European approach towards identifying the most suitable technology for each type of transmission project. This would enable the efficient expansion of the current grid that is required to effectively integrate increasing shares of electricity from renewable sources.