e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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WP 3	**Technology portfolio to meet the 2050 scenarios**		
D3.1	**Technology assessment from 2030 to 2050**		

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Written by	A. Vafeas, T. Pagano, E. Peirano (Technofi)	25-07-2014
Checked by	E. Peirano (Technofi)	29-08-2014
Validated by	G. Sanchis, B. Betraoui (RTE)	10-10-2014

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document information

General purpose

Deliverable 3.1 (D3.1) deals with the assessment of the most impacting technologies for the power system in the EU28 at the 2050 time horizon. The scope of power system technologies is the following: generation, storage, transmission (passive and active transmission technologies) and demand.

The assessment of the power system technologies consists in the construction of a database displaying *variables (i.e. technical performances, costs, environmental impact, etc.) that characterize the different technologies from today to 2050. The core of the deliverable provides general principles explaining how the database was designed and populated with data. A dedicated chapter addresses the costs of transmission technologies.*

The present document is complemented by annexes. These annexes are organized in pairs, i.e. a TAR (Technology Area Reports, Word files) with a database (Excel files). A TAR addresses a particular technology or a set of technologies, for example HVDC converters, and provided explanations on the hypotheses, methodologies, models, etc., used to build the associated database (Excel file). The collection of all Excel files constitutes the e-Highway2050 technology data base.

The results displayed in D3.1 result from a collective work performed within Work Package 3 under the management of TECHNOFI.

Disclaimer

The techno-economic database developed and presented in D3.1 addresses the technology input data needs which the project's partners will use to meet some of their computational tasks. At the time of submission of D3.1 (August 2014), these computational tasks are ongoing, thus contributing to a pragmatic validation of these input technical and cost data (with a specific attention paid with transmission technologies). Numerical results coming from such intensive computations may show specific sensitivity to some of the data sets (especially costs) and/or the need for extra data to address a limited number of new technologies. Under such circumstances, the deliverable D3.1 will be upgraded accordingly with relevant addenda. Consequently, D3.1 might be complemented by the end of the computational tasks with this set of addenda.

Key contributors

Data gathering:

- Generation: Eurelectric/VGB Power Tech, EWEA, IEN.
- Storage: Eurelectric/VGB Power Tech and University of Comillas.
- Demand: TECHNOFI.
- Transmission: Europacable, T&D Europe, TSO Pool (Amprion and RTE).

Quality review:

- WP3: RSE, RTE, KUL, TECHNOFI (Quality Pool), Amprion and three internal workshops (WP3 partners).
- Stakeholders' feedback: 15th April 2014 workshop in Brussels.
- E-Highway2050: according to the quality rules set by the project (Quality Management Plan).

Confidentiality

D3.1 was confidential until the project end. Project partners agreed for a public access after the project end.

Executive summary

Deliverable 3.1 (D3.1) deals with the assessment of the most impacting technologies for the power system in the EU28 at the 2050 time horizon. The scope of power system technologies is the following: generation, storage, transmission (passive and active transmission technologies) and demand. This assessment consists in the construction of a database displaying data (i.e. technical performances, costs, environmental impact, etc.) that characterize the different technologies for the next four decades, i.e. from today to 2050. The construction of the techno-economic database is the result of a collective work performed within Work Package 3 under the management of TECHNOFI and involving key European stakeholders of the electricity value chain (manufacturers, TSOs, academia).

The technology assessment reflects the common views of the e-Highway2050 experts regarding the most likely evolutions of the selected technologies mainly in terms of technical performances, maturity, and costs, thereby providing the project partners with data to feed the different simulation tasks (e.g. scenario quantification, grid simulations, cost benefit analyses).

The data gathering process for generation and storage technologies was mainly carried-out by a professional association, partner of the project (Eurelectric with its subcontractor VGB Power Tech) and an academic institution (University of Comillas) for electrochemical storage technologies. A professional association (EWEA, European Wind Energy Association) delivered the data for wind energy. The Institute of Power Engineering (IEN) completed the data sets for generation with specific data related to biomass-fired CHP (combined heat and power) plants. The data gathering process for demand-side technologies (electric vehicles, heat pumps and lighting) was performed by TECHNOFI. For transmission technologies, data were provided by T&D Europe for active transmission technologies (HVDC converters, FACTS, transformers, etc.), Europacable for cables (passive transmission technologies) and a pool of TSOs (RTE and Amprion), partners of the project, for overhead lines (passive transmission technologies).

The construction of the data base was implemented by performing tasks relevant for the following three steps: 1) selection of a set of technologies relevant for the e-Highway2050 context (scenarios), 2) selection of a set of variables (costs, performances, etc.) for each technology, and 3) construction of the trajectories (from today to 2050, for each decade, i.e. today, 2020, 2030, 2040, 2050) for each variables and each technology. The main conclusions and outcomes of this construction process are detailed hereafter.

Generation technologies

Eurelectric/VGB Power Tech proposed a qualitative technology assessment of a portfolio of generation technologies considered as relevant for the project. Levelized costs of electricity (LCoE) were provided for each generation technology (2013 figures and estimated figures for 2030 and 2050). Thanks to a specific methodology, allowing variance reduction, the accuracy range for the proposed 2050 figures remains within a ±20% range, as maximum deviation.

An evaluation of the innovation and improvement potential of generation technologies at the 2050 time horizon was also proposed following a consistent approach based on the identification of the main factors impacting the improvement potential (and the costs) of generation technologies.

Carbon Capture and Sequestration (CCS) For hard coal, lignite and gas turbine power plants with CCS, several options are possible. The technology to be implemented will probably be the well-known post-combustion technique. Future demonstrations shall focus on system optimization and improvements are expected in terms of component design (increase of efficiency, material development) and simplification of the overall design. The investment costs could be reduced, for instance for of a hard coal power plant with CCS, one could reach about 2600 €/kW$_{el}$ in 2050 (3000 €/kW$_{el}$ today).

Photovoltaic The Eurelectric/VGB PowerTech assessment of future investment costs for PV power plants was subject to debate: a target of 1600 €/kW$_{el}$ at 2050 was proposed, even though this target is already reached today. Experts argued that this conservative position (building on a scenario where market economy prevails, i.e. there are no incentives along the whole PV value chain) could be challenged by a study (yet to be published) by Energiewende and the Fraunhofer Institute where projected costs could reach vales much lower than the ones observed today.

Wind power Wind energy manufacturers foresee bigger, lighter and more cost-effective wind turbines for the next decades. Improvements are expected in more adapted wind turbine designs for large-scale offshore operation while low wind speed sites will be developed onshore. The industry expects a major trend to easy-to-maintain and more reliable systems with the aim to reduce the amount of moving parts through the evolution of drive trains and conversion systems. The main innovations will be driven by materials, structural design and composites breakthroughs.

Electricity demand-side technologies

A two-step methodology was developed around the concept of criticality of an end use [the criticality of a given end-use is characterized in terms of energy (volume of electricity consumed) or power (load profile)]. This approach supported the selection of the most impacting demand-side technologies with regard to the forecasted electricity consumption at 2050. Three demand-side technologies were selected: *heat pumps* for space heating/cooling end uses (residential and commercial sectors), e*lectric vehicles (EVs)* for the electro-mobility end-use (transport sector); *LED/OLED technologies* for the lighting end use (residential and commercial sectors).

For EVs, the total electricity demand in 2050 could range from 200 to 300 TWh/year, with a penetration of Battery EVs (BEVs) ranging from 50 to 160 million units. Regarding heat pumps, a strong consensus exists among experts on the improvement of performances (Coefficient of Performance) in both heating/cooling modes by 2050, despite some different appraisals of the extent of the performance gains (+20 to +60%). Electricity demand related to heat pumps could range from 170 to 300 TWh/year. For the lighting end-use (LED), a reduction by a factor 4 in terms of electricity consumption seems achievable at the 2050 time horizon.

Electricity storage (centralized and decentralized) technologies

Three technologies of electricity storage have been considered: PHS (Pumped Hydro Storage), BESS (Battery Energy Storage Systems), and CAES (Compressed Air Energy Storage) technologies. The future deployment of such technologies depends on the evolution of some drivers, exogenous to the storage industry, e.g. the penetration of electric vehicles and intermittent renewable energy sources, the emergence of smart and micro grids and the evolution of the regulatory context.

For BESS, the forecasted development, in terms of costs and performances, slows down at around 2020 or 2030 since the progress in mature technologies should saturate after roughly twenty years of development. For diabatic CAES, relatively flat costs and performance profiles have been adopted to describe future trends since the technology is relatively mature, and no significant changes are expected. For adiabatic CAES, costs and performances improvements are expected up to 2030 thanks to a larger market and economies of scale. Most components are already available and only incremental innovations are foreseen. After 2030, costs and performances should remain unchanged. It is foreseen that the improvements in design and performance will be offset by the increasing intensity of operations due to the penetration of renewables.

Passive transmission technologies

Cables

At the 2050 time horizon, the most significant progress is expected for the HVDC XLPE technology. Research and Development in Mass Impregnated (MI) HVDC cables has already reached an asymptote and no significant improvement are expected in the future. For XLPE HVDC cables, voltage levels of underground and underwater links should increase considerably and with switchgear equipment gaining market experience, meshed HVDC networks will thus become available. These technologies will facilitate the building of an HVDC overlay network, which will be a significant contribution to future full integrated electricity markets in Europe.

The major technical evolution expected for XLPE HVAC cables is an increase in transmission capacity beyond today´s 500 kV technology. With these improvements, partial undergrounding solutions will complement overhead lines in sensitive areas thus strengthening Europe´s meshed AC transmission networks.

High Temperature Superconducting (HTS) cables will eventually become available and Gas Insulated Lines (GIL) may be deployed, both in specific projects but not in an electricity highways context.

Overhead lines

Designing an overhead line (OHL) will remains a difficult optimization exercise which is specific for each reinforcement project. One should take into account many factors such as the type of conductors, the tower design, the environmental issues (including social acceptance), etc., while minimizing costs.

Different reinforcement solutions are possible for HVDC OHLs, ranging from 320 kV to 1100 kV. For the standard reinforcements to be considered for HVAC OHLs, two-conductor technologies (AAAC and ACSS) are proposed for double circuit OHLs at 400 kV (4 conductor bundle), with a possible extension at 750 kV if proven necessary in the grid simulations and cost benefit analyses to come.

Active transmission technologies

The portfolio of active transmission technologies is integrated in the database according to different families: HVDC converters (VSC and CSC), FACTS (shunt and series compensation), transformers (PST and tap changers) and breakers, and protection and control.

For HVDC systems, an increase of the existing rated voltage and power is expected. Incremental improvements of CSC (Current Source Converter) technologies are foreseen from today's levels. In parallel, the performances of the VSC technology (Voltage Source Converter) will be significantly increased (higher capacity, lower losses) at a level close to the conventional CSC technology. As a consequence, VSC could become the predominant HVDC technology in Europe at the 2050 time horizon.

For FACTS, the SVC technology, as a mature technology, will experience incremental improvements while the STATCOM technology could see significant incremental improvements (higher rated voltages and powers with decreasing losses). FACTS deployment should be accelerated in Europe and with a constant growing penetration of shunt FACTS, while series FACTS may become also an option for TSOs in the future.

Both Phase Shifting Transformers (PST) and tap changers are conventional and mature technologies. Incremental improvements will therefore be driven by evolutions of market requirements.

For protection (at substation level and at system level), there will be a need to adapt protection components and systems to new market requirements. New material could emerge, which changes the possibility to commercialize solutions, such as Fault Current Limiters (FCL) with superconductive materials.

Future costs of transmission technologies

Estimating likely evolutions of costs of transmission equipment, beyond a short-term "grid planning" time horizon, remains a complex exercise. Several sources propose models for estimating costs of technologies according to their maturity. These learning curve or experience curve based models have been explored in-depth for generation and demand technologies. They predict cost dropping rates per time period according to the market penetration of the technologies. Scientific literature the on experience curve approach applied to power transmission is less abundant[1].

Predicting costs of transmission technologies is a difficult exercise since several exogenous factors might significantly impact the forecasts, i.e. the prices of commodities such as copper (cost multiplied by a factor 3 in few years) or the price of oil. Furthermore, each transmission project is very specific and the costs depend largely on the selected technologies and on local constraints (terrain, labor costs, social acceptance, etc.). When considering the cost structure of transmission project, one can observe that the variations in costs due to different initial conditions (terrain, etc.) can offset by an order of magnitude the uncertainties related to the forecast exercise. This means that a lot effort should be spent on the initial conditions, i.e. attention must be paid to at least two key factors: the archetypal configuration (the precise description of the installed transmission system) and the geographical factor (terrain).

Time evolution of cost trajectories can then be modelled by a systematic breakdown of costs in five distinct components (equipment, installation, civil work, project management, authorizations and right of ways) whose evolutions can be calculated thanks to tentative forecasts of a series of indices: commodity prices for energy and metals, labour and engineering costs as well as dropping rates (experience curve approach or other proxy).

If costs need to be forecasted for a variant of a given archetype, it is proposed to resort to multipliers, e.g. for other power, terrains, conductors, etc.

[1] One could mention the FP7 EC-funded IRENE40 project aiming at building a technology database of power transmission systems with simple cost evolution models until 2050.

Glossary and acronyms

Database A comprehensive set of data for each decade (from today to 2050) characterizing power system technologies (organized per technology and data type).

Data type Classes of data such as technical performances, environmental impact and public acceptance, costs (there are eight data types).

Datasheet Excel file including a set of data for one technology retained in the e-Highway2050 scope. It is related to a Technology Assessment Report (TAR).

TAR Report detailing the assumptions and comments relative to the data displayed in the datasheet(s).

TRL Technology Readiness level is an index used to assess the maturity of each evolving technology during its development and in early operations.

Technology Area

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

Generation technology area

A generation technology is any centralized or decentralized power technology generating electricity.

RES Renewable Energy Sources

PV Photovoltaic

CSP Concentrated Solar Power

OCGT Open Cycle Gas Turbine (steam turbine and combustion turbine)

CCGT Combined Cycle Gas Turbine

IGCC Integrated Gasification Combined Cycle

CFBC Atmospheric Circulating Fluidised Bed Combustion

PFBC Pressurised Fluidised Bed Combustion

Nuclear Power

Generation 1: early prototypes, all nuclear reactors before 1967.

Generation 2: commercial power nuclear reactors built between 1967 and 1996.

Generation 3: advanced Light Water Reactors built between 1996 and 2011. Based on developments of generation 2 with significant evolutionary design improvements.

Generation 3+: evolutionary designs. Improvements of generation 3 (economics and safety).

Generation 4: nuclear reactors under research, not expected for commercial exploitation before 2030.

CCS Carbon Capture and Storage (or sequestration) is a process capturing waste CO_2 from large point sources, such as fossil fuel power plants, transporting and depositing it to a storage site with no possibility to enter again in the atmosphere.

Storage technology area

In this report storage refers to electricity storage technologies (both centralised and decentralized).

BESS Battery Energy Storage System

SOH State of Health

SOC State of Charge

ESG Energy Storage Generation

ESS Energy Storage System

PHS Pumped Hydro Storage

SMES Superconducting Magnetic Energy Storage

CAES Compressed Air Energy Storage

A-CAES Adiabatic Compressed Air Energy Storage

AA-CAES Adiabatic-Air CAES.

PEMFC, SOFC Proton exchange membrane fuel cell (PEMFC) and Solid Oxide Fuel Cell (SOFC)

Demand technology area

Demand-side technology

Any technology consuming electricity.

Demand-side enabling technology

Technologies needed to monitor and control demand-side technologies, e.g. smart meters, concentrators, communication channels and protocols, etc.

Sector Residential, Commercial (sometimes called Services), Industry and Transport sectors are considered.

Electricity end-use

Electricity is consumed in a variety of uses by technologies, appliances, devices, processes. Electricity end-uses represent a segmentation of these uses by final consumers in the residential, commercial, industry, transport sectors.

"Technology mix" of an end-use segment

In a given end-use segment, the typical technology/appliances/device consuming electricity is called the typical average "technology mix": it should be understood as a theoretical "average" system addressing the considered electricity end-use.

Criticality A criticality is any major modification of the demand main characteristics at different time and space scales (daily load curve, yearly consumption, etc.) resulting from the use of electricity, following an evolution of a demand-side technology or of a typical use. Criticality might result either from a significant evolution of a given end-use (decrease or expansion of the end use), or from the evolution or emergence of a specific technology meeting this end-use (evolution of performances or new technology). Therefore, the criticality can be related to energy or power (load profile). Criticality is measured by the three indicators defined below: "volume effect", "energy efficiency improvement effect", "load controllability potential".

Volume effect For the residential sector, number of units of typical technologies/appliances/devices required to meet a given end-use (in EU27 in 2050). It is thus defined by a dimensionless number characterizing the energy consumption of the considered electricity end-use segment (in EU27 in 2050) assuming a typical average "technology mix". This definition is generalized to the commercial and industrial sector.

Efficiency improvement effect

It is characterized by the evolutions of a level of electricity consumed per unit over the period 2012 to 2050, where a unit is a typical average technology mix meeting a considered end-use.

Load controllability potential

It measures the ability of a remote operator to control part of the load of a given end-use.

Drivers Drivers are factors impacting the electric demand at 2050. They have been organized into four categories: *technology efficiency* (improvement of electricity consumption due to incremental innovation or a breakthrough technology), *socio-economics and demography*" (any evolution of the end-user's electricity needs in nature or in volume), *shift to/from electricity* (any change in electrification or new uses -or shift from industry to services-) *ICT and power* (expected convergence of the ICT world and the power system, which will overall increase the ability to control the electric load).

Transmission technology area: lines

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

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

HVAC High Voltage Alternating Current

AAAC All Aluminum Alloy Conductor

ACSS Aluminum Conductor Steel Supported

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

ACCR Aluminum Conductor Composite Reinforced

ACCC Aluminum Conductor Composite Core

MMC Metal Composite Conductor

PMC High Performance Organic Composite Core conductor

TACSR Thermal resistant Aluminum alloy Steel reinforced

KTAl High Strength Thermal Resistant Aluminum Alloy

KTACSR High strength thermal resistant Aluminum alloy Steel reinforced

GTACSR Ultra thermal resistant Aluminum alloy Steel reinforced

GZTACZR Gap type Ultra thermal resistant Aluminum alloy Steel reinforced

TACIR Thermal Resistant Aluminum Alloy Conductor, Invar Reinforced

TACSR Thermal Resistant Aluminum Alloy Conductor, Steel Reinforced

TAl Thermal-resistant Aluminum (aluminum zirconium alloy)

ZTACSR Aluminum Clad Steel Reinforced

ZTACIR Aluminum Clad Invar Reinforced

Transmission technology area: cables

AC Alternate Current

CIGRE International Council on Large Electric Systems

DC Direct Current

DTS Distributed Temperature Sensing

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

Transmission technology area: active equipment

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

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

VSC Voltage Source Converters are self-commutated converters using devices[2] suitable for high power electronics applications. The VSC technology can rapidly control both active and reactive power independently from each other.

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

PST Phase Shifting Transformer

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

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

RTTR Real Time Thermal Rating

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

SVC Static VAR Compensator

STATCOM STATic Syncrhonous COMpensator

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

Common glossary

Archetype: A very typical example of a certain person or thing (Oxford dictionaries)

Archetypal configuration:

Formulation used in this study to specify a particular technology with well-defined characteristics in order to be able to provide a cost estimation as of today (and in turn cost projections). The term technology variant is also used as a synonym.

Technology family and variant

Classes and sub-classes respectively of a technology area. Example: for the storage technology area, BESS is a technology family and Lithium Ion batteries represent a variant.

Contextualisation

Contextualization means the fine-tuning of the values of a given variable describing a set of technologies at the 2050 time-horizon (for instance, costs or efficiency) according to a given e-Highway2050 scenario.

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1 Introduction

1.1 Purpose

This document aims at characterizing the generation, storage and demand-side technologies selected by the e-Highway2050 project in Work Package 1 (WP1). It consists of a series of technology assessment reports and of a techno-economic database organized by technology (these reports and data sheets are provided in electronic form as annexes: a complete list of the different filenames is given in chapter 7). The database covers the next four decades, in line with the e-Highway2050 scope (from today to 2050). More specifically two complementary objectives are addressed in the present report:

- to provide other Work Packages of the project with valuable information on cost and technical performances of power system technologies, e.g. with estimations of a level of uncertainty and the underlying assumptions for the next decades;
- to provide the power system stakeholders with structured information on cost and technical performances of technologies beyond the end of the project according to the exploitation rules which will be agreed upon before the project completion.

The database characterizing most technologies relevant for the power system at a mid/long-term time horizon (over the next four decades) should provide answers to the following questions, consistent with the two above mentioned work packages objectives.

<u>For the e-Highway2050 partners:</u>

- *Which technologies are the most likely to play a significant role in the next decades for the power system (from generation to demand including storage and transmission)?*
- *For a given technology considered as of interest for the power system at that time horizon:*
    - o *What could be a likely evolution of costs (CAPEX/OPEX)?*
    - o *How could this technology evolve (development and technological evolutions) ?*
- *What is the degree of uncertainty on the provided figures?*
- *To which extent the values provided by the partners in charge (mainly professional associations representing manufacturers) of the data gathering process are representative of a wider perspective gathering all stakeholders of the electricity value chain?*

<u>For stakeholders of the power after the end of the e-Highway2050 project:</u>

- *How will the e-Highway2050 database be updated and by whom?*
- *Who will be granted access to the database?*

This second list of questions will be addressed according to the project exploitation rules to be agreed upon by the e-Highway2050 consortium before the project end.

1.2 General organisation of the deliverable

The present deliverable is organized in two parts.

- <u>A main document</u> focusing on the description of the technology areas at 2050 as well as the rationale for selecting/prioritizing the related portfolio of technologies.
    - o Chapter 2 recalls the challenges of the European power system and the e-Highway2050 scenario-based approach to address the possible evolutions at the 2050 time horizon. It also includes an overview of the impacts of each retained scenario on the technologies to be considered and the methodology used to build the technology database.
    - o Chapters 3 details the architecture of the database and the management of uncertainties.

- Chapter 4 explains the generic process for gathering, building, and cross-checking the data.
- Chapter 5 focuses on the approach followed to forecast trajectories of costs for a selection of transmission technologies and systems.
- Chapter 6 describes the quality process to validate the data.
- Chapter 7 explains how to use the database.

- Annexes which are organized per provider

Key contributors are detailed below. The corresponding matrix between technology areas and key providers is as follows, cf. Table 1. **TAL** means Technology Area Leader, i.e. the partner in charge of the data construction process for the technology or the family of technologies; **c** means contributor to this process and the **r** refers to a reviewer activity.

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

|PARTNER TECHNO|	VGB /EURELECTRIC	EWEA	TECHNOFI	U. COMILLAS	IEN	EUROPA CABLE	T&D EUROPE	TSO POOL	QUALITY POOL
SUPPLY BLOCK/ FOSSIL FUEL	**TAL**								**r**
SUPPLY BLOCK/ NUCLEAR	**TAL**								**r**
SUPPLY BLOCK/ RENEWABLES: WIND	**c**	**TAL**							**r**
SUPPLY BLOCK: OTHER RENEWABLES	**TAL**								**r**
SUPPLY BLOCK: CHP	**TAL**				**c**				
DEMAND			**TAL**					**c**	**c, r**
STORAGE	**c**			**TAL**					
TRANSMISSION: LINES								**TAL**	**r**
TRANSMISSION: CABLES						**TAL**		**c, r**	**r**
TRANSMISSION:ACTIVE						**c**	**TAL**	**c, r**	**r**
OPEX-DRIVEN INNOV.								**c**	**r**

For generation and storage technologies, the data gathering process was carried-out by a professional association and its members, partner of the project (EURELECTRIC - VGB Power Tech) and an academic institution (University of Comillas) for data on battery storage technologies. A professional association (EWEA) provided inputs regarding wind energy. Current involvement of WP3 partners includes also the Institute of Power Engineering (IEN) on the data trajectories 2013-2050 of combined heat and power generation technologies.

The data gathering process for demand-side technologies was carried out by Technofi.

For the transmission technology area, the involved partners were T&D Europe for active transmission technologies, Europacable for cable technologies and a pool of TSOs partners (the TSO pool) of the project for overhead lines.

A list of annexes is given hereafter (a complete list of the different filenames is given in chapter 7).

- For Generation: the Eurelectric-VGB Power Tech report is supplemented by a series of corresponding data sheets[3] which detail the characteristics of the selected technologies. The TAR on Wind Energy has been written by the European Wind Energy Association (EWEA).
- For Storage: the Comillas University report on electrochemical storage is supplemented by a series of corresponding data sheets which detail the characteristics of the selected storage technologies.

[3] Data sheets: Excel files where the data is displayed (cf. chapter 7)

- For demand-side technologies: a methodological report details the rationale for selecting the critical end-uses and related demand-side technologies. For each of the three selected demand-side technologies, a TAR describes the specific assumptions for gathering, building, cross-checking and validating the data. These reports are supplemented by associated data sheets.
- For passive transmission technologies: EUROPACABLE's TAR on cable technologies, supplemented by a series of corresponding data sheets, details the characteristics of the selected cable technologies. The TAR on overhead lines, supplemented by a series of corresponding data sheets, details the characteristics of the selected overhead line technologies.
- For active transmission technologies: T&D Europe's TAR is organized per family of technologies (e.g. transformers, FACTS, etc.) and supplemented by a series of corresponding data sheets.

A specific work compiling available literature on costs of transmission technologies and their likely evolutions over the 2013-2050 period has been carried out by Technofi. It is detailed in chapter 5.

1.3 Approach

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

Data gathering, modelling and calculations were mainly ensured by professional associations per domain of expertise: Eurelectric (generation and storage), EWEA (wind power), IEN (CHP), University of Comillas (storage), T&D Europe (active transmission technologies), Europacable (cables), RTE and Amprion (overhead lines) and TECHNOFI (demand). The data validation tasks were carried out by the e-Highway2050 consortium members (via a Quality Pool including project partners and internal workshops) as well as by external stakeholders via a dedicated workshop held on April 15th 2014 in Brussels.

It should be noted that for some specific renewable energy technologies (wind power and CHP with biomass), different points of view from professional associations (either partners of the e-Highway2050 consortium or external actors) have been gathered and presented. In order to take into account complementary or possibly divergent visions regarding future evolutions of these technologies on cost and performances until 2050, it was decided to present these specific point of views in separate reports rather than synthetizing an "average" view (i.e. EWEA report on wind power and IEN report on biomass-fired CHP). In case of possible dissent, the point of view of the technology leader (TAL in the Table 1 above) should be retained.

The specifications of the database resulted from an inter-WP task, including mainly leaders of Work Packages WP1, WP2 and WP6, as the first users of the database. Indeed, the present work is closely related to the WP1 deliverables on scenario definition and boundary conditions.

Possible adjustments of some data might be necessary during the final year of the project to take into account specific needs of the e-Highway2050 partners in charge of the simulations. As a consequence, the present report will be amended when required.

In the following chapter, a link between the five e-highway2050 scenarios and the selected sets of technologies is provided. This will help the reader to consider the present deliverable in a general framework.

2 The technology database in the 2050 vision of the power system

The technology (generation, transmission, storage, demand) database is an enabling tool in support of other critical tasks of the project, in particular simulations tasks where techno-economic data is needed to carry out scenario quantification computations, system simulations, cost benefit analyses, etc., cf. Figure **1**. The database is also closely related to the e-Highway2050 scenarios since the rationale for selecting the technologies of interest for the power system at 2050 has been built upon these scenarios.

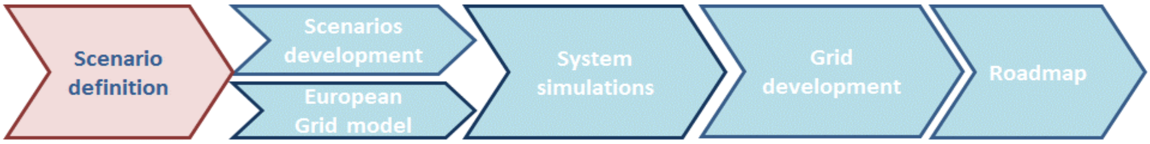


Figure 1: The e-Highway 2050 general process

2.1 The five retained e-Highway2050 scenarios

Five "extreme but realistic" scenarios have been built as a result of a process combining the so-called *Strategies* (endogenous options upon which decision makers have control) and *Futures* (exogenous uncertainties upon which decision makers have no control). The key criterion for such a process was to retain the most challenging scenarios with respect to their impact on the power system at 2050, cf. Table **2**. The five retained scenarios therefore define an envelope of possible extreme evolutions for the power system at 2050: whatever the coming evolution of the power system at 2050, the resulting constraints on the grid will always be less stringent than the ones resulting from these extreme scenarios.

Table 2 - The five e-Highway2050 scenarios

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

2.2 Resulting technology challenges per scenario

For each of the five scenarios, some general considerations can be anticipated with respect to the expected constraints for the grid:

- higher level of electricity demand mainly due to new uses and electrification of transport/heating for instance,
- increasing needs for balancing due to the intrinsic intermittency of renewable generation,
- increasing role of the distribution grid in case of massive penetration of decentralized generation and/or decentralized storage,
- possible new imports of electricity from neighbouring macro-area (Africa for solar power and North Sea wind power).

The table below lists the criticality of technological challenges per technology area for each of the five retained e-Highway2050 scenarios. Some examples (non-exhaustive list) of typical technological solutions that need to be considered for the pan-European power system at 2050 are highlighted. This analysis will guide the rationale for selecting the most relevant technologies for the power system at 2050.

The color code consists in a graduation of intensity based on the scenario color: four-grades from N/A (blank) to + (first degree-light color); ++ (second degree with a higher intensity color); +++ (third degree with the darkest color).

Table 3 – Criticality of challenges for the technology area for each e-Highway2050 scenario.

Scenario	**Challenges: generation technologies**	**Challenges: storage technologies**	**Challenges: demand-side technologies**	**Challenges: transmission technologies**
Large scale RES	**Criticality: ++** - Large PV and wind parks (onshore; offshore)	**Criticality: +++** - Large-scale centralized storage (PHS, CAES)	**Criticality: ++** - Demand-side management - Efficiency of appliances, EVs, heat Pumps	**Criticality: +++** - HVDC XLPE Cables; - HVDC VSC - Overlay grid - Wind and PV short term forecast
Big and market	**Criticality: ++** - Carbon sequestration and storage	**Criticality: ++** - Large-scale centralized storage (PHS, CAES)	**Criticality: ++** - Demand-side management - Efficiency of appliances, EVs, heat Pumps	**Criticality: ++** - Long distance HVDC - Revamping of overhead lines - Coordinated use of interconnections for cross-border exchanges - Market design
Large fossil fuel	**Criticality: +** - Nuclear (security and life time) - Carbon sequestration and storage	**- Criticality: N/A**	**Criticality: +++** - Efficiency of appliances, EVs, heat Pumps	**Criticality: +** - Revamping of overhead lines
100% RES el.	**Criticality: +** - Phasing out of nuclear	**Criticality: +++** - Large-scale and small-scale storage	**Criticality: ++** - Demand-side management	**Criticality: +++** - HVDC, PST, FACTS - Overlay grid
Small and local	**Criticality: ++** - Decentralized generation	**Criticality: ++** - Decentralized storage (batteries)	**Criticality: +++** - Aggregators; - Demand-side management; - Active distribution network	**Criticality: +** - Revamping of overhead lines - Coordinated operations (TSO/DSO - Flexibility

The construction of Table 3 is illustrated in Table 4 below for one particular scenario, i.e. the “100% electricity RES” scenario. This extreme scenario with 100% RES penetration[4] is in line with the scenario named “High RES”[5] in the EU Energy Roadmap 2050. The described approach was implemented for all the five scenarios: based on this first macro analysis, a detailed process for selecting the technologies of each technology area was then implemented, cf. Chapter 2.3.

Table 4 – Key features of the “100% RES electricity” scenario and associated technologies

Key features of the scenario "100% RES electricity"	**•Consequences in terms of technological challenges**
The global community has not succeeded in reaching a global agreement for climate mitigation. Fossil fuels consumption is generally medium to high worldwide which makes fuel prices high. Still, Europe is fully committed to its target of 80-95% GHG reduction and the CO2 costs in EU are high due to these strict climate mitigation targets. The strategy to achieve this target has a higher ambition than the ***Large scale RES solutions*** scenario by making Europe's energy system 100% based on renewable energy.	•Both large scale and small-scale RES generation: offshore wind parks in the North Sea and Baltic Seas and solar power in the Desertec project in North Africa (share of centralized renewables is assumed at 60%) combined with EU-wide deployment of de-centralized RES (including CHP and biomass) solutions (decentralized renewables at 40%). Phasing out of nuclear. No fossil fuel with CCS. •Both centralized storage solutions (PHS, CAES) and de-centralized solutions needed to balance the variability in renewable generation (deployment of centralized or decentralized storage at 50%) •Development of forecast systems for anticipating RES generation variability (PV, Wind)
On the consumer side, also high increase of energy efficiency is needed. New uses of electricity in transport, heating and industry considered to occur both at centralized (large scale) and de-centralized (domestic) level will both reduce resulting energy demand as well as provide complementary flexibility and storage to account for variability of RES production from PV and wind	•Major improvement in energy efficiency •Demand side management and increased flexibility of new uses (e.g. electromobility) •Electricity storage to address the variability of RES production from PV and wind.
GDP growth in EU assumed medium while demographic change assumed to be growth. A convergent and strong policy framework in place to ensure successful development of available RES potential in all European regions. CO2 costs are high and Europe is fully committed to its target of 80-95% GHG reduction. Only renewable sources are imported from outside EU. Strong drive towards 'greener' behaviours in the population with active involvement towards more energy efficiency, more use of sustainable energy and clean transport etc.	•Imports of RES generation (solar) from North Africa will require a power transmission connection to North Africa (HVDC technologies) •Increase of power transmission needs requiring electricity highways type solutions (overlay grid, passive transmission reinforcements or more active control)

[4] Its key characteristics have been defined as a result from Work Package 2 combining a FUTURE (GREEN EU) and a STRATEGY (100%RES): see deliverable D2.1

[5] In which the RES reaches 83% with a remaining generation is supplied by fossil fuels -with and without CCS- and nuclear

2.3 The technological scope

As explained above, the exercise displayed in Table 4 has been carried out for each of the five e-highway2050 scenario. This analysis shows the link between the scenarios and the main technological families needed to develop the power system at the considered time horizon (2050). In the following, a deeper insight is provided to explain how the technology portfolio was built. For each of the technology retained in the portfolio, a set of techno-economic data will be provided. This set of data will make the technology data base.

2.3.1 Overview of the technology areas

The candidate technological options considered in the technology database are organized per technology area. The addressed technology areas cover the whole electricity value chain. Seven technology areas have been initially considered (in the Description of Work of the Grant Agreement) organized into three main categories, cf. Figure 2:

– **generation-related technologies:** generation technologies (centralized and decentralized) and centralized storage technologies;
– **network-related technologies**: passive transmission technologies, active transmission technologies and OPEX-driven innovation;
– **consumption-side technologies**: decentralized storage as well as demand -side technologies.

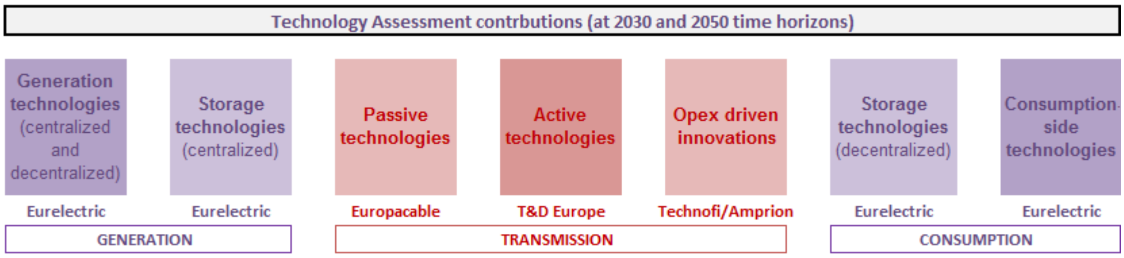


Figure 2: the e-Highway2050 technology areas covering the whole electricity value chain.

2.3.2 The technologies selected per technology area

The technologies selected for each technology area are the result of the analysis on the technological challenges (Table 3 and Table 4) raised by each of the five retained "e-Highway2050" scenario. They were discussed with technology experts and are reported in the figure next page.

- **The generation technology area** includes technologies that are already mature or still under development:
    - o fossil fuel generation: gas turbine, lignite, hard coal generation (with and without co-firing), fluidized bed combustion with coal or lignite,
    - o renewable generation (centralized and decentralized generation): photovoltaic, CSP, wind onshore, wind offshore, geothermal, biomass, hydropower (with and without reservoir),
    - o Combined Heat and Power.
- **The storage technology area** encompasses centralized and decentralized electricity storage solutions: Battery Energy Storage System (BESS), Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES). The main focus of interest has been:
    - o BESSs that are already mature technologies, close to commercialization, or promising candidates for the time horizon set by the e-Highway2050 project including redox flow technologies,

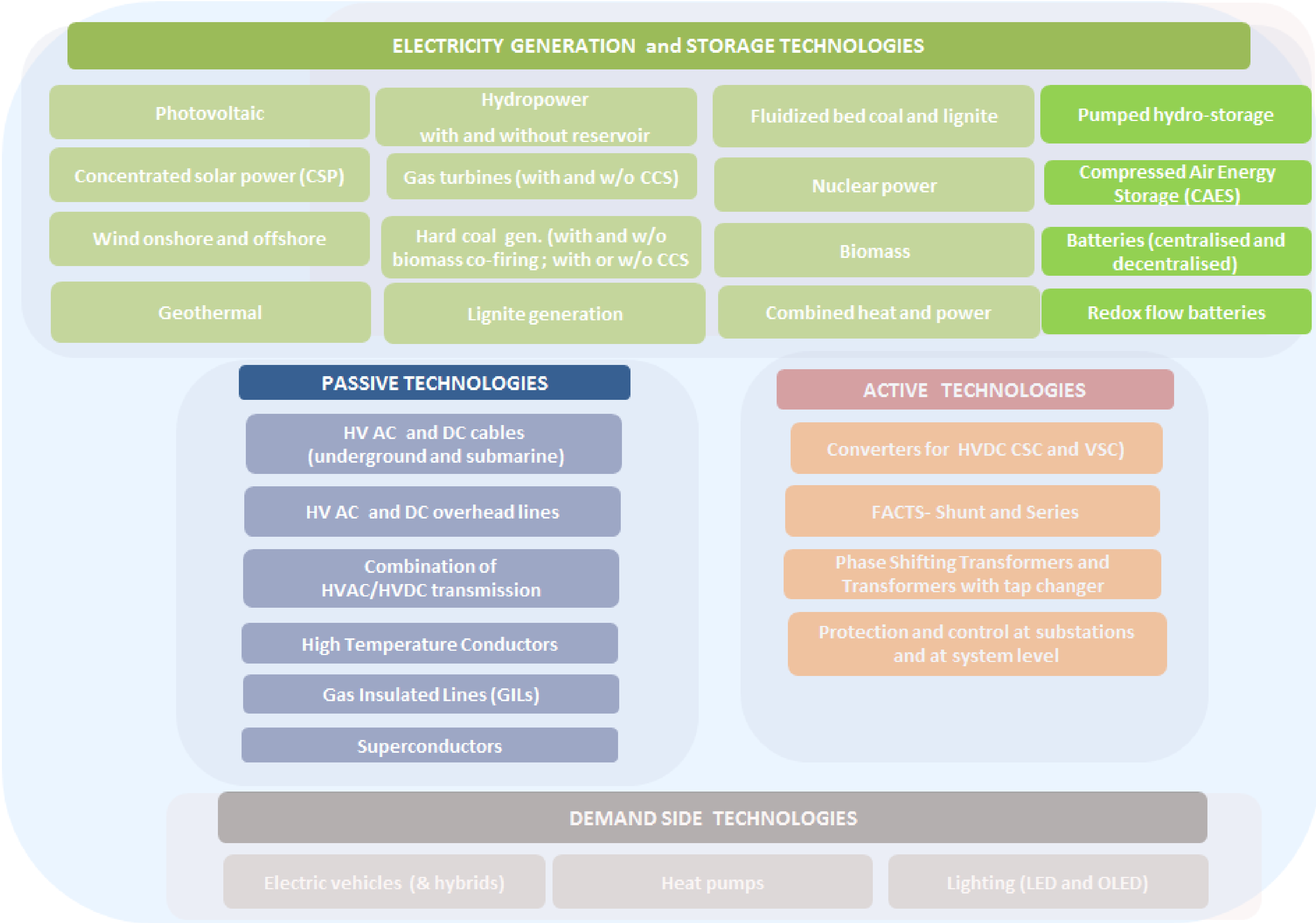


Figure 3: Technological scope of the e-Highway2050 technology database

  - o diabatic and adiabatic CAES technologies (since they can be considered either already commercial or promising candidates at 2050).

- The **transmission technology area** includes both active transmission and passive transmission (cables and OHL) technologies. The selected active transmission technologies are:
  - o HVDC converter technologies (self-commutated Voltage Source Converters (VSC) and line-commutated Current Source Converter (CSC) with DC breakers) are considered for long-distance power transmission with e.g. submarine cable links and interconnection of asynchronous system.
  - o FACTS (both shunt and series FACTS have been covered),
  - o PST (Phase Shift Transformers) and transformers with tap changers together with the switching gear and breakers,
  - o equipment for protection and control at substation and at system level.

The **OPEX-driven innovation area** was excluded from the technological scope for the following reason: collecting data on such a topic would have required a review on a "per TSO" basis at the European level and an aggregation to pinpoint issues of common interest. A comparison of breakdown of TSOs' OPEX+CAPEX structure would have been beyond the scope of the project[6]. A topic of EU interest is probably Condition-Based Maintenance (CBM) aiming at reducing the maintenance component of OPEX.

2.3.3 Focus on the chosen technologies

For each technology area, a prioritization allows addressing first the most important ones. The process of selection has been performed by experts of the project for generation, transmission and storage technologies. For demand-side technologies, a dedicated methodology was used to select the most critical technologies with respect to electricity demand at 2050 (cf. *report_demand technologies_selection_a* and *report_demand technologies_selection_b* in annex).

Figure 4 below describes the rationale for discarding a candidate technology from the portfolio. The main reasons for not retaining a particular technology can be categorized according to two main dimensions:

- a first dimension is the *degree of consensus* regarding this technology. It may occur that different classes of stakeholders disagree on the role that this technology will play in the power system at the 2050 time-horizon,
- a second dimension is relative to the *assessment of the commercial deployment of the technology* with the following cases (non-exhaustive list):
  - o technical legitimacy is not proven for at least one class of stakeholders (manufacturers or transmission operators), for instance superconducting technologies requiring additional investment in cryogenic systems that might negatively impact the energetic balance of the transmission process,
  - o insufficient maturity for an operational deployment in 2050,
  - o necessity of heavy investment in infrastructures or a full surrounding economy to enable its deployment (example of hydrogen driven vehicles requiring a "Hydrogen economy"),
  - o the technology might be mature but at high costs due to scarce implementation,

[6] Some benchmarking works are addressing this topic, such as:
- e3Grid (regulatory benchmarking of European Electricity Transmission System Operators on behalf of Council of European Energy Regulators (CEER), Work stream Incentive Regulation and Efficient benchmarking (WS EFB), 2008
- ITOMS, The International Transmission Operations & Maintenance Study, consortium of international Transmission companies that work together with UMS Group, identifying best transmission industry practices worldwide.
- ICTSO, the International Comparison of TSO, exchanges information on TSOs' current and future operating practices for benchmarking. It is managed by a Steering Committee consisting of six selected members and supported by KEMA.

- some implementation barriers (e.g. environmental or related to supply chain) may hamper its development.

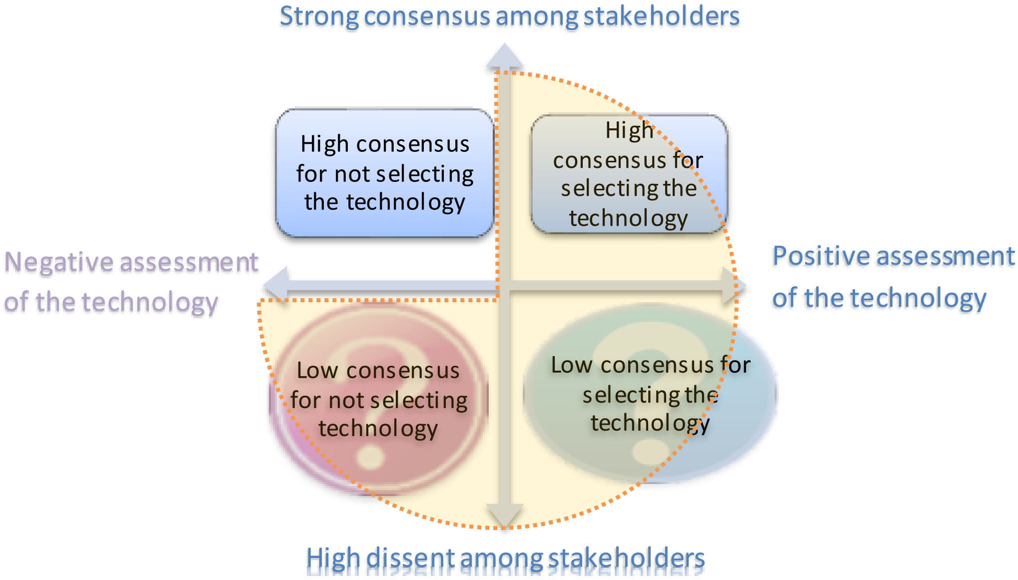


Figure 4. Typology of technology selection by stakeholders.

The selected technologies are the ones for which at least one category of stakeholders considers that this technology will play a major role for the power system at the 2050 time horizon (they are in the three-quarter area highlighted in Figure 4).

Table 5 next pages gives, for each technology (all candidate options are presented by technology area), the following information:

- the technology denomination and its possible variants (for selected technologies);
- the rationale for not selecting the technology (for discarded technologies).

2.3.4 Technology areas, technology families and variants

Before moving to the architecture of the data base and the construction process, some terminology issues need to be addressed. The technological scope is organized in a tree-like structure with three different levels: the technology area, the technology family and the variant, cf. Figure 5. In this example the variant "Lithium Ion batteries" belongs to the "BESS" technology family, which was retained in the technology area of decentralised storage. This terminology will be reused in the chapter related to the management of uncertainty (chapter 3).

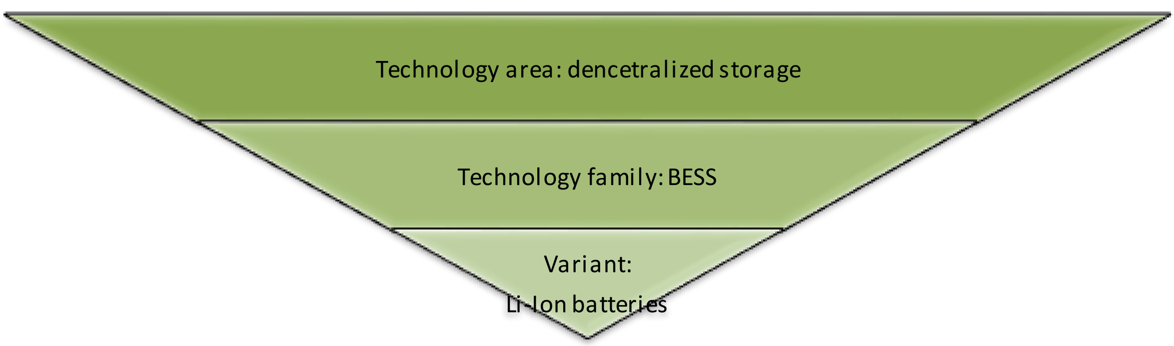


Figure 5. Example of technology areas, technology families and variants.

Table 5: The rationale for selection/discard in the technology portfolio

Sectors	Id	End use segment	Candidate technologies	Retained technology and rationale for discarding (if any)
Electricity demand in residential sector	D1	White goods	Base technologies: washing machines, dishwashers, dryers, washer-dryers, refrigerators, freezers Expected innovations at 2050: smart appliances in Home Area Network (HAN), radio-frequency identification (RFID), remote control capabilities for demand response programmes or consumption optimisation, higher efficiency: European standards	"White goods" end use not retained due to a limited impact on the evolution of residential electricity demand at 2050
	D2	Cooking appliances	Base technologies: ovens Expected innovations at 2050: smart appliances in HAN, RFID, higher efficiency : European standards, etc.	"Cooking appliances" end use not retained due to a limited impact on the evolution of residential electricity demand at 2050
	D3	Lighting	Base technologies: halogen lamp, LED, OLED, bulb lamp Expected innovations at 2050: smart lighting (presence, etc.); sensors, lighting controls	Two datasheets are proposed: LED and OLED as breakthrough technologies
	D4	Water heating	Base technologies: solar heating, geothermal energy, heat pumps, biomass boiler Expected innovations at 2050 :better performing heating systems with renewables, smart thermostats water heaters	One datasheet on Heat Pumps is proposed including information on heat pumps for both water heating and space heating usages
	D5	Electronic appliances	Base technologies: TV, computer, Cable TV receiver, stereo recorder, telephone Expected innovations at 2050: multiservice device: home energy management system, sensor plug and socket, alarm	Despite an expected significant impact on peak demand, no technology was selected due to the multiplicity of appliances as well as the fast technological evolution with respect to the targeted time horizon.
	D6	Space heating	Base technologies: Heat pumps, insulation, electric heaters Expected innovations at 2050: more effective insulation; efficiency of heat pumps, ; remote control capabilities for demand response programmes or consumption optimisation ; micro-cogeneration	One datasheet on Heat Pumps is proposed including several reversible technologies (air, water, ground sourced heat pumps)
	D7	Space cooling	Base technology: Heat pumps Expected innovations at 2050: insulation more effective insulation; remote control capabilities for demand response programmes or consumption optimisation; higher efficiency; smart thermostats	One datasheet on Heat Pumps is proposed including several reversible technologies (air, water, ground sourced heat pumps)

Sectors	Id	End use segment	Candidate technologies	Retained technology and rationale for discarding (if any)
Electricity demand in commercial sector	D8	Office equipment	Base technology: office equipment (laptop and communication appliances) Expected innovations at 2050: difficult to predict but one can foresee new uses of computer related technologies in an evolving economy more and more service-oriented	Despite an expected criticality on energy due to the expected growth in the next decades, no technology was selected due to the multiplicity of office equipment (communication, laptop, etc.) as well as the fast technological evolution with respect to the targeted time horizon.
	D9	Cooling and ventilation in tertiary buildings	Base technology: cooling and ventilation systems Expected innovations at 2050: efficient HVAC	One datasheet on Heat Pumps is proposed including several reversible technologies (air, water, ground sourced heat pumps)
	D10	Commercial lighting	Base technology: Expected innovations at 2050: sensors, remote control capabilities for demand-response programme and consumption patterns	Two datasheets are proposed: LED and OLED as breakthrough technologies
	D11	Outdoor lighting	Base technology: LED, electronic ballasts, PLC Expected innovations at 2050: intelligent outdoor lighting (steering on presence, weather, etc.), adaptive light to brightness, wireless protocols	
	D12	Commercial refrigeration	Base technology: refrigerators Expected innovations at 2050: remote control capabilities for demand-response programme and consumption optimisation	"Commercial refrigeration" end use not retained due to an expected limited impact on the evolution of electricity demand in the commercial sector at 2050
	D13	Heating in tertiary buildings	Base technology: Heat pumps Expected innovations at 2050: heating controls	One datasheet on Heat Pumps is proposed including several reversible technologies (air, water, ground sourced heat pumps)
	D14	Data management	Base technology: cloud, data sharing Expected innovations at 2050: infrastructure optimisation, higher efficiency, digital signature	Despite an expected increase in the coming decade of the consumption, the tradeoff between energy efficiency improvement and deployment ("volume effect") appears difficult to assess. Fast evolution of the IC Technologies adds to this complexity.

Sector	Id	end use segment	Candidate technologies	Retained technology and rationale for discarding (if any)
Electricity demand in industry and agriculture	D15	Steel	Base technologies: Recovery of Basic Oxygen Furnace (BOF) gas, BOF gas sensible heat recovery. Expected innovations at 2050: raw materials reduction and reuse of existing products	Technology and processes in industry have not been retained due to a low visibility on the "volume" and "energy efficiency improvement" effects.
	D16	Paper and Pulp	Base technologies: Pumps, material processing, material handling, refrigeration, compressed air, boiler, motor system, combined heat and power Expected innovations at 2050: improvement in pulp and paper making process	
	D17	Aluminium	Base technologies: Process heating/burners, compressed air systems, electric motor systems, pumping systems Expected innovations at 2050: enhanced aluminum making process	
	D18	Zinc	N/A	
	D19	Cement	Dry process, clinker production (wet and dry)	
	D20	Chemical industry	Speed drives, refrigeration, compressed air, relighting, steam flow boiler	
	D21	Food processing	Steam system, motor and pump system, refrigeration system, compressed air system Expected innovations at 2050: improvement in food making process	
	D22	Agriculture	Irrigation	Agriculture electricity consumption represents today less than 2% of the overall electricity consumption in Europe. No significant evolution is expected.
Electricity demand in transport	D23	Electric vehicles and plug-in vehicles	Base technologies: battery, KERS, AC (Type 2, Type 3), DC fast charging (CHAdeMO) charging, inductive charging Expected innovations at 2050: better performing and long-lasting batteries; fast charging; smart charging infrastructure, remote interaction with SCADA systems, integration with DER, new standard for fast charging	Two datasheets are proposed: Battery Electric Vehicle (BEV) and Plug-in Hybrids Electric Vehicle (PHEV)
	D24	Freight	Base technologies: Regenerative breaks	"Freight" end use not retained due to a limited impact on the evolution of transport electricity demand at 2050
	D25	Buses	Base technologies: batteries; distributed inductive recharge or in-road inductive recharge Expected innovations at 2050: a mix of several alternative fuels needed to replace fossil fuels	"Buses" end use not retained due to a limited impact on the evolution of transport electricity demand at 2050
	D26	Electrified railways	Base technologies: power converters, storage systems, regenerative braking, automation systems Expected innovations at 2050: energy saving, increased transportation capacity, voltage stability, increase in power quality, integration with renewable energies	"Electrified railways" end use not retained due to a limited impact on the evolution of transport electricity demand at 2050

Sector	id	Group of technologies	Candidate technologies	Retained technology and rationale for discarding (if any)
Centralized storage	cS1	Pumped hydro storage (PHS)	Large scale hydro storage, micro hydro, sea water	One datasheet on large scale Pumped Hydro Storage facilities is proposed (small scale PHS and sea water PHS were not considered due to no obvious applications at large scale)
	cS2	Compressed Air Energy Storage	CAES; (A)-CAES ; AA-CAES	2 data sheets on CAES are proposed for diabatic and adiabatic technologies (including AA-CAES)
	cS3	Batteries	Hot Batteries, Lithium-Ion, Ni-Cd, Lead-acid	6 data sheets for centralized and decentralized batteries: Lead-acid; Lithium-ion; Nickel cadmium (NiCd); Hot batteries (Sodium sulfur and Zebra); Metal (Li&Zn) Air; Li S. Only commercial or pre-commercial technologies have been considered. Less mature technologies such as Li-Air have not been retained since technological development time is of the order of magnitude of the targeted project time horizon (30 years).
	cS4	Redox flow batteries	Vanadium, Br-S (RegenesysTM), Zn-Br	3 data sheets: Vanadium redox; Regenesys; Zinc bromine (ZnBr). All available commercial or pre-commercial solutions have been considered.
	cS5	Flywheels	Mechanical bearings, active magnetic bearings, passive magnetic bearings	Flywheels not retained since main applications are outside the eHighway2050 scope (power applications for quality of supply and balancing -e.g., primary reserve)
	cS6	Other power storage	SMES, Super capacitor	*Super capacitors not retained since main applications are outside the eHighway2050 scope (power quality enhancement) *Superconducting Magnetic Energy Storage (SMES) not retained since most likely not available for commercial applications at 2050
	cS7	Hydrogen storage	Liquefied Hydrogen, solid metal hydrides, nanotubes	Due to the high level of efficiency losses, hydrogen cannot compete with the direct use of electricity. Nevertheless, Hydrogen can be used in the transport sector in the long-term and in special niche applications (provided that infrastructures and technologies are available).
	cS8	Molten Salt		This technology is closely related to the CSP technology which was not considered as a major generation technology in the scenario quantification. It is expected that the contribution of CSP electricity generation in the energy mix will remain marginal at 2050 horizon.
	cS9	Power to gas		Power to gas technologies refer either to Hydrogen or methane production. The case of Hydrogen was not considered neither for electricity production (see above) nor for the electrification of transport (assumption in coherence with the technology selection for demand). The second option (methane) was not considered since not consistent with the decarbonization goals of the EU at 2050. However, for the two scenarios where CCS is available ("large fossil fuel" and "big and market") this technology could be of interest.

	id	Group of technologies	Candidate technologies	Retained technology and rationale for discarding (if any)
	cS10	Pumped Heat Energy Storage		Pumped Heat Electrical storage (PHES) makes use of a reversible heat pump to store electricity (electricity to thermal energy and thermal energy to electricity). The concept is rather straightforward and most components are already available. Foreseen commercial applications are in the range of few MW with response times of the order of magnitude of a minute with round trip efficiencies comparable to PHS. There are no commercial applications (or pilot) in operation so far: it is therefore very difficult to find reliable data which could be used to forecast the evolution of performances and costs at 2050. As a consequence, PHES has not been investigated in the e-Highway2050 project. This technology will probably find its applications in distribution networks: it could be interesting for the X16 scenario.
	cS11	Liquid Air Energy Storage		Liquid Air Energy Storage (LAES) is similar to PHES: electricity is stored in the form of thermal energy (liquefied air with a compressor) and recovered by evaporated high-pressure air to drive a turbine. LAES is an innovation at system level, i.e. the components and subsystems being already available technologies. As for PHES, there are no commercial applications (one pilot) in operation so far: it is therefore very difficult to find reliable data which could be used to forecast the evolution of performances and costs at 2050. As a consequence, LAES has not been investigated in the e-Highway2050 project. This technology (potentially covering power outputs ranging from 5 to 50 MW) could be interesting for both TSO and DSO applications.
	id	**Group of technologies**	**Candidate technologies**	**Retained technology and rationale for discarding (if any)**
Decentralized storage	dS1	Batteries	Hot batteries, Lithium batteries, Lead batteries, Nickel Batteries	See cS3 above
	dS2	Redox flow batteries	Vanadium, Br-S (RegenesysTM), Zn-Br	See cS4 above
	dS3	Other power storage	SMES, Supercapacitor, flywheel	See cS5-cS6 above
	dS4	Hydrogen storage	Liquefied Hydrogen, solid metal hydrides, nanotubes	See cS7 above

Sector	id	Technologies	Candidate technologies	Retained technology and rationale for discarding (if any)
Generation	G1	Photovoltaic	Crystalline silicon technologies: Multi-crystalline Silicon, single crystalline Silicon, hetero-junctions (Si based)	Only crystalline silicone technologies have been considered. 2 datasheets for crystalline technologies in two configurations: PV (roof) and PV (system). Indeed this technology is expected to represent most of the installed capacity even at 2050. Furthermore, since these data are mostly used to compute production time series we can assume that the technical performances of PV alternative technologies (thin layers) will be in 2050 at a similar level as the crystalline silicone technologies. The third technology option is expected to remain marginal in continental Europe.
			Thin layers: Amorphous Silicon, Cadmium Telluride, Copper Indium Gallium Selenide	
			CPV: Gallium Arsenide (multi-junctions)	
	G2	Concentrated Solar Power (CSP)	Parabolic troughs	2 datasheets are proposed on parabolic through and central receivers
			Central receivers	
			Linear Fresnel reflectors	We have assumed that the Parabolic Trough technology will be more competitive than the Fresnel technology due to better efficiency at similar costs
			Parabolic dishes	This technology is considered as not competitive in the time frame of the project since too complex technically and therefore too expensive for grid connected applications
			Integrated solar combined cycle: ISCC (the solar resource partially substitutes the fossil fuel)	No application for mainland Europe is expected
	G3	Wind offshore	Foundations: Jacket, tripod, monopile, bucket, gravity	1 datasheet wind offshore is proposed
			Floating	
	G4	Wind onshore	Wind onshore	1 datasheet wind on shore is proposed
	G5	Geothermal	Organic Rankine Cycle (ORC) and Hot Dry Rock (HDR)	Only few countries in continental Europe (e.g. Italy) have suitable geological conditions to allow implementing such technologies which will remain marginal at the 2050 time horizon in Europe.
	G6	Hydro: run-of-river	Small to medium hydro power	1 datasheet without reservoir is proposed
	G7	Hydro with reservoir	Large hydro power	1 datasheet with reservoir is proposed
	G8	Gas turbines	OCGT Open cycle gas turbine (steam turbine and combustion turbine)	1 datasheet OCGT is proposed
			CCGT Combined cycle gas turbine	1 datasheet CCGT is proposed
	G9	Hard coal generation (with or without biomass co-firing; with or without CCS)	Steam cycle IGCC Integrated gasification combined cycle Fluidised Bed Combustion	Five data sheets: steam cycle 600°C (2 datasheets), steam cycle 700°C, fluidized bed and IGCC

	G10	Lignite generation	steam cycle IGCC Integrated gasification combined cycle Fluidised Bed Combustion	
	G11	Oil for power generation	Boilers	This technology is considered as obsolete in power generation with respect to technical performances
	G12	CCS	Gas generation with CCS	Four data sheets: steam cycle 600°C (two datasheets) and steam cycle 700°C (both for coal and lignite) and CCGT
			Hard coal with CCS	
			Lignite with CCS	
	G13	Nuclear power	Generation 1: Early prototypes, all nuclear reactors before 1967 : shipping port, Dresden, Magnox	These technology variants at 2050 will be decommissioned (and obsolete)
			Generation 2: Commercial Power nuclear, reactors built between 1967 and 1996: PWRs, BWRs, CANDU	
			Generation 3: Advanced LWRs, reactors built between 1996 and 2011: CANDU6, System 80+, AP600	2 data sheets for generation III are proposed (LWR and HTR)
			Generation 3 +: Evolutionary designs: ABWR, ACR1000, AP1000, APWR, EPR, ESBWR	1 data sheet for generation III+ is proposed
			Generation 4: Revolutionary Designs, after 2030	1 data sheet for generation IV is proposed
			Nuclear power < 400 MW: Small nuclear modular reactors	This option was not retained since the level of investment is not balanced by the revenues of electricity production (power) as in the case of large scale nuclear
	G14	Biomass	Direct combustion: bagasse, wood	1 data sheet (direct combustion) is proposed. Gasification of biomass was not considered since difficult to foresee a massive deployment
			Gasification: Combustion of syngas	
	G15	Biogas	Anaerobic digestion: Combustion of methane in gen-sets	Not relevant for large scale production of electricity. For small scale applications this technology is considered as non-competitive even at the 2050 time horizon.
	G16	Marine technologies	Wave, tidal	Competitiveness of marine technologies even at 2050 horizon will not be achieved. Furthermore the technical potential for tidal applications will remain low, while for wave applications efficiency of conversion devices will remain an issue
	G17	Combined heat and power	Waste to energy Small and medium size steam turbines	Five data sheets: waste to energy, small and medium steam turbines (woodchips and straw)
	G18	Any other distributed generation (incl. hydrogen fuel cells, etc.)	Fuel cells: SOFC, PEMFC; micro-turbines	These technologies could play a role in only one out of the five eHighway2050 scenarios ("small and local"). Fuel cells (either with CH4 or H2) only a coupling with power to gas deployment could be relevant. Micro turbines potential remain limited due to economic performances
	G19	Nuclear fusion		Not retained since not mature at 2050

Sector	id	Technologies	Candidate technologies	Retained technology and rationale for discarding (if any)
Active transmission	A1	HVDC technologies	CSC : Current Source Converters for HVDC	Two data sheets are proposed for CSC and VSC type converters for HVDC
	A2		VSC : Voltage Source Converters for HVDC	
	A3		DC breakers	
	A4		Tapping	
	A5		DC/DC Converters	
	A6	FACTS	Shunt: SVC, STATCOM	Two data sheets are proposed on shunt type FACTS including SVC and STATCOM
	A7		Series: TCSC, SSSC, TSSC	One data sheet is proposed on series type of FACTS and the rationale behind this limitation is detailed in the technology assessment report.
	A8		Combined devices: DFC, UPFC/IPFC, TCPST	No data sheet is proposed on these devices since they are of academic interest put not seen as commercially viable since the other FACTS and HVDC technologies cover these features (see the related technology assessment report in annex).
	A9	Transformers, AC breakers, PST	Phase Shift transformers and Transformers with tap changer	Three data sheets are proposed on PST, tap changers and circuit breakers
	A10	Protection and control at substations	HVDC - DC breaker	Included and described in the report for HVDC technologies
	A11		AC breaker ; FCL (High Temperature Superconducting FCL; Solid state FCL; Hybrid)	One data sheet is proposed on the AC Breakers (see A9) while the FCL are explained to be of academic interest rational behind this limitation is given in the technology assessment report.
	A12	Protection and control at system level	RTTE; WAMS/PMUs	Two data sheets are proposed on RTTE and PMU_WAM
	A13	OTHER	Offshore substations design	Not considered as an active transmission technology
	A14		Other HV substation equipment	Not considered as an active transmission technology

Sector	id	Technologies	Candidate technologies	Retained technology and rationale for discarding (if any)
Passive transmission: cables and lines	C1	Cable technologies (underground and submarine)	XLPE HVDC cables (underground and submarine)	Voltage levels of DC underground and subsea cables will increase considerably With switchgear equipment gaining market experience, meshed HVDC networks will become available
	C2		XLPE HVAC 380-420 kV cables (underground and submarine)	Further increase in transmission capacity above today´s 500kV. Partial undergrounding will complement overhead lines in more and more sensitive areas thus strengthening Europe´s meshed AC transmission networks.
	C3		Mass Impregnated HVDC cables (underground and submarine)	Mainly used with LCC Converters but also with VSC. MI Cables will still continue to be used for many years. Europacable does not expect major development of this technology
	C4		Self-Contained Fluid Field (underground and submarine)	SCFF cables are practically abandoned for land applications. Europacable would not expect any future land SCFF cable projects to be realised in the 2050 perspective. Europacable expects similar scenario for submarine applications, despite the fact that SCFF is still deployed for some specific submarine connections up to 50 km.
	C5	Other type of cables or of design	Gas Insulated Lines	Europacable considers GIL to be suitable for specific applications to carry very high power for short lengths. GIL technology will only offer a very limited contribution to the eHighway2050 network. This said, they may be deployed in specific projects ensuring safe use
	C6		Superconducting conductor (high temperature or low temperature)	Europacable does expect that High Temperature Superconducting Cables will eventually become available for wider scale deployment notably in urban areas
	C7		Partial undergrounding	Europacable expects partial undergrounding to be the most pre-eminent evolution of the Europe´s AC Networks up to 2050.
	C8		Hybrid HVAC-HVDC solutions	This hybrid type option is justified by socio-economic reasons (social acceptance) optimizing the use of existing corridors
	O1	Overhead lines: classic conductors	Copper and Aluminum (400 kV ; 750 kV; 1100 kV)	Copper is penalized by its weight and cost ; aluminum performances are not enough to undertake mechanical constraints of EHV OHL ; <u>For all type of conductors :</u> 1100 kV is considered of too high visual impact to be considered as a realistic solution ; for the same reason, 750 kV will be considered for only classical conductors
	O2		Almelec (400 kV ; 750 kV)	Good compromise between technical and mechanical aspects with possibilities of optimized design (Z wires)
	O3		Aluminium and Steel (400 kV)	Its mechanical properties make them optimised conductors for mountain areas only
	O4		Almelec - Steel (400 kV)	
	O5	Overhead lines: high temperature conductors	ACSS (400 kV)	It presents a very good mechanical strength and a quite high power flow capacity ; this conductor has been selected to represent the HTLS technology in this project
	O6		MMC (400 kV)	Similar performances compared to ACSS with a lower weight, but the cost has been considered too high => useful only in very specific situations
	O7		PMC (400 kV)	Good mechanical strength with a relative low weight, this conductor is penalized by its electrical performances (far lower than ACSS ones)
	O8		(G)TACSR (400 kV)	The good performances with low sag are allowed only with Gap type version ; but this version present difficulties for its implementation
	O9		ZTACIR (400 kV)	Equivalent capacity of ACSS conductor, but it presents lower mechanical performances and its cost is higher

2.4 Overview of the methodology for assessing technologies for future power system

Once the technology portfolio has been determined, a general framework must be provided to build the database that will characterize each technology. The approach to build a **technology characterization database for the next forty years** has three different building blocks.

1. <u>Defining the technological scope:</u> *What are the most relevant technologies to be considered for the power system at 2050 in each of the area of the electricity value chain (from generation to demand)?* This point has been developed above in section 2.3.
2. <u>The characterization variables:</u> *What are the critical parameters that are needed to characterize each selected technology?* The level of details needed by the canvas should be in line with the needs of future grid simulations.
3. <u>Uncertainty management</u>***:*** *How to cope with the increasing uncertainty intrinsic to the time horizon addressed by the e-Highway2050 project?*

The two last points are addressed in the next chapter (chapter 3) and the general data construction process is detailed in chapter 4.

The technological scope refers to the wideness of the database, the characterization variables to its depth in terms of appropriate granularity, and uncertainty management addresses the time dimension: data forecasting a forty-year period will include some assumptions resulting both from the scenarios and best guess or modelling from experts.

These three dimensions are clearly independent, as shown in Figure 6 next page. The wideness of technology areas is illustrated in brown color for the four considered technology areas (generation, storage, transmission and demand-side technologies). The depth of the database is represented in blue color with examples of variables characterizing the selected technologies, including technical performances and costs at 2050. Finally the vertical axis is for illustration purpose: each data or range of data at the intersection of the horizontal plane (one technology X one variable) is qualified by a qualitative degree of confidence resulting from its uncertainty. This degree is estimated in the context of the five scenarios of the e-Highway2050 project.

The technology database is then composed by records for each intersection point "Technology area X characterization variable" including either:

- quantitative data, i.e. precise values or ranges of values according to the degree of uncertainty and in a separate document (Technology Assessment Report) a description of assumptions and models used by experts,
- or qualitative data, i.e. data relative to the maturity of an innovation for a technology.

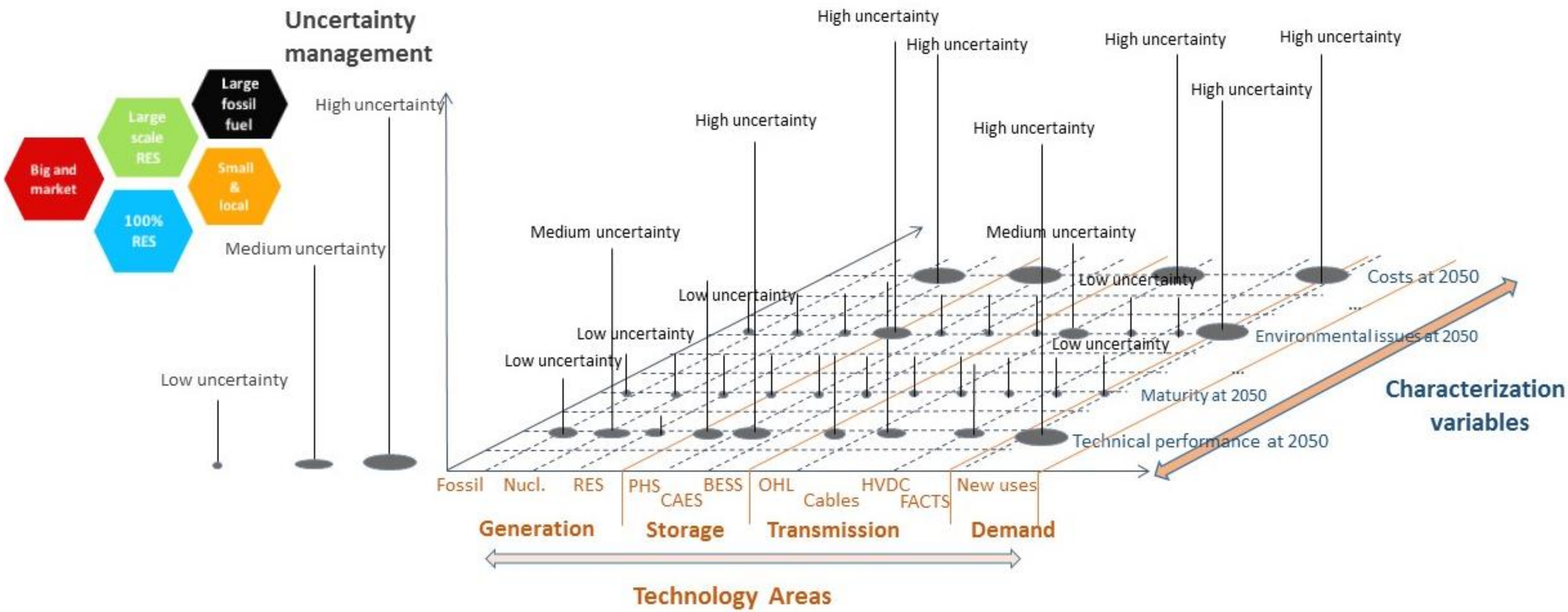


Figure 6: The three dimensions of the e-Highway2050 technology characterization database

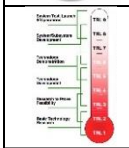
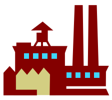
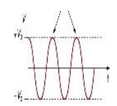
3 Architecture of the technology database and uncertainties

3.1 Architecture of the technology database

The database architecture consists in the definition of a list of key variables to be considered in order to characterize a given technology. The database is organized per technology (variant) and sub-technology[7], when relevant. For each technology, a set of variables is documented on costs, performances and other characteristics. These variables are organized according to a set of data types detailed in Table 6. For each variable a value is given for each decade: today (2013), 2020, 2030, 2040 and 2050.

This architecture is found in all data sheets (Excel files) supplementing the TARs (Word file) in annex to this report. The set of Excel files makes the technology database.

Table 6: Architecture of database per data types

Data type		Description
	**Technology performance characteristics**	Overview of the performance characteristics of a technology, e.g. rated power and efficiency levels for generation and storage technologies.
	**Technology readiness and maturity**	The Technology Readiness Level (TRL) scale allows assessing the maturity of the most probable innovations for each technology (e.g. sources of major cost/performance improvement in the future).
	**Possible implementation constraints**	Analysis of the barriers hindering the deployment of the technologies.
	**Costs**	Investment and Operation and Maintenance (O&M) costs including relevant variables such as lifespan in order to life cycle costs (LCC) of the selected technologies
	**Environmental impacts and public acceptance**	Assessment of different variables, such as the CO_2 footprint, land use, visual impact, etc.
	**Market and supply chain variables**	Estimation of market penetrations and identification of possible supply-chain bottlenecks (e.g. possible shortages of raw materials, lack of production capacities and/or transport and installation means, etc.).
	**Dynamic performances of power technologies**	Set of variables on load profile and flexibility, such as the dynamic performance of the technologies which are of relevance when performing critical network dynamic simulations to investigate the new network (at 2050) robustness to disturbances.

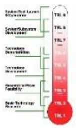
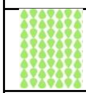
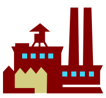
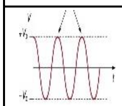
Within this general framework, the most impacting variables describing technologies in a given technology area are detailed in the following sections. The two data types *technology performance characteristics* and *costs* are the ones that have been detailed in-depth since of the highest interest for the power system simulations to be performed by the project.

3.1.1 Variables used for generation technologies

Table 7 presents the variables characterizing the selected generation technologies, cf. portfolio of section 2.3.

[7] For example wind power (technology or variant) is divided into two sub-technologies, i.e. on-shore and off-shore.

Table 7: Variables describing generation technologies

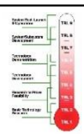
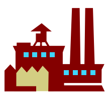
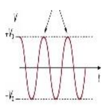
Data type	Variables	Comments
	**Efficiency**	For fossil-fuel based generation units, efficiency should be considered for a complete system, i.e. one should address all losses. Efficiency is therefore defined as the ratio of electrical energy to primary energy. For fossil fuels or biomass as primary energy source, the lower heating value is used. For wind power, efficiency is not considered (instead the load factor is used).
	Capacity rating	It is the maximum capacity or amount of power that can be installed for one unit (expressed in MW).
	Outage rate (%)	Fraction of energy not produced by the power plant due to failures - unplanned maintenance- supplemented by mean-time to repair.
	Availability (%)	Time availability i.e. the time fraction of the year where the power plant is available for electricity production.
	Operation hours (h) (at base load)	Availability of the power plant to produce energy over the whole year (unavailability is due to maintenance, repairs, etc.) at base load (i.e. ratio of the produced energy annually by the capacity rating).
	Specific variables	Technology performance characteristics are also described by specific variables which depend on technologies. For instance for wind power: rated power; diameter; cut-in wind speed; nominal wind speed ; maximum wind speed ; cut-out wind speed ; drive train - geared drive; type of generator.
	**Maturity of the innovation**	The metric used to assess this variable is the Technology Readiness Level (TRL) scale. Innovations are specific for each technology (carbon-fibre reinforces bales for wind power for instance).
	**Constraints for implementation**	Possible variables are geographical constraints, acceptability constraints, ease of sitting, surface occupation, etc.
	**Investment costs**	Investment costs (i.e. CAPEX) include engineering, procurement and construction costs.
	O&M costs	Fixed operation and maintenance costs (personnel costs, maintenance costs, insurance, etc.) and variable costs (fuel costs and CO_2 emission allowances, taxes). In the VGB report only the fixed O&M costs have been taken into account as a % of CAPEX.
	Life time	Expected life time of the technology in operation (in years).
	**Environmental impact**	Environmental impact is assessed through three main variables: CO_2 emissions, NO_x emissions and SO_2 emissions[8] for thermal technologies.
	**Market data**	Maximum amount of power that can be installed at the European scale depending upon e.g. geographical constraints, resource (wind, solar, hydro), etc.
	Supply chain issues	Scarcity of raw materials, constraints induced by the industrial process, etc. For wind power, the project lead time has been chosen as a good proxy of all supply chain issues.
	**Dynamic performance**	According to the considered technologies, a set of variables such as ramp rate, start-up time (cold and warm) are proposed to characterize the dynamic behaviour of the equipment.

[8] Additional data will be provided (in the form of short notes) upon WP6 requests.

3.1.2 Variables used for storage technologies

The table below presents the variables characterizing the selected storage technologies, cf. portfolio of section 2.3.

Table 8: Variables describing storage technologies

Data type	Variables	Comments
	**Efficiency**	Full cycle efficiency: electricity out/electricity in. For CAES, efficiency should be related to the whole plant.
	Energy storage capacity	Maximum rated energy capacity of a typical unit (only for centralized storage systems).
	Maximum power	Maximum power of a typical unit (only for centralized storage systems).
	**Maturity of the innovation**	The metric used to assess this variable is the Technology Readiness Level (TRL). Innovation are specific for each technology, improvement of the estimation of the SoH and SoC for BESS for instance.
	**Constraints for implementation**	Constraints are for example on technological limits (max installed power, etc.), geographical constraints (e.g. availability of hydro resources), acceptability constraints, geological constraints (e.g. caverns for CAES, hydro resources for pumped hydro), safety issues (e.g. batteries), etc.
	**Investment costs**	Same definition as of generation. A distinction has to be made between power-dependent investment costs and capacity-dependent investment costs. For the latter, a difference generally exists between the gross energy content and the usable energy content. For CAES, investment should only be related to the storage part (compressor, reservoir, heat exchanger, etc.).
	O&M costs	Fixed O&M costs (personnel, spare parts, insurance, etc.) and variable costs, i.e. the possible price of the stored electricity (which will be defined in the e-Highway2050 scenarios).
	Life time	Expected life time of the technology in operation (in years)
	**Environmental impact**	Environmental impact for storage technologies (BESS) can be characterized by a set of variables related to recyclability and toxicity.
	**Market data**	Maximum amount of power that can be installed at the European scale depending upon e.g. geographical constraints, resource (wind, solar, hydro), etc.
	Supply chain issues	A qualitative description of supply chain constraints (e.g. scarcity of raw materials, constraints induced by the industrial process, etc.).
	**Dynamic performance**	The dynamic performance of BESS for instance are characterized by the ramp rate, and the maturity of active control ability of each BESS (frequency, voltage and harmonics controls, and the fault-ride-through capability).

3.1.3 Variables used for the selected demand-side technologies

The next three tables (Table 9 to Table 11) detail the variables for the three selected demand-side technologies: electric vehicles (EV/PHEV), lighting (LED/OLED), and heat pumps for cooling, space and water heating.

Table 9: Variables describing electric vehicles (EV/PHEV)

Data type	Example of variables
Technology performance characteristics	Overview of the performance characteristics of electric vehicles: maximum power; battery capacity; consumption
Charging infrastructure characteristics	- Slow charging power - Fast charging power - Typical slow charging profile (for one single unit and for one country) - Typical fast charging profile (for one single unit and for one country)
Technology readiness and maturity	Sources of significant cost/performance improvement in the future: - increased efficiency and autonomy - fast charging batteries - light weight cars
Constraints for implementation	Possible barriers hindering the deployment of the technology, e.g. driving range and availability of charging points.
Investment cost	The anticipated unit costs, both for vehicle and battery. The lifespan is assessed as well. Total capital costs (battery, body, chassis); lifespan of vehicle; lifespan of batteries.
O&M costs	- total O&M costs - O&M costs for batteries
Environmental impact	This data type is limited to variables on CO_2 content and recyclability.
Market data	Assessment of the market penetration inside EU (cumulative market).
Supply chain issues	- Spare parts availability - Material shortages
Dynamic performance	This data type is limited to the assessment of the share of the controllable fleet. Typical modulation profile (slow charging).

Table 10: Variables describing lighting technologies (LED/OLED)

Data type	Example of variables
Technology performance characteristics	Overview of the performance characteristics of LED and OLED - Luminous efficacy ('cool' white LED) - Efficiency ('cool' white LED) - Luminous efficacy (LED lamp) - Efficiency (LED lamp) - Colour Rendering Index - Color temperature
Technology readiness and maturity	Sources of significant cost/performance improvement in the future, assessed with the TRL scale - Value-based market share - Price ratio - Dimmability and controllability
Constraints for implementation	N/A
Investment cost	The anticipated unit costs: Lamp retail price; Package price. Life span
O&M costs	N/A

Environmental impact	- Energy payback time - Life cycle energy - Level of blue radiation - Mercury content - Recyclability
Market data	- Assessment of the penetration level inside EU. - Cumulative market materials
Supply chain issues	N/A
Dynamic performance	N/A

Table 11: Variables describing Heat Pumps

Data type	Example of variables
Technology performance characteristics	Overview of the performance characteristics of the heat pumps: power and efficiency data, typical size (residential and service sector). Variables include: Coefficient Of Performance (COP), Energy Efficiency Ratio (EER), seasonal COP (SCOP), heating seasonal performance factor (HSPF), seasonal EER (SEER).
Technology readiness and maturity	Sources of significant cost/performance improvement in the future (compressor efficiency and system integration for instance), assessed with the TRL scale.
Constraints for implementation	Possible barriers hindering the deployment of the technology, especially availability of skilled workforce and implementation time.
Investment cost	The anticipated unit capital costs and lifetime of equipment.
O&M costs	Anticipated O&M costs.
Environmental impact	Noise disturbance and environmental impact of refrigerants.
Market data	Assessment of the market volume and cumulated number of units in Europe.
Supply chain issues	N/A
Dynamic performance	Assessment of load flexibility share.

3.1.4 Variables used for passive transmission technologies

The following tables describe variables for cables and overhead lines.

Table 12: Variables describing cable transmission technologies

Data type		Example of variables
	Transmission distance	- Maximum length of the cable link.
	Losses	- Losses a typical system: conducting material, section (mm²), nominal power, soil properties, etc.
	Capacity	- Max Voltage - Current rating - Max Power - Impedances (R+jX) - Depth (deep sea installations)
	Maintenance	- Unavailability rate (referred to a 100 km circuit) - Failure rate - Mean time to repair failures
	Maturity of the innovation	- Technology readiness of the overall cable system assessed with TRL scale (e.g. commercial availability of superconducting solutions).
	Constraints for implementation	- N/A
	Investment cost	- Investment costs (capital expenses and installation expenses) - Lifespan
	O&M costs	Operation and Maintenance costs (O&M)
	Land use	- Mean surface occupation of a typical system
	Environmental impact	- Recyclability at end of life
	Market data	- Market volume at world and/or European level (installed km) - Penetration rate of automated installations (%) out of total.
	Supply chain issues	N/A
	Dynamic performance	- Dynamic performance of technology components is provided when relevant

Table 13: Variables describing overhead lines transmission technologies

Data type		Example of variables
	Transmission distance	- Maximum length of the line (km)
	Losses	- Losses in the line/circuit (under typical operating conditions) - Losses in the line/circuit rated courant
	Capacity	- Nominal voltage - Maximum temperature of operation - Maximum current in continuous operation/circuit - Number of conductor par phase - Number of circuit per tower - Resistance per unit length and impedances (R+jX)
	Maintenance	- Failure rate - Mean Time to repair failures
	Maturity of the innovation	- Technology readiness of the overall overhead lines system (Tower+ foundation + conductors)

	Constraints for implementation	- Public acceptance[9]
	Investment Cost	- Investment costs include: Capital expenses and installation expenses - Lifespan
	O&M costs	- Operation and Maintenance costs (O&M)
	Land use	- N/A
	Environmental impact	- Tower height - Recyclability at end of life (%)
	Market data	N/A
	Supply chain issues	N/A
	Dynamic performance	N/A

3.1.5 Variables used for active transmission technologies

The following tables detail the variables used for HVDC systems and FACTS.

Table 14: Variables describing HVDC active transmission technologies

Data type		**Example of variables**
	Transmission distance	- Maximum length of the line/cable for a given converter
	Losses	- Losses per converter station
	Capacity	- Voltage (line to ground) for converters - Voltage (line to ground) for cables - Current - Max Power per VSC substation (bipole)
	Security of Supply	- Reliability and availability (per station) - Maintenance: frequency and outage time
	Maturity of the innovation	- Monopole (sym/assym) and bipole solutions - Regional DC grid (multi-terminal, one protection zone) - Inter-regional DC grid (several protection zones) - DC breaker - Tapping (series/parallel) - DC/DC converter - Overall HVDC-CSC system
	Constraints for implementation	- Size of the CSC /VSC station
	Investment Cost	- Investment costs of the system components include capital expenses and installation expenses - Economic lifetime
	O&M costs	- Operation and Maintenance costs (O&M)
	Environmental impact	- Land use - Noise generation - EMC - Health and safety - Life time of equipment

[9] Public acceptance is one of the major issue today when developing new overhead lines. Alternative solutions such as undergrounding or partial undergrounding might be used to alleviate this constraint.

	Market data	- Market volume at world/European level (total installed km)
	Supply chain issues	- Operational experience
	Dynamic performance	- Commercial availability of adaptative/self-tuning control - Ability to comply with existing grid codes - Commercial availability of Virtual rotating mass - Necessity of network /model simulations - Duration of the fault clearing phase (DC side) - Commercial availability of DC fault ride through function

Table 15: Variables describing FACTS active transmission technologies

Data type		**Example of variables**
	Losses	- Series connected capacitor (FSC), per convertor station
	Capacity	- Voltage (line to ground) for converters - Rated reactive power - Current
	Security of supply	- Reliability and availability (per station) - Maintenance: frequency and outage time
	Maturity of the innovation	- Technology readiness scale of overall FACTS system
	Constraints for implementation	- Size of the capacitor bank(FSC), size of the converter station
	Investment Cost	- Investment costs of system components - Economic lifetime
	O&M costs	- O&M costs
	Environmental impact	- Land use - Noise generation - EMC - Health and safety - Life time of equipment
	Market data	- Market volume at world/European level (total installed km) - Market volume at world/European level (number of capacitor banks)
	Supply chain issues	- Operational experience
	Dynamic performance	- Commercial availability of adaptative control - Commercial availability of Self tuning control - Ability to comply with existing grid codes - Commercial availability of Virtual rotating mass - Necessity of network /model simulations - Enhanced power oscillation damping - Enhanced voltage stability - Time response for a full step - Enhanced transmission capacity

3.2 Data uncertainties management

3.2.1 Uncertainties and imprecisions

Two concepts are needed when considering the likelihood of future events, or in the context of e-Highway2050, the likely evolution of technologies:

- the concept of uncertainty refers to the condition of being unsure about something or of lacking confidence on a fact or a data. By contrast with a risk which can be quantified, measured, mitigated or more generally managed, uncertainty is not measurable and thus cannot be quantified or managed,
- imprecision refers to the fact that data might be expressed in a way which could be vague or inaccurate.

In the database, the characterisation of a technology according to the variables defined in the previous chapter is subject to uncertainties due to the relative confidence one could have in the appraisal of future trends. In addition, each data introduced in the technology database (either qualitative or quantitative) presents a degree of imprecision. Data could for example be precise (if a numerical value is provided) or imprecise, meaning that only a range (typically a min-max interval) is provided.

There is usually a trade-off between uncertainty and precision for a particular data. We could say that imprecision is a way of addressing uncertainty. Precision is typically reduced to increase confidence, as illustrated in the figure below. Out of the four quarters only the one in the upper left quarter is a tradable and valuable situation.

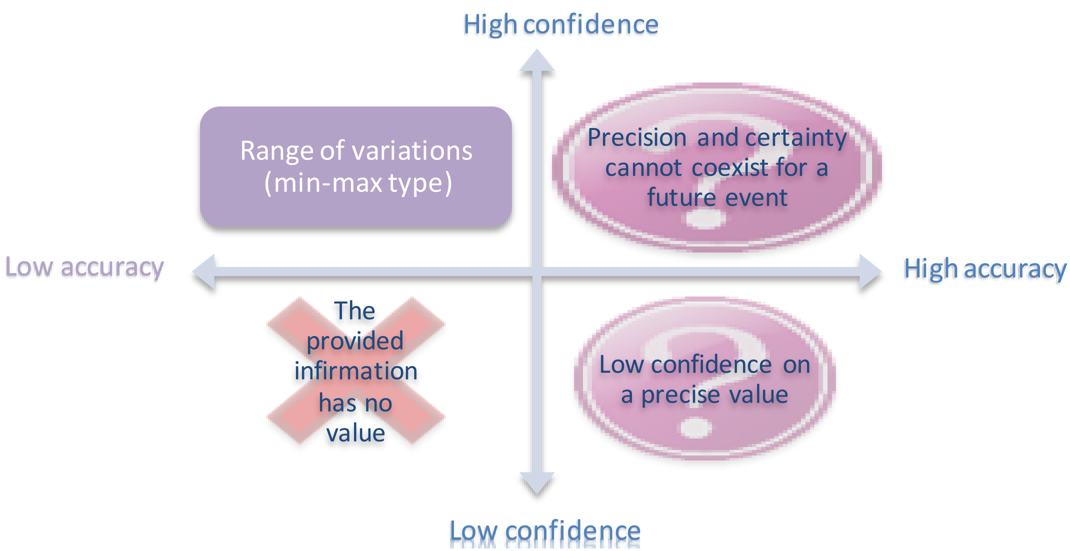


Figure 7. Appraisal of a particular entry of the database in terms of confidence and accuracy

3.2.2 Nature of uncertainties in the technology database

Uncertainties might result from three main different sources, cf. Table **16**.

Table 16. Main sources of uncertainties in the technology database.

Sources of uncertainty	
	**Diversity of variants in a given technology family** (e.g. the various types of redox flow batteries, different capacity ratings of a given thermal plant, etc.), which will impact ratings and therefore investment costs
	**Diversity of the installation sites**[10] (e.g. country, geography, labour costs, etc.) which will impact mainly installation and O&M costs.
	**Time horizon**: forecasts at 2050 are more uncertain than the ones targeting 2020, i.e. uncertainty grows with time.

The first two components are easy to address by focusing on a particular technological variant under given installation conditions. The remaining uncertainty will then be dealt with by considering ranges for the studied variables.

[10] For DEMAND technology area some wording adjustments are necessary (e.g. installation site replaced by consumer site).

3.2.3 Reducing the uncertainty level

As mentioned above, two out of the three components of uncertainty, i.e. the uncertainty due to technological variants and the uncertainty due to the installation site can easily be addressed. However, the **uncertainty due to the distance to the time horizon** cannot be easily captured and therefore it must be described through ranges of possible evolutions of the variables characterizing each technology.

In particular for costs (CAPEX and OPEX), this uncertainty is due to a variety of key factors such as evolutions of fuel prices, raw material prices, carbon prices, assumptions made for calculating costs (discount rate for capital-intensive technologies), learning rates, economies of scale, etc. This uncertainty was tackled at three different levels, cf. Figure 8. At the project level: the scenario-based thinking allows grasping the variety of evolutions of the power system at 2050. At the work package (WP3) level, the data contextualization of the typical ranges depending on the considered scenarios and at the technology level with a specific methodological focus on the performance and costs evolution for a given variant.

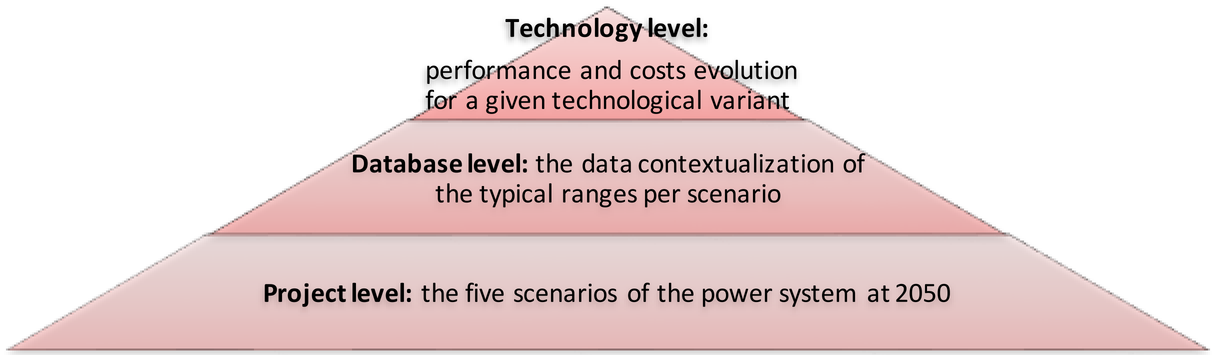


Figure 8: Approach to reduce the uncertainty resulting from a remote time horizon

3.2.3.1 Project level: the e-Highway2050 scenarios

The e-Highway 2050 project addresses the uncertainty due to the long-term horizon by defining five possible evolutions of the power system. In Work package 1 (WP1), five scenarios were defined to characterize five situations covering the time period 2020-2050 and taking into account technological, financial/economic, environmental and socio-political issues. These situations are considered as extreme but realistic cases from the perspective of the power system as a whole at 2050.

3.2.3.2 Database level: the data contextualization process

An approach to contextualize the typical ranges of data with respect to the five selected e-Highway2050 scenarios has been proposed as a key question for the simulations to be performed in WP2 is the following: *How to adjust the typical ranges of technology data according to the five selected scenarios?*

Consequently, an approach called **data contextualization** was developed aiming to allocate, for a given technology, typical values to key variables descriptive of this technology, at the 2050 time horizon, and this for each of the five considered scenarios. This allocation process is fed by the extreme values, both quantitative (min/max) and qualitative (high/low), for each variable (costs, efficiencies and other performances) and the associated ranges.

The data contextualisation methodology was first developed for generation technologies by Eurelectric and then extended by TECHNOFI to storage, transmission and demand technologies. The main assumption of this methodology is that, for each of the critical identified technologies, the main driver for contextualization is the penetration rate of the technology (cumulated number of units at a given time). It is indeed assumed that the cost and performance trends of the technologies by 2050 are directly correlated to their level of deployment.

An illustration of the implementation of data contextualization methodology is proposed below for the electric vehicle technologies.

Six successive steps are foreseen to build adjusted values consistent with the five e-Highway2050 scenario, cf. Figure 9 next page:

Step 1. A given scenario is a combination of a "future", characterized by a set of "uncertainties", and a "strategy", characterized by a set of "options". The future deployment of EVs by 2050, i.e. the penetration level, is impacted by some of these uncertainties and options. A selection of uncertainties and options is therefore made according to their potential impact on future EV deployment: uncertainties and options are assessed in terms of their potential support or barrier to EV deployment. Only uncertainties and options with a significant impact (i.e. incentive/barrier to penetration) are considered.

Step 2. Depending on the future and strategy, each uncertainty and option has a specific value. The potential impact related to this value on EVs deployment is assessed in a qualitative way, i.e. on a three degree scale (Low, Medium, High)

Step 3. By aggregating these individual assessments of each selected uncertainty and option, an overall qualitative assessment (Low, Medium, and High) is made, which reflects the impact of the given scenario on the deployment level of EVs.

Step 4. In parallel, a subset of key technology variables describing EVs is selected. The selection focuses on penetration level (number of units by 2050), performances (efficiency) and costs (battery and vehicle).

Step 5. From the value ranges attached to the selected EV key technology variables, the minimum, average, and maximum values are extracted, and are then allocated to the market penetration assessment scale (Low, Medium, High –see step 3).

Step 6. By combining the scenario assessments made at step 3 and the EV value tables built at step 5, specific values are allocated to the subset of EV variables (key technology variables) according to each given scenario[11]

3.2.3.3 *Technology level: methodology for cost (transmission only)*

The methodology to build the future cost of transmission systems is detailed in section 5.

[11] See TAR on Electric Vehicles for more details

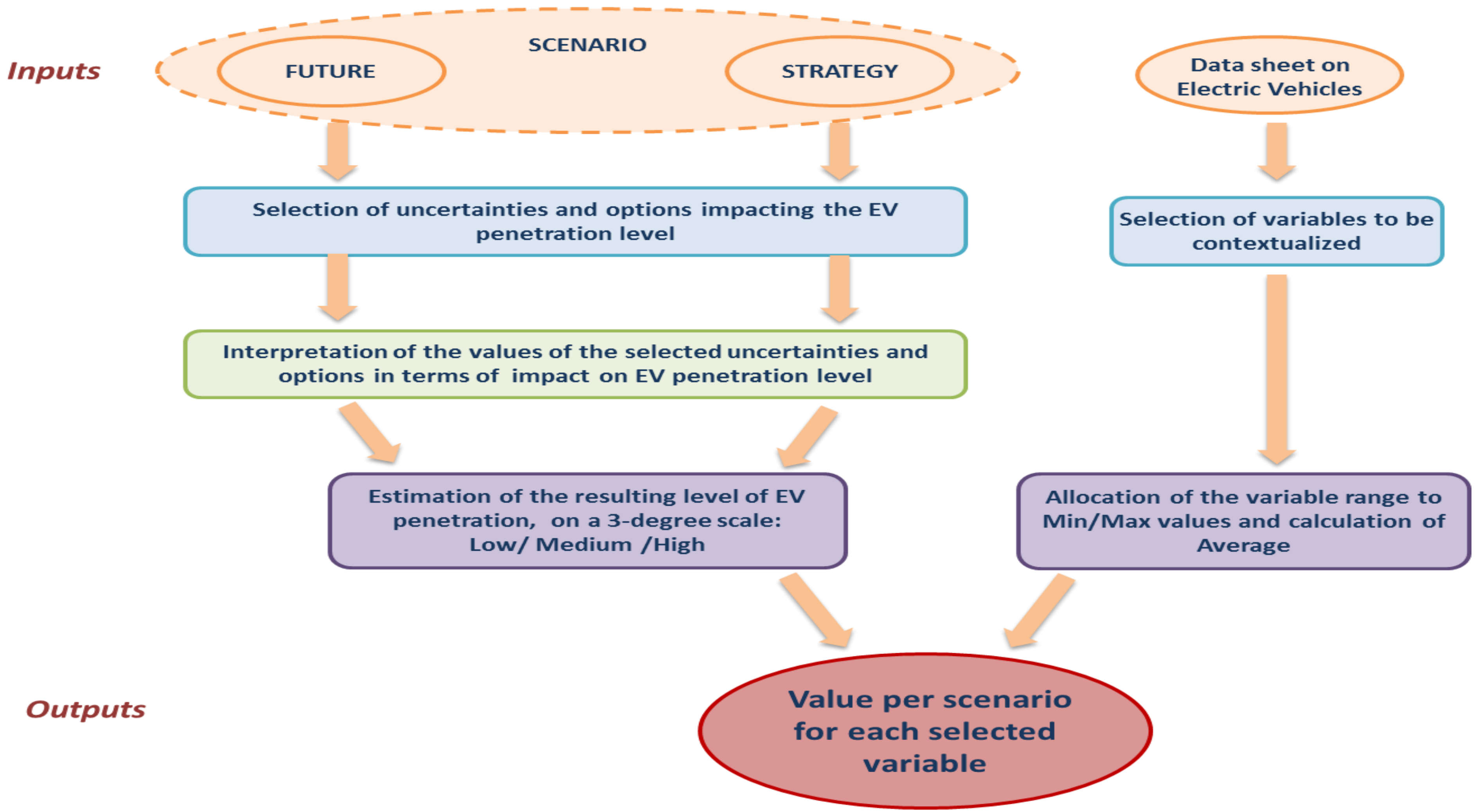


Figure 9: Contextualisation process (example for electric vehicles).

4 Data construction process

The process of building the techno-economic data is detailed in section 4.1. The main principles are presented in section 4.2, while contributors are presented in section 4.3.

4.1 Overview of the data construction process

The data construction process is generic for each technology area and is documented by specific Technology Area Reports (TARs). Figure 10 below shows the different steps of the data construction process and how the data uncertainty challenges are addressed, as explained in the previous chapter.

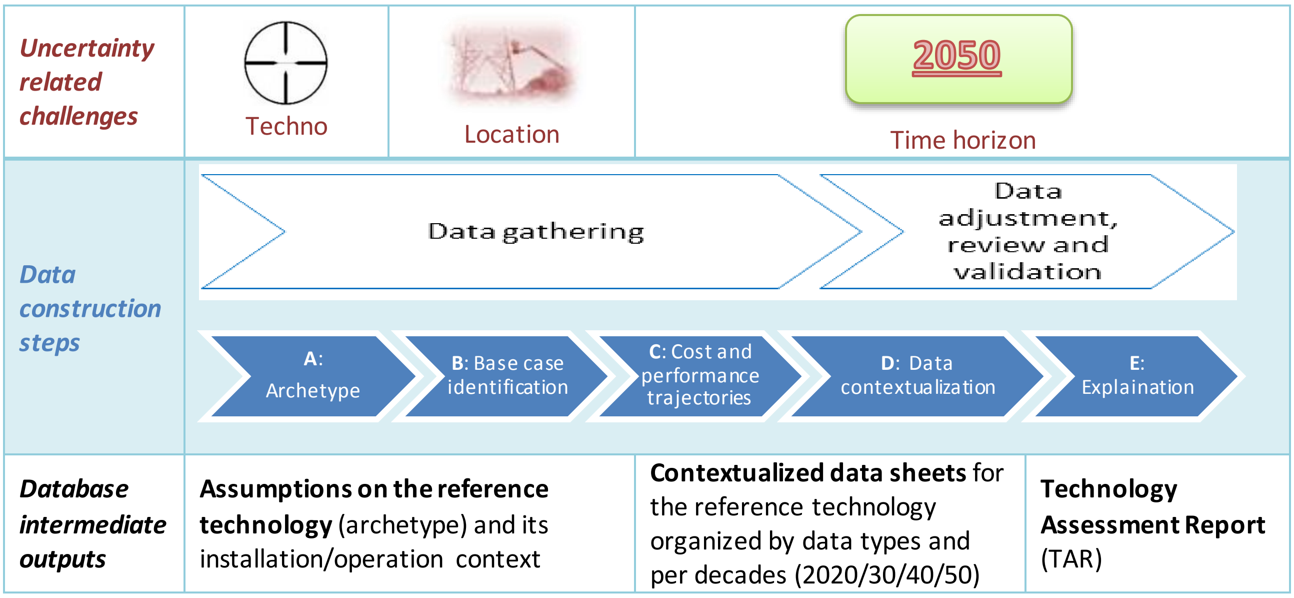


Figure 10: The data construction process for each technology area

The first three steps (A, B, C) of the data construction process deal with the gathering by the experts of performances and costs data of a given technological variant (step A for an **A**rchetypal representative of the technology family) and under a reference installation context (step B for **B**ase case identification). Under these assumptions, typical trajectories of cost and technical performances (step C for **C**ost and performance trajectories) are built including uncertainty margins. The result is the production of min-max intervals for a selection of variables.

The fourth step (step D for **D**ata adjustment) deals with the fine-tuning of these min-max ranges according to the five scenarios defined by the project while the final one (step E for **E**xplanation) deals with quality and transparency issues of the whole process (TAR produced for each technology family gathering the construction assumptions and introducing the corresponding datasheet).

4.2 Principles and process

In order to build cost and performance data, three main families of approaches are typically used:

i. data gathering from existing studies (sector and technology roadmaps) and published articles;

ii. data gathering by interviewing experts on such data trajectories of cost and performance forecasts (expert's views);

iii. building or using models allowing such forecasts. One particular family of such models are the maturity based models and the learning rate models, which rely on penetrations rate of a given new technology.

These approaches were used by WP3 experts according to their specific needs. Let us now detail the five (A, B, C, D, E) steps.

4.2.1 Archetype definition (A)

As explained before, in order to grasp the diversity of technological variants in a given technology family, it was necessary to define a relevant representative of the technology family or of a variant. This best representative of a technology family is called **archetype**.[12] This "archetype" was defined by the experts of WP3. The definition of the archetype should be precise enough in order to provide valuable information to the database users (e.g. different capacity ratings of a given thermal plant, etc.), since such sizing will impact ratings and therefore investment costs.

The following principles have been used to define an archetype:

- "Best Available Technologies" approach at a given time horizon. For example, for transmission technologies, the highest expected performance in term of transmission capacities was assumed;
- The archetype could be defined as of a given date (e.g. after 2030) so that information on expected performances are given from that date onwards.

The consecutive steps to build the technology characterization database are described below.

4.2.2 Base case identification (B)

As a result the archetype in a base case installation (e.g. defining the nature of the location site) or operation context (e.g. fixing the voltage level) defines the reference variant which will be used for the next step.

4.2.3 Cost and performance trajectories (C)

This is the core step aiming at providing a datasheet (database) for each of the archetype with the associated base case. Ranges for each variable are provided by experts: these ranges are then "contextualized" per scenario as illustrated in section 3.2.3.2

Data was gathered from available literature and experts' interviews, with a selection criteria based on the value of the source (renowned experts, top-ranked peer review journals, publications from specialized conferences such as CIGRE, etc.). All data sources are listed in the annexed reports (TAR). Data extracted from literature review and experts' interviews might have been adjusted:

- either to fit the archetype which was defined. Typically such adjustments consist in a direct calculation and results from sizing issues;
- or to take into account discrepancies between sources. This process is less intuitive than the previous one and its implementation requires analysis and additional assumptions as described in the approach below:
    - Analysis of data discrepancies. Large discrepancies might exist between different sources for a given variable: they are mainly related to different assumptions on technology penetrations on the long term (specific deployment scenarios). These discrepancies were analysed in the annexed reports (TAR) in order to formulate assumptions, when required for calculation. As much as possible, ranges of values were kept for each variable: the extent of ranges reflects both the variety of perspectives from the different sources, and the margin of uncertainty assessed by each source on a given variable.
    - Adjustment of value ranges. Based on the analysis of data discrepancies regarding performances, and when required, costs and market penetrations, recommendations were made to adjust the value ranges.
    - Review of adjusted value ranges. The recommended adjusted value ranges were reviewed in collaboration with the experts (technology area leaders) and the representatives of WP3 quality pool.

[12] "Archetype: A very typical example of a certain person or thing" (Oxford dictionaries)

4.2.4 Data contextualization (D)

The resulting data proposed by TA leaders is then contextualized according to the e-Highway2050 scenarios as described in section 3.2.3.2.

4.2.5 Explanation (E)

A Technology Assessment Report (TAR) synthesizes the main assumptions and introduces the datasheet (data base) for each considered technology.

4.3 Contributors to the data gathering

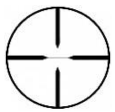
As already mentioned in section 1.2 contributors are defined per technology area.

For generation and storage technologies, the data gathering process was carried-out by a professional association and its members, partner of the project (EURELECTRIC - VGB Power Tech) and an academic institution (University of Comillas) for data on battery storage technologies. A professional association (EWEA) provided data for wind energy. IEN gathered specific data for biomass-fired CHP (combined heat and power) boilers.

The demand-side technologies area was addressed by TECHNOFI.

For the transmission technology area, the partners in charge were T&D Europe, for active transmission technologies, Europacable for cable technologies and a pool of TSOs partners of the project for the AC and DC overhead lines.

Table 17: Addressing uncertainties specifically in each technology area

Nature of uncertainty	Factors	Captured by	Specific features for uncertainty management for each technology area				
			Generation	Storage	Demand-side	Passive transmission technologies (cables and lines)	Active transmission technologies
Breadth of technology family 	Diversity of technological variants in the family will impact ratings, capacity and therefore investment costs	Definition of a technology variant **("archetype")** for each technology family	**Typical (maximum) plant sizes** are given for each variant. The provided technical data have to be understood as the achievable targets for the operation of the plants.	No specific feature	**A dedicated methodology** to define the most "critical end-use segments" and the related consumption technologies was developed: 3 technologies were further detailed	**Maximum transmission capacities** are given for each variant of cable and lines. They are achievable targets for each time horizon	No specific feature
Installation context 	Country, geography, labour costs will impact installation and maintenance costs	Definition of a **Base case** and a scaling factor for installation cases different from such reference case	**Boundary plant conditions** are assumed for each installation	Not a major issue for batteries. For large scale storage installation context is to considered as for transmission technologies.	Consumption location was not considered	**Installation in plain, urban context, mountains, in low labour cost and high labour costs countries** See chapter 5 for the proposed "terrain" factors and data on cost of equipment in different countries in Europe	

Nature of uncertainty	Factors	Captured by	Specific features for uncertainty management for each technology area				
			Generation	Storage	Demand-side	Passive transmission technologies (cables and lines)	Active transmission technologies
Distance to time horizon 2050	Costs: Investment costs and O&M are impacted by factors such as, evolutions of fuel prices, raw material prices, carbon prices, learning rates, economies of scale, etc. Performances: one should distinguish mature technologies (for which learning rates are well known by manufacturers) from emerging ones.	Min-max ranges have been considered increasing with the considered time horizon. They result from available studies.	For generation technologies, a detailed analysis of the variables influencing costs, based on qualitative scale **[-/-+/+/++/+++]** scale allowed building uncertainty ranges for costs (OPEX and CAPEX) as follows: **+/-8% at 2030, +/-10% at 2040 and +/-12% at 2050**	Uncertainty ranges derived from the considered studies.	Most of the available data provide penetration rates and unit consumption figures at the 2030 time horizon.	Time evolution of cost trajectories can be modelled by the methodology detailed in chapter 5. The approach is based on a **breakdown of cost in five distinct components (equipment, installation, civil work, project management and authorizations & right of ways)** whose evolution can be predicted thanks to forecasts of few indices (commodity index in energy, metals, cost index of labor and cost index of engineering and experience curve of this family of product in industry). Short to mid-term qualitative evolutions of the series of driving indices have been made and it appears that their effects are compensating each other. The expected short to mid-term evolutions of the considered indices are: "up" for commodities on price and energy, "down" for labor cost, "up" for engineering index and "down" again for experience curve due to the increasing maturity of transmission technology.	
	"Future" and "strategies" as defined in WP1 scenarios	The "contextualization process" fixed one unique value from the min/max range to run the required simulations for each scenario. According to the verbal description of a given scenario, the min or max or a median value is retained.	No specific feature: contextualization per scenario implemented	No specific feature: contextualization per scenario implemented	Contextualization per scenario implemented based upon the main criterion: the penetration rate of the considered demand-side technology	These effects seem to be independent to the five e-Highway2050 scenarios. Thus no contextualization per scenario for building the cost trajectories of equipment. See chapter 5.	

5 Building trajectories of costs for transmission technologies in the e-Highway2050 context

5.1 Scope and challenges

It is proposed to detail the methodology developed to build the cost trajectory of the most critical transmission systems to be used in e-Highway2050 simulations:

- converters for HVDC systems (HVDC VSC ; HVDC LCC),
- AC, DC and hybrid overhead lines (OHL) including conventional and high temperature conductors,
- underground and underwater cables (HVAC and HVDC),
- FACTS.

For each of these technology families, it is requested to build trajectories with estimated costs for each decade from today to 2050. Table 18 gives an overview of the variables and costs components to be considered.

Table 18: Variables describing the cost components of transmission technologies

Data type	Variables	Comments
€	**Investment Cost**	- Costs of equipment, installation, engineering, project management - Economic lifetime and discount rate
	Operational Cost range	- Level of Operation and Maintenance

According to the general methodology described in chapter 4, it is assumed that each of these technologies is characterized by their most likely technological variants (e.g. voltage levels), variants which are expected to be commercially mature and operational for each time horizon 2020, 2030, 2040, 2050. In addition a standard reference for installation sites is assumed.

Two main categories of factors are expected to contribute to the variability and uncertainty of transmission costs from today to 2050.

- Macro techno-economic factors: evolutions of fuel prices, raw material prices, carbon prices (emission allowances), personnel costs, etc., are typical exogenous factors that influence costs. Uncertainties on these factors are expected to be reduced by the scenario-type approach implemented in the project and by a main assumption consisting in focusing only on long-term fluctuations (order of magnitude of decades).

- Maturity-type factors: they are closely related to the considered technology and they reflect its maturity. One can mention technology learning rate approaches based for instance on penetration rates and economies of scale. The literature on technology learning rate models is rich but mainly for generation and demand technologies. The use of learning rate models for transmission technologies at the 2050 time horizon is discussed in the present document.

Building costs at such a long time horizon (up to 2050) is a complex exercise that has already been performed in the FP7 IRENE40 project[13], cf. ref. [8] (deliverable presenting the technological development forecast methodology and the associated database). Areva, ABB, Siemens and academics (RWTH, ECN, ICCS NTUA, ETH Zurich) have proposed a cost forecast methodology which was considered in the present work.

Building a cost trajectory based on models of evolutions of various factors has a first key prerequisite: to have a common view on the costs today. This view must be shared by various stakeholders of the electricity value chain (mainly transmission system operators and manufacturers). In the present work, the general methodology to build the cost trajectories includes three steps which are specified hereafter.

1. Defining the starting point: a breakdown of the total costs into categories (cost components) including for instance labour, and materials for each component of the considered system.

[13] www.irene-40.eu

2. Building the evolution laws: for each cost component, an evolution law is built based on indices that are extrapolated from recent history. Interval margins (min-max) increasing with the time horizon are proposed.

3. Aggregating the costs: the CAPEX and OPEX in the attached datasheets are directly resulting from the previous assumptions providing min-max intervals. Then the contextualization process per scenario is be applied to infer the min, the max or the median value of the interval according to the estimated maturity / commercial deployment at each time horizon.

A first example of the implementation of this three-step methodology is provided for OHL (overhead lines) in the next section (section 5.2) as a dry-run test. Strong points and limitations of this methodology are then discussed based on this OHL case study. In a second stage, based on lessons learned from the OHL exercise and from data gathering for other transmission systems, a slightly adapted approach is deployed in section 5.10 for building the costs trajectories of transmission equipment. Thus chapter 5 is organized as follows:

- dry-run test on overhead lines and discussion on the proposed approach in section 5.2,
- cost data gathering on HVAC underground cables in section 5.3,
- cost data gathering on HVAC submarine cables in section 5.4
- cost data gathering on HVDC transmission systems in section 5.5
- cost data gathering on HVAC substations and transformers in section 5.6
- cost data gathering on FACTS in in section 5.7
- recommendations on evolution laws and intermediate conclusions in section 5.8 and 5.9, respectively.

The deployment of the approach to model costs of key archetypal transmission equipment over the period 2014-2050 is detailed in section 5.10.

5.2 Implementation of the methodology: case of HVAC Overhead lines

This sub-section illustrates the deployment of a first dry-run test over the 2013-2050 period for HVAC overhead lines.

5.2.1 Defining the starting point

The first step is to select the technology variant including the operational mode to reduce the imprecision resulting from the "archetype" or the "installation case" as defined in the previous chapters. The unit cost of overhead lines depends (non-exhaustive list) on the transmitted power, the distance of transmission, the voltage (for instance 380 kV or 220 kV), the number of circuits (e.g. single or double), the terrain (e.g. rural or urban[14] combined to mountain or plain), the country (e.g. labor cost in Northern Europe vs. Southern Europe), etc. In the following, we focus on an overhead line system (HVAC) under the following assumptions (for OHL operated in DC, see section 5.5.2):

- HVAC operated at 380 kV, double circuit,
- in four different environments to reflect the space variability (environment 1 in rural area, plain in Northern Europe; environment 2 in rural area, plain in Southern Europe; environment 3 in urban area, plain in Northern Europe ; environment 4 in urban area, plain in Southern Europe).

The following table provides a country review of HVAC asset costs (including several ratings, 2011 data) collected by [6].

Table 19: Average reference values of overhead lines in different countries in Europe [6]

	Average reference values for OHL single circuit	Average reference values for OHL double circuit
Italy	• 380 kV 500-600 k€/km • 220 kV 350-420 k€/km • 120÷150 kV 270-320 k€/km	• 380 kV 750-900 k€/km • 220 kV 450-540 k€/km • 120÷150 kV 410-490 k€/km

[14] In the present work, "urban" means both urban areas and densely populated areas.

Germany	• 380 kV 700-800 k€/km	• 380 kV 1000-1200 k€/km
France	• 380 kV 700-800 k€/km • 220 kV 350-500 k€/km	• 380 kV 1000-1400 k€/km • 220 kV 450-550 k€/km
The Netherlands		• 380 kV 1000-1200 k€/km • advanced, 380 kV 2300-2500 k€/km
Austria		• 380 kV 1000-1500 k€/km • 220 kV 700-1000 k€/km
Ireland	• 220 kV 700-1000 k€/km • 110 kV 400-500 k€/km	• 400 kV 1400-1600 k€/km
UK	• 400 kV 1100-1300 k€/km	• 400 kV 1300-1500 k€/km
Finland	• 400 kV 400-500 k€/km • 220 kV 200-300 k€/km	• 400 kV 500-700 k€/km
Portugal	• 380 kV 400-500 k€/km	• 380 kV 500-600 k€/km
Poland	• 380 kV 400-500 k€/km	• 380 kV 900-1000 k€/km
Spain	• 380 kV 400-600 k€/km	• 380 kV 600-800 k€/km
Estonia	• 330 kV 200-300 k€/km	• 330 kV 300-400 k€/km
Lithuania	• 330 kV 300-400 k€/km	
Belgium		• 380 kV 1000-1200 k€/km • advanced, 380 kV 2300-2500 k€/km
Albania	• 400 kV 250-300 k€/km • 220 kV 100-150 k€/km	
Malta	• 132 kV 150-200 k€/km	
Sweden	• 400 kV 400-500 k€/km • 220 kV 200-300 k€/km	• 400 kV 500-700 k€/km
Romania		• 400 kV 300-500 k€/km
FYROM	• 400 kV 200-300 k€/km • 220 kV 100-150 k€/km	
Bulgaria	• 400 kV 300-400 k€/km	
Czech Rep.	• 400 kV 600-800 k€/km	• 400 kV 1000-1100 k€/km
Norway	• 420 kV 700-1100 k€/km	
Bosnia-Herzegovina	• 400 kV 200-300 k€/km	
Denmark		• 400 kV 1000-1200 k€/km • advanced, 400 kV 2000-2200 k€/km
Greece	• 400 kV 300-400 k€/km	
Slovakia		• 400 kV 800-1100 k€/km
Hungary	• 400 kV 300-400 k€/km	• 400 kV 500-650 k€/km
Croatia		• 400 kV 500-600 k€/km
Slovenia		• 400 kV 700-900 k€/km
Serbia	• 400 kV 200-300 k€/km	
Montenegro	• 400 kV 250-350 k€/km	
Cyprus	• 132 kV 50-100 k€/km	• 220 kV 200-250 k€/km
Iceland	• 132 kV 200-250 k€/km	
Ukraine	• 750 kV 500-600 k€/km • 330 kV 200-250 k€/km	

The data set displayed is supplemented by the German study of BET[15], cf. ref. [15]. This study compares in particular the option of intermediate partial cabling with regard to OHL and provides recommendations for grid planners based on a comparison of capital costs, energy loss costs and bottleneck costs over the whole

[15] Büro für Energiewirtschaft und technische Planung GmBh

life time of the assets. We have in particular retained the assumptions set on overhead lines (for a line of 68 km length) to complement the data of the above table.

The Grid deployment Plan in Germany (2013) [1] allows some comparison for the reference data of double circuit OHL. These costs are consistent the ones used by BET [15], cf. Table 20.

Table 20: Complementary data on investment costs of overhead lines in Germany [15] [1]

	Average reference values for OHL (double circuit)
BET (Germany) [15]	2X4X265/35[16] 750 k€/km; 2X4X385/35 850 k€/km; 2X4X560/50 1400 k€/km
Grid Deployment Plan (Germany) [1]	• 380-kV New construction in existing line double line or 380-kV- New double-circuit line: 1400 k€/km • Compensation systems: 380-kV-SVC 3,2 M€/piece 100 Mvar variable compensation (w/o switching field)

Here, it should be pointed out that the differences in costs of Table 19 might not specifically depend on the labour costs in the given country but also on the terrain (example Sweden where the total costs are low probably as a result of terrain conditions, even though labour costs are very high compared to other EC countries), and the transmitted power. This latter data, which is not specified in Table 19, is of paramount importance. This can be clearly seen in Table 20 where costs are directly related to section area and thus to transmitted power (cf. the conductor size for the first line of the table where a doubling in conductor size roughly gives a doubling in total costs).

A more recent source from National Grid, UK [11] gives a range of 1570 to 1990 £k/km as a cost per route for a 400 kV double circuit (HVAC OHL).

Another complementary source has been used as a sanity check to fix the assumptions for the OHL case study: the US WREZ project for the Western Governors Association [2]. Again the set of data appears consistent. In the same source, a simple model is presented to estimate the capital cost per unit length (km) for some of the key specificities impacting the transmission line design, e.g. the conductor type, the structure, the length of the line.

Table 21**:** Average reference values of Overhead lines in the US [2]

Voltage	Base line for an OHL single circuit ACSR conductor, line longer than 16 km, tubular or lattice pole structure (2008 values; EUR/USD=1,35)	Base line for an OHL double circuit (same assumptions)
230 kV	• 426 k€/km	• 683 k€/km
345 kV	• 598 k€/km	• 956 k€/km
500 kV	• 853 k€/km	• 1365 k€/km

Table 19 to Table 21 present costs as a function of the voltage level, the number of circuits, and the location (country). As mentioned above, other factors are of importance such as the type of conductors, the transmitted power, and the terrain. It is not straightforward to present this multifactor dependence: Table 22 and Table 23 give possible multipliers when considering, for a given OHL variant, different terrains, distances and conductor types (the unit value -1- corresponds to the base line while the multiplicative factor helps computing the costs taking into account the unit costs of the base line).

Table 22: Average reference ratio for Overhead lines [2]

	230 kV single	230 kV double	345 kV single	345 kV double	500 kV single	500 kV double
Aluminium Conductor, Steel Reinforced (ACSR)	1	1	1	1	1	1
Aluminium Conductor, Steel Supported (ACSS)	1,08	1,08	1,08	1,08	1,08	1,08
High Tensile Low Sag (HTLS)	3,6	3,6	3,6	3,6	3,6	3,6
Lattice	0,9	0,9	1	1	1	1

[16] 4 x 560/50: 4 stands for the number of conductors for each bundle (i.e. 4 conductor bundle). The numerical values "560" and "50" indicate the areas of the aluminum conductor and the core, respectively (which allow to calculate the diameter of the conductor). The diameter of a conductor and the numbers of conductor defines the maximum applied voltage.

Tubular Steel	1	1	1,3	1,3	1,5	1,5
Length >16 km	1	1	1	1	1	1
Length 5-16 km	1,2	1,2	1,2	1,2	1,2	1,2
Length < 5km	1,5	1,5	1,5	1,5	1,5	1,5

Table 23: Terrain cost multipliers for overhead lines in different installation contexts [2] [5] [6] [10]

Terrain nature	**400 kV single**	**400 kV double**	**225 kV double**	**Sources**
Rural plain	1	1	1	Cigre 2006 [10]
Urban plain	1,38	1,38	1,39	
Mountain[17]	2,15	2,05	2,15	
Rolling hill (2-8% slope)	1,30 to 1,4			PG&E, SCE
Rolling hill (>8% slope)	1,50 to 2			PG&E, SCE, SDG&E
Suburban	1,20 to 1,33			PG&E, SCE, SDG&E
Urban	1,15 to 1,67			PG&E, SCE, WREZ
Hilly landscape	1,2			REALISEGRID [5] [6]
Mountain of urban area	1,5			REALISEGRID [5] [6]

At last, Table 24[18] displays other multipliers for the voltage level, the number of circuits, the number of conductor per bundle and the type of conductor.

Table 24. Multipliers for the overall costs of AC OHL.

Multiplier for higher voltages (from 400 kV to 750 kV)	1.63
Multiplier for higher voltages (from 400 kV to 550 kV)	1.25
Multiplier from double to single circuit	2/3
Multiplier for from 4 to 3 conductor bundle	3/4
Multiplier type of conductor (AAAC to ACSS)	1.25

The multifactor analysis displayed in the above tables (voltage level, terrain, country, etc.) shows that significant ranges can be observed for CAPEX of HVAC OHL. As a result, the choice of the technology variant for a given environment is key when attempting to appraise the future costs. It is thus proposed to define reference technology variants in their associated environment with a tentative level of costs, in order to carry out the dry-run test.

In the following, the text highlighted in blue frames will depict the tentative assumptions needed to carry out the dry-run exercise on HVAC OHL before proposing a final methodology for key transmission technologies in section 5.10. These assumptions concern both the starting point (costs at 2013 based on recent sources) and the evolution laws 2013/2014 to 2050. At this stage it could be observed that the construction of an OHL in an urban area in Europe may face major public acceptance barriers. These four installation types (and especially installation 3 and 4) have therefore to be considered as theoretical extreme configurations to carry out this dry-run test.

Assumption 1. The assumptions retained for the unit costs at 2013 for the HVAC OHL dry-run test are given for four installations (with different values for the transmitted power):

- OHL double circuit operated at 380 kV: 750 k€/km for installation 2 and 1200 k€/km for installation 1 (rural area respectively in Southern and Northern Europe)
- OHL double circuit operated at 380 kV: 1030 k€/km for installation 4 and 1650 k€/km for installation 3 (urban area respectively in Southern and Northern Europe)[19]

[17] In the AC OHL TAR, a multiplier of 1.7 is given. Costs for OHL are most of the time computed for a distance corresponding to a beeline. As a matter of fact, a coefficient of 1.2 should be applied to the value given in the TAR in order to account for the real length of the line due to the terrain, i.e. 1.7 x 1.2 ~ 2 (which is line with the values given in the table).

[18] Data extracted from the AC OHL TAR (RTE).

[19] We have used a ratio of 1.38 as recommended in reference [10] to compute the effect of changing the context into "urban plain". In the same way, the ratio of 2.15 upon the investment cost in a flat rural plain should be used if one considers a fifth installation in

5.2.2 Identifying the main components of the costs

Several sources detail the cost component of a new OHL as function of different environments (country, terrain, conductor type, etc.). In the present work, it is assumed that the cost components are:

- equipment costs,
- installation costs,
- civil works costs,
- project management costs,
- authorizations costs and rights of way costs.

As explained above, these costs components should be a function of several factors, i.e. the terrain, the voltage, the type of conductors, etc. Table 25 shows costs components a function of the terrain. As expected, it is observed that the share for equipment costs (in % of the total investment cost) is lower for more complex installations, i.e. civil works increase with increasing complexity of the terrain.

Table 25: Typical breakdown of cost components of overhead lines in different installation contexts [10]

Terrain	Rural plain	Urban plain	Mountain
Equipment	34%	29%	25%
Installation	33%	35%	38%
Civil works	8%	9%	16%
Project Management	15%	15%	16%
Authorizations	7%	8%	3%
Rights of Way	3%	5%	1%

Typical ranges of the share of equipment ratio are taken at 25% for a line in a mountainous area and 34% in a rural, flat area. As a consequence:

Assumption 2. For the dry-run exercise on HVAC OHL on the share of equipment with regard to the total investment costs, the following assumptions are made:

- For both installation 1 and 2 (rural plain), the retained ratio of equipment is 34% (of the total investment cost)
- For both installation 3 and 4 (urban plain), the retained ratio of equipment is 29% (of the total investment cost)[20]

5.2.3 Evolution laws for each component

Modelling the evolution in time of cost components is the most difficult step since it should capture or simplify the forecast uncertainty induced by the distance to a remote time horizon. As already indicated, the proposed approach aims at proposing a simple evolution law for cost components: this simple approach should reflect likely evolutions within a given confidence interval.

Three types of costs components should be distinguished with regard to evolution laws:

- cost components highly dependent on local constraints requiring a spatial analysis (terrain, country),
- cost components highly dependent on factors for which forecasts at a long-term time horizon remain difficult due to a disruptive event (external factor or disruptive technology),
- cost components for which evolution laws for the next decades could be built based upon basic assumptions under uncertainty margins.

a mountain-type context. The US sources mentioned in the table "terrain cost multipliers" are detailed in the 2012 Black & Veatch report for WECC [2].

[20] With the observation that due to public acceptance issues in Europe in urban context, installation 3 and 4 have to be considered as theoretical case and not as a prescriptive solution for an OHL (see sections on underground cables and on partial undergrounding)

For the sake of simplicity, and in order to come up with a methodology which remains tractable, assumptions for drafting evolution laws of the costs components for the next decades are necessary. The following assumptions have been made:

- no disruptive change in the macro-economic context (geopolitical instability, major economic crisis, no force majeure event),
- evolution laws of rights of way and authorizations will depend on local constraints. This cost component, representing 4-10% of the overall costs [10], is excluded from the present analysis (i.e. no evolution law),
- evolution laws of installation, civil works and project management will mainly depend on future evolutions of energy and labor costs.
- There is a continuity in the technological evolution. The long-term trend for the future will thus result from the recent past trend and take into account a classical technology learning curve[21]. Such an assumption has some limitations on the short term-fluctuations that might create some bias but we assume that for long-term time horizons these short term fluctuations will be averaged.
- Evolution laws of equipment (1): since transmission equipment (and especially lines and cables) include raw materials (e.g. aluminum, copper), long-term trends of commodity prices should be considered.
- Evolution laws of equipment (2): a technology experience curve approach (assuming no disruptive technology) can be applied.

Based on the above hypotheses, an analysis (dry-run test) of the expected evolutions of each cost component is carried out. Then, for each cost component, a methodology is proposed to estimate the trajectories in time (evolution laws) of each cost component, cf. Table 26. In this analysis, typical ranges for the equipment cost component are 25% for an OHL in a mountainous area and 34% in a rural, flat area.

Table 26: Factors impacting each investment cost component of overhead lines

Cost component	Factors likely to impact costs	Expected evolutions until 2050	Proposed index and model
Equipment	Experience curve of the transmission system based on maturity (excluding costs of raw material)	Experience curve of technology will reduce cost of equipment according to a decreasing exponential law	The progress ratio (PR)[22] of the technology determines the exponential decrease. For this dry-run test, a PR of 90% and a doubling of cumulative production every 20 years have been assumed.
	Price of commodities (steel, aluminum, zinc, etc.)	Price of metals is expected to increase following the trend observed in the recent years	Commodity indexes: based on recent evolutions, a strong increase until 2020 is assumed, then a slower evolution (+0.5%/year over the 2020-2050 period)
Installation	Labor cost	A slow but steady reduction of labor cost is assumed. The high variability of labor cost according to the countries should be mentioned.	Labor index for the sector: linear extrapolation based on recent trends
	Cost of energy	See World Bank data on evolutions for some commodities (until 2025). On	Oil index: 120 USD/bbl at 2020 and a strong increase +1.5%/y base 2020 over the 2020-2050 period

[21] The "learning curve" approach describes how marginal labor costs decline with cumulative production. The "experience curve" generalizes the labor productivity learning curve by including all costs necessary to research, develop, produce and market a given product. The general form of the experience curve is a power curve defined with a progress ratio $PR=2^{-b}$, where b is the learning coefficient. Thus, for each doubling of cumulative production, the marginal cost decreases by (1-PR). For example with a PR of 90%, doubling of cumulative production within 20 years implies a 10% reduction in marginal cost. It should be noted that the "classical experience curve" includes "all costs necessary to…": in our study we have separated two effects (the industrial product and the raw material due to its importance for transmission equipment).

[22] See previous footnote.

		a longer run the cost of energy is expected to increase.	
Civil works	As above (installation). The relative ratio, labor cost/energy, should be different	As above (installation).	As above (installation).
Project Management	Skilled labor costs	Slow steady increase due to the scarcity of skilled engineers	Engineering index : a linear evolution based on recent trends has been assumed
Authorizations	Local constraints	No estimation in this component	Flat model
Rights of Way	Local factors		

Assumption 3. Thus, based upon the analysis of Table 26, the following approach for the evolution laws is proposed for three categories of indices:

- Labor cost and engineering: linear evolution law based on recent evolutions (last 10 years), in Figure 11 below (grey cells).
- Progress ratio: progress ratio defining the level of the exponential decrease reflecting the experience curve gained by industry in the related offer (product and services) and commodity price indices (metals) in orange color Figure 11 below (orange cell).
- Commodity price indices: evolution laws based on commodity price indices including metals and energy needs Figure 11 below (pink cells).

Figure 11: Breakdown of cost components in indices and type of model of time evolution for each category of indices

Indices		Type of model
LAB	Personnel costs	Linear based on recent trends
ENG		
OIL	Commodity: energy / metal	Linear evolutions based on recent trends for the short term (until 2020). Ad hoc assumptions beyond.
METAL		
EXP	"Experience-based curve" on the product/system excluding material	Estimation of a progress ratio or use of dropping rates from previous similar studies (IRENE40)
L/Z	Depending on Local or Zonal factors	N/A

5.2.4 Aggregating the costs

The final step results in the aggregation per time period of each cost component by resorting to the evolution laws proposed in the previous sub-section. This aggregation exercise is supplemented by an estimation of the uncertainty, i.e. by a min-max interval (confidence interval) taking into account the uncertainties on the current cost breakdown and the future estimated indices. The indices for each time period are detailed in the table below.

Table 27: Tentative quantification of cost components of overhead lines

Cost component	Cost in 2013 k€/km	2014	2020	2030	2040	2050
Interval range		±10%	± 15%	± 20%	± 25%	±30%

Equipment	**34%** of 750 k€/km for installation 2 and 1200 k€/km for installation 1 *** **29%** of 1030 k€/km for installation 4 and 1650 k€/km for installation 3	Linear combination of: * EXP: 96,9 [23] * ALU: 1800[24]	Linear combination of: *EXP 94,9 *ALU: 2014	Linear combination of: *EXP 90 *ALU: 2149	Linear combination of: *EXP 85,4 *ALU: 2259	Linear combination of: *EXP 81 *ALU: 2374
Installation	**33-35%** of investment cost according to nature of terrain	Linear combination of *LAB: 100 [25] *OIL 105 [26]	Linear combination of *LAB: 98 *OIL: 120	Linear combination of *LAB: 95 *OIL: 139	Linear combination of *LAB: 92 *OIL: 162	Linear combination of *LAB: 89 *OIL: 188
Civil works	**8-9%** of investment cost according to nature of terrain					
Project Management	**15%** of investment cost	ENG: 100 [27]	ENG: 117	ENG: 137	ENG: 158	ENG: 178
Authorisations & Right of Way	**10-13%** according to nature of terrain	No estimation in this component: “flat” assumption				

The evolution laws of the above mentioned indices are not contextualized per scenario. The proposed evolutions are identical for the five e-Highway2050 scenarios, this is why a rather large confidence interval (±30% at 2050) has been kept for the 2050 figures.

The results of the computations of the dry-run test are displayed in Tables 28 for installations 1 and 3 as an example.

The computations for high temperature conductors could be easily derived using the multiplier factor given in Table 22 for ACSS and HTLS conductors.

All analyses carried so far are relevant for CAPEX. For OPEX, a level of O&M (Operation and Maintenance) costs has been appraised using a reference value of 2% of the CAPEX for annual expenses. Reference [16] suggests for annual O&M expenses an annual cost of 1% of the CAPEX while source [6] suggests a higher level of operation and maintenance for HVAC OHL in the range of 1.5 to 5% of the CAPEX.

5.2.5 Discussion on the limitations of the proposed approach

The dry-run test carried out so far, i.e. sections 5.2.1 to 5.2.4, suggest that more than half of the CAPEX of an overhead line is the sum of installation, civil works, authorization and right of ways costs, which are highly dependent on local factors (land use, nature of terrain, labor and energy costs in the considered country). The variability resulting from such factors, when setting up the starting point, is more important than that coming out of the tentative evolution laws formulated to grasp likely evolutions of averaged indices over the next decades.

As an example, there is a ratio of 2.2 when comparing the 1650 k€/km for installation 3 (urban area, Northern Europe) to the 750 k€/km for installation 2 (rural area in Southern Europe) whereas the cost variation over time is of the order of magnitude of 20 to 30%. Three observations are made upon these results on the long term prices of considered commodities, on the sensitivity to experience curves index and on the importance of local considerations and of a “space factor”.

[23] Experience curve index EXP 96,9 (base 100 in 2010)
[24] Commodity index for conductor is Aluminum (ALU): 1800
[25] Labor cost index: base 100 in 2010. Evolution is based on linear extrapolations based on recent trends
[26] Commodity index for energy is the price of crude oil (avg. spot): 105
[27] Index for engineering: 105. Evolution is based on linear extrapolations based on recent trends

Tables 28: Examples of cost evolutions for an overhead line, double circuit operated at 380 kV in 2 different configurations (country and terrain)

1200	k€/km				0,9	1,1			0,85	1,15		0,8	1,2		0,75	1,25		0,7	1,3
Breakdown per component		costs for each component			k€/km 2013		indexes		k€/km 2020			k€/km 2030			k€/km /km 2040			k€/km /km 2050	
Key components	**%**	**Labor**	**Commodity**	**Experience**	**min**	**max**		index	**min**	**max**	index	**min**	**max**	index	**min**	**max**	index	**min**	**max**
Equipment	**34%**		**50%**	**50%**	367	449			341	462		318	477		300	499		282	523
							EXP	0,97			0,95			0,85			0,81		
							ALU	1,00			1,00			1,10			1,16		
Installation	**33%**	**60%**	**40%**		356	436			352	476		349	523		347	578		346	643
							LAB	0,98			0,95			0,92			0,89		
							OIL	1,14			1,33			1,54			1,79		
Civil works	**8%**	**50%**	**50%**		86	106			87	117		87	131		89	148		90	167
							LAB	0,98			0,95			0,92			0,89		
							OIL	1,14			1,33			1,54			1,79		
Project Managnt	**15%**	**100%**			162	198	ENG	1,17	178	241	1,37	198	296	1,58	213	355	1,78	225	418
Authorization and Right of Ways	**10%**				108	132	N/A	1,00	102	138		96	144		90	150		84	156
CAPEX (k€/km)	**100%**				**1080**	**1320**			**1060**	**1434**		**1048**	**1572**		**1038**	**1731**		**1027**	**1907**
OPEX (p.a.)	**2,0%**				**22**	**26**			**21**	**29**		**21**	**31**		**21**	**35**		**21**	**38**

1656	k€/km				0,9	1,1			0,85	1,15		0,8	1,2		0,75	1,25		0,7	1,3
Breakdown per component		costs for each component			k€/km 2013		indexes		k€/km 2020			k€/km 2030			k€/km 2040			k€/km 2050	
Key components	**%**	**Labor**	**Commodity**	**Experience**	**min**	**max**		index	**min**	**max**	index	**min**	**max**	index	**min**	**max**	index	**min**	**max**
Equipment	**29%**		**50%**	**50%**	432	528			402	544		374	562		353	588		331	615
							EXP	0,97			0,95			0,85			0,81		
							ALU	1,00			1,00			1,10			1,16		
Installation	**34%**	**60%**	**40%**		507	619			500	677		496	744		493	822		493	915
							LAB	0,98			0,95			0,92			0,89		
							OIL	1,14			1,33			1,54			1,79		
Civil works	**9%**	**50%**	**50%**		134	164			134	182		136	204		138	229		140	260
							LAB	0,98			0,95			0,92			0,89		
							OIL	1,14			1,33			1,54			1,79		
Project Managnt	**15%**	**100%**			224	273	ENG	1,17	246	333	1,37	273	409	1,58	294	490	1,78	310	576
Authorization and Right of Ways	**13%**				194	237	N/A	1,00	183	248		172	258		161	269		151	280
CAPEX (k€/km)	**100%**				**1490**	**1822**			**1465**	**1983**		**1451**	**2176**		**1439**	**2399**		**1425**	**2646**
OPEX (p.a.)	**2,0%**				**30**	**36**			**29**	**40**		**29**	**44**		**29**	**48**		**28**	**53**

- **Issue 1: long term prices of considered commodities**

The proposed methodology to build cost trajectories based on the evolution laws of indices is relevant for short to mid-term prediction forecasts of equipment for which the time uncertainty factor remains limited. Indeed the estimations on long-term prices of commodities (on metals and even more on energy) are largely dependent on exogenous factors so that any quantitative projection beyond 2025 remains difficult (2025 is the time horizon set by the World Bank in its Commodities Price forecast edition [38]). As an illustration, when consulting two successive releases of the World Bank Commodities Price forecast edition for aluminium, issued in 2013 and in 2014, for the trend until 2025, significant differences are observed on the rates (see [38] and [39]).

The above statement is confirmed by the available literature on long-term prices of primary commodities. Several authors have examined the properties of secular time series of commodities including in particular the ones that are relevant for e-Highway2050 (e.g. oil, aluminium, copper and zinc). The classical hypothesis known as the Prebish-Singer (PS) hypothesis and formulated in the 50s claims that such prices present a downward secular trend.

The PB hypothesis has been re-examined by recent studies due to the current uprising trends on commodity prices [36] [37]. These studies reassess the evidence for a long-run trend in primary commodity prices based on the commonly used Grilli-Yang data set of commodity prices time series. Reference [36] confirms that major commodities show robust evidence of long-run decline confirming thus the PB hypothesis (ind. aluminium and zinc) whereas for others (among them copper, nickel and oil) no significant trend was detected over the considered period. More recently, models based on piecewise linear trends for 25 commodities (and among them aluminium and copper) were elaborated [34]. This model identifies consecutive time periods upon which a linear trend of commodity price evolution is relevant. A slope was then defined for each commodity and for aggregate commodity prices. Over the period 1900-2010, the slopes of the estimated piecewise linear trends for the commodity price index for metals (based on the Grilli Yang data set) are split in four time periods: -1.81 from 1900-1946; 0.42 from 1946 to 1972; -0.9 from 1972 to 2000 and 3.33 from 2000 to 2010.

The UN-DESA working paper [35] formulates the possibility of super-cycles of 30-40 years during the 1865-2009 period, with amplitudes in the range of 20-40% higher or lower than the long-run trends. Four super-cycles with a correlation of non-oil commodity prices with world GDP, while real oil prices follow a long term upward trend interrupted temporality during the 20th century, cf. Figure 12 next page.

More particularly, real commodity prices trended very slightly upwards from 1865 to the mid 1910s, trended downward until late 1990s, and then trended upward again through the end of the sample. Metal prices follow the same general pattern (increase, decrease, increase) with minor differences. They have entered a downward trend earlier (breakdown year 1881) until the mid-1970s with an annual compound growth estimated at -0.7%, a rapid rise at about +1%/year is estimated for the recent period 1974-2010, cf. Table 29. The existence of these four long-term cycles and the observation that for non-oil commodities the mean of each super-cycle has a tendency to be lower than that of the previous cycle, is a confirmation of the PB hypothesis. The figure and the table below illustrate findings of [35] useful for any tentative estimation of evolution laws of commodity related indices for e-Highway2050.

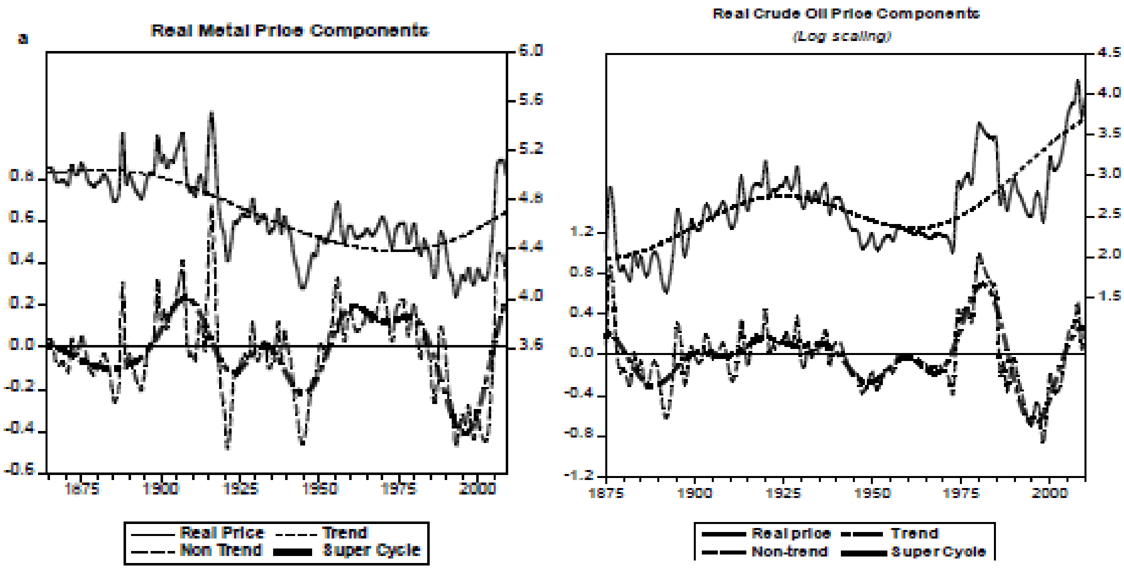


Figure 12: Real price decompositions for metals and crude oil into a long term trend, super cycle and short term cycle components [35]

In Figure 12, the actual real price are in the upper curve of the graph (real price and long term trend in a log scale on the right hand side of each graph). The long-term general pattern “up”, “down”, “up” appears clearly. In the bottom of the figure the non-trend component (difference of the actual time series and the trend) is represented. One could observe the cyclical fluctuations in the range of 40% maximum deviation from the long term range (left scale).

Table 29: Descriptive statistics of the long-term trends in some real commodity prices [35]

	Upward trend	Downward trend	Upward trend
Periods for metal prices	**1865-1881**	**1881-1974**	**1974-2010**
Annual compound growth rate	0.1%	-0.7%	1.0%
Cumulative growth rate	1.7%	-48.2%	43.8%
Duration (years)	16	93	36
Periods for crude oil prices	**1875-1925**	**1925-1962**	**1962-2010**
Annual compound growth rate	1.5%	-1.1%	2.8%
Cumulative growth rate	114.2%	-32.5%	280.0%
Duration (years)	50	37	48

Finally to focus on some particular commodities relevant for our project, Figure 13 illustrate the piece wise linear trends over the period 1900-2010 for a selection of metals as estimated by [36].

- **<u>Issue 2: sensitivity to experience curves index</u>**

The model on experience curve of the above described OHL case has been built upon the qualitative analysis and assumptions of Table 26 (i.e. a PR of 90% and a doubling of cumulative production every 20 years). This assumption may be considered as optimistic but one should have in mind that a forecast error of say 20% on the experience curve index (EXP) in 2040 or 2050 will in fact impact the CAPEX of the OHL by less than 3% (20% * half of the 29%, cf. Table 30 next page -extract of Tables 28-). This shed in light the rather low sensitivity of such factor in the total cost[28].

[28] The assumption of 50/50 for the respective component of the main commodity and of the experience index for the transmission equipment could be further fine-tuned for each type of equipment but the main conclusions on its low sensitivity remains valid due to the 29% share of equipment (urban area) and 34% for rural area.

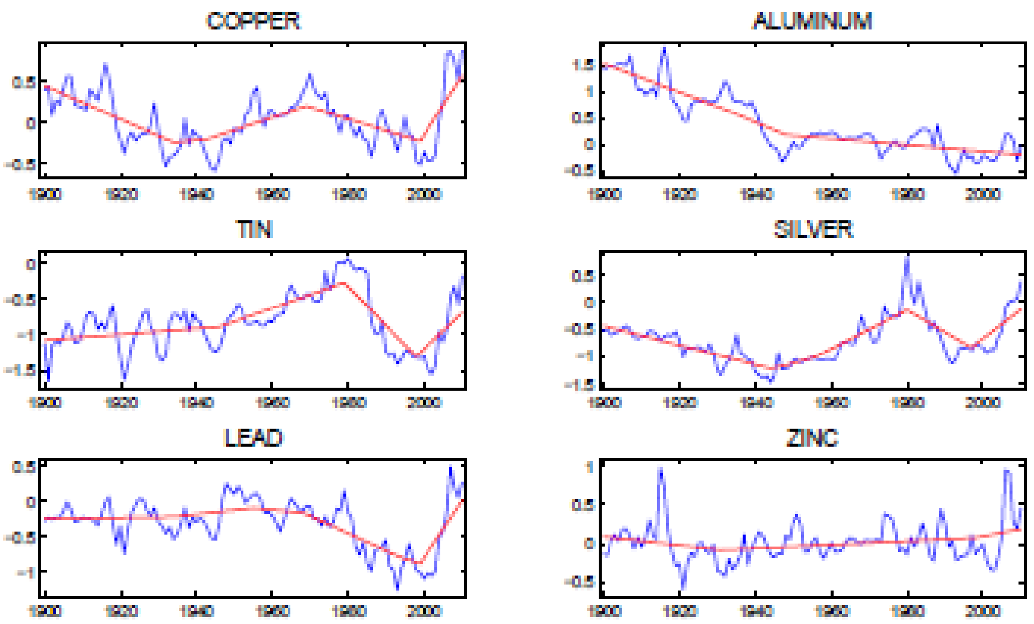


Figure 13: Primary commodity prices and their piece wise linear trends over the period 1900-2010 for a selection of metals [36]

Table 30: Sensitivity of a forecast error on an index for the OHL studied case (urban area)

Breakdown per component		Breakdown per nature of costs for each component		
Key components	**% investment cost**	**Labor**	**Commodity: materials and energy**	**System: Experience curve**
Equipment	**29%**		**50%**	**50%**

Here we should mention the IRENE40 project and its particular focus on technology forecast methodology. In deliverable D2.2 [8] issued in 2010, a dedicated methodology to forecast future costs of key transmission system has been elaborated according to their current maturity levels. The approach does not detail price commodity evolutions, nor installation and engineering costs but provides directly an integrated approach for costs at 2020, 30, 40, 50 for the following technologies based on a collection of reference data:

- HVDC: back to back, OHL, submarine cable
- FACTS: SVC, STATCOM and TCSC.
- HVAC: OHL single circuit, Cable, transformers.

In addition performance forecast for OHL, transformers, cables and HVDC efficiency levels (LCC/VSC) are detailed, cf. pages 108-114. The value of the IRENE40 approach has two dimensions:

- its direct nature allowing to get experience curve indices at 2020, 30, 40, 50 time horizons for a given equipment (integrating our two indices related to experience curve and commodity prices),
- the nature of the consortium including manufacturers and well-known academics.

- **Issue 3: importance of local considerations and the "special factor"**

When observing the outputs of the computations of the proposed dry-run tests, cf. Tables 28, and the high country dispersion of costs as shown in Table 19, it appears that the local factors will have a significant impact on the total costs (starting point) and in turn in the its cost evolution. This local factor has somehow to be taken into account when building the cost evolutions over the period 2013-2050. To that purpose it is of paramount importance to pay attention to the archetypal technology and installation configurations to be retained as a starting point (2013 data in technology features and costs).

Contrarily to issue 2, the sensitivity of a 20% error or bias in the 2013 data will be totally and directly impacted to all following decades (2020; 2030; 2040; 2050). To that purpose, a space index factor representative of the local context could be used. A country wise approach has been presented in [10] and reported in Table 31. It results from a "cost unit approach" detailing costs of transmission equipment in a non-dimensional scale upon which a cost unit value is applied, depending on the country in Europe. The table has been built with a value of 10 Euros the unit cost for Italy as reference by analysing a report[29] for DG TREN/EC by ICF.

Table 31: Cost unit values for a double circuit 400 kV OHL constructed in different countries [10]

Country	Value of the Cost Unit (€)	Specific cost factors
Finland, Sweden	6	Flat land (fewer towers)
Greece, Portugal	6	Low costs (land, labour)
Denmark, Norway, Spain	8	N/A
Belgium, Netherlands, Italy	10	Heavily populated
France, Germany	12	Heavily populated ; high labour cost
UK (England & Wales)	16	"n-2" standard applied and more towers/.km high right-of-way costs; heavily populated
Austria, Switzerland	16	High environmental issues; topography; high wind pressure limits; high labour costs
NB : the effect of the land condition on the line costs for the different countries is not captured		

The above table provides further information regarding assumption 1 where a ratio of 1.6 has been assumed between Northern and Southern Europe. If needed, Europe could be split in more than two areas (Southern and Northern Europe) according to e.g. Table 31.

5.2.6 Recommendations on cost trajectories construction for the e-Highway2050 project

Based on the dry-run test carried out so far (for the AC OHL), the recommendations for the evaluation of the cost of technologies are the following:

- TSO and manufacturers should first agree on the archetypal technology variants of transmission equipment, for instance the candidate reinforcements for HVAC and/or HVDC OHL and/or cables (with the relevant categories of power and voltage ratings).
- The geographical factor (mainly terrain) whose variability in Europe has a major impact on costs should be taken into account: some elements have been given in the present section.
- Time evolution of cost trajectories can be modeled with a strong confidence for the next 10-15 years by the methodology detailed in the present section (and applied in the case of OHL), i.e. the breakdown of costs in five distinct components (equipment, installation, civil work, project management and authorizations & right of ways) whose evolution can be predicted thanks to forecasts of few indices (commodity index in energy, metals, cost index of labor and cost index of engineering and experience curve of a family of product in industry).
- Short to mid-term qualitative evolutions of the series of driving indices have been made and it appears that their effects are compensating each other. The expected short to mid-term evolutions of the considered indices are: "up" for commodities on price and energy, "down" for labor cost, "up" for engineering index and "down" again for the experience curve due to the increasing maturity of the considered transmission technologies.
- The costs are at first analysis independent to the five e-Highway2050 scenarios.
- Beyond a mid-term time horizon (2025-2030), the increased level of uncertainty suggests a much simpler approach by assuming a rather flat evolution of prices for equipment cost component over the period 2025-2050 beyond the predictability horizon of costs which could be assumed by such an approach. This

[29] "Unit costs of constructing new transmission assets at 380 kV within the European Union, Norway and Switzerland" Final Report October 2002 prepared for the DG TREN/European Commission study by ICF Consulting Ltd.

is also the approach followed by a key reference output of IRENE40 on simple evolution laws of transmission equipment (see the deliverable on technology database and technological development forecast methodology [8] developed by manufacturers and academics).

Therefore the two key factors for using the gathered data on costs of transmission are:
- the validation by manufacturers and TSO of the archetypal configuration to be retained for each transmission requirements (lines, cables, converters, transformers, FACTS, etc.)
- the geographic factor (mainly terrain) impacting both the complexity of installation, the labor costs and engineering costs.

As a consequence, in the following sections, the focus has been made on the data gathering of costs of typical transmission systems as reported in recent studies as of today. Evolutions laws for some key components are synthetized taking also account the IRENE40 outputs (see section 5.8).

5.3 Underground cables (HVAC)

Based on the above conclusions of the case study on HVAC OHL, a similar approach could be implemented for underground insulated cables (UGC) operated in High Voltage AC. As explained above, the data gathering process of cost of cables at 2013 from public sources is a critical step (starting point).

It is proposed to use the data of R. Benato, 2012 in Electra N°265 [16] and to cross check the obtained values and ratios with other sources. The study compares the overall whole life cycle costs of OHL and UGC. In this work, the technology variant identified as representative and relevant for e-Highway2050 is the following:

- underground XLPE cables, nominal voltage 380 kV, double circuit, cross section 2500 mm^2; resistance at 90°C (50Hz) 13.3 $m\Omega$/km; inductance 0.576 mH/km; shunt leakance (50Hz) with tanδ=0,0007 is 51.5 nS/km; capacitance 0.234 μF/km (with ε_r=2,3);
- Installation site: total undergrounding in a flat land area (non-urban);
- Length of 25 km[30];
- Financial assumptions: 40-year project duration, discount rate at 5%.

In this section, attention is focused on HVAC full undergrounding solutions. However, data related to costs of partial undergrounding solutions, complementing overhead line projects in sensitive areas, are discussed in subsection 5.3.4.

5.3.1 Costs of the technology variant as of 2013 and main components

Data on breakdown of costs of fully undergrounded cable installations have been extracted from reference [16]: the data represents mean reference values resulting from world-wide industry surveys. The study distinguishes the following cost components:

- Capital costs and underground cable shunt compensation investment[31];
- Energy losses costs;
- Burden on territory;
- Dismantling costs;
- Operation and maintenance costs.

The reference values for the overall costs are the following for the double circuit UGC [16]:

[30] Thanks to an inductive shunt compensation length of over 25 km can be achieved. Here the 25-km length corresponds to the project under scrutiny.

[31] Main components for capital costs and UGC compensation include cost of acquisition of rights of way and of further portions of land; costs of purchase of equipment components; costs of transportation of materials; costs of civil and electrical works on site for installation of equipment; cost of civil works (excavation, trench); costs for swathe reinstatement after works; engineering cost; project management costs and other contingency costs; costs for provision of reactive power compensation for long distance UGC [16].

- CAPEX is 3.5 M€/km for the cable and 6 M€ for the two 150 MVAR shunt reactors needed at each end station for compensation (i.e. an additional 0.24 M€/km when assuming a 25 km length);
- Energy losses per unit length are estimated at 0.594 M€/km;
- Burden on territory is clearly dependent on the economic value of the corridor. For an 18-meter wide corridor, an estimation[32] of $0.018*w_x$ is given. Unit is M€/km;
- Main reference value for O&M yearly costs is 0.1% of initial investment. The present value of the sum of such expenses over the project life time is estimated at 0.035 M€/km;
- Decommissioning costs are calculated based on the assumption that end of life costs sum up to about 5% of the initial investment[33]. The calculation of the costs discounted to the present time (40 years; 5%) yields 0.0265 M€/km;
- The level of repair costs of an HV XLPE cable is low due to its high reliability and is estimated at 0.03 M€/km (mainly due to the shunt compensation equipment).

Under these hypothesis, the overall cost discounted to the present time per unit length for such an XLPE HV underground cable is estimated in M€/km at $4.4255+0.018*w_x$. With a land economic value at 32€/m2, the estimated overall cost is about 5 M€/km (while initial investment cost is 3.5 M€/km) which shows a 1.43 factor from initial investment to total cost over project life time (40 years; 5%) under the conditions of the proposed case study [16]. Table 32 summarizes the total costs over project life time (40 years).

Table 32: Typical breakdown of overall costs of a fully undergrounded HV XLPE Cable double circuit, 380 kV, 2500 mm^2 [16]

	Total costs over project life time (M€/km)	Base initial investment I0	Comments
Initial investment (I0)	3,5	100	Excluding land costs.
Ishunt	0,24	6,9	Due to reactive compensation needed for HVAC cables over long distance.
Energy losses	0,594	17	Cost of energy losses represents a significant component in lifetime operational costs.
Territory	0,576	16,5	Assuming a land economic value fixed at 32€/m^2, this amount is however highly dependent on local conditions.
Decommissioning	0,0265	0,8	Appears as negligible at the first order.
O&M	0,035	1	This estimation appears as underestimated when considering other sources. The retained value was 2% of initial investment of equipment.
Repair	0,03	0,9	Low level due to the high reliability of HV XLPE cable.
Total	**5,00**	**142,9**	

5.3.2 Sanity check with other sources

A very first cross-check could be done with actual recent HVAC Cable projects aiming at grid infrastructure reinforcement. Table 33 next page presents an overview of such projects based on a compilation of manufacturers news[34]

[32] w_x is the economic value of the corridor in €/m^2

[33] Assumption for both lines and cables.

[34] source Europacable, news flow over the period 2009 to 2014; filtering of underground and partial undergrounding HVAC projects; news related to a land connection to a plant (wind farm, desalination unit, pumped storage hydroelectric plant) have not been retained in the table

Table 33: Review of recent underground HVAC cable projects on grid infrastructure reinforcement (source Europacable)

date news	Voltage	Transmission Technology	km land	M$	M€	Connection
2013	500	Installation of 500 kV XLPE cables in underground tunnel, including power accessories, joints and terminations. 3 separate 7-km lengths (one per phase), single-core cable at 2500mm2 copper cross section.	7X3		11	State Grid Corporation of China: grid reinforcement in Beijing, Pilot Project
2012	400	400 kV extra high voltage insulated cable with a coating with enamel cable to reduce transmission losses by more than 20%	N/A	110		Grid infrastructure reinforcement in Kuwait
2012	400	3 orders including 400 kV cables and connectors in Kuwait (110 MUSD), a Saudi Arabia (1.44 MUSD) and Qatar (1.36 MUSD)	101,8	110		Grid infrastructure reinforcement in Kuwait, Saudi Arabia and Qatar
2010	400	400 kV underground cable system, triple circuit route of 25 km for a total of 230 km of XLPE cable and related network components	230		250	Contract with Abu Dhabi Transmission and Dispatch Company (TRANSCO): replacement of existing OHL by underground cable system
2010	400	About 60 km of 400 kV cable circuits in underground of Dubai with associated accessories and construction of the underground cable tunnels	60		90	Construction of Dubai's first EHV underground cable operating at 400 kV
2010	400	400 kV underground cable system, 12 km long double circuit for a total of 72 km of 400 kV XLPE cable and related terminations and joints	72		40	Underground cable system in the North of Athens (Public Power Corporation, Greece)
2009	400	EHV underground power cables on three 22 km circuits for a total of 66 km of 400 kV cable and associated accessories	66		47	Development of a power transmission project in Doha, Qatar (KAHRAMAA)
2013	380	Extra High Voltage cable systems for Amprion and Terna	N/A		20	Terna : electricity network reinforcement in Sicilia; Amprion: line connecting 2 substations with partial undergrounding.
2011	380	Supply of 380kV extra HV cable in the Netherlands	2,6		0,95	Cables supplied to Tennet (NL)
2009	380	Three contracts awarded to Prysmian including (i) the upgrading of an existing 380 kV cable interconnection in Rotterdam (13.2 km of underground HV cables) ; (ii) 36.9 km of 380 kV connecting a new gas-fired power plant in Rotterdam to the Dutch grid; (iii) 8.4 km of 380b kV cable system connecting a new gas-fired power plant outside Frankfurt to the German grid	58,5		20,3	Upgrade and development of EHV power transmission systems in the Netherlands and Germany
2012	380/ 230	380 kV and 230 kV upgrade underground extra high voltage cables	N/A	19		Grid reinforcement in Saudi Arabia
2012	330/ 132	Double circuit of 330 kV XLPE cables over a 15.5 km distance and installation of a single circuit for 4km length	19,5	83, 1		Grid infrastructure reinforcement in New South Wales, Australia (Transgrid)
2010	275	275 kV underground transmission cable (AUD 72 million)	18		50	Underground cable system in Adelaide, South Australia.
2014	275/ 230	3 contracts awarded to Taihan Electric Wire include a 275 kV cable from Los Angeles Department Water and Power (24 MUSD), a 230 kV substation in New Jersey (8 MUSD) and a 230 kV project in San Diego Gas & Electric		34		Grid reinforcement in the USA
2012	245	1000 km of 245 kV HV, MV, LV (33/15 kV) transmission systems	1000		110	Grid infrastructure reinforcement in Lybia
2013	230	230 kV Extra High Voltage underground and connectors	1,5	12, 7		Grid reinforcement for Smeco (Maryland, USA)

date news	Voltage	Transmission Technology	km land	M$	M€	Connection
2012	230	230 kV underground extra high voltage XLPE cable 7.5 billion yen, length of about 100km	100	69,5		Grid reinforcement in Singapore
2012	230	230 kV cables	N/A	30		HV power for San Diego (California)
2014	220	Extra HV underground 220 kV and related network components	173		80	Kahramaa: Qatar Power Transmission System Expansion project including also replacement of OHL by an UGC.
2014	220	220 kV supply of HV cable	N/A		56	Grid reinforcement in Qatar
2011	220	Supply of 220 kV cables , 157 km	157	91		Grid infrastructure reinforcement in Qatar
2010	220	Supply of 220 kV EHV cable and binders to Bahrain (120 MUSD) and of 4118 km of 400 kV gap conductors to Kuwait (34 MUSD)	N/A	120 +34		Grid infrastructure reinforcement in Bahrain and Kuwait
2009	220	Five complete circuits of 220 kV cable and associated accessories to provide an extra 300 MVA of power carrying capacity for the underground network linking EHV substations across Mumbai	N/A		15	Grid infrastructure reinforcement in Mumbai (Tata Power Company, India)
2011	220/132	Supply of 220 and 132 kV cables and joints in India (45 KRW billion)	N/A	42		Grid infrastructure reinforcement in India
2009	220/132	HV cables in Spain supplied by Iljiin Electric	N/A		18,4	Grid infrastructure reinforcement in Spain (ENDESA)
2011	150	250 km of 150 kV underground cables and accessories: 1500mm2 aluminium conductor cross section, three separate double circuits (130 km+73 km OHL+49km)	250	33		Grid infrastructure reinforcement in Italy (Terna)
2014	132	XLPE cable	N/A	30		New South Wales (Australia): cable upgrade project by Ausgrid around Sydney
2012	132	210 km of 132kV XLPE underground cable. Single phases circuits will have copper sections of 800mm2, 1000mm2 and 1200mm2	210		72,7	Grid infrastructure reinforcement in Abu Dhabi City, UAE.
2012	132	Replacement of a 158 km long, 132 kV line (48 MUSD) and construction of a power substation and HV line of 80 km (40 MUSD)	158+ 80	92		Building of HV lines in Kuwait and Saudi Arabia
2010	132	132 kV cable system and accessories	N/A		60,9	Contract of Tahian Electric Wire with Energy Australia
2010	132	210 km of 132 kV XLPE underground power cable: single-phase cables will have copper cross-sections of 800, 1000, 1200 mm2	210		72,7	Upgrade for TRANSCO of HV underground power cable infrastructure in Abu Dhabi City, UAE.
2012	110	110 kV XLPE cable: 145 km of 110 kV 2000mm2 Aluminium cable, 130 km of 110 kV, 2500mm2 cable, 2.5 km of 50 kV 1200mm2	280		20	HV connection between two stations in the Netherlands (Tennet)
2013	N/A; N/A; 500	Taihan Electric Wire: supply of ultra high voltage cables to Kuwait (32 MUSD), underground cable for the United Arab Emirates (6 MUSD) and 500 kV ultra high voltage cables Kazakhstan (4 MUSD)	N/A	42		Supply of Ultra HV cables to Kuwait, U.A.E and Kazakhstan
2012	N/A	Two orders include the building of a 49-km HV line in Saudi Arabia (26.5 MUSD) and a HV transmission network in Russia (22 MUSD)	49	26,5		Building of power lines in Saudi Arabia and Russia (N.B.:length missing for project in Russia)
2012	N/A	HV cables and accessories	N/A	59		Grid infrastructure reinforcement in Kuwait
2009	N/A	HV underground cables	N/A		69,3	Grid infrastructure reinforcement in New Zealand (Transpower)

Additional sources allow to cross-check the data and ratio presented above. In the REALISEGRID deliverable D3.3.2 [6], the average investment cost (CAPEX) of HVAC XLPE cables at 380 kV in continental Europe is detailed (throughput power of 1000 MVA per circuit) and reported in the table below.

Table 34: Investment cost for HVAC underground XLPE cables (in Europe 1000 MVA can be achieved in ground with 2000mm^2 Cu or in tunnel with 1600 mm^2 Cu)

	Average reference values for HVAC underground XLPE cable (single circuit)	Average reference values for HVAC underground XLPE cable (double circuit)
HVAC XLPE	• 380 kV, 1000 MVA power rating 1000-3000 k€/km	• 380 kV, 2X1000 MVA power rating 2000-5000 k€/km

These data could be further fine-tuned when considering for example the Europacable passive transmission report (in annex) as well as the study[35] jointly carried out by ENTSO-E and Europacable. These studies give ranges of investment cost in Europe of undergrounding in comparison to OHL of 5 to 10 (over the 2000-2010 decade) and it is claimed that such ratios could be reduced down to 3 for links with limited ratings and under good soil conditions. According to ENTSO-E and Europacable, factors above 10 can be reached for high capacity double circuit links with specific structures, e.g. projects involving the construction of cable tunnels (factors above 15 are expected in these cases) due to the cost for civil works.

The breakdown of the initial investment I_0 in different cost components, as performed in the previous section for OHL, can be carried out provided that further assumptions are made. The passive transmission report[36] provides a tentative breakdown for cables (in ideal conditions such as rural plain):

- Cost of equipment: around 40% of total investment costs;
- Installation & civil works: up to 60% of total investment costs[37].

As expected the installation due to civil works (trench) is much above the similar ratio for OHL (41-44% without right of ways and authorizations: see Table 25). The above ratios can vary depending on the type of conductor (aluminum or copper) and the nature of the underground.

With regard to the Operation and Maintenance costs, the two studies considered for OHL provide typical reference level for annual expenses for a cable. Both agree that O&M cost estimation for cable should be about one tenth of that of the OHL which require much more monitoring and repair. Indeed, reference [16] suggests for annual O&M expenses an annual cost of 0.2% of the initial investment cost (maintenance plus repairs) while reference [6] (REALISEGRID) suggests a higher level of operation and maintenance for HVAC Cables in the range of 0.15 to 0.5% of the CAPEX.

Another source in the UK detail the cost of cables in different cost components and in function of the cable size. We report the 220kV and 400 kV configurations from a study of the SDEG in the UK [14] (2008 data).

Table 35: HVAC Cable costs from a source in the UK

	HVAC cables costs (£/m) 3 core or set of three single core [14]			
Voltage	**Cable size (mm^2)**	**Supply (£/m)**	**Lay and Bury[38] [39](£/m)**	**Total (£/m)**
400 kV	1000	995	555	1550
	1200	1130	570	1700
	1400	1265	585	1850

[35] ENTSO-E and Europacable joint paper: Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines, 2010.

[36] See chapter 7 of passive transmission report

[37] 60% is usually reached in difficult areas. In ideal conditions such as rural plain, ratios of installation and civil works are ranging between 29% and 34% (cf. Table 35).

[38] To be understood as installation and civil works.

[39] The data presented in this column implies that the installation of a 1000mm^2 400kV cable costs more than twice as much as the installation of a 1000 mm^2 225 kV cable, which is probably overestimated. As a consequence, these data on installation costs of HVAC cables should be handled with care.

	1600	1400	600	2000
	2000	1535	615	2150
220 kV	800	440	220	660
	1000	460	230	690

5.3.3 Considerations on cost variations of partial undergrounding as of 2013 and main components.

In the following, costs of partial undergrounding in an overhead line project are compared to a fully undergrounded cable solution. When addressing partial undergrounding solutions, the following features need to be accounted for:

- potential losses which are no longer relevant due to shorter cable lengths;
- potentially no need for compensation in the underground section (to be evaluated case by case);
- transition station at either end required only for voltages of 380kV or more;
- potentially shorter route;
- reduced costs due to land occupation; and
- potentially shorter time to project implementation due to better public acceptance.

While every project will need consideration on a case by case basis, for the purpose of this exercise, we assume underground sections of no more than 20 km as outlined in the Joint Europacable ENTSO-E paper[40]. According to this paper the ratio for partial undergrounding to OHL can be reduced to levels between 1.8 and 2.4 depending on the system configurations and project context.

When applying the costs reported in this document and based on the following assumptions, a cost ratio for 20% partial undergrounding (a transmission line of 100 km composed by 80 km OHL and 20 km UGC was considered) can be estimated as follows:

- OHL single circuit cost from Table 19 = 700-800 €/m
- Two cable circuits (having the same rating of one OHL) from table 33 = 2000-5000 €/m
- Two transition stations OHL/UGC cost 0.5-4 M€ (the cost of the transition station depends on the complexity of bus bar, switchgear to be realized).

These assumptions lead to cost ratio ranging from 2.8 to 6.3 for the full undergrounding solution and from 1.5 to 2.1 for the 20% partial undergrounding solution. If we consider only 10% of undergrounding the ratio ranges from 1.2 to 1.6.

Reference values including the above can be taken from the recent German study [15] on the opportunity of partial cabling.

Table 36: Typical ratios for undergrounding in respect to overhead lines (single circuit, case study in Germany) [15]

	Investment costs for OHL	Investment costs for partial cabling in 3 or 4 systems
68 km length	• OHL 4X265/35 750 k€/km	• Partial cabling 3 systems 4X265/35 1810 k€/km
	• OHL 4X385/35 850 k€/km	• Partial cabling 3 systems, 4X385/35 1910 k€/km
		• Partial cabling 4 systems, 4X385/35 2010 k€/km
	• OHL 4X560/50 1400 k€/km	• Partial cabling 4 systems, 4X560/50 2500 k€/km

40 ENTSO-E and Europacable joint paper: Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines, 2010.

Another Europacable communication paper[41] provides even lower cost ratio for partial undergrounding in the range of 1.2 to 1.8 of OHL costs (for a 10% to 20% undergrounding of the total length of the line and for underground sections up to 20 kilometers).

For high voltages, when the cost of transition stations (connections between underground cables/overhead lines) has to be taken into account, the following data provided by Transpower (New Zealand TSO) could be used[42] (underground installation of a 2 X 400 kV 1000 MW cable circuit through an urban area where a cost estimation[43] is provided to the electric authority):

- installation costs of a 2 X 400 kV 1000 MW cable circuits ranges from 7.3 to 8.1 M€/km,
- 1.8 M€ installed cost of outdoor cable terminations at both ends of 2X400 kV 1000 MW cable circuits,
- 3.8 M€ 400 kV line to cable transition stations at both ends of the 2X400 kV 1000 MW cable circuits.

Assumption 4.
Based on the above, the assumptions retained for the unit costs at 2013 for the considered fully undergrounded HVAC underground XLPE cable is (rural area, flat land):
- double circuit, 380 kV, power rating 2X1000 MVA: **3500 k€/km + land costs**
- single circuit, 380 kV, power rating 1000 MVA: **1800 k€/km + land costs**

The above data have to be adjusted depending on the terrain (urban/rural), the number of circuits, etc., under consideration by resorting to multipliers. Note that the above costs represent the lower bound of the ratios recommended by ENTSO-E and Europacable, i.e. 3 (cf. assumption 1), irrespective of the land costs.

Reference [10] details elements of costs of HV underground cables: For cables 400 kV 2000 mm2 of section (double and single circuits) as well as 220 kV in 1600 mm2 section (double circuit). The reference country is Italy (country index is 10 according to the Table 31). The table below provide costs in k€/km (taking into account the X10 multiplication from the source).

Table 37: Breakdown of costs of HV underground cables in k€/km for Italy (2005 data) [10]

	400 kV double 2000 mm²			400 kV single 2000 mm²			220 kV double 1600 mm²		
	Rural plain	Rocky area	Urban area	Rural plain	Rocky area	Urban area	Rural plain	Rocky area	Urban area
Equipment	2139	2139	2139	1073	1073	1073	507	507	507
Installation	119	119	119	66	66	66	34	34	34
Civil works	254	393	380	203	316	305	119	184	178
Project managnt	503	530	528	268	287	289	132	145	144
Authorisations	180	180	360	180	180	360	180	180	360
Rights of way	45	45	90	32	32	64	16	16	32
Total	**3240**	**3408**	**3618**	**1822**	**1953**	**2156**	**988**	**1066**	**1255**

Based on the above data one could easily infer some typical breakdowns of costs for undergrounding computed from a used case in Italy [10].

5.3.4 Evolution laws for each cost component and computation of the costs for next decades

We shall focus in this section on the initial investment of the HVAC underground XLPE cable (double circuit) for the base installation (without any multiplier ratio) at 3.5 M€/km. A similar deconstruction/reconstruction process as of the one detailed above for HVAC OHL has been deployed with the following specificities:

Relative share of equipment, installation, civil works, project management, authorizations and right of way have to be adjusted, a first proxy being

- Table 37;

[41] 2008 Europacable communication on life cycle costs for partially undergrounded sections
[42] Source dated 2005, see page 26 https://www.ea.govt.nz/dmsdocument/4670
[43] Costs exclude property purchase. Transition station costs are given for a site with no geotechnical problems, cost of a 500m long access is included. A currency rate of 1.35 EUR/USD has been used.

- Evolution laws of equipment will depend on the evolution of two components:
    - o the experience curve with a lower Progress Ratio (PR) since the technology is less mature (for example assumed at 85%, having in mind the observation already made on the low sensitivity of the total costs -CAPEX- to such a factor)
    - o a composite commodity index reflecting the evolutions of copper, aluminum and polyethylene
- Evolution laws for civil works and installation: same as for OHL.

Table 38: Typical terrain factors for HV underground cables based on the rural plain reference [10]

	400 kV double 2000 mm2			400 kV single 2000 mm2			220 kV double 1600 mm2		
	Rural plain	**Rocky area**	**Urban area**	**Rural plain**	**Rocky area**	**Urban area**	**Rural plain**	**Rocky area**	**Urban area**
	% total	*Terrain factors*[44]		*% total*	*Terrain factors*		*% total*	*Terrain factors*	
Equipment	**59%**	1,00	1,00	**59%**	1,00	1,00	**51%**	1,00	1,00
Installation	**4%**	1,00	1,00	**4%**	1,00	1,00	**3%**	1,00	1,00
Civil works	**11%**	1,55	1,50	**11%**	1,56	1,50	**12%**	1,55	1,50
Project managnt	**15%**	1,06	1,05	**15%**	1,07	1,08	**13%**	1,10	1,09
Authorisations	**10%**	1,00	2,00	**10%**	1,00	2,00	**18%**	1,00	2,00
Rights of way	**2%**	1,00	2,00	**2%**	1,00	2,00	**2%**	1,00	2,00
Total	**100%**	1,05	1,12	**100%**	1,07	1,18	**100%**	1,08	1,27

As already mentioned, IRENE40 has proposed some time evolution laws of transmission equipment based on 2010 costs. They are reported in section 5.8.

All in all, and at the proposed level of analysis required by the project, the resulting cost components for all decades are impacted by the same factors identified for the analysis on overhead lines. Such dependence on the costs at 2013 and on the spatial factor is more important than tentative time wise evolutions.
It is recommended to take into account the special variability resulting from the country and terrain nature by using the series of multiplier factors proposed above.

5.4 Submarine cables (HVAC)

In this section, the HVAC submarine cables are considered. The submarine cables operated in HVDC systems will be reviewed in the next section. Technical data relative to submarine cables are included in the technology assessment report and in the associated datasheets for HVAC 380-420 kV XLPE cables.
A review of 47 recent submarine projects provided by Europacable and announced during the period going from 2011 to 2014 has been made and is reported in Table 39 hereafter[45]. In particular technical details and cost elements are given for each project which will allow:
- to facilitate the definition of an archetype representative for HVAC submarine cables,
- to collect measures of cost per kilometer as sanity check when defining the range of CAPEX of transmission equipment.

For submarine installations, both in HVAC or HVDC, the costs may vary considerably depending on the nature of installation.[46] A distinction needs to be made between cables laying in shallow water (i.e. up to a maximum depth of 500m) and deep water cables (laying at a depth from 500m up to 2.000m). This distinction is mainly a consequence of the risk of mechanical damage along the route:

- For cable systems in shallow water, burial is mandatory to protect the cable against the risk of damage from fishing gear and anchors;

[44] The terrain factor is the multiplicative coefficient to be applied to the rural plain cost (used as reference). The table should be read vertically for rural plain column (breakdown in % of total cost). Then for the two other types of terrains these terrain factors allow to compute the costs based on the rural plain reference. For example the respective coefficients for the rocky terrain and urban area are 1.05 and 1.12 for the total 400 kV 2000 mm^2 underground cable.
[45] Only AC projects operated at voltages above 132 kV have been retained.
[46] Europacable Introduction to High Voltage Direct Current (HVDC) Subsea Cables Systems, 2012

- For deep water applications, the threats from fishing gear and anchors are non-existing and consequently a burial operation is not needed.

Consequently, cable installation in shallow water may be more expensive than in deep water as cable burial and potential protection measure may have to be implemented.

After analysis of the reported projects in Table 39, it is proposed to select the following generic configurations for further analysis:

- HVAC XLPE single core (three parallel cables for a 3-phase AC connection): see the recently announced project by Nexans in Norway (90 km, 420 kV, 390 m max depth) and the related budget of 78M€

- HVAC XLPE 3-core
  - either in two circuits: cf. Prysmian project on the connection to the BorWin cluster at 155 kV (2X31 km and the related budget of 50M€, announced in 2013),
  - or in three circuits as the connection by Nexans through the Gulf of Evia (Greece) operated at 150 kV over a sea route of 21 km and 3km underground, with a total cost of 64 M€ (announced in 2010).

Table 39: Review of recent submarine cable projects operated in AC (source Europacable)

date news	AC / DC	Voltage	Transmission Technology	km subsea	km land	M$	M€	Connection
2014	**AC**	**420**	**Longest and deepest 420 kV XLPE cable, 90 km single core XLPE, max 390m depth in three parallel length to create a three-phase AC connection**	**3X30**			**78**	**Crossing of two fjords in Norway**
2010	AC	420	3000 MVA, 13 km route, 3 X 420 kV XLPE submarine and 6 X 420 kV paper insulated submarine cables, 200 to 250 m depth	117			104	Replacement of cable in Norway, 13 km route over a fjord
2011	AC	345	345 kV HVAC submarine and land transmission line (13 km) 660 MW and B2B station	<13	N/A	175		New Jersey to New York City
2010	AC	245	245 kV AC, cross section of 3 X 1600mm2 Aluminum, diameter of 260 mm capacity of 400 MW	25			18	Connection Anholt offshore Wind Farm to Denmark
2012	AC	245	Submarine XLPE cable transferring 381 MW, 245 kV, the 14 km section consist of 3 copper core, each 400mm2, the 43 km section comprises three 1000mm2 copper cores (with 1200mm2 over a 4 km section)	43+14			300	Connection: Northwind (North Sea) to Belwin phase 2 and to Zeebruge
2013	AC	230	Twin subsea cable link, 230 kV, 240 MVA, two 41km 3-core submarine together with six 5-km single core underground cable	2X41	6X5		120	Connection Scotland, water deep>100m
2014	AC	220	HVAC submarine and underground 220 kV	25	32	30		Burbo Bank Extension 258 MW
2014	AC	220	200 km of 220 kV HV submarine cable	200			165	Offshore wind farm in North Sea (NL) 600 MW
2014	AC	220	220 kV HVAC 3-core extruded cables	90	3		250 (730)	Wind park German Baltic Sea
2014	AC	220	220 kV HVAC double circuit	21			40	ESB Ireland: Shannon river crossing
2010	AC	220	3X 630mm2 submarine XLPE cables, 220 kV, 200MW, HVAC, water depth 150m, buried 1 meter below the seabed and 25km underground cable for the connection to the Ragusa substation	100	25		178	HVAC connection Malta Sicily and 220 kV station in Malta
2009	AC	170	170 kV	52			39	Connection Belwind to the Belgian power network (165 MW, located 46 km off the coast of Zeebruge)
2013	**AC**	**155**	**Two 3-core 155 kV XLPE HVAC OWP to the BorWin cluster including a connection from the OWP platform to the offshore HVDC converter station**	**2X31**			**50**	**Connection of Offshore wind park (North Sea) to the mainland grid**
2013	AC	150/275	150 kV submarine & 275 kV EHV cable to Southeastern Coast of the UK	N/A	N/A		16	Dong

date news	AC / DC	Voltage	Transmission Technology	km subsea	km land	M$	M€	Connection
2011	AC	155	50 km cable 155kV AC cable	50			80,6	Connection Riffgrat Wind Farm (108 MW, 20 km north-west of Borkum island) to the substation Emden Borssum
2014	AC	150	HVAC XLPE 200 MVA 150 kV	108	2		95	Islands interconnection Greece
2013	AC	150	150 kV HVAC power cable connection	30	1		70	Connection Capri Naples
2011	AC	150	60 km of 150 kV AC 3-core				95	Connection Baltic 2 (distance 32 km north of the island Rügen)
2010	**AC**	**150**	**Undersea: 150 kV, three subsea circuits over a 21 km subsea route, max depth of 85 m. Each circuit has a nominal capacity of 200 MVA. 2 circuits in normal use and one spare to ensure continuity of operation. 3 power cores with copper cross section of 630 mm2 with XLPE insulation. Bury 1 meter below the seabed. Underground: single core design in three circuits. Each circuit comprising three individual cables over a 2.75+0.33 km route.**	**3X21**	**9X3**		**64**	**Connection across the Gulf of Evia (Greece) (to facilitate development of wind projects totaling around 400MW)**
2010	AC	150	150 kV, offshore transformer station and cables	30	3	125		Connection wind farm 30km off the coast of Belgium to mainland
2010	AC	150	3 single core, 12 km length each for the undergrounding connection and 2X60 km submarine transmission cables, 150 kV	2X60	3X12		195	Connection of Baltic 2 wind farm (288MW)
2012	AC	145	World's longest AC link, 145 kV 3-core XLPE up to 55MW, 370 m at the deepest	162		170		Subsea7, connection to oil and gas field, 115 m depth
2012	AC	132	Two 100km long circuits (200 km) of 132 kV cables incl. 3 core power cables for a total of 100 MW power transmission	2X100		440	345	Qatar : Halul Island
2013	AC	132	XLPE HVAC cable 118 MVA, 132 kV, depth up to 750m	115	8,6		85	Connection Balearic islands (REE)
2012	AC	132	Two circuits 2X14 km, 132 kV, three-core AC submarine cable	2X14		15		Connection : Humber gateway offshore wind farm (219 MW capacity)
2011	AC	132	Extension of 115 km XLPE AC 100MW link to Ibiza (132 kV)	115	24		90	Connection Mallorca Ibiza (based on the Spain Mallorca interconnection in 2011 400 MW HVDC, 400 kV, 240 km)
2010	AC	132	HV submarine cable 85 km, 132 kV	85			35	Connection of Welsh wind farm "Gwynt y Môr" (576MW capacity)

5.5 HVDC systems: cables, lines and converter stations

5.5.1 HVDC solutions as a function of voltage, distance and transmission power

Reference [5] details benefits of High Voltage Direct Current (HVDC) technology over conventional HVAC. Such technology has proven its reliability and attractiveness for various applications such as long distance power transmission, long submarine cable links and interconnection of asynchronous systems. The most recent technology, self-commutated Voltage Source Converter (VSC), is more flexible than the more conventional line-commutated Current Source Converter (CSC) since it allows controlling active and reactive power independently. HVDC key benefits are thus in terms of increased transmission capacity compared to conventional HVAC, and power flow controllability, which in turn enhance the grid stability.

Although the investment costs of a VSC-HVDC converter station are higher than those of an AC substation, the overall investment costs of a DC transmission link can be lower than those ones of a corresponding AC interconnection if a certain transmission distance is reached (i.e. “break-even” distance)[47]. The break-even distance upon which DC is more economical is project dependent (typically between 80 and 120 km for offshore submarine cable connections, while for onshore applications, the break-even distance between an AC and DC OHL is in the order of magnitude of 700 km [5]) and the decision of using AC or DC should result from a techno-economic analysis including the line, station and losses components of costs.

Reference [18] provides also basic insights on economic of HVDC solutions and indicates a break-even distance for lines around 800 to 1200 km. More particularly, reference [18] compares different configuration of DC line designs with regard to costs. Voltages from ±300 to ±800kV, powers from 700 to 6000 MW and transmission distances from 750 to 3000 km have been considered. The study puts in evidence the concept of optimal voltage according to a power transmission and transmission distance as inputs. For instance, the frontier to change optimal voltage for a 1500 km length is 3500 MW: below this limit a voltage of ±600 kV appears to be the most economical solution.

The table below details the thresholds of power transmission for four levels of voltage and three categories of distance length.

Table 40: Optimal voltage as a function of station power and distance transmission [18]

	750 km	1500 km	3000 km
±300 kV	<1550 MW	<1100 MW	<850 MW
±500 kV	1550-3050 MW	1110-2200 MW	850-1800 MW
±600 kV	3050-4500 MW	2200-3400 MW	1800-2500 MW
±800 kV	>4500 MW	>3400 MW	>2500 MW

If we focus, for example, on the cost of a 1500 km line, the same reference provides the breakdown of cost for a set (MW, kV). The breakdown includes costs of line, costs due to corona effect, costs of losses per joule effect, costs of converter.

[47] For a given power rating, DC lines (including DC stations) might be less expensive than AC lines (3 phases) since only 2 poles are needed.

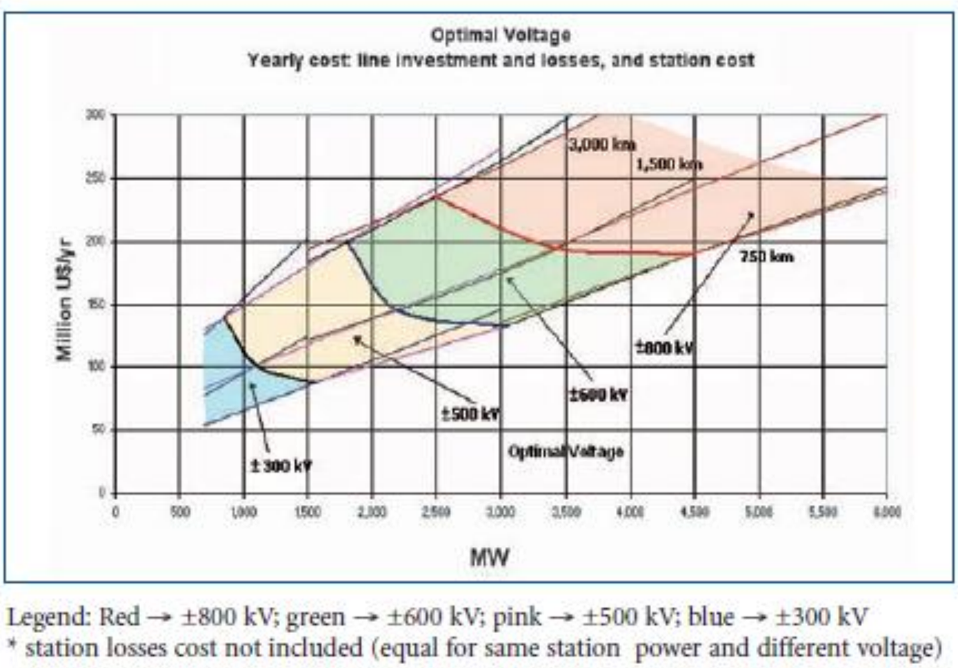


Figure 14: Optimal voltage as function of converter station power and transmission distance [18].

Table 41: Breakdown of full turn-key cost for a 1500 km HVDC line according to different configurations of power and voltage [18]

	700 MW	1500 MW	3000 MW	4500 MW
	±300 kV	±500 kV	±600 kV	±800 kV
	2 conductors / pole	2 conductors / pole	4 conductors / pole	4 conductors / pole
	1155 mm2 Aluminum	1274 mm2 Aluminum	1136 mm2 Aluminum	1274 mm2 Aluminum
Line	42.9%	33.7%	32.4%	26.9%
Corona	2.4%	4.0%	2.3%	2.2%
Joule	15.2%	15.2%	15.9%	13%
Converter	39.4%	47.1%	49.4%	57.9%
Total	100%	100%	100%	100%

In the following, the detailed costs of HVDC systems (cables, lines, converter stations) are investigated. The main focus will be on CAPEX components of the costs whereas for OPEX typical rations will be proposed (as a function of CAPEX, i.e. % of CAPEX/year).

5.5.2 Review of costs for HVDC systems (cables, lines, converter stations)

In a HVDC system, the main transmission assets include the overhead line (respectively the cable) and the converter stations (LCC or VSC). For a given liaison (line or cable), average values of typical costs are reported in the REALISEGRID deliverable [6] in which technical and scientific literature as well as project partners and stakeholders inputs has compiled been compiled.

Table 42: Costs of typical HVDC systems (underground, submarine and overhead lines) [6]

	Cost of typical HVDC XLPE underground cables	Cost of typical HVDC XLPE submarine cables	Cost of typical HVDC OHL
±150 kV	N/A	• 500 MW, 2600 k€/km • 650 MW, 3400 k€/km	• 830 k€/km
±300 kV	• 600 MW, 1500 k€/km • 800 MW, 1800 k€/km • 1000 MW, 2200 k€/km • 1200 MW, 2500 k€/km	• 700 MW, 1900 k€/km • 1000 MW, 2600 k€/km • 1200 MW, 3200 k€/km	• 940 k€/km
±600 kV	N/A	N/A	• 1200 k€/km

On the particular case of subsea installation of cables one could use data from the technology appendix of the Electricity Ten Year Statement of National Grid (November 2013) [11]. Typical costs according to the type of installation are (in £):

- Subsea installation of a single cable, single trench 310 to 730 £k/km
- Subsea installation of a twin cable, single trench 520 to 940 £k/km
- Subsea installation of two single cables, 2 trenches, 10m apart: 630 to 1260 £k/km.

The already mentioned Grid Deployment Plan in Germany [1] provides cost data for HVDC OHL:

- 1400 k€/km for 3 bipolar circuits, each with 1,3 - 2 GW;
- revamping cost from HVAC to HVDC at 200 k€/km.

Another reference compiling costs of transmission systems was used: this study[48] issued in December 2009 at the request of the Alberta Department of Energy (Canada) focuses in particular on the comparison between conventional overhead High Voltage Alternating Current (HVAC) transmission lines, underground HVAC transmission cables, and High Voltage Direct Current (HVDC) systems. Although in the Canadian context, relevant information have been extracted for the needs of e-Highway2050 and reported in the table below. When cross checking with other sources provided in the present deliverable, some of the data provided below might appear low. This analysis will be made in the final subsection 5.10 when defining the archetypes and related costs. Costs are given in Euros[49].

Table 43: Costs of typical underground and overhead lines HVDC systems (LCC HVDC, VSC HVDC) [9]

	Full turnkey costs[50] of EPC (engineering, procurement and construction costs) of typical HVDC systems			
	LCC underground	**VSC Underground**	**LCC OHL (bipolar)**	**VSC OHL (bipolar)**
±200 kV	N/A	• Cable of 20 km, 400MW, 4.5M€ + 5k€/piece for splice + 14k€/piece for termination costs • Engineering + project management + civil work + installation: 812k€ • 2 VSC converters (400MW): 105 M€ • 2 VSC converters (600MW): 142 M€	N/A	• OHL 600 MW, 365 k€/km • 2 VSC converters (400MW): 111 M€ • 2 VSC converters (600MW): 154 M€
±500 kV	• MI Cable 2000mm2 copper conductor 2 bipole cable 2000MW, 500 k€/km + 40k€/pc for splice + 200k€/pc for termination costs • Engineering + project management + civil work + installation: 1180 k€/km • 2 LCC converters 750MW, monopole 77 M€ • 2 LCC converters 1000MW, bipole 111 M€ • 2 LCC converters 2000MW, bipole 160 M€	N/A	• OHL 3000MW, 470 k€/km • 2 LCC converters (2000MW): 154 M€ [51] • 2 LCC converters (3000MW): 204 M€	N/A

[48] Authors: Stantec, Areva and other power delivery consultants see source [9]. http://www.energy.alberta.ca/electricity/pdfs/transmissionsystemsstudy.pdf

[49] They are expressed in Canadian Dollars (CAD) in the Stantec report for the Alberta Department of Energy [9].

[50] The currency exchange rate used at the time of the study (2009) is 1,62 CAD=1 EUR.

[51] This source provides lower EPC (engineering, procurement and construction) costs for 2 LCC converters stations (2000MW, bipole) operated at ±500kV in HVDC OHL than 2 LCC converters stations (2000MW, bipole) operated at ±500kV in HVDC underground configuration, 250 MCAD and 260 MCAD respectively (i.e. 154M€ and 160M€ at the considered currency rate). This data should be handled with care since the cost of converter stations associated to OHL should be higher than cost of converter stations of the same power and voltage associated to cables (source Europacable).

±800 kV	N/A		• OHL 3000MW, 873 k€/km • 2 LCC converters (4000MW): 414 M€ (estimated • 2 LCC converters (6400MW): 565 M€ (estimated)	N/A

Additional sources from the UK were consulted ([11] [12] [13] [14]). They all include cost details on different configurations of HVDC cables (as well as other elements of transmission systems which could be used as cross-checking elements when defining the transmission reinforcement archetypes). Below we have reported a few excerpts from their respective appendices.

Table 44: Costs of various HVDC cables from various UK sources [11] [12] [13] [14]

	HVDC cable costs (£/m) - 2013 data [11]			
	Cable size (mm^2)	**HVDC Extruded Subsea Cable – 320 kV (£/m)**	**HVDC Mass Impregnated Cable – 400 kV (£/m)**	**HVDC Mass Impregnated Cable – 500 kV (£/m)**
	1200	314-471	N/A	N/A
	1500	346-471	366-576	418-576
	1800	314-524	418-576	418-628
	2000	366-576	418-628	418-681
	2500	N/A	627-733	524-785

	HVDC cable unit costs (£/m) set of two DC single core (VSC) 300 kV			
	Cable size (mm^2)	**Supply (£/m)**	**Lay and Bury (£/m)**	**Total (£/m)**
300 kV	1000	440	415	855
	1200	510	430	940
	1400	575	440	1015
	1600	640	450	1090
	2000	710	465	1175

	HVDC cable unit costs[52] (£/m) and other data - Bipole - ODIS[53] 2010 data [12]			
	1 GW HVDC (XLPE)	**2 GW HVDC (MI)**	**2 GW HVDC (XLPE)**	**3 GW HVDC (MI)**
Unit cost £/m	1300	1520	1410	1700
Kg Cu/m	28	43	45	45
Kg Pb/m	25	29	32	34
Kg Fe/m	15	17	18	19
Installation passes	1	1	1	2
Overall weight/m	2X41 kg	2X53 kg	2X59 kg	2X60 kg

	HVDC Subsea[54] cable costs (£/m) 300 kV Bipole - ODIS 2009 data [13]			
	Conductor Area (mm^2)	**Capacity (MW)**	**Weight (kg/m)**	**Total (£/m)**
±300 kV	1400	841	86	1286
	2000	1031	106	1580
	2400	1146	122	1776
	3000	1306	140	2070

[52] Unit costs represent an "installed" costs incl. consenting, land purchase, materials, installation and construction

[53] Offshore Development Information Statement

[54] The source assumes an installation cost of 500£/m with a 1 meter burial, sea soil temperature of 15°C, thermal resistivity 1 kW/m, copper conductor, steel wire armour.

	HVDC Underground cable costs (£/m) for Onshore use - 300 kV Bipole - ODIS 2009 data [13]			
	Conductor Area (mm²)	Capacity (MW)	Weight (kg/m)	Total (£/m)
±300 kV	1400	770	11	989
	2000	966	14	1161
	2400	1089	16	1276
	3000	1253	18	1449

With regards to converter costs, a rather simple model is proposed by a UK source (reported in [6]). It shows that the cost of the converter is a linear function of the capacity (assuming a currency ratio of 1 €=0.8 £).

- **Cost (CSC) [M€] = 0.075*P [MW] +37,1**
- **Cost (VSC) [M€] = 0.093*P [MW] +31,5**

The REALISEGRID project provided also cost ranges for typical HVDC system components which are detailed in [5]. The ranges below correspond to an installation over flat land, while assuming multiplier factor of 1.2 for hilly landscape and 1.5 for installations over mountains or urban areas.

- HVDC OHL bipolar (voltage from ± 150 kV to 400 kV; power rating from 350 to 3000 MW): 300-700 k€/km;
- HVDC underground cable pair (voltage ±350 kV; power rating 1100 MW): 1000-2500 k€/km;
- HVDC undersea cable pair (voltage ± 350 kV; power rating 1100 MW): 1000-2000 k€/km;
- HVDC VSC terminal, bipolar (voltage from ±150 kV to 350 kV; power rating 350-1000 MW): 60-125 k€/MW;
- HVDC CSC terminal, bipolar (voltage from ± 350 kV to 500 kV; power rating 1000-3000 MW): 75-110 k€/MW.

Finally a recent (2012) CIGRE reference from the working group B4.46 [17] detailed economic aspects of HVDC. In particular, data are provided for HVDC converter station costs. The specific cost of 0.102 M€/MVA is used for all power ratings and voltage levels for a particular project (the 500 MW Italy Greece HVDC link) as a reference for LCC-HVDC station cost of 40 M€.

Table 45: Costs of typical substations [17]

Rating	Investment costs per station		
	HVAC	HVDC (LCC)	HVDC (VSC)
500 MW	• 16 M€ per terminal	• 40 M€ per terminal	• 51 M€ per terminal
1000 MW	• 28 M€ per terminal	• 90 M€ per terminal	• 110 M€ per terminal [55]
1500 MW	• 40 M€ per terminal	• 120 M€ per terminal	• 153 M€ per terminal

The same source [17] provides also transmission line costs of HVDC and HVAC links gathered from various authors.

Table 46: Costs of transmission lines and cables [17]

	Transmission system costs			
	HVAC		HVDC	
Rating	Cable	Over Head Transmission Line	Cable	Over Head Transmission Line
500 MW	• 0,92 M€ /km	• 0,35 M€ /km	• 0,8 M€ /km	• 0,26 M€ /km
1000 MW	• 1,67 M€ /km	• 0.33 M€ /km	• 1,6 M€ /km	• 0,25 M€ /km
1500 MW	N/A[56]	• 0.45 M€ /km	• 2,4 M€ /km	• 0,34 M€ /km

[55] The value of 110 M€ is considered for a configuration of 2X500MW, when considering a 1X1000 MW this cost might be lowered to 90M€.

[56] The value provided in the source was eliminated since the same as the one for 1000MW.

A case study in Scandinavian is also detailed by reference [17] in order to show the variability of costs. The technology is a new 100 km 420 kV OHL between central Norway and Sweden. For 25 km of this transmission line; the incurred costs included 0.32 M€ of project management, 0.86 M€ of engineering, 10.9 M€ of procurement and installation and 1.1 M€ of right-of-way. The resulting cost per km of 530 k€/km for a standard 420 kV OHL is due to the high level of fixed costs with respect to the "rather short" length of the line.

Other data for both LCC and VSC converters is available thanks to a study carried out by National Grid in the UK [11]. Data are in GBP and per unit. They allow enriching the database of converters costs with the following inputs:

- VSC 500 MW 300 kV: 68-84 £M
- VSC 850 MW 320 kV: 89-110 £M
- VSC 1250 MW 500 kV: 108-136 £M
- VSC 2000 MW 500 kV: 131-178 £M
- CSC 1000 MW 400 kV: 73-94 £M
- CSC 2000 MW 500 kV: 136-168 £M
- CSC 3000 MW 600 kV: 178-209 £M

Finally, for HVDC OHL, costs data have been provided by Amprion (TAR on DC OHL), cf. Table 47 below, for a single circuit HVDC line as a function of voltage, power and the number of conductors per bundle.

Table 47. CAPEX and OPEX in 2014 for a single circuit HVDC OHL as a function of voltage, power and number of conductor per bundle.

Voltage (kV)	320	500	800	1100
Power (GW)	1.7	4.0	11.2	25.5
CAPEX (k€/km)	1200	1599	2000	2500
OPEX (k€/km/year)	7,20	9,59	12,00	24,07
Number of conductors per bundle	4	4	6	8

5.5.3 Submarine cables in HVDC systems

In section 5.4, a review of recent submarine cable projects was provided, focusing on HVAC systems. Here, we have filtered from the same source (Europacable and manufacturers communication) the submarine HVDC projects. Table 48 next page displays selected submarine HVDC projects: possible generic configurations for submarine HVDC cables are identified in bold style, e.g. HVDC MI cable in bipolar configuration (2X600 MW) as implemented in the HVDC link between Italy and Montenegro (announced budget of 300 M€ for 393 km subsea and 22 km underground for the onshore connection).

The data of Table 48 suggests that most interconnections between transmission networks are made with MI insulated cables, while connections with offshore platforms are performed with XLPE insulation.

Table 48: Review of recent submarine cable HVDC projects (source Europacable).

date news	AC / DC	Voltage	Transmission Technology	Insulation Technology	km subsea	km land	M€	Connection
2011	**DC and AC**	**320 / 155**	**VSC rating 864 MW, 320 kV, HVDC XLPE 159km sea route+45km land route cable and completed by XLPE 155kV HVAC submarine from the wind farm to the offshore converter station**	**XLPE**	**159**	**45**	**250**	**Connection SylWin1 (North Sea) to German power grid (located 160 km offshore)**
2012	**DC**	**500**	**Two 500 kV HVDC cables in a bipolar configuration (2 X 500 MW)**	**MI**	**393**	**22**	**300**	**HVDC link Italy Montenegro**
2010	**DC**	**500**	**700 MW HVDC DK-Norway, depth up to 530 m, 500 kV Mass Impregnated Non Draining cable)**	**MI**	**140**	**12**	**87**	**HVDC connection Energinet Statnett Skagerrak4**
2010	DC	450	650 MW HVDC 145 km submarine and 12 km underground, single cable 450 kV DC IRC cable (Integrated Return Conductor)	MI	145	12	180	HVDC link Finland Estonia EstLink2
2013	DC	350	Submarine HVDC, 1100 km MI cable, rated 900 MW, 350 kV	MI	100	N/A	80	Connection : Newfoundland and Labrador (Canada)
2014	DC	320	320 kV HVDC submarine + land bipole rating 900 MW	XLPE	130	29	250	TenneT: offshore wind farm connection BorWin cluster (located 120 km North of Germany)
2013	**DC**	**320**	**320 kV HVDC XLPE cable rating 900 MW**	**XLPE**	**83**	**78**	**350**	**DolWin3 (offshore wind farm North Sea) linking for Tennet**
2011	DC	320	HVDC Light, rating 900MW, 320 kV, 135 km and converter stations	XLPE	N/A	N/A	1000	Connection North Sea wind farms to German power grid
2011	DC	320	VSC 690 MW and 130 (=85+45) km HVDC connection XLPE cable, 320 kV, completed with XLPE 155kV from the wind farm to the offshore converter station	XLPE	85	45	200 for (cable), 600 in total	Connection HelWin 2 (North Sea) to German power grid (located 55 km offshore)
2010	DC	300	**VSC rating 800 MW, 300 kV, HVDC XLPE 125 km sea route+75km land route cable and completed by 39 km XLPE 155kV HVAC submarine from the wind farm to the offshore converter station**	XLPE	125	75	200	**Connection BorWin2 North Sea to mainland Germany (located 125 km offshore)**
2010	DC	250	VSC rating 576 MW, 250 kV, HVDC XLPE 85 km sea route+45km land route cable and completed by XLPE 155kV HVAC submarine from the wind farm to the offshore converter station	XLPE	85	45	150	Connection HelWin1 North Sea to mainland Germany (located 85 km offshore)
2014	DC	200	Two 200kV HVDC cables on about 170 km subsea distance, 500 MW Maritime Link	XLPE	50	300	175	Island interconnection : Newfoundland Nova Scotia (Canada)

5.5.4 Defining the technology variants and the costs as of 2013

Assumption 5. Reference technology variant for HVDC cables:

- The technology variant for HVDC underground cable is a XLPE cable bipolar 320 kV, 1000 MW, underground over a rural area, flat land and two converters VSC of 1000 MW at each cable end. The proposed reference for 2013 costs is **1600 k€/km**[57] for the cable and **125 M€** per terminal (VSC), which is consistent with the above mentioned sources[58]
- The technology variant for HVDC submarine solutions is a XLPE cable bipolar 300 kV, 2000mm2, 1031 MW. The proposed reference for 2013 costs is assumed at 1580 £/m –i.e. about **1900 k€/km** (including about 600 k€/km installation with a 1 meter burial)[59]

Assumption 6. Reference technology variant for HVDC overhead lines:

- It is proposed to retain the data provided by Amprion for the HVDC OHL, cf. Table 47, and consider the four provided voltage levels as archetypes.
- For the converters: the two LCC converters (1000 MW) could be estimated at about 220 M€ while the two VSC converters (1000 MW) at about 250 M€.

5.5.5 Evolution laws for the computation of the costs for next decades

- For HVDC underground cables: the breakdown proposed by Europacable (40% equipment and up to 60% for installation and civil works) could be used as a first proxy for HVDC cables.
- For HVDC overhead lines: it is proposed to use the breakdown of HVAC OHL, see above section 5.2.
- For HVDC converters: see Table 49 for which sources [19] and [20] have been used to get the costs components for the HVDC converters.

Table 49: Breakdown of HVDC converter costs (LCC and VSC) [19] [20]

	Breakdown per component (% investment cost)	
Key components	**LCC 1000MW**	**VSC (2X500MW)**
Valve groups	21%	30,5% [60]
Control-protection-command	8%	8,5%
Converter transformer	22%	20%
AC & DC switchyard, filtering, auxiliaries	18%	4% [61]
Civil works	14%	22%
Project engineering and administration	17%	15%

Based on these cost components, tentative evolution laws could be build according to the approach proposed for overhead lines. The alternative, "more direct" approach based on IRENE40 methodology is discussed in section 5.8.

[57] Corresponding to a breakdown of 700 k€/km for cable equipment + 900 k€/km for engineering, project management, installation, civil works and right-of-ways. Regarding the cost of the VSC terminal, we have selected the upper limit of the range provided by the REALISEGRID source [5] on HVDC VSC terminal, bipolar (which was 60-125 k€/MW).

[58] At the upper limit of cost range as proposed by the Realisegrid source.

[59] Issued from ODIS 2009, Table 44

[60] Including convertors costs, DC switchyard and cooling

[61] AC equipment only

5.6 HVAC substations and transformers

5.6.1 Typical costs of HVAC substations

Costs of HVAC substations depend on their configuration: number of transformers, number of bus bars, etc. REALISEGRID [6] provides two reference values (2011 figures) which are sufficient for the big picture:

- 15-25 M€ for transforming air-insulated substation 220/110 kV,
- 20-30 M€ for transforming air-insulated substation 380/220 kV.

For more details and a model of costs for substations, one could consult the US study [2]. This reference gives an overview of base costs for a new substation. A series of additional components have to be accounted for according to the number of lines entering/terminating at the station, the number of breakers, the number of transformers, the number of reactors needed.

5.6.2 Typical costs for transformers

They are provided in reference [6] (based on a UK source) and [2] (US source):

- 5,2 k€/MVA[62] for a 115/230 kV or a 138/230 kV transformer in a 230 kV station;
- 7,4 k€/MVA[63] for a 115/345 kV or a 138/345kV or a 230/345 kV or a 138/500 kV transformer (respectively in a 230 kV 345 kV and 500 kV station);
- 11 k€/MVA for a 400/220 kV transformer of 400 MVA;
- 10 k€/MVA for a 400/220 kV transformer of 500 MVA;
- 10,3 k€/MVA for a 400/220 kV transformer of 500 MVA.

The Australian source AEMO [3] gives additional cost estimates[64] for transformers:

- 13.3 M€ for a 1000 MVA 500/330 kV transformer (3 X 1 phase);
- 8.1 M€ for a 370 MVA 500/275 kV transformer (3 X 1 phase);
- 13.3 M€ for a 1000 MVA 500/220 kV transformer (3 X 1 phase);
- 11.8 M€ for a 750 MVA 500/220 kV transformer (3 X 1 phase);
- 11.1 M€ for a 600 MVA 500/220 kV transformer (3 X 1 phase);
- 8.9 M€ for a 700 MVA 330/220 kV transformer (3 X 1 phase);
- 6.7 M€ for a 400 MVA 330/220 kV transformer (3 X 1 phase);
- 5.9 M€ for a 225 MVA 330/220 kV transformer (3 X 1 phase);
- 3.7 M€ for a 150 MVA 220/110 kV transformer (3 phase units).

For costs in Europe, reference [17] reports some data used in the 2005 dena study[65] for the HVAC investment with a cost amount of 12 k€/MVA for the transformer and a cost of 1,85M€ for a 380 kV switching field. More recent data in Germany are indicated in the 2nd draft (2013) Grid development plan in Germany [1]. This report uses the following data for the costs of HVAC stations:

- 380 kV: 4 M€ /Switching field (including cost of plant adaptation / expansion);
- 380/110-kV transformer 300 MVA: 6.5 M€/transformer (including cost of ancillary plants and EHV and HV switching field).

One should mention data reported from a recent source (UK, 2013 data, cost elements are in GBP [11]).

- HVAC Switchgear 275 kV: 3.04 to 3.46 £k;
- HVAC Switchgear 400 kV: 3.98 to 4.29 £k;
- Transformers 400/132 kV 240 MVA: 1.88 to 2.30 £M;
- Transformers 275/132 kV 240 MVA: 1.57 to 2.09 £M;
- Shunt reactors 200 MVAR/400 kV: 2.51 to 2.72 £k (supplied costs);
- Shunt reactors 100 MVAR/275 kV: 2.30 to 2.51 £k (supplied costs);

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62 7 000 $/MVA at 1.35 currency rate

63 10 000 $/MVA at 1.35 currency rate

64 Currency exchange rate assumed at 1 EUR=1.35USD

65 Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020, Studie im Auftrag der deutschen Energie-Agentur GmbH, Köln, February 24th, 2005

- Shunt capacitor banks 200 MVAR of capacitive reactive compensation: 4.19 to 7.33 £M (installed costs);
- Shunt capacitor banks 100 MVAR of capacitive reactive compensation: 3.14 to 5.24 £M (installed costs).

Finally, the Offshore Transmission Technology report from ENTSOE [4] gives costs which are consistent with the above data:

- HVAC GIS switchgear (total cost per installed substation including civil works, cost per bay)
  - HVAC GIS Switchgear 132 kV: 1.26 to 1.61 M€ ;
  - HVAC GIS Switchgear 275 kV: 3.34 to 3.68 M€;
  - HVAC GIS Switchgear 400 kV: 4.37 to 4.72 M€.

- Transformers (cost supplied and assembled but excluding civil works or associated bay works which can approximately double the total installed bay cost but are likely to be an element of a main works contractor costs)
  - Transformer 400/132 kV 240 MVA: 2.07-2.53 M€;
  - Transformer 275/132 kV 240 MVA: 1.73-2.3 M€;
  - Transformer 275/33 kV 120 MVA: 1.4-1.84 M€.

- Shunt reactors (supplied costs, based upon a unit, delivered and assembled but exclude all civil and structural works associated, associated civil costs can approximately double the total installed bay cost but are likely to be an element of a main works contractor costs)
  - Shunt reactors 200 MVAR/400 kV: 2.53 to 2.76 M€;
  - Shunt reactors 100 MVAR/275 kV: 2.76 to 2.99 M€.

- HVAC Shunt capacitor banks (total installed cost including associated site works)
  - 200 MVAR of capacitive reactive compensation: 4.6 to 8.05 M€;
  - 100 MVAR of capacitive reactive compensation: 3.45 to 5.75 M€.

5.6.3 Evolution laws for the computation of the costs for next decades

For transformers and substations, section 5.8 reports tentative time evolution indexes gathered from [8].

5.7 FACTS

Typical investment costs ranges at 2010 for FACTS device are detailed in REALISEGRID [6]. The list also includes investment costs for a Phase Shifting Transformer (PST) and Fixed Series Capacitor (FSC) presented for comparison even though they cannot be considered as FACTS (they may be used in similar contexts). Indeed, since mechanically controlled, their degree of reactivity, flexibility and precision are not at the same level as the ones ensured by FACTS equipment.

- PST, 400 kV, 100-1600 MVAR/MVA available power rating: 10-40 k€/MVA;
- FSC, 400 kV, 100-1000 MVAR/MVA available power rating: 10-20 k€/MVAR;
- SVC, 400 kV, 100-850 MVAR/MVA available power rating: 30-50 k€/MVAR;
- STATCOM, 400 kV, 100-400 MVAR/MVA available power rating: 50-75 k€/MVAR;
- TCSC, 400 kV, 25-600 MVAR/MVA available power rating: 35-50 k€/MVAR;
- SSSC, 400 kV, 100-400 MVAR/MVA available power rating: 50-80 k€/MVAR;
- TCPST (TCQBT)[66], 220 kV, 50 MVAR/MVA available power rating: 12-36 k€/MVA;
- TCPST (TCQBT)[67], 115 kV, 150 MVAR/MVA available power rating: 40-70 k€/MVA;
- UPFC, 400 kV, 100-325 MVAR/MVA available power rating: 90-130 k€/MVA.

Next section 5.8 details tentative indexes for FACTS issued from [8] that could be used to build cost for these active transmission systems.

A more recent source provides unit installed costs for Static VAR compensators and STATCOMs. Data are in GBP [11]:

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[66] Data from a single case (source EPRI 1994)
[67] Data from a single case (source EPRI 1994)

- Static VAR compensators- 100 MVAR of reactive compensation: 3.14 to 5.24 £M (installed costs);
- Static VAR compensators- 200 MVAR: 10.47 to 15.71 £M (installed costs);
- STATCOMs 50 MVAR of reactive compensation: 3.14 to 5.24 £M (installed costs);
- STATCOMs 100 MVAR of reactive compensation: 10.47 to 15.71 £M (installed costs);
- STATCOMs 200 MVAR of reactive compensation: 15.71 to 20.94 £M (installed costs).

These data (i.e. [11]) are partially compliant with the data displayed in the Offshore Transmission Technology report from ENTSOE [4] (total installed cost including associated site works):

- Static VAR compensators- 100 MVAR of reactive compensation: 3.45 to 5.75 M€ (consistent with [11]),
- Static VAR compensators- 200 MVAR: 11.5 to 17.25 M€ (consistent with [11]),
- STATCOMs 50 MVAR of reactive compensation: 3.45 to 5.75 M€ (consistent with [11]),
- STATCOMs 100 MVAR of reactive compensation: 5.75 to 11.5 M€ (not consistent with [11]),
- STATCOMs 200 MVAR of reactive compensation: 11.5 to 23 M€ (only the upper limits is consistent with [11]).

In this work, it is recommended to retain the ENTSOE data of [4] for the STATCOMs 100 and 200 MVAR of reactive compensation rather than the data of reference [11].

The ENTSO-E data is consistent with the costs data displayed above, i.e. REALISEGRID data [6] and IRENE40 data [8] (see Table 51).

5.8 Recommendations for building evolution laws for the next decades

Based on the IRENE40 outputs, this section reports the proposed progress ratios per category of transmission systems: OHL, cables, HVDC converters, FACTS, transformers.

5.8.1 HVDC systems

The dropping rates for each decade are based on qualitative estimations by manufacturers. For example, for HVDC systems, it is estimated that installation demand will increase in the period 2010-2020, leading to a unit cost decrease of the order of magnitude of 10-15% within these 10 years. After 2020 a slowing down of installations will result in a dropping rate half of that in the previous decade. By such step by step (one step is 10 years) approach, a simple prediction curve of unit costs is built [8]. Three configurations of HVDC are detailed: back to back HVDC, OHL HVDC and a submarine Cable.

Table 50: Estimated indices for HVDC components (starting year is 2010) [8]

	Unit cost of equipment for HVDC components (€/kW) [68]		
	Back to back HVDC	Over Head Transmission Line	Submarine Cable
2010	95	83	171
2020	76-84 [±5%]	57-63 [±5%]	52 – 58 [±5%]
2030	68-82 [±10%]	49.5-60.5 [±10%]	49.5-60.5 [±10%]
2040	62-80 [±15%]	44.2-59.8 [±15%]	44.2-59.8 [±15%]
2050	56-84 [±20%]	40 - 60 [±20%]	40 – 60 [±20%]

5.8.2 FACTS

The same approach is implemented to estimate the dropping rates for each decade for three types of FACTS: SVC, STATCOM, TCSC.

Table 51: Estimated indices for FACTS (starting year is 2010) [8]

[68] The unit cost of HVDC in Euro/kW refer to 1998/1999 price [8]. The initial values of costs set in 2010 are mentioned for completion purposes but the main interest is to report the extrapolated indexes for 2020, 2030, 2040, 2050 for the costs of the considered transmission technologies. These prices do not include prices of cables or overhead lines and are based on HVDC systems providers' available prices gathered by [8].

	Unit cost of equipment for FACTS (€/kVAR) [69]		
	SVC	STATCOM	TCSC[70]
2010	37	52	40
2020	31.35-34.65 [±5%]	54 - 60 [±5%]	31.35-34.65 [±5%]
2030	27 - 33 [±10%]	45 - 55 [±10%]	27 - 33 [±10%]
2040	23 - 31 [±15%]	38 - 52 [±15%]	23 - 31 [±15%]
2050	20 - 30 [±20%]	32 - 48 [±20%]	20 - 30 [±20%]

5.8.3 HVAC OHL, cables and transformers

Dropping rates for each decade have been estimated by [8] for three types of passive transmission equipment: OHL, cables and transformers. The observation on the 2010 cost data is still relevant for the below table. The main added value is in the estimated dropping rate as seen by manufacturers.

Table 52: Estimated indices for passive transmission technologies (starting year is 2010) [8]

	Unit cost of equipment for passive transmission technologies (M€/km)		
	OHL single circuit (M€/km)	Cable (M€/km)	Transformer (€/kVA)[71]
2010	0.64	2.94	0.55
2020	0.5-0.56 [±5%]	2.3 – 2.63 [±5%]	0.5-0.56 [±5%]
2030	0.43 – 0.53 [±10%]	2.0 – 2.48 [±10%]	0.43 – 0.53 [±10%]
2040	0.38 – 0.52 [±15%]	1.78 – 2.42 [±15%]	0.38 – 0.52 [±15%]
2050	0.33 – 0.51 [±20%]	1.6 – 2.4 [±20%]	0.33 – 0.51 [±20%]

5.9 Intermediate conclusions

The compilation of cost data for a selection of transmission equipment has been performed in the objective of use for the e-Highway2050 simulations.

The gathered data on costs in Euro of 2010-2013 should help the partners in charge of the simulations selecting an appropriate level of cost per type of transmission technology, and which will be the starting point of each cost trajectory.

Then a computation through evolution laws, either with models of evolutions for cost component as implemented in the dry-run test for overhead lines, or with dropping rates as carried out in the IRENE40 project allows building tentative cost trajectories for the next decades.

The limitations of these approaches have been examined as well as the sensitivity to factors such as the "space factor" and the features of the transmission equipment (technical performances). Next section proposes an implementation of a slightly adjusted approach taking into account:

- the lessons learned from the dry-run exercise on HVAC lines and cost trajectories of key transmission equipment as proposed by a recent EC funded project [8],
- the 2013 cost data of transmission equipment as extracted from recent sources.

The proposed approach in section 5.10 should be adopted from now on for the computation of costs for all transmission technologies.

[69] As for HVDC, the initial values set by [8] originate from various sources referenced in the IRENE40 deliverable. They have to be possibly adjusted according to the collection of data in the FACTS section. The main value of this table is to report the level of dropping rate per retained by IRENE40 for FACTS.

[70] Forecast data for TCSC seem to be the same as the data for SVC as indicated in table 3.12 of [8] page 109.

[71] Same remark as above. Source is table 3.14 of [8] page 111

5.10 Costs of key transmission equipment: archetypes and their cost trajectories over the period 2014-2050

5.10.1 HVAC OHL

The proposed approach to build the costs of overhead lines builds on the lessons learned from the previous sections and the principles set out in section 5.9.

- There are major variations in total costs for OHL depending on the context (power, terrain, etc.). These cost variations are of the same order of magnitude, if not higher, that the uncertainty related to the forecast at 2050. As a consequence, most effort should be focused on an accurate appraisal of the costs today.
- When the cost structure of an OHL project is known (equipment, installation, civil works, project management and right of ways), and when excluding the zonal/local cost components, costs forecasts can be achieved with a few indices: labor and engineering costs indices, energy-oil costs indices) as well as a complementary index capturing the experience gained by industry for producing the equipment/system. These five indices (LAB, OIL, ENG, METAL, EXP) could thus be reduced to four (LAB, OIL, ENG and a fourth one integrating EXP and METAL).
- IRENE-40 project has proposed trajectories for this fourth integrated EXP+METAL index reflecting the time evolution of key transmission equipment as seen by industry. In the following we will call "progress ratio" this integrated index. Figure 15 below depicts the simplified approach thanks to the contribution of IRENE-40.

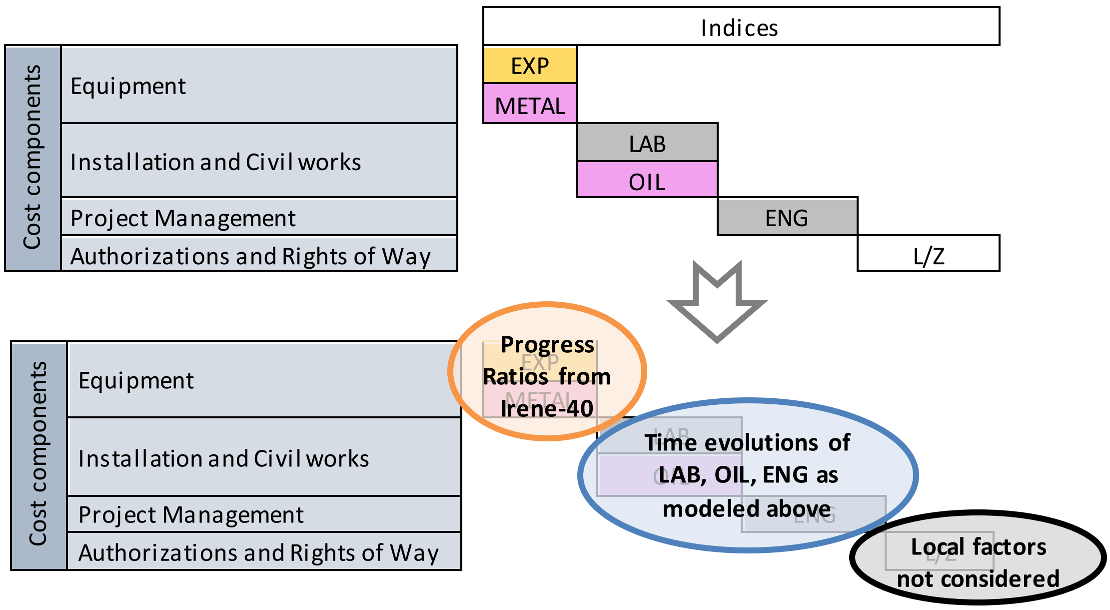

Figure 15: Simplified approach to model cost trajectories based on cost breakdown and representative indices

As a consequence, the following methodology is proposed:

- an accurate appraisal of the cost structure of an HVAC OHL archetype is provided in order to forecast the evolution of the cost structure from today to 2050 based upon three indices (labor, engineering and energy costs) and a progress ratio,
- for all other variants, a multiplier approach is used based upon the cost trajectory of the archetype. For the AC OHL technologies, the archetype is a 400 kV double circuit OHL installed in a rural plain terrain, with the following characteristics: 4 conductor bundle, AAAC, 4.3 GW per circuit. The variants can be 750 kV OHL, single/double circuit(s) OHL, OHL installed in other terrains (mountain environment for instance).

The inputs needed for such a methodology are detailed in Table 53.

Table 53: Archetype HVAC OHL and characterization variables.

	Source	Rationale for decision / comments
Archetype	e-Highway2050	400 kV double circuit OHL installed in a rural plain terrain, with a 4 conductor bundle, AAAC, 4.3 GW per circuit.
Total cost	1200 k€/km cf. assumption 1	The highest value from assumption 1 corresponding to a rural area in Northern Europe has been selected.
Cost structure	data of Table 25	
Indices LAB, OIL, ENG	projections of Table 27	The trajectories of these indices can be modified and adapted to be in line with the five e-Highway2050 scenarios and the assumptions made in WP2 for instance (scenario quantification task).
Progress Ratio	data of IRENE40 in Table 52	It has been assumed that the mean trajectory of Table 52 is a good proxy of the cost reductions that can be expected on equipment. This mean factor has been applied to the equipment component of the overall costs structure
Uncertainty on the costs components	Table 52	The uncertainty level provided by the manufacturers in IRENE40 (Table 52) for each decade is a relevant estimation of the expected uncertainty on the overall costs.

Table 55 shows the results of the computations[72]: the total costs of the archetype at 2050 should be in a range of 1077 k€/km to 1615 k€/km

For any other variants of the AC OHL technologies, multipliers should be applied. For the influence of the installation environment (terrain), the data of Table 23 should be used. It is assumed that this data remains valid whatever the chosen variant: 1.4 for urban terrain and 2.1 for mountain. The value for mountainous environment is in line with the values displayed in the AC OHL TAR in annex. Table 54 below displays other multiplier for the voltage level, the number of circuits, the number of conductor per bundle and the type of conductor (cf. AC OHL TAR).

Table 54. Multipliers for the overall costs of AC OHL.

Multiplier for higher voltages (from 400 kV to 750 kV)	1.63
Multiplier for higher voltages (from 400 kV to 550 kV)	1.25
Multiplier from double to single circuit	2/3
Multiplier from 4 to 3 conductor bundle	3/4
Multiplier type of conductor (AAAC to ACSS)	1.25
Multiplier type of terrain	1.4 (urban) 2.1 (mountain)

72 An OPEX of 2% of the CAPEX per annum has been assumed.

Table 55. Costs projection at 2050 of the AC OHL archetype, 400 kV, 4.3 GW, in rural plain

1200	**k€/km**			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		k€/km **2014**		k€/km **2020**				k€/km **2030**			k€/km **2040**			k€/km **2050**		
		Labor	**OIL**	**min**	**max**		**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**
Equipment	**34%**			408	408			345	381		296	361		262	354		230	345
						EXP	0,89			0,81			0,76			0,70		
Installation	**33%**	**60%**	**40%**	396	396			393	434		392	480		393	532		396	594
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	**8%**	**50%**	**50%**	96	96			97	107		98	120		100	136		103	154
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project Managmt	**15%**	**100%**		180	180	ENG	1,14	195	216	1,34	218	266	1,55	237	320	1,75	252	378
Right of ways	**10%**			120	120	N/A		114	126		108	132		102	138		96	144
CAPEX (k€/km)	**100%**			**1200**	**1200**			**1144**	**1264**		**1112**	**1359**		**1094**	**1480**		**1077**	**1615**
OPEX (p.a.)	**2,0%**			**24**	**24**			**23**	**25**		**22**	**27**		**22**	**30**		**22**	**32**

Table 56. Costs projection at 2050 of the 1100 kV DC OHL archetype.

2500	**k€/km**			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		k€/km **2014**		k€/km **2020**				k€/km **2030**			k€/km **2040**			k€/km **2050**		
		Labor	**OIL**	**min**	**max**		**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**
Equipment	**34%**			850	850			657	726		570	697		509	689		461	691
						EXP	0,81			0,75			0,70			0,68		
Installation	**33%**	**60%**	**40%**	825	825			819	905		817	999		819	1109		825	1237
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	**8%**	**50%**	**50%**	200	200			202	223		205	250		209	283		214	321
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project managmt	**15%**	**100%**		375	375	ENG	1,14	407	450	1,34	454	554	1,55	493	667	1,75	525	787
Right of ways	**10%**			250	250	N/A		238	263		225	275		213	288		200	300
CAPEX (k€/km)	**100%**			**2500**	**2500**			**2321**	**2566**		**2271**	**2776**		**2243**	**3035**		**2225**	**3337**
OPEX (p.a.)	**0.6-1,0%**			**25**	**25**			**23**	**26**		**23**	**28**		**22**	**30**		**22**	**33**

5.10.2 HVDC OHL

In order to derive the costs of HVDC OHL at 2050, it is proposed to duplicate the computations performed for HVAC OHL with the following hypotheses detailed in Table 57.

Table 57. Archetype HVAC OHL and characterization variables.

	Source	Rationale for decision / comments
Archetype	HVDC OHL TAR	Four archetypes provided in Table **47**
Total cost	HVDC OHL TAR	Total costs are provided in Table **47**
Cost structure	data of Table 25	The cost structure of an HVDC OHL project is similar to the one of an HVAC OHL project for a rural plain terrain
Indices LAB, OIL, ENG	projections of Table 27	Indices remain the same as for HVAC OHL
Progress Ratio	data of IRENE40 in Table 52	Same hypothesis as for HVAC OHL
Uncertainty on the costs components	Table 52	Same hypothesis as for HVAC OHL

Table 56 displays a computation performed for the HVDC OHL 1100 kV archetype. Table 58 shows the results for all archetypes supplied by Amprion.

Table 58. CAPEX and OPEX[73] in 2050 for a single circuit HVDC OHL as specified in Table 47

Voltage (kV)	320	500	800	1100
CAPEX (k€/km)	1068-1602	1423-2134	1780-2670	2225-3337
OPEX (k€/km/year)	6-10	9-13	11-16	22-33

For any other variant, it is proposed, as for HVAC OHL, to resort to multipliers as displayed in the table below.

Table 59**.** Multipliers for the overall costs of HVDC OHL.

Multiplier for single/double circuit	1.5
Multiplier type of conductor	N/A
Multiplier type of terrain	1.4 (urban) 2.1 (mountain)

5.10.3 HVAC underground cables

For fully HVAC underground cable solutions, a reference cost of 3500 k€/km has been fixed irrespective of the burden on territory (based on assumption 4) for the following archetype: double circuit XLPE cable 380 kV (2500 mm2 conductor) of 2x1 GW installed in a rural plain environment. In order to derive the costs of this archetype of HVAC cables, it is proposed to use the same methodology as for HVAC OHL.

Table 60: Archetype HVAC Cable and characterization variables

	Source	Rationale for decision / comments
Archetype	e-Highway2050	Double circuit XLPE cable 380 kV (2500 mm2 conductor) of 2x1 GW installed in a rural plain environment
Total cost	3500 k€/km	From assumption 4
Cost structure	data of Table 38	The closest variant correspond to a cable of 400 kV, 2000 mm^2, double circuit, rural plain
Burden on territory	12% of CAPEX	As indicated in Table 38, i.e. about 500 k€/km. Thus the total cost of the reference HVAC cable (including the land costs) is 4000 k€/km

[73] An OPEX ranging from 0.6 to 1% of the CAPEX per annum has been assumed in accordance with the data provided by Amprion (cf. TAR and datasheets for HVDC OHL).

Indices LAB, OIL, ENG	projections of Table 27	The trajectories of these indices can be modified and adapted to be in line with the five e-Highway2050 scenarios and the assumptions made in WP2 for instance (scenario quantification task).
Progress Ratio	data of IRENE40 in Table 52	The data of IRENE40 has been used in the same manner as for OHL. It therefore assumed that the mean trajectories of Table 52 (underground HVAC cables) is a good proxy of the cost reductions that can be expected on equipment and the uncertainty provided by the manufacturers in IRENE40
Uncertainty on the costs components		
OPEX	0.2% of the CAPEX per annum	

Table 68 shows the results of the computations: the total costs of the archetype at 2050 should be in a range of 3172 k€/km to 4758 k€/km (including land costs). For any other variants of the HVAC underground cable technology, multipliers should be applied.

Table 61. Multipliers for the overall costs of AC underground cables.

Multiplier for higher voltages	N/A
Multiplier for single/double circuit	2
Multiplier terrain	1.1 (rocky area) and 1.2 (urban area)
Multiplier tunnel	2 to 3

5.10.4 HVAC submarine cables

For HVAC submarine cables, it is proposed to use source [4] which details costs in Euro per meter of cable supplied (not installed) and the elements of costs for subsea cables installation.

From [4], the archetype HVAC 3-core subsea cable, 400 MVA operated at 245 kV, is supplied at a cost of 949 ±201 k€/km (i.e. 748-1150 k€/km excluding installation). Multiplying factors are provided in brackets for lower capacities and voltages below: they have been estimated based on median values of each proposed interval.

Table 62. HVAC 3-core subsea cable archetype and proposed multipliers to derive supplied HVAC 3-core cables costs based on **[4]**

Costs in k€/km of supplied HVAC 3-core subsea cable [multiplier index]		
MVA Rating	**Voltage (kV)**	**Supplied Cost (**k€/km)
200	132	518-805 k€/km [69.7]
300	220	575-863 k€/km [75.8]
400	**245**	**748-1150** k€/km [100]

The above values for the cost of equipment have to be adjusted based on the typical costs provided in the previous sections (see values on subsea installations provided below Table 42).

A first cross-check can be made using the AEMO source [3] for HVAC submarine cables which provides CAPEX for:

- the 3 core 132 kV 189 MVA estimated at about 1300 k€/km (1.70 in $M/km);
- the 3 core 220 kV 314 MVA estimated at about 1700 k€/km (2.18 in $M/km).

Both sources appear consistent in this first cross check. A second sanity check can be made based on the review of HVAC submarine projects detailed in Table 39 on some particular projects with actual cost elements (including installation costs)

- o HVAC XLPE cable, **single core** with a 3-phase AC connection: cf. the recently announced project by Nexans in Norway (3X30 km, 420 kV, 390 m max depth) and the related budget of **78 M€**

- HVAC XLPE cable, **3-core in two circuits**: cf. the Prysmian project to connect the BorWin cluster at 155 kV (2X31 km) and the related budget of **50 M€**, (announced in 2013)
- HVAC XLPE cable supplied by Nexans, **3-core in three circuits** in the Gulf of Evia (Greece) operated at 150 kV over a sea route of 21 km and 3 km underground, and amounting **64 M€** (announced in 2010).

When observing the last two projects and when assuming a cost of about 5 M€/km for the underground section of Gulf of Evia project, the sanity check leads to a cost of 50 M€ for the subsea connection for a total of approximately 60 km (either 2X31 km for the two circuits in 3-core or 3X21 km for the three circuits in 3-core also). This leads to a total cost of 0.8 M€/km[74] for the subsea 3-core for the 2nd and 3rd project: such cost might appear low with respect to the cost data provided by [4] (cable supplied, without installation) and [3] (cable supplied and installed). The discrepancy between these two data sets could be explained by many factors such as variability in installation sites and ratings.

5.10.5 HVDC underground cables

For HVDC underground cable, the following archetype has been chosen: XLPE cable, bipolar, 320 kV 1000 MW, installed in a rural plain environment at a reference cost of 1600 k€/km (including land costs).

Table 63: Archetype HVDC Underground Cable and characterization variables

	Source	Rationale for decision / comments
Archetype	e-Highway2050	XLPE cable bipolar 320 kV 1000 MW installed in a rural plain environment
Total cost	1600 k€/km	From assumption 5
Cost structure	data of Table 38	In order to forecast the costs at 2050, it was assumed that all computational parameters used for HVAC underground cables remain the same for HVDC underground cables, i.e. the cost structure, the burden on territory, the progress ratio and the uncertainty, the three indices as well as the OPEX.
Burden on territory	12% of CAPEX (see Table 38)	
Indices LAB, OIL, ENG	projections of Table 27	
Progress Ratio	data of IRENE40 in Table 52	
Uncertainty on the costs components		
OPEX	0.2% of the CAPEX per annum	

Table 69 displays the results of the computation: the total costs of the archetype at 2050 should be in a range of 1269 k€/km to 1903 k€/km (irrespective of additional burden on territory). For any other variants of this HVDC underground cable technology, multipliers should be applied. The multipliers of Table 61 should be used when relevant.

When considering HVDC underground cables costs displayed in Table 44 and Table 46 for various ratings of cables, one could propose a linear interpolation (proxy for a multiplier relative to power) as follow[75]:

- **Cost (HVDC underground Cable XLPE, 2013 value) [k€] = 1.35*P [MW] +278**

5.10.6 HVDC submarine cables

Based on the collected data in the previous sections, two archetypes could be considered:

- **XLPE submarine cable (HVDC):** see typical recent cost values in Table 42 and in Table 44 which could be combined to the progress ratios of Table 52 and multipliers derived from [4],

[74] This cost of 0.8 M€/km remains also valid for the first project in Norway: 90 km *0.8 = about 72M€ close to the 78 M€ announced by the manufacturer.

[75] This interpolation is robust for the cost of the proposed archetype.

- **Mass Impregnated Insulated submarine cable in HVDC**: see cost data provided in Table 43 and Table 44 and inputs from [4].

The 2000 mm² (cross-section) XLPE submarine cable operated at 320 kV is supplied at a cost estimated at 531.5 ±128 k€/km (403-660 k€/km excluding installation) [4].

The cost per route-km will depend for instance upon the number of poles and the number of cables per pole and consequently the above data should be used with suitable multipliers according to the desired configuration. Typical costs of installations are provided below Table 42 allowing several subsea installation combinations (e.g. single cable-single trench or twin cable-single trench or two single cables-two trenches).

When considering different cross sections and different voltages one should resort to the costs of cables supplied (not installed) provided by ENTSOE [4] and reproduced hereafter, i.e. Table 64. In this table, the proposed HVDC submarine archetype is highlighted in blue color. Multipliers (indices) are proposed in bracket with reference to the archetype [base 100]. Calculations of the indices are based on the median value of the min-max cost interval. Again, all costs related to installation have to be counted for afterwards (i.e. after application of the index) according to the specified configuration.

Table 64. Archetype of HVDC XLPE submarine cable and proposed multipliers to derive supplied HVDC XLPE submarine cables costs based on **[4]**

Costs in k€/km of supplied Subsea HVDC XLPE cable [multiplier index]		
Voltage **Cross sectional area (mm²)**	**150 kV**	**320 kV**
1200 mm²	230-460 k€/km [64.9]	345-518 k€/km [81.2]
1500 mm²	280-460 k€/km [69.6]	345-518 k€/km [81.2]
1800 mm²	345-518 k€/km [81.2]	345-575 k€/km [86.5]
2000 mm²	345-575 k€/km [86.5]	**403-660 k€/km** [100]

A cross-check of the above data can be made by using other sources:

- first with source [3] for HVDC submarine cables, which provides CAPEX for three configurations:
  - 2 M€/km (1.57 in $M/km) for a ±150 kV 352 MW bipole submarine cable,
  - 2.1 M€/km (1.64 $M/km) for a ±300 kV 704 MW bipole submarine cable,
  - 4 M€/km (3.12 $M/km) for a ±300 kV 1306 MW bipole submarine cable.
- then with the reference values already provided and based on the REALISEGRID source [5] for an HVDC undersea cable pair (voltage ± 350 kV; power rating 1100 MW), i.e. CAPEX estimated in a range of 1000-2000 k€/km,
- or with source [6] in Table 42 with typical values for HVDC XLPE submarine cables at ±300 kV as follow: 1900 k€/km for 700 MW, 2600 k€/km for 1000 MW, 3200 k€/km for 1200 MW.

The second archetype corresponds to a Mass Impregnated cable for HVDC submarine application. Data from different sources ([4] and the first part of Table 44 relative to ranges of costs of HVDC MI at 400 kV and 500 kV) are considered as consistent modulo the currency rate (GBP/EUR) which has evolved.

For consistency with the approach followed for the other HVDC archetype we propose to consider the ENTSOE data [4] relative to the MI subsea cable. Again the archetype is highlighted in blue color in the table below and the multiplier (indices) are indicted in bracket with respect to that archetype.

Table 65. Archetype of HVDC MI submarine cable and proposed multipliers to derive supplied HVDC XLPE submarine cables costs based on [4]

Costs in k€/km of supplied Subsea HVDC MI cable [multiplier index]		
Voltage **Cross sectional area (mm²)**	**150 kV**	**320 kV**
1500 mm²	403-660 k€/km [73.9]	460-660 k€/km [77.9]
1800 mm²	460-660 k€/km [77.9]	460-690 k€/km [80]

2000 mm²	460-690 k€/km [80]	460-748 k€/km [84]
2500 mm²	575-805 k€/km [96]	**575-863 k€/km [100]**

5.10.7 HVDC converters

The two archetypes chosen both VSC and LCC are the ones of assumptions 5 and 6, respectively VSC terminal, bipole 1 GW for 125 M€ and LCC Terminal 1 GW for 110 M€.

In order to derive the costs of these archetype of HVDC converters, it is proposed to use the same methodology as for HVAC/HVDC OHLs and cables:

Table 66: Archetype HVDC converters and characterization variables

	Source	Rationale for decision / comments
Archetype	e-Highway2050	VSC terminal, bipole 1 GW for 125 M€ LCC Terminal 1 GW for 110 M€.
Total cost	125 M€ for the VSC; 110 M€ for the LCC	From assumptions 5 and 6
Cost structure	Table 49	Installations costs and rights of way, which are not available are set to zero
Indices LAB, OIL, ENG	projections of Table 27	The trajectories of these indices can be modified and adapted to be in line with the five e-Highway2050 scenarios and the assumptions made in WP2 for instance (scenario quantification task).
Progress Ratio	data of IRENE40 in Table 45	It assumed that the mean trajectory of Table 45 (back to back HVDC) is a good proxy of the cost reductions that can be expected on equipment and the uncertainty provided by the manufacturers in IRENE40
Uncertainty on the costs components		
OPEX	2% of the CAPEX per annum	

Table 70 and Table 71 below show the results of the computations: the total costs of the LCC archetype at 2050 should be in a range of 90 M€/GW to 135 M€/GW, and the total costs of the VSC archetype at 2050 should be in a range of 105 M€/GW to 158 M€/GW. For any other variants of LCC and VSC technologies, multipliers should be applied.

Table 67. Multipliers for the overall costs of HVDC VSC and LCC converters (C_0 and P_0 represent the power and the costs of the archetypes), cf. section 5.5.2.

Multiplier for higher power (LCC)	$C = C_0 + 0.075\ (P-P_0)$
Multiplier for higher power (VSC)	$C = C_0 + 0.093\ (P-P_0)$

Table 68. Costs projection at 2050 of the HVAC cable archetype, double circuit XLPE 380 kV (2500mm2 conductor) of 2X 1 GW in rural plain environment

4000	k€/km			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		k€/km 2014				k€/km 2020			k€/km 2030			k€/km 2040			k€/km 2050	
		Labor	OIL	min	max		index	min	max	index	min	max	index	min	max	index	min	max
Equipment	59%			2360	2360			2010	2221		1730	2115		1532	2073		1373	2060
						EXP	0,90			0,81			0,76			0,73		
Installation	4%	60%	40%	160	160			159	176		159	194		159	215		160	240
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	11%	50%	50%	440	440			444	490		451	551		460	623		471	707
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project Management	14%	100%		560	560	ENG	1,14	607	671	1,34	677	828	1,55	736	996	1,75	783	1175
Right of ways	12%			480	480	N/A		456	504		432	528		408	552		384	576
CAPEX (kEUR/km)	**100%**			**4000**	**4000**			**3675**	**4062**		**3449**	**4215**		**3295**	**4458**		**3172**	**4758**
OPEX (p.a.)	**0,2%**			**8,00**	**8,00**			**7,35**	**8,12**		**6,90**	**8,43**		**6,59**	**8,92**		**6,34**	**9,52**

Table 69. Costs projection at 2050 of the HVDC cable archetype, XLPE cable bipolar 320 kV 1000 MW in rural plain environment

1600	k€/km			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		k€/km 2014				k€/km 2020			k€/km 2030			k€/km 2040			k€/km 2050	
		Labor	OIL	min	max		index	min	max	index	min	max	index	min	max	index	min	max
Equipment	59%			944	944			804	888		692	846		613	829		549	824
						EXP	0,90			0,81			0,76			0,73		
Installation	4%	60%	40%	64	64			64	70		63	78		64	86		64	96
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	11%	50%	50%	176	176			177	196		180	220		184	249		189	283
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project managnt	14%	100%		224	224	ENG	1,14	243	269	1,34	271	331	1,55	294	398	1,75	313	470
Right of ways	12%			192	192	N/A		182	202		173	211		163	221		154	230
CAPEX (k€/km)	**100%**			**1600**	**1600**			**1470**	**1625**		**1380**	**1686**		**1318**	**1783**		**1269**	**1903**
OPEX (p.a.)	**0,2%**			**3,20**	**3,20**			**2,94**	**3,25**		**2,76**	**3,37**		**2,64**	**3,57**		**2,54**	**3,81**

Table 70. Costs projection at 2050 of the HVDC LCC converter archetype.

110	M€/MW			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		M€/GW 2014				M€/GW 2020			M€/GW 2030			M€/GW 2040			M€/GW 2050	
		Labor	**OIL**	**min**	**max**		**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**
Equipment	**69%**			76	76			71	78		60	74		54	72		47	71
						EXP	0,98			0,89			0,83			0,77		
Installation	**0%**	**60%**	**40%**	0	0			0	0		0	0		0	0		0	0
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	**14%**	**50%**	**50%**	15	15			16	17		16	19		16	22		17	25
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project managnt	**17%**	**100%**		19	19	ENG	1,14	20	22	1,34	23	28	1,55	25	33	1,75	26	39
Right of ways	**0%**			0	0	N/A		0	0		0	0		0	0		0	0
CAPEX (M€/GW)	**100%**			**110**	**110**			**106**	**118**		**99**	**121**		**94**	**128**		**90**	**135**
OPEX (p.a.)	**2,0%**			**2,20**	**2,20**			**2,13**	**2,35**		**1,98**	**2,42**		**1,89**	**2,55**		**1,79**	**2,69**

Table 71. Costs projection at 2050 of the HVDC VSC converter archetype.

125	M€/MW			1	1			0,95	1,05		0,9	1,1		0,85	1,15		0,8	1,2
Breakdown per component (% of investment cost)		costs for each component		M€/GW 2014				M€/GW 2020			M€/GW 2030			M€/GW 2040			M€/GW 2050	
		Labor	**OIL**	**min**	**max**		**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**	**index**	**min**	**max**
Equipment	**63%**			79	79			67	74		60	73		53	72		50	74
						EXP	0,90			0,84			0,80			0,79		
Installation	**0%**	**60%**	**40%**	0	0			0	0		0	0		0	0		0	0
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Civil works	**22%**	**50%**	**50%**	28	28			28	31		28	34		29	39		29	44
						LAB	0,98			0,95			0,92			0,89		
						OIL	1,14			1,33			1,54			1,79		
Project managnt	**15%**	**100%**		19	19	ENG	1,14	20	22	1,34	23	28	1,55	25	33	1,75	26	39
Right of ways	**0%**			0	0	N/A		0	0		0	0		0	0		0	0
CAPEX (M€/GW)	**100%**			**125**	**125**			**115**	**127**		**111**	**135**		**107**	**145**		**105**	**158**
OPEX (p.a.)	**2,0%**			**2,50**	**2,50**			**2,31**	**2,55**		**2,21**	**2,70**		**2,14**	**2,89**		**2,10**	**3,16**

5.11 Sources used for cost of transmission systems

5.11.1 Sources used for data on costs

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5.11.2 Sources used for building evolution laws

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6 Quality issues

The validation of the database, i.e. all data gathered in the Excel files in annex, was performed based on a process involving an increasing number of reviewers. Each step aimed at gathering feedback to increase the robustness of the produced data on technologies:

- experts of professional associations validated the data produced by their organization (e.g. ABB experts for T&D Europe on active transmission technology),
- the Quality Pool, consisting of RSE, KUL, RTE and TECHNOFI, acted as reviewers of the data handed out by the different associations and experts (including academia and research centres),
- stakeholders' consultations and workshops (both internal and external) were held to challenge the data providers and enrich the technology database.

6.1 Preliminary work on technology boundary conditions

An upstream task was carried out before launching the data construction process in order to provide useful insights on technology data in terms of extreme ranges per technology for some variables, such as costs, capacity, and operations at two time horizons: today and 2050. They were based on the literature review performed by Eurelectric. This work revealed some difficulties which shed light on the construction of the database:

- a direct comparison of the data (costs and performances) found in the literature, for the same technology, was difficult to perform due to lack of information[76].
- a lack of data for some technologies still in demonstration phase, such as marine technologies or CCGT with CCS, or for some technologies that could be obsolete by 2050 (NiCd or NiMH batteries as it is suggested by many electrochemical storage experts that these batteries will no longer be in use by 2050).
- for storage technologies, EASE, the European storage association, underlined that storage technologies must be considered for a given application/service in a given location since the costs and technical characteristics might differ

6.2 Validation by professional associations

Professional associations, representing industry and involved in Work Package 3, played two specific roles:

- build and validate data trajectories characterizing technologies for each decade from today to 2050,
- for transmission technologies, provide a feedback on the technology archetypes identified in chapter 5. Europacable and T&D Europe did not provide any validation on cost data produced by Technofi with the assistance of TSOs.

6.3 Validation by the Quality Pool

The Quality Pool, acting on behalf of WP3 partners, performed the validation of the data produced by WP3. A systematic review by Quality Pool members (RSE, KUL, RTE, and Technofi) was made all along the data gathering process. One or two revision loops were necessary to reach the required standards of quality. Criteria of quality used by the Quality Pool were:

- Completeness of the critical variables included in the data sheets,
- Consistency of the data sheets with state-of the art knowledge for each technology: current deployment and expected maturity trends,
- Completeness and consistency of a technology assessment report describing the data and the technology outlook at 2050.

[76] E.g. for wind power most of the publicly available sources do not distinguish between "wind offshore far from coast" and "wind offshore close to coast", whereas industry experts, i.e. EWEA, were able to provide this kind of information.

6.4 Consultations and stakeholders workshop

Further to the validation by Quality Pool, the database was discussed during several consultations including:

- the project partners (through the consortium review of the current deliverable and three internal workshops for generation, storage and transmission technologies),
- external stakeholders, including professional associations and players, beyond the project consortium.

In particular an external stakeholders' workshop was organized on April 15th 2014 in Brussels in order to collect stakeholders' feedback.

7 Using the technology characterization database

A datasheet is closely linked to the corresponding Technology Assessment Report (TAR) which sets the hypotheses and provides additional information and explanations relative to the data contained in the Excel file. The annexes are organized per technology: for each technology, there is a pair of documents (datasheet; technology assessment report).

7.1 List of datasheets and technology reports for generation and storage technologies

Table 72: Collected data sheets and TAR for generation[77] and storage[78]

	Technology	Filename	Nature of document	Author
G	Portfolio of generation technologies and storage technologies	report_generation_Eurelectric VGB report_generation_annex1_Eurelectric VGB	Technology assessment report for the whole area	EURELECTRIC/VGB Power Tech
G1	Photovoltaic[79]	data_solar_VGB	Data	EURELECTRIC/VGB Power Tech
G2	Concentrated Solar Power		Data	EURELECTRIC/VGB Power Tech
G3/4	Wind (onshore, offshore)[80]	report_wind power_EWEA	TAR	EWEA
		data_wind power_VGB&EWEA	Data	EWEA EURELECTRIC/VGB Power Tech
G6/7	Hydro (run of river, reservoir)	data_hydro_VGB	Data	EURELECTRIC/VGB Power Tech
G8	Gas turbines (OCGT, CCGT)	data_gas_VGB	Data	EURELECTRIC/VGB Power Tech
G9/10 G12	Hard coal and lignite (with and w/o CCS)	data_thermal_VGB	Data	EURELECTRIC/VGB Power Tech
G13	Nuclear Generation III, III+ and IV	data_nuclear_VGB	Data	EURELECTRIC/VGB Power Tech
G14	Biomass stand-alone[81]	data_biomass_VGB	Data	EURELECTRIC/VGB Power Tech
G17	Combined Heat and Power	report_CHP_IEN data_CHP_IEN	TAR and Data	IEN
cS1	Pumped hydro storage	data_pumped hydro_VGB	Data	EURELECTRIC/VGB Power Tech

[77] This table includes also technology cS1 Pumped Hydro which has been described by Eurelectric VGB Tech in the "supply block generation"

[78] The University of Comillas focused on BESS and CAES technologies. For BESS, the main attention was focussed on the following technologies: lead acid, nickel cadmium, sodium sulphur, zebra, lithium-ion, vanadium redox, Zinc Bromine, Regenesys. No distinction was made between centralized and distributed BESS: since BESS are highly modular, size is a secondary factor in the assessment of the BESS technology. All datasheets on BESS and CAES technologies are documented by two dedicated reports, one for BESS and one for CAES.

[79] The data provided by VGB Power Tech regarding PV has been assessed as very conservative (both in performances and costs) by external experts. There is an ongoing study carried out by Agora Energiewende and the Fraunhofer Institute in which the assessments of costs of PV at 2050 strongly differ from the ones provided by VGB. This study is not available yet but it should be considered when published, i.e. in the fall 2014.

[80] **The reference data for wind power is that of EWEA and the data of VGB is given as information**. It is clearly stated in the datasheet (color code) if one refers to the data of EWEA or VGB.

[81] Biomass co-firing (with coal and lignite) is addressed in the hard coal and lignite data sheet.

S	Portfolio of electrochemical storage technologies	report_batteries_Comillas	TAR and data	U. Comillas
cS2	Compressed Air Energy Storage	report_CAES_Comillas data_CAES_Comillas	TAR	U. Comillas
cS3 cS4 dS1 dS2	Batteries- (centralized and decentralized)	data_batteries_Comillas including 6 spreadsheets - Lead-acid,- Lithium ion, - Nickel cadmium (NiCd),- Hot batteries (Sodium sulfur and Zebra),- Metal (Li&Zn) Air, - Li S and 3 spreadsheets Vanadium redox, Regenesys, Zn Br.	Data	U. Comillas

7.2 List of datasheets and technology reports for demand-side technologies

Table 73: Collected data sheets and TAR for demand-side technologies

	Technology	Filename	Nature of document	Author
D	Demand-side technologies	report_demand technologies_selection_a report_demand technologies_selection_b	Technology assessment report for the whole area and rationale for selection	Technofi
D23	Electric vehicles	report_electric vehicles_Technofi data_electric vehicles_Technofi	TAR and data	Technofi
D4- D6- D7- D13	Heat Pumps	report_heat pumps_Technofi data_heat pumps_Technofi	TAR and data	Technofi
D3- D10- D11	LED/OLED	report_ LED and lighting_Technofi data_LED and lighting_Technofi	TAR and data	Technofi

7.3 List of datasheets and technology reports for transmission technologies

Table 74: Collected data sheets and TAR for transmission technologies

	Technology	Filename	Nature of document	Author
C	Overview on cables technologies	report_cables_Europacable	Technology assessment report for the whole area and rationale for selection	Europacable
C1	XLPE HVDC Cables	data_XLPE HVDC cables_Europacable	Data	Europacable
C2	XLPE HVAC 380-420 kV Cables	data_XLPE HVAC cables_Europacable	Data	Europacable
C3	MI HVDC Cables	data_MI HVDC cables_Europacable	Data	Europacable
C6	Superconducting conductors	data_superconducting cables_Europacable	Data	Europacable

A1 to A5	HVDC converters	report_HVDC_T&D Europe data_HVDC_VSC_CSC_T&D Europe	TAR and data	T&D Europe
A6 A7 A8	FACTS	report_FACTS_T&D Europe data_FACTS_T&D Europe	TAR and data	T&D Europe
A9	Transformers, AC breakers	report_transformers AC breakers_T&D Europe data_transformers AC breakers_T&D Europe	TAR and data	T&D Europe
A12	Protection (system level)	report_protection and control_T&D Europe data_protection and control_T&D Europe	TAR and data	T&D Europe
O1 to O4	OHL-classic conductors	data_DC_OHL_Amprion data_AC_OHL_RTE report_AC_OHL_RTE report_DC_OHL_Amprion	TAR and data	RTE; Amprion
O5 to O9	OHL-high temperature conductors			