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Abstract

Focus of this report is to assess transmission grid assets costs in Europe. The analysis of the infrastructure costs performed has concerned both conventional and innovative HVAC (High Voltage Alternating Current) devices as well as HVDC (High Voltage Direct Current) technologies at national and international (cross-border) level.

For different HVAC conventional technologies, also a specific country review across many European countries has been conducted with the aim to compare the costs.

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ACRONYMS AND DEFINITIONS

AC: Alternating Current

B2B: Back-to-back

CSC: Current Source Converter

DC: Direct Current

DFC: Dynamic Flow Controller

DTR: Dynamic Thermal Rating

EC: European Commission

ENTSO-E: European Network of Transmission System Operators for Electricity

EU: European Union

FACTS: Flexible Alternating Current Transmission System

FSC: Fixed Series Capacitor

HTC: High Temperature Conductor

HTLS: High Temperature Low Sag Conductor

HVAC: High Voltage Alternating Current

HVDC: High Voltage Direct Current

IPFC: Interline Power Flow Controller

LCC: Line Commutated Converter

MSC: Mechanically Switched Capacitor

MTDC: Multi-terminal DC

OHL: Overhead Line

PAR: Phase Angle Regulator

PST: Phase Shifting Transformer

RES: Renewable Energy Source

RSVC: Relocatable Static VAR Compensator

RTTR: Real Time Thermal Rating

SC: Series Compensator

SSSC: Static Synchronous Series Compensator

STATCOM: STATic Synchronous COMpensator

STATCON: Static Condenser

SVC: Static VAR Compensator

TCPAR: Thyristor Controlled Phase Angle Regulator

TCPST: Thyristor Controlled Phase Shifting Transformer

TCQBT: Thyristor Controlled Quadrature Boosting Transformer

TCSC: Thyristor Controlled Series Capacitor

TSO: Transmission System Operator

UGC: Underground Cable

UPFC: Unified Power Flow Controller

VSC: Voltage Source Converter

XLPE: Cross Linked Polyethylene Extruded Insulation

1 EXECUTIVE SUMMARY

Transmission network planning is a very complex process and recent trends and challenges make it even more complicated.

Nowadays, in a liberalised environment, the European Transmission System Operator (TSO), only responsible for the transmission, shall plan the expansion of its network by minimising transmission costs (investment and operation), overcome bottlenecks and pursuing maximum social welfare, when requested by specific regulation, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation. Moreover, the penetration of variable Renewable Energy Sources (RES) brings additional uncertainties posing further challenges to transmission planners: they have in fact to reliably integrate variable RES power plants into the grids and cope with rapid and less predictable flows changes so as to preserve an adequate level of security for the system. Socio-environmental constraints must also more and more be duly taken into account in the planning process.

In this frame, European TSOs have then to deal with several techno-economic, market, regulatory, environmental and socio-political issues.

Central element of the transmission planning process is the cost-benefit analysis of the different transmission reinforcement options. It is then crucial to quantitatively assess not only the possible benefits but also the costs associated with transmission expansion towards decision-making.

Focus of this report is to assess transmission grid assets costs in Europe.

It has to be remarked that each transmission project is a specific case. Total expenditures for transmission system assets are highly dependent on different parameters, such as: equipment type, rating and operating voltage; technology maturity; local environmental constraints and geographical characteristics; population density; material and manpower cost; right-of-way; safety, environmental and regulatory requirements.

The analysis of the infrastructure costs performed has concerned both HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) technologies at national and international (cross-border) level.

The review of the costs of HVAC transmission technologies has also regarded both conventional and innovative devices.

Among conventional HVAC technologies, the following ones have been analysed:

- Overhead lines (OHLs)
- XLPE (Cross Linked Polyethylene Extruded) underground cables (UGCs)
- Reactive compensators
- Transformers
- Substations

Among innovative HVAC technologies, the following ones have been considered:

- PSTs (Phase Shifting Transformers)
- FACTS (Flexible Alternating Current Transmission System) devices
- GILs (Gas Insulated Lines)

For conventional HVAC technologies, also a country review across many European countries has been conducted. By comparing the costs for HVAC OHLs, it emerges that the countries where these assets are more costly result to be Ireland and the United Kingdom, whereas the lowest HVAC OHL investment values can be found among some Balkan countries (Albania, FYROM, Serbia).

2 INTRODUCTION

2.1 Objectives of this deliverable

Transmission network planning is a very complex process and recent trends and challenges make it even more complicated.

In the past, before the electricity market liberalisation, in a centrally managed power system the system operator could in general control the whole power system: the transmission network was then expanded with the aim to minimise both generation and transmission costs, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

Nowadays, in a liberalised environment, the Transmission System Operator (TSO), only responsible for the transmission, shall plan the expansion of its network by minimising transmission costs (investment and operation), overcome bottlenecks and pursuing maximum social welfare, when requested by specific regulation, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation. Moreover, the penetration of variable Renewable Energy Sources (RES) brings additional uncertainties posing further challenges to transmission planners: they have in fact to reliably integrate variable RES power plants into the grids and cope with rapid and less predictable flows changes so as to preserve an adequate level of security for the system. Socio-environmental constraints must also more and more be duly taken into account in the planning process.

The basic tasks of transmission grid planners can be summarised as in the following: to forecast the power and energy flows on the transmission network, drawing upon a set of scenarios of generation/demand evolution for the targeted period, within the market and regulatory framework; to check whether or not acceptable technical limits might be exceeded within the unchanged network, in standard conditions as well as in case of loss of system components (security analysis); to devise, in presence of criticalities, a set of possible transmission reinforcements/strategies that overcome the constraints and to select the one(s) having the best cost-benefit performance.

Central element of the transmission planning process is the cost-benefit analysis of the different transmission reinforcement options. It is then crucial to quantitatively assess not only the possible benefits but also the costs associated with transmission expansion. Focus of this deliverable is to assess grid assets costs in Europe.

2.2 Expected outcome

The goal of the present report is to collect and assess transmission infrastructure cost across European countries.

Chapter 3 introduces the main elements of transmission system in Europe as well as the HVAC cost components.

Chapter 4 reviews the costs for HVAC assets like overhead lines (OHL), underground cables, substations, transformers and reactive compensation devices. A comparison between the3 costas in several European Countries is included. Furthermore, it considers some innovative technologies and solutions.

Chapter 5 focuses on HVDC assets costs.

2.3 Approach

The information and the data contained in this report are based on the technical and scientific literature available on HVAC and HVDC technologies, on internal knowledge and experience as well as on responses to questionnaires from REALISEGRID project TSOs. In addition, public documents, sources, and links to projects and applications existing in Europe and worldwide have been consulted and compared in order to have a broad and consistent picture on the topics treated within this report.

The gathering and the consistency check of some cost figures have proved to be arduous, mostly due to the scarce availability of public sources (often outdated) addressing those issues. This report is closely linked to REALISEGRID deliverables D1.4.1 and D1.4.2, which aim at preparing a roadmap of innovative technologies for power transmission in Europe. For the part focusing on HVDC, this report completes and complements the information contained in REALISEGRID deliverables D1.1.1 and D1.2.1.

A steady interaction and information exchange with other project partners (TSOs, manufacturers, and other industrial stakeholders) has been fundamental to validate and consolidate the report outcomes.

3 TRANSMISSION INFRASTRUCTURE IN EUROPE

3.1 The European system

The European power system of ENTSO-E (European Network of Transmission System Operators for Electricity) encompasses five synchronous areas, namely the former UCTE (continental Europe network), NORDEL (Nordic countries network), BALTSO (Baltic countries network), UKTSOA (United Kingdom's network), ATSOI (Irish network). It is important to note that, even if BALTSO is now part of ENTSO-E system, it is still synchronously interconnected with the Russian IPS/UPS system. To complete the picture, the Turkish system, operated by TEIAS, is to be synchronously interconnected with the European continental network by 2011-2012, while islands like Cyprus, Iceland and Malta are still isolated [2].

There exist several full HVDC links in the European power system of ENTSO-E, mainly used for long submarine ties and/or asynchronous systems interconnections. There is currently also an installation of HVDC back-to-back station (between Finland and Russia).

Currently, the European transmission system is mainly based on HVAC assets at 220/275/300/330 kV and 380/400 kV level.

3.2 Transmission assets

The overhead lines (OHLs) are the main transmission infrastructure for power transport. They are based on towers or pylons, and the wires and conductors that they support, to transfer electricity. Towers or pylons are generally made of a lattice steel structure with a number of cross arms as they need to firmly carry the weight of the conductors and wires and maintain electricity safety clearance. The type, size, height and spacing of towers or pylons are determined by geographical, operational, safety and environmental considerations. A typical OHL route will involve three types of tower: suspension (used for straight lines), deviation (where the route changes direction) and terminal (where the lines connect with substations or underground cables). In some networks, other types of towers are present to prevent "cascade failure" in the event of heavy storms [10].

A suspension tower is typically 40 to 60 metres high with a span of 7 to 25 metres, depending on the type of tower. The width of the structure right-of-way depends on the level of power to be transported but typically ranges 30 to 50 metres for 380 kV. For 380 kV, towers are in general spaced around 350 to 450 metres distant and provide ground clearance of at least 7 metres in all weather conditions. Higher clearances usually apply if the route crosses motorways or high-pressure water pipes and minimum clearance for trees and public street lighting also apply. The towers or pylons are designed to carry either a single or double circuit in three phases. Each phase can carry between one and four conductors (single, twin, triple or quad bundles). The number of conductors per phase will depend on the technical requirements and geographical factors, but more bundles help protect against stress and "corona" discharge, reduce noise and line losses and can increase the MVA rating allowing more capacity to flow. The additional weight, however, can lead to a narrowing of the distance between towers or more expensive (weight bearing) towers.

The conductors need to be insulated from the ground and OHLs use air as the main insulator although the live conductors are hung from a string of toughened glass (or porcelain) insulating chains that are suspended from the pylons. The number of insulating discs depends on the voltage (around 20 discs for 380 kV OHLs, 10 - 12 for 220 kV OHLs). There is also usually an earthwire strung between the top of the pylons which protects the conductors from lightning [10].

OHLs do have a visual impact on the landscape and in dense urban areas they are often impractical or unacceptable to residents. Underground cables are used in almost all European countries, mainly for parts of the transmission and/or distribution electricity networks in urban areas, as well as in the countryside where ecological or historical interests need to be preserved. Underground cables are therefore an alternative, yet more expensive, form of transporting electricity. The reasons why underground cables will always cost more than OHLs for a certain power rating and link distance are [9]:

- Additional insulation is required because the cables are often laid only 1 metre below ground;
- Extra land is needed for the sealing end (transition station) where the cables need to be connected to OHLs;
- Access to the cables is essential for repairs and maintenance purpose, therefore the land above the cables cannot be used for farming or industrial purposes;
- HVAC underground cables, above a certain distance, need reactive compensation (at 380/400 kV, this may require reactive compensation every 20 to 25 km);
- Within an existing network of OHLs, it may be difficult to integrate underground cables due to the differences in impedance. To solve this, in the case of e.g. parallel operation (ring structure) of cable and OHL, the installation of series reactors for equal impedance is needed, resulting then in additional investments.

For all these reasons, cost differences between OHLs and underground cables are not linear. In general, though, as power ratings increase, the cost of underground cable rises more than the cost of equivalent OHL.

On land, cables made with copper are generally laid in a trench in groups of three in a mixture of cement and sand below ground, 1 metre distant. The cables generate significant heat and due to the absence of air, the conductors need to be much thicker. In deep water, the cables have a steel wire armour between the layers of plastic. They are generally buried at depths of up to 3 metres to reduce the risk of damage from trawlers and anchoring ships [10]. (Further details on cables features and installation issues can be found in the technical literature, e.g. [4][6][9].

Important elements of transmission grids are the substations. A substation can be defined as that part of a power system, concentrated in a given place, including mainly the terminations of transmission or distribution lines, switchgear and housing and which may also include transformers. It generally includes facilities necessary for system security and control (e.g. protective devices); any building or outdoor location at which electric energy in a power system is transformed, converted, or controlled. Substations are usually contained within secure sites to ensure public safety. Most substations today are unmanned sites although road access is necessary for staff and for the transport of equipment, maintenance or repair [10].

In a substation a switchgear is composed of different busbar bays. A busbar bay can be defined as a three-phase assembly consisting usually of one circuit breaker or switch, its associated disconnectors, instrument transformers interconnecting busbar up to and including the line disconnect switch (if applicable), and the section of main busbar (if applicable) [7].

Although a TSO generally owns the land occupied by its substations, in general it does not own the land that is crossed by OHLs. An agreement with the land owners allows then access rights to the land at any time. Local compensation is agreed on an individual basis and is passed through to users. If the land has to be leased, the costs of the lease would be passed through to the user [10].

3.3 Transmission assets cost elements

In order to evaluate the costs for transmission infrastructure in Europe, different elements have to be preliminarily introduced.

Total expenditures for transmission system assets are highly dependent on different parameters, such as:

- equipment type
- equipment rating and operating voltage
- technology maturity
- local environmental constraints and geographical characteristics
- population density
- material cost
- manpower cost
- right-of-way
- safety, environmental and regulatory requirements.

The variability on the latter item includes also the fact that the introduction of advanced OHL towers profile, recently implemented in some European countries to comply with stricter safety/environmental regulations (e.g. in terms of visual impact or EMF[1] abatement) [3], may increase the overall OHL cost.

In general, environmental constraints increase costs and implementation time - e.g. for OHLs - while technological advances in manufacturing usually reduce costs: this is the case for power electronics components or for underground XLPE (Cross-Linked Polyethylene Extruded) cables. It has also to be noted that transmission planning criteria may also indirectly impact on assets costs: this applies e.g. when more stringent network planning strategies are adopted by the TSO, requiring then a more redundant transmission grid and consequently a higher level of investments. This is for example the case of British TSO applying n-2 security criteria [10].

Another aspect that plays a role in the determination of transmission assets costs (especially for innovative technologies) is that equipment prices continuously change due to a dynamic world market: costs of European transmission assets are then influenced and driven by external factors.

Assets investments expenditures can be grouped in capital investment expenses (CAPEX), operating expenses (OPEX) and other expenses.

Cost components of CAPEX for transmission assets include expenditures for: equipment, installation, civil works, auxiliaries, engineering and project management, studies, test, right-of-way, freight and insurance, financing, tax.

Cost components of OPEX for transmission assets include expenditures for: operation, maintenance, relocation, losses.

Other cost elements refer to: land acquisition, local compensations, dismantling.

This cost subdivision applies to both HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) technology types.

In Chapter 4 and Chapter 5, details on cost elements breakdown as well as specific figures on both HVAC (conventional and innovative) and HVDC infrastructure assets in Europe are respectively provided.

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[1] EMF: Electro-magnetic field.

4 HVAC TRANSMISSION TECHNOLOGY COST

4.1 Introduction

The analysis of the costs of HVAC transmission technologies has concerned both conventional and innovative devices.

Among conventional HVAC technologies, the following ones have been analysed:
- OHLs
- XLPE Underground Cables (UGCs)
- Transformers
- Reactive compensators
- Substations

Among innovative HVAC technologies, the following ones have been considered:
- PSTs (Phase Shifting Transformers)
- FACTS (Flexible Alternating Current Transmission System) devices
- GILs (Gas Insulated Lines)

All cost data shown in the following sections are based on the interaction with REALISEGRID partners, TSOs and stakeholders as well as on the analysis of the available technical information and scientific literature: this exercise has started within REALISEGRID WP1 [1][3][4].

4.2 Conventional HVAC technologies

4.2.1 OHLs

As seen in Chapter 3, different cost components contribute to the total transmission infrastructure investment cost. In the case of 380 kV OHLs, also depending on local constraints and regulation, two typical examples of investment cost (including expenses for local compensation) breakdown for different cases in Europe are shown in Figure 4.1 and Figure 4.2.

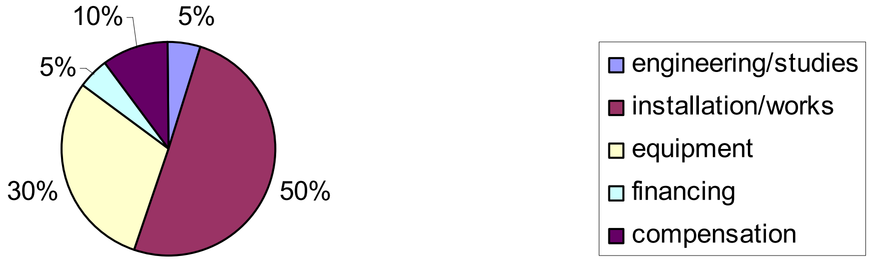

Figure 4.1: Example of cost breakdown for 380 kV OHL (case 1)

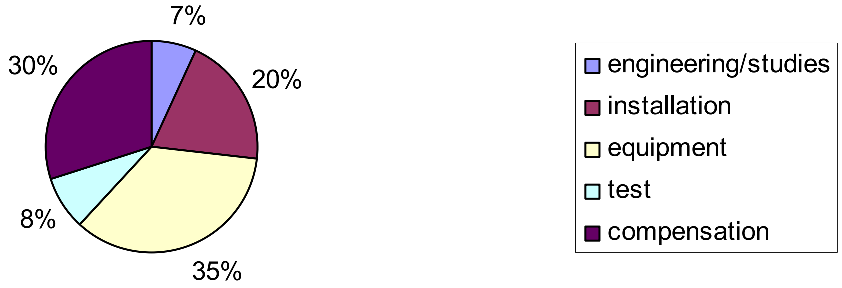

Figure 4.2: Example of cost breakdown for 380 kV OHL (case 2)

The main differences between the two cases lay on the fact that case 1 refers to a situation where installation plays a major role (e.g. due to geographic constraints or higher manpower costs), whereas case 2 shows the relevant impact due to local compensation money (e.g. to repay land owners and/or population crossed by the OHL).
Some similar examples can be also found in [10].

OHLs equipment costs include expenses for: conductors, pylons/towers, foundations, insulators, clamps and related devices.
Table 4.1 shows average investment costs (CAPEX) of HVAC OHLs at 380 kV in continental Europe (for a throughput power of 1500 MVA per circuit).

System component	Voltage level	Power rating	Cost range		Unit
			min	max	
HVAC OHL, single circuit(1)	380 kV	1500 MVA	400	700	kEUR/km
HVAC OHL, double circuit(1)	380 kV	2×1500 MVA	500	1000	kEUR/km

(1) cost ranges correspond to the base case, i.e. installation over flat land. For installations over hilly landscape +20% and +50% for installations over mountains or urban areas have to be factored in.

Table 4.1: Typical investment cost ranges (average) for selected HVAC OHLs ([1])

In Table 4.1 the average investment cost ranges for HVAC OHL include all costs related to the transmission medium (due to equipment, engineering, installation, civil works etc.) except from HVAC substation equipment.
In Table 4.1 the lower limit (min value) refers to installation costs in continental European countries with low labour costs, while the upper limit (max value) refers to installation costs in European countries with high labour costs, e.g. Germany, Netherlands or France.
It shall be clearly pointed out that the presented cost ranges represent typical average values and shall not be taken as absolute data. The actual overall project costs may differ from the provided average values if exceptional technological, geographical, and/or environmental circumstances apply [1]. Investment costs for HVAC OHLs can be also much influenced by recently emerged innovative design towers, making them more expensive in some cases: this is for example the case of the Netherlands (see also 4.2.6) [3].

Capital costs for HVAC OHLs refer to the base case, wherein the installation of OHLs over flat landscape and in sparsely populated areas is considered. In this base case, high towers with a large span length can be used which directly results in lower overall installation costs. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are taken into account by a surcharge of +20% and +50%, respectively.

Concerning OPEX, for HVAC OHLs the level of operation and maintenance (O&M) costs is generally in a range 1.5 – 5 % of the capital investment costs.

4.2.2 XLPE UGCs

As seen in Chapter 3, due to the complexity of the cable technology, installation costs of an HVAC cable solution per km will always be higher than those ones for an equivalent OHL on the same distance. In fact, costs of a XLPE cable system depend on the specific requirements defined for the system. In addition to the cable itself with its joints and terminals, accessories like joint bays, transition station, optic fiber cable, earthing etc. need to be accounted for as components of the total equipment cost. Furthermore, the costs for civil works may be high or very high (up to 60% of the total cost), as they depend on the type of soil that the cable is going to be placed in (sand, rocks etc.) as well as the presence of other existing infrastructure the route may cross.

For the installation of 380/400 kV XLPE cable systems buried in soil and completed in Europe over the past 10 years the range of investment cost has been generally 5 to 10 times compared to an equivalent OHL. These cost ratios are directly related to the capacity of the link. A cost ratio down to 3 can be reached for links with limited rating and under special favourable conditions for cable laying or in case of expensive OHL. Cost ratios above 10 can be reached for high capacity double circuit links and if specific structures are needed like projects involving the construction of cable tunnels (cost ratios above 15 may be expected in these specific cases) due to the cost for civil works [6].

Table 4.2 shows average investment costs (CAPEX) of HVAC XLPE cables at 380 kV in continental Europe (for a throughput power of 1000 MVA per circuit).

System component	Voltage level	Power rating	Cost range		Unit
			min	max	
HVAC underground XLPE cable, single circuit	380 kV	1000 MVA	1000	3000	kEUR/km
HVAC underground XLPE cable, double circuit	380 kV	2×1000 MVA	2000	5000	kEUR/km

Table 4.2: Typical investment cost ranges (average) for selected HVAC UGCs ([1])

In Table 4.2 the average investment cost ranges for HVAC cables include all costs related to the transmission medium (due to equipment, engineering, installation, civil works etc.) except from transition substation equipment.

As for HVAC OHLs, the presented cost ranges represent typical average values for HVAC underground XLPE cables and shall not be taken as absolute data. The actual overall project costs may differ from the provided average values if exceptional technological, geographical, and/or environmental circumstances apply [1].

Once in operation, a cable system itself is nearly maintenance free. Monitoring systems allow partial discharge surveillance. As any transmission corridor, the cable route requires regular inspection. The level of operation and maintenance (O&M) costs is generally one-tenth of equivalent HVAC OHLs, i.e. 0.15 – 0.5 % of the capital investment costs [6][9].

4.2.3 Reactive compensation

The reactive compensation needed for HVAC XLPE cables depends on the link length and on the voltage level. As seen in Chapter 3, at 380/400 kV, reactive compensation may be necessary every 20 to 25 km for HVAC XLPE cables. At this voltage level, the cost for reactive compensation is in the range 15-20 k€/MVAR [1][8].

4.2.4 Transformers

Figure 4.3 shows the cost curve for a typical transformer installation.

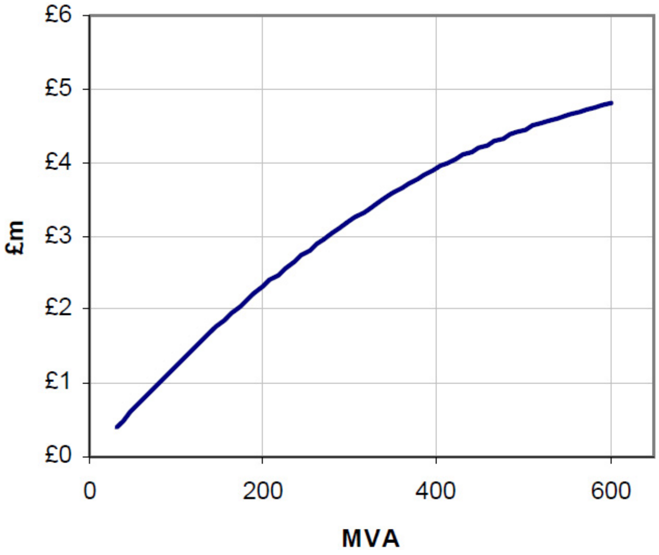

Figure 4.3: Typical cost curve of transformer ([8])

From Figure 4.3 some cost data for transformers can be extracted (1 € = 0.9 £):

Transformers 400 MVA, 400/220 kV	4.4 M€
Transformers 500 MVA, 400/220 kV	5.0 M€
Transformers 600 MVA, 400/220 kV	5.5 M€

4.2.5 Substations

The costs for HVAC substations depend on the different elements therein contained, especially the type and amount of transformers. For transforming air-insulated substations 220/110 kV range costs may typically reach 15-25 M€, while for transforming air-insulated substations 380/220 kV typical range costs may amount up to 20-30 M€.

4.2.6 Country review of HVAC assets costs

In the following, a review of HVAC investment costs related to different HVAC assets (for several rating and voltage levels) in many European countries is presented.

■ Italy (average reference values):

• OHL single circuit, 380 kV	500-600 k€/km
• OHL double circuit, 380 kV	750-900 k€/km
• OHL single circuit, 220 kV	350-420 k€/km
• OHL double circuit, 220 kV	450-540 k€/km
• OHL single circuit, 120÷150 kV	270-320 k€/km
• OHL double circuit, 120÷150 kV	410-490 k€/km
• XLPE UGC, 1200 MVA, 380 kV	3200-4000 k€/km
• XLPE UGC, 550 MVA, 220 kV	2800-3400 k€/km
• XLPE UGC, 400 MVA, 220 kV	2000-2400 k€/km
• XLPE UGC, 250 MVA, 150 kV	1700-2050 k€/km

■ Germany (average values):

• OHL single circuit, 380 kV	700-800 k€/km
• OHL double circuit, 380 kV	1000-1200 k€/km
• XLPE UGC, 2x1300 MVA, 380 kV	4800-5200 k€/km

■ France (average values):

• OHL single circuit, 380 kV	700-800 k€/km
• OHL double circuit, 380 kV	1000-1400 k€/km
• OHL single circuit, 220 kV	350-500 k€/km
• OHL double circuit, 220 kV	450-550 k€/km
• XLPE UGC, 220 kV	2000-2800 k€/km
• Air-insulated 400/220 kV substation	25-30 M€

■ Netherlands (average values):

• OHL double circuit, 380 kV	1000-1200 k€/km
• OHL advanced double circuit, 380 kV	2300-2500 k€/km
• XLPE UGC, 1000 MVA, 380 kV	4200-5000 k€/km
• XLPE UGC, 4x1000 MVA, 380 kV	12000-13000 k€/km
• XLPE UGC, 150 kV	2400-2600 k€/km

■ Austria (average values):

• OHL double circuit, 380 kV	1000-1500 k€/km
• OHL double circuit, 220 kV	700-1000 k€/km
• Air-insulated 380 kV substation	4-4.5 M€

■ Ireland (average values):

• OHL double circuit, 400 kV	1400-1600 k€/km
• OHL single circuit, 220 kV	700-1000 k€/km
• OHL single circuit, 110 kV	400-500 k€/km
• XLPE UGC, 500 MVA, 220 kV	1900-2900 k€/km
• XLPE UGC, 250 MVA, 110 kV	1800-2600 k€/km
• XLPE UGC, 120 MVA, 110 kV	800-1300 k€/km
• Air-insulated 400/220 kV substation	35-42 M€
• Air-insulated 400/110 kV substation	34-40 M€

- UK (average values):

OHL single circuit, 400 kV	1100-1300 k€/km
OHL double circuit, 400 kV	1300-1500 k€/km
XLPE UGC, 230 MVA, 132 kV	2000-2200 k€/km
XLPE (submarine) cable, 220 MVA, 132 kV	1400-1600 k€/km
XLPE UGC, 360 MVA, 220 kV	2200-2400 k€/km
XLPE (submarine) cable, 360 MVA, 220 kV	1700-1900 k€/km
XLPE cable, 750 MVA, 400 kV	3700-3900 k€/km

- Finland (average values):

OHL single circuit, 400 kV	400-500 k€/km
OHL double circuit, 400 kV	500-700 k€/km
OHL single circuit, 220 kV	200-300 k€/km

- Portugal (average values):

OHL single circuit, 380 kV	400-500 k€/km
OHL double circuit, 380 kV	500-600 k€/km

- Poland (average values):

OHL single circuit, 380 kV	400-500 k€/km
OHL double circuit, 380 kV	900-1000 k€/km

- Spain (average values):

OHL single circuit, 380 kV	400-600 k€/km
OHL double circuit, 380 kV	600-800 k€/km
XLPE UGC, 2x860 MVA, 380 kV	5800-6200 k€/km

- Estonia (average values):

OHL single circuit, 330 kV	200-300 k€/km
XLPE UGC, 330 kV	1700-1900 k€/km

- Latvia (average values):

OHL double circuit, 330 kV	300-400 k€/km
XLPE UGC, 330 kV	1700-1900 k€/km

- Lithuania (average values):

OHL single circuit, 330 kV	300-400 k€/km

- Belgium (average values):

OHL double circuit, 380 kV	1000-1200 k€/km
OHL advanced double circuit, 380 kV	2300-2500 k€/km
XLPE UGC, 2x1000 MVA, 380 kV	6500-7000 k€/km

- Albania (average values):

OHL single circuit, 400 kV	250-300 k€/km
OHL single circuit, 220 kV	100-150 k€/km

■ Malta (average values):	
• OHL single circuit, 132 kV	150-200 k€/km
• XLPE (submarine) cable, 220 kV	1500-2000 k€/km

■ Sweden (average values):	
• OHL single circuit, 400 kV	400-500 k€/km
• OHL double circuit, 400 kV	500-700 k€/km
• OHL single circuit, 220 kV	200-300 k€/km
• Air-insulated substation, 400 kV	9-11 M€

■ Romania (average values):	
• OHL double circuit, 400 kV	300-500 k€/km
• Air-insulated substation, 400/220 kV	18-20 M€
• Air-insulated substation, 400/110 kV	16-18 M€

■ FYROM (average values):	
• OHL single circuit, 400 kV	200-300 k€/km
• OHL single circuit, 220 kV	100-150 k€/km

■ Bulgaria (average values):	
• OHL single circuit, 400 kV	300-400 k€/km

■ Czech Rep. (average values):	
• OHL single circuit, 400 kV	600-800 k€/km
• OHL double circuit, 400 kV	1000-1100 k€/km
• Air-insulated substation, 400/110 kV (2x350 MVA trafos)	12-30 M€

■ Norway (average values):	
• OHL single circuit, 420 kV	700-1100 k€/km

■ Bosnia-Herzegovina (average values):	
• OHL single circuit, 400 kV	200-300 k€/km

■ Denmark (average values):	
• OHL double circuit, 400 kV	1000-1200 k€/km
• OHL advanced double circuit, 400 kV	2000-2200 k€/km
• XLPE UGC, 132-150 kV	500-600 k€/km
• Gas-insulated substation, 400 kV	8-10 M€

■ Greece (average values):	
• OHL single circuit, 400 kV	300-400 k€/km
• Air-insulated substation, 400/220 kV	18-20 M€

■ Slovakia (average values):

• OHL double circuit, 400 kV	800-1100 k€/km

■ Hungary (average values):

• OHL single circuit, 400 kV	300-400 k€/km
• OHL double circuit, 400 kV	500-650 k€/km

■ Croatia (average values):

• OHL double circuit, 400 kV	500-600 k€/km

■ Slovenia (average values):

• OHL double circuit, 400 kV	700-900 k€/km

■ Serbia (average values):

• OHL single circuit, 400 kV	200-300 k€/km

■ Montenegro (average values):

• OHL single circuit, 400 kV	250-350 k€/km

■ Cyprus (average values):

• OHL double circuit, 220 kV	200-250 k€/km
• OHL single circuit, 132 kV	50-100 k€/km
• XLPE UGC, 2x200 MVA, 132 kV	500-600 k€/km

- Gas-insulated substation, 132/23-11.5 kV (1x40 MVA trafo) 3 M€
- Gas-insulated substation, 132/23-11.5 kV (2x40 MVA trafos) 4 M€

■ Iceland (average values):

• OHL single circuit, 132 kV	200-250 k€/km

■ Ukraine (average values):

• OHL single circuit, 750 kV	500-600 k€/km
• OHL single circuit, 330 kV	200-250 k€/km

By comparing the costs for HVAC OHLs, it emerges that the countries where these assets are more costly result to be Ireland and the United Kingdom, whereas the lowest HVAC OHL investment values can be found among some Balkan countries (Albania, FYROM, Serbia).

4.3 Innovative HVAC technologies

Table 4.3 shows capital investment cost ranges for a selection of FACTS devices.

The investment costs for a Phase Shifting Transformer (PST) and a Fixed Series Capacitor (FSC) are also presented as a comparison. Although both of these technologies are generally associated with FACTS, as they may be applied in similar situations, they cannot be considered as FACTS devices. This is due to the fact that these equipments are mechanically controlled and do not possess the same level of precision, flexibility, promptness of response and the added features that FACTS devices have.

Components	Voltage level (in kV)	Available Power Rating (in MVAR/MVA)	Cost Range		Unit
			Min	Max	
PST[(1)]	400	100-1600	10	40	kEUR/MVA
FSC[(1)]	400	100-1000	10	20	kEUR/MVAR
SVC	400	100-850	30	50	kEUR/MVAR
STATCOM	400	100-400	50	75	kEUR/MVAR
TCSC	400	25-600	35	50	kEUR/MVAR
SSSC	400	100-400	50	80	kEUR/MVAR
TCPST (TCQBT)[(2)]	220	50	12	36	kEUR/MVA
TCPST (TCPAR)[(2)]	115	150	40	70	kEUR/MVA
UPFC	400	100-325	90	130	kEUR/MVA

(1) Related device, not a FACTS
(2) Single case

Table 4.3: Investment cost ranges for FACTS ([1])

The values presented in Table 4.3 refer to the base case, wherein the installation of these equipments applies in standard environmental conditions (over flat land and in sparsely populated areas). The lower limit (min value) refers to countries with low labour costs and the upper limit (max value) concerns countries with higher labour costs.

GIL technology is still in the development stage.

For a double-circuit GIL at 400 kV, 2000 MVA rating, the capital investment cost can be estimated in a range 4000 – 7000 k€/km, depending on different environmental and installation conditions.

5 HVDC TRANSMISSION TECHNOLOGY COST

In an HVDC system the main transmission assets are represented by the present OHL(s) and/or cable(s) and by the CSC (Current Source Converter) or VSC (Voltage Source Converter) HVDC converter stations.

All cost data shown in the following sections are based on the interaction with REALISEGRID partners, TSOs and stakeholders as well as on the analysis of the available technical and scientific literature.

The costs of some typical HVDC OHL and HVDC cable (underground and undersea) are here reported for different conditions (average values):

• XLPE (submarine) cable, 500 MW, ±150 kV	2600 k€/km
• XLPE (submarine) cable, 650 MW, ±150 kV	3400 k€/km
• XLPE (submarine) cable, 700 MW, ±300 kV	1900 k€/km
• XLPE (submarine) cable, 1000 MW, ±300 kV	2600 k€/km
• XLPE (submarine) cable, 1200 MW, ±300 kV	3200 k€/km
• XLPE (underground) cable, 600 MW, ±300 kV	1500 k€/km
• XLPE (underground) cable, 800 MW, ±300 kV	1800 k€/km
• XLPE (underground) cable, 1000 MW, ±300 kV	2200 k€/km
• XLPE (underground) cable, 1200 MW, ±300 kV	2500 k€/km
• OHL, ±150 kV	830 k€/km
• OHL, ±300 kV	940 k€/km
• OHL, ±600 kV	1200 k€/km

Figure 5.1 shows a typical characteristic of a converter (CSC) cost curve respect to its rating. The linear relation can be expressed by: Cost [M€] = 0.067*P [MW] + 33 (1 € = 0.9 £).

Analogously, Figure 5.2 shows a similar cost curve for a VSC, whose equation is:
Cost [M€] = 0.083*P [MW] + 28 (1 € = 0.9 £).

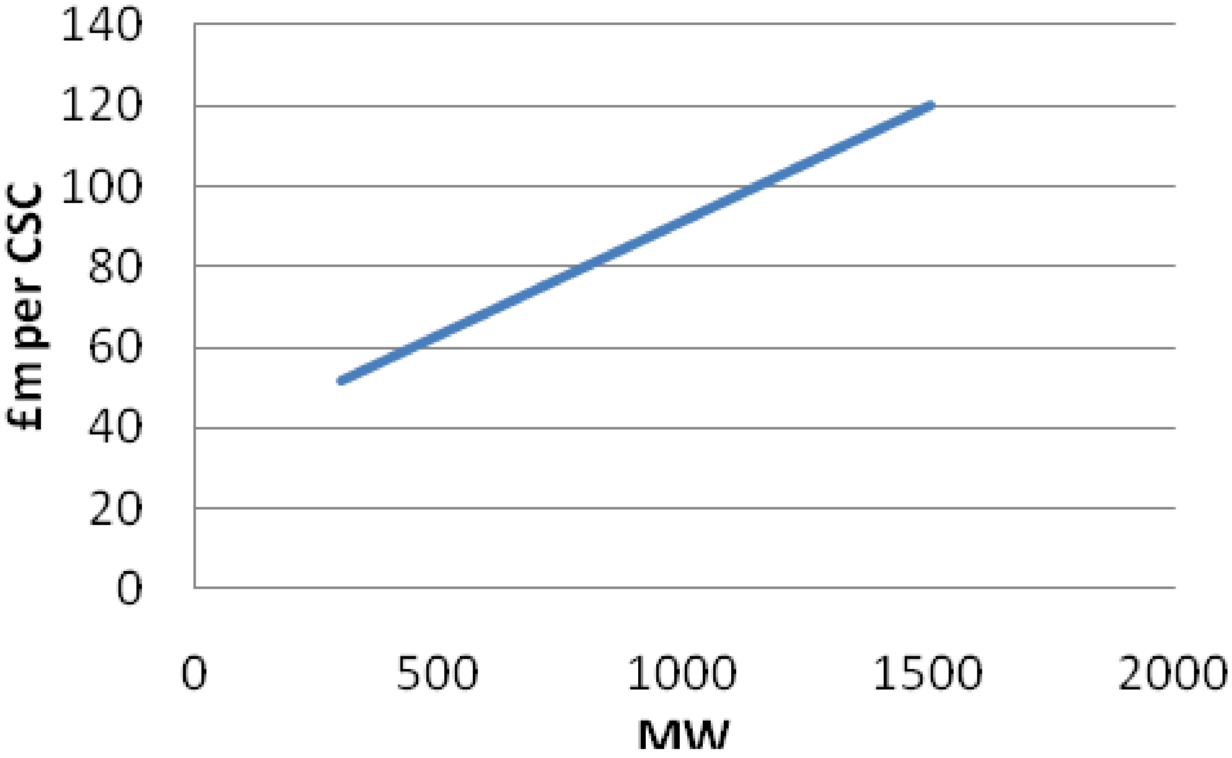

Figure 5.1: CSC converter cost vs. capacity rate ([8])

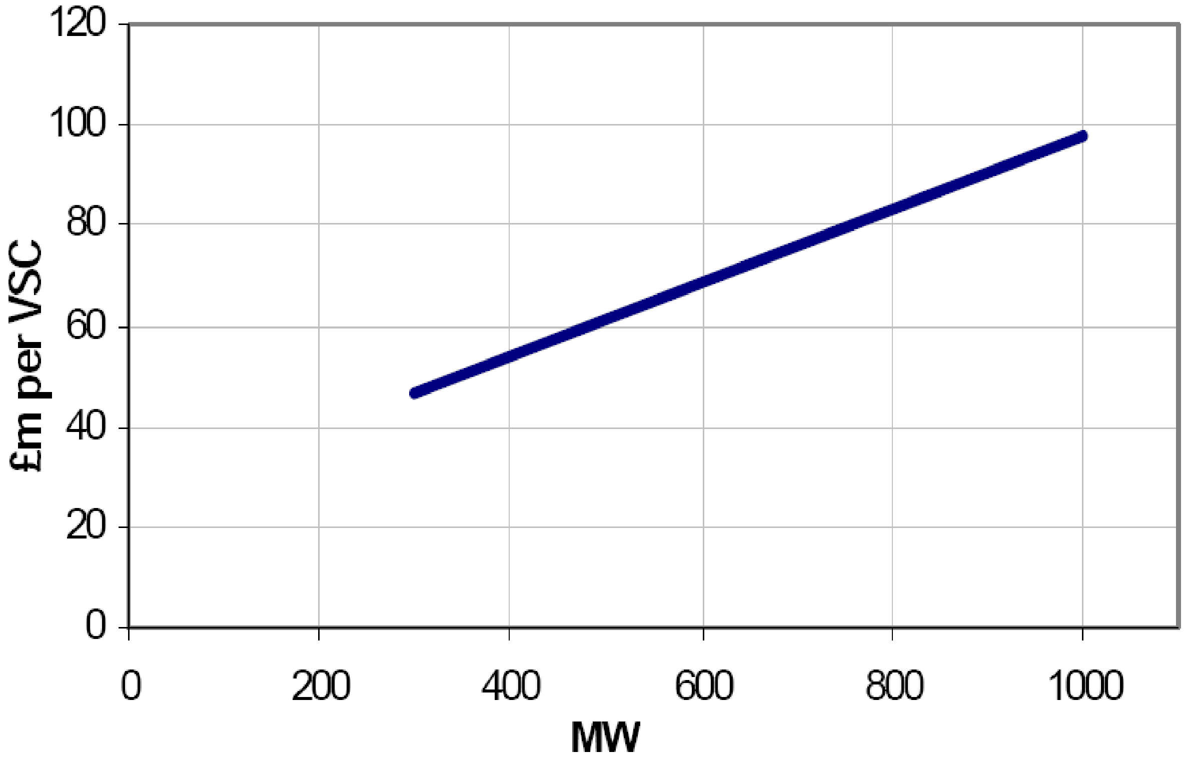

Figure 5.2: VSC converter cost vs. capacity rate ([8])

Costs ranges in Table 5.1 are reported to consider HVDC devices (for a throughput power ranging between 350 and 3000 MW for HVDC OHLs and 1100 MW for HVDC cables).
As for HVAC technologies, also here the lower limit (min value) refers to installation costs in European countries with low labour costs, while the upper limit (max value) refers to installation costs in European countries with high labour costs, e.g. Germany, The Netherlands or France.
Similarly to the HVAC case, it shall be also clearly pointed out that the proposed cost ranges represent typical average values and shall not be taken as absolute data. The actual overall project costs may differ from the provided average values if exceptional technological, geographical, and/or environmental circumstances apply.

System component	Voltage level	Power rating	Cost range		Unit
			min	max	
HVDC OHL, bipolar(1)	±150÷±500 kV	350÷3000 MW	300	700	kEUR/km
HVDC underground cable pair	±350 kV	1100 MW	1000	2500	kEUR/km
HVDC undersea cable pair	±350 kV	1100 MW	1000	2000	kEUR/km
HVDC VSC terminal, bipolar	±150÷±350 kV	350÷1000 MW	60	125	kEUR/MW
HVDC CSC terminal, bipolar	±350÷±500 kV	1000÷3000 MW	75	110	kEUR/MW

(1) cost ranges correspond to the base case, i.e. installation over flat land. For installations over hilly landscape +20% and +50% for installations over mountains or urban areas have to be factored in.

Table 5.1: Typical investment cost ranges (average) for selected HVDC transmission components [1])

Investment costs for HVDC overhead lines refer to the base case, wherein the installation of overhead lines over flat landscape and in sparsely populated areas is considered. In this base case, high towers with a large span length can be used which directly results in lower overall installation costs. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are taken into account by a surcharge of +20% and +50%, respectively, as in the HVAC case.
The proposed investment cost ranges for HVDC overhead include all costs related to the transmission medium (i.e. equipment costs, engineering costs, installation costs). The OHL equipment cost includes cost for conductors, pylons/towers, foundations, clamps and related devices.
The cost ranges provided for HVDC converter equipment are presented “per terminal”, wherein a terminal includes all equipment at one side of the bipolar transmission line: both converters, reactive compensation (if needed), active filtering, AC/DC switchgear, engineering, project planning, taxes etc. except any costs related to the transmission medium. This accommodates the facts that on the one hand a voltage source converter is by nature bipolar and on the other hand that bipolar HVDC installations are preferred within a synchronized power grid for system security reasons. In case of a bipolar transmission line, the provided converter cost ranges need to be multiplied by the factor of 2, i.e. one bipolar converter terminal at each the feeding and the receiving end of the transmission line, in order to yield the overall installation costs (excluding the costs for the transmission line).

Concerning maintenance of HVDC systems, it is comparable to the one of HVAC systems. The high voltage equipment in converter stations is comparable to the corresponding equipment in AC substations, and maintenance can be executed in the same way. Maintenance will focus on: AC and DC filters, smoothing reactors, wall bushings, valve-cooling equipment, thyristor valves. Normal routine maintenance is recommended by manufacturers to be about one week per year. The newer systems can even go for two years before requiring maintenance. In fact, in a bipolar system, one pole at a time is stopped during the time required for the maintenance, and the other pole can normally continue to operate and depending on the in-built overload capacity it can take a part of the load of the pole under maintenance. In addition, preventive maintenance shall be pursued so that the plants and equipment will achieve optimally balanced availability with regard to the costs of maintenance, operating disturbances and planned outages.

O&M costs for HVDC systems can be assumed in a range 1.5 – 5 % of the investment costs, like for HVAC OHLs. The main difference is related to the presence of the converter stations, having their level of losses (CSC converter losses can be comprised in a range 0.5-1% per converter at full load, while VSC converter losses can be in a range 1-2% per converter at full load [1].

Recent/ongoing cross-border HVDC infrastructure projects:

- Fenno-Skan 2 FI-SE, 130 M€, 800 MW, 500 kV, 103 km DC OHL, 200 km DC submarine cable
- NorNed NO-NL, 600 M€, 700 MW, ±450 kV, 2x580 km DC submarine cable
- Estlink 1 EE-FI, 110 M€, 350 MW, ±150 kV, 2x31 km DC underground cable, 2x74 km DC submarine cable
- East-West 1 IE-GB, 550 M€, 500 MW, ±200 kV, 2x75 km DC underground cable, 2x186 km DC submarine cable

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