# e-HIGHWAY 2050

## Modular Development Plan of the Pan-European Transmission System 2050

| | | | |
|---|---|---|---|
| **Contract number** | 308908 | **Instrument** | Collaborative Project |
| **Start date** | 1st of September 2012 | **Duration** | 40 months |
| **WP 3** | **Technology portfolio to meet the 2050 scenarios** | | |
| **D3.1** | **Technology assessment from 2030 to 2050** | | |

# Annex to D3.1 - Technology Assessment Report

## *Transmission Technologies: HVAC Overhead lines*



| Revision | Organisation | Date |
|---|---|---|
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| Project co-funded by the European Commission within the Seventh Framework Programme | | |
|---|---|---|
| Dissemination Level | | |
| PU | Public | |
| 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) | X |

# Document information

### General purpose

This document is an annex of deliverable D3.1 focusing on the technology assessment (technical and economic performances) of generation, storage, transmission and demand-side technologies. It includes the assessment and outlook of the key components of the HVAC overhead lines technology i.e. conductors. It details the rationale of the line design assumptions made for this study and provides an explanation of the key variables selected by RTE, the methodology for the data construction as well as a technical outlook as of today and 2050 regarding HVAC OHL.

### Change log

| Revision | Date | Changes description | Authors |
|---|---|---|---|
| V1 | 10-07-2014 | First draft | RTE |
| V2 | 29-08-2014 | Updated version further to project review | RTE |

### Acknowledgements

This document was drafted by the technical experts of RTE, as a contribution to D3.1

### Legal disclaimer

The present report reflects the best knowledge of RTE experts at the moment of its writing.

# Table of content

## Glossary and acronyms

### *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 Aluminium Alloy Conductor |
| **ACSS** | Aluminium Conductor Steel Supported |
| **ACSS/TW** | Aluminium conductor Steel Supported, Trapezoidal shaped Wire strands |
| **ACCR** | Aluminium Conductor Composite Reinforced |
| **ACCC** | Aluminium Conductor Composite Core |
| **MMC** | Metal Composite Conductor |
| **PMC** | High Performance Organic Composite Core conductor |
| **TACSR** | Thermal resistant Aluminium alloy Steel reinforced |
| **KTAl** | High Strength Thermal Resistant Aluminium Alloy |
| **KTACSR** | High strength thermal resistant Aluminium alloy Steel reinforced |
| **GTACSR** | Ultra thermal resistant Aluminium alloy Steel reinforced |
| **GZTACZR** | Gap type Ultra thermal resistant Aluminium alloy Steel reinforced |
| **TACIR** | Thermal Resistant Aluminium Alloy Conductor, Invar Reinforced |
| **TACSR** | Thermal Resistant Aluminium Alloy Conductor, Steel Reinforced |
| **TAl** | Thermal-resistant Aluminium (aluminium zirconium alloy) |
| **ZTACSR** | Aluminium Clad Steel Reinforced |
| **ZTACIR** | Aluminium Clad Invar Reinforced |

# 1 Introduction

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

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

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

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

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

# 2 HVAC OHL performance characteristics

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

## 2.1 Assumptions on optimized parameters in line design

This section explains the optimized parameters selection for the calculation of HVAC OHL performance.

### 2.1.1 <u>Type of bundle</u>

The number of conductor per phase will greatly impact the performance of the line.

First, the higher the number of conductors, the higher the transmitted power, and consequently it is more efficient when considering losses (at the same current flow). On the opposite, mechanical constraints are increased on the towers which induces additional costs.

For the present study, a 4 conductor bundle for each phase appears to be a good compromise (see rationale for these assumptions in section 2.3.1).

### 2.1.2 <u>Number of circuits</u>

The performance of the line is also affected by the number of circuits installed per tower. The optimum commonly used is two circuits per tower. Increasing the number of circuits per tower could have a good effect on land use because it increases the transmission line capacity.

However, a safe grid operation requires that a single failure (N-1) has to be of limited and controllable effect. More than 2 circuit on a single tower would lead to great risks of high electrical constraints in case of failure. Moreover, the shape of the tower would be very massive with such a visual impact that public acceptance specifications would not be met any longer.

#### 2.1.3 Voltage level

As mentioned above, an increase of the voltage level seems to be hardly acceptable by the public: increasing the voltage level results in higher towers, higher level of electric fields, possibly specific insulators design and more noise disturbance issues.

Though, it could be useful to examine the increased performances than can be reached with a higher voltage level (especially on losses), for long transmission corridors (over 500 km) and huge power flows (several GW), and to compare them with the standard solutions. In order to make possible such a comparison, some data are provided for 750 kV HVAC OHL (see joined Excel file) - the voltage level of the line will not affect the conductor design but only the global geometry, and of course the electrical performances (see rationale for these assumptions in section 2.3.1).

### 2.2 Performance of HVAC related to conductor choice

#### 2.2.1 Maximum current capacity [kA]

Maximum current capacity of a conductor technology depends on the following conductor properties:

- Conductor design (stranding, type of wire, cross-section, diameter, etc.)
- Maximal allowable temperature in the conductor under continuous operation.

Computation (performed using “thermal balance equation” from CIGRE with the following climatic data:

- Wind speed of 0.5m/s with 45° angle between wind and conductor
- Air temperature of 15°C
- Solar radiation of 300 W/m²

#### 2.2.2 Losses through the line [%/km]

Losses through the line have to be calculated considering the line operation at nominal current. The nominal current value has to be representative of the normal operation of the line. For this study, a nominal current of 4 kA per circuit has been considered.

The dissipated power will depend on the resistivity of the conductor used (see Excel files), but for a first estimation, losses at nominal current can be considered at 0.01%/km.

### 2.3 Assumptions for the expected evolutions of technical data from 2013 to 2050 for conductor technology

This section is organized in two subsections:

- a presentation of conductors existing technologies with a focus on the most interesting ones
- a technical outlook at 2050.

#### 2.3.1 Technical outlook today (2013)

The expected functionality of an Overhead Line (OHL) is to carry electric power, which means a certain amount of current in conductors under a certain voltage by solving several issues in the most optimal way:

- Electrical performances of conductors
- Mechanical performances of towers and conductors under normal and severe climatic conditions
- Third party security
- Environmental issues:
  - Visual impact of the line
  - Electric and magnetic fields in the vicinity of the line
  - Noise
- Minimum cost depending on:
  - Conductor technology, i.e. electrical performances and behavior (thermal dilatation) versus mechanical features (weight, maximum temperature, etc.)
  - Overall line design including tower design (height, quantity of raw material, etc.)
  - Civil works depending of the mechanical constraints induced by the towers.

The final design of the line is thus a difficult optimization exercise, which is specific for each reinforcement project.

The difficulty of the data gathering exercise is to propose standard overhead lines that can be directly used when defining the reinforcements to be proposed in the project. The following choices were made by the eHighway2050 project (cf. annex B for the selection process):

- Selection of candidate conductors (see Figure 1).
- Selection of the voltage level:
  - 400kV
  - No real trend towards Ultra High Voltage in Europe where EMF constraints are important. However, a voltage of 750kV was considered in the case of a high performance conductor. Should on-going or future grid simulations conclude on critical needs for grid development, dedicated comparative impact analysis would be needed between implementing a high number of 'standard OHL' versus a limited number of more impacting 'UHV OHL'.
- No consideration of the specific design of the towers taking into account aesthetic issues.
- A «reasonable» overall design of 2 three-phase circuits on one tower; as we are looking for rather high level of transmitted power, more than 2 circuits on the same tower would lead to too high electrical constraints on the grid in case of tower failure.
- 4 conductor bundle for each phase; an increased number of conductors on the same bundle would lead to mechanical constraints that we do not consider as an optimal solution.

***Figure 1*** below shows the conductors to be considered in the selection process of HVAC OHL technologies for eHighway2050 (highlighted in red).

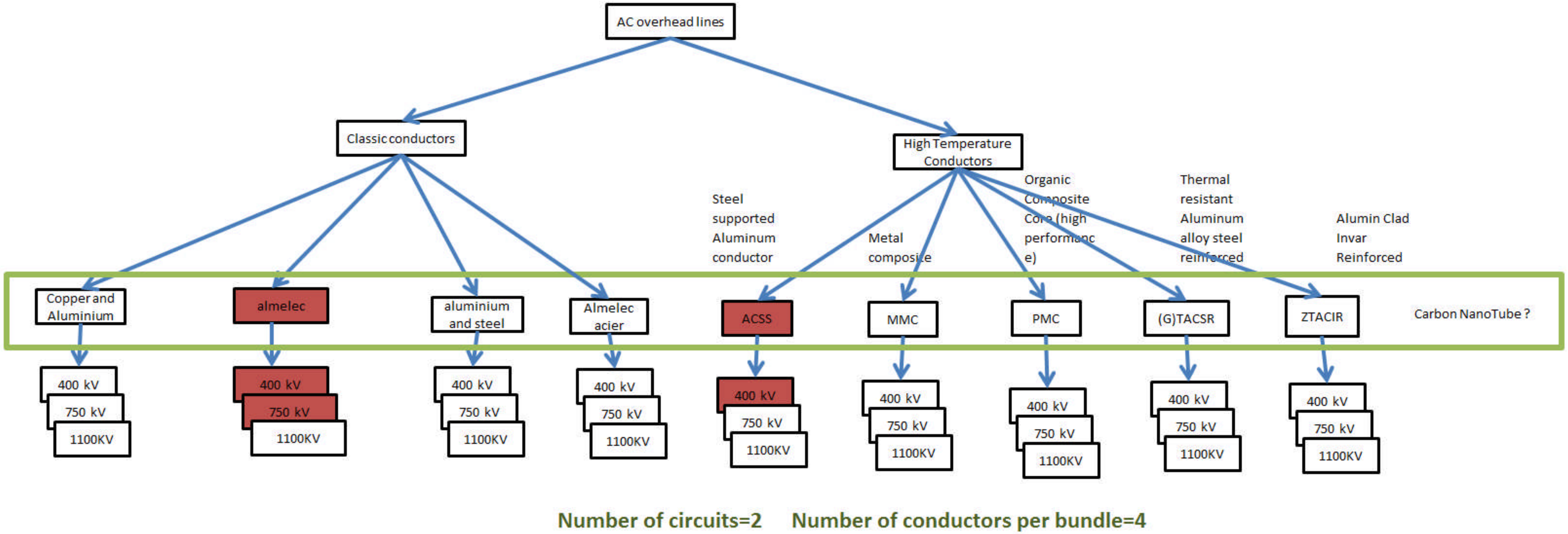



**Figure 1 : HVAC OHL technology options and selected technologies in the e-Highway2050 portfolio** *(in red color)*

The following sections detail the reasons of selection/discard for each particular HVAC OHL technology.

#### 2.3.1.1 Old technologies; considered of no interest for e-Highway2050

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

#### 2.3.1.2 Technologies considered of interest for e-Highway2050

- **AAAC** (All Aluminum Alloy Conductor) – Standard conductor: it appears as a good compromise between technical and economic aspects; it is a well-known technology (over 50 years of field experience). RTE uses a specific Aero-Z AAAC, which is considered to be the best technical optimization technique with AL4 Aluminum Alloy.

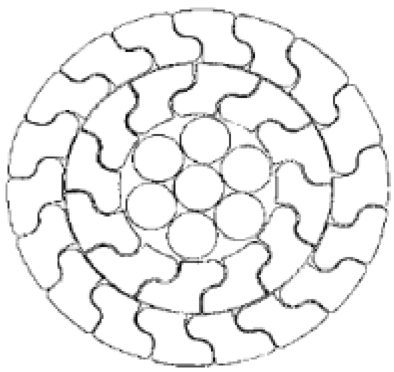


**Figure 2 : AAAC structure**

- **ACSS** (Aluminum Conductor Steel Supported) - HTLS conductor: the high operation temperature (more than 200 °C) requires the use of Annealed Aluminum; this conductor presents a very good mechanical strength but is heavy compared to AAAC.

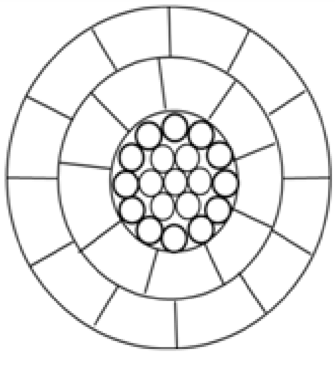


**Figure 3 : ACSS structure**

The installation needs a pre-stressing operation, and a careful handling of the conductor. (about ten years of field experience)

#### 2.3.1.3 Other conductor not selected for this study:

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

**Table 1: Advantages and limitations of the selected technologies for HVAC OHL**

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

The technology portfolio for HVAC OHL with respect to the whole technology portfolio of passive transmission technologies is depicted in the Figure 4 below. The three HVAC overhead line reference cases include the two types of conductors (AAAC, ACSS) at 400 kV, the third one being AAAC at 750 kV.

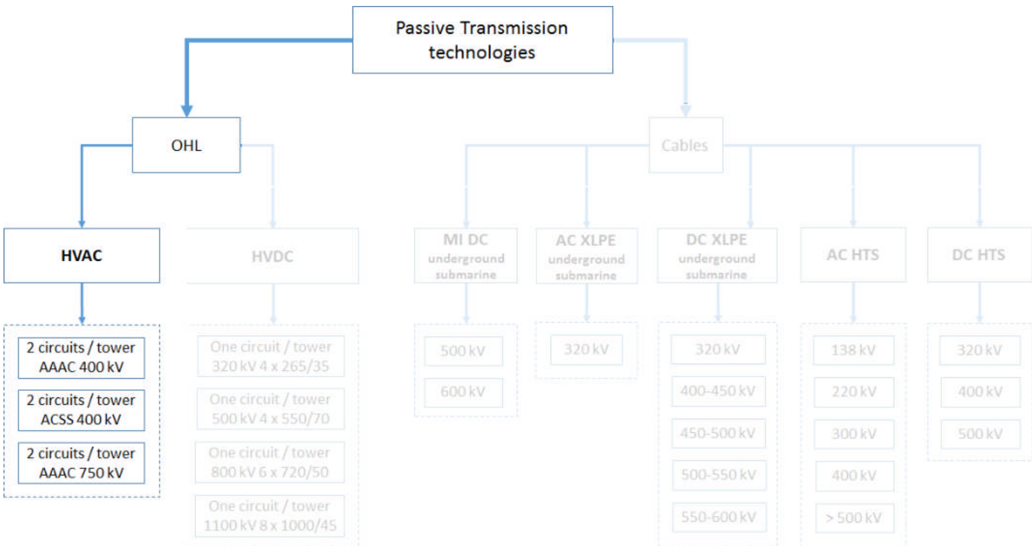



**Figure 4: The HVAC OHL portfolio as part of the passive transmission technologies portfolio**

### 2.3.2 Technical outlook at 2050

In the long term, PMC is expected to become a mature technology but, as far as it can be foreseen, it will probably have equivalent performances compared to the current ACCR conductors. Reduction of costs are likely to occur.

In the future, nanotechnology could emerge providing a great increase in conductor performances (ampacity, weight, mechanical behavior, etc.) This field is under early investigations, and it is risky to formulate reasonable projections for the time horizon of the commercial exploitation stage.

## 2.4 General performance and limitations of HVAC OHL

Considering the previous assumptions, some performance characteristics will not depend on the conductor choice. These characteristics are listed below:

- Maximum allowable length of the line:
  Unlike for underground cables, the generation of reactive power is not a limiting factor for the length of an OHL operation. But another phenomenon lies at the root of the length limitations. A given OHL is characterized by a specific maximum transmissible power, which depends on its impedance and operating voltage (see Annex A). Since the impedance is linearly linked with length, there is a length limitation to operate an OHL at its full capacity[1].
- Losses: ~0,01 %/km at 4 kA
- Failure rate per 100 km: see Working Group 22.13, "Management Of Existing Overhead Transmission Lines", Cigré, 2000
- Mean time to repair failure: see Working Group 22.13, "Management Of Existing Overhead Transmission Lines", Cigré, 2000

# 3 Technology readiness and maturity

All the conductor technologies selected for the e-Highway2050 study are mature (AAAC and ACSS).

# 4 Costs

Cost data are provided in the main deliverable D3.1 and are based on several bibliographic sources.

The assumptions foresee the installation of a *HVAC overhead line, in plain, terrain, with lattice towers for the two types of conductors (AAAC, ACSS) at 400 kV, and AAAC at 750 kV*.

For the ACSS conductors, the costs include the pre-stretching operation that decouples steel (sustaining the mechanical constraints) from annealed aluminum (part directly contributing to the power flow), an operation which provides two major advantages:
- the damping of the conductor’s vibration, and
- the limitation of the sag to benefit from the maximum available capacity.

In order to estimate the cost elements on configurations different from the reference case studies, some multiplicative corrective factors (multipliers) must be applied. These cost ratios are based on RTE’s experience and are detailed in the table below.

[1] Series capacitor or SVC/Statcom could help to improve the limit but the huge amount of GVAR required to do so are generally not worth the increase.

They are expressed with regard to the reference case : ***400 kV HVAC OHL, 4 AAAC conductor bundle, 2 circuits, in rural plain area*****.**

**Table 2: Cost ratios for HVAC OHL (relatively to the reference case 400 kV HVAC OHL, *4 AAAC conductor bundle*, 2 circuits, in rural plain area**)

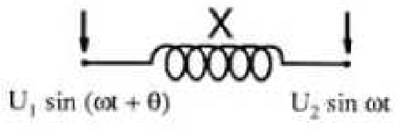
| | **Proposed cost ratio with regard to reference case** | |
|---|---|---|
| **Configuration modification** | **Cost ratio** | **Rationale** |
| Four-conductor to three-conductor bundle | x 3/4 on linear cost | Average ratio from available data |
| Double circuit to simple circuit | x 2/3 ratio on linear cost | Average ratio from available data |
| Plain to mountain | x 1,7 ratio on linear cost | Over-cost due to higher mechanical constraints (e.g. icy conditions) and the more difficult access conditions. |

It should be noticed that the linear cost given by RTE for terrain (plain to mountain) has to be applied on the actual length of the considered OHL, starting from point A and ending on point B, which is different from the distance (length measured on a map directly) between A and B.

For example, in mountain areas, it is common to observe a +15/+20 % increase of the actual length compared to the direct distance (due to scarce locations fitting for tower building, height differences).

# 5 Annex A: maximum transmissible power

In a strong and well-meshed transmission system, the voltage can be considered as well maintained at its nominal value everywhere in the system. The power flow in a link between two nodes of this system is ruled by the well-known equation:




$$P = \frac{U_1 U_2}{X} \sin\theta$$

*(with U : phase to phase voltage)*

For a given OHL, the impedance is fixed by the length and by the structure (geometric structure especially linked with the number of conductor per bundle, number of circuit and of course the operating voltage).

The maximum power that can flow in steady state through this OHL is reached for $\theta = 90$ °, and is equal to:

$$P_{max} = U_1 U_2 / X$$

*(assuming that voltage is controlled and maintained at both ends of the OHL)*

Figure 5 illustrates a range of maximum transmissible power for typical OHL.

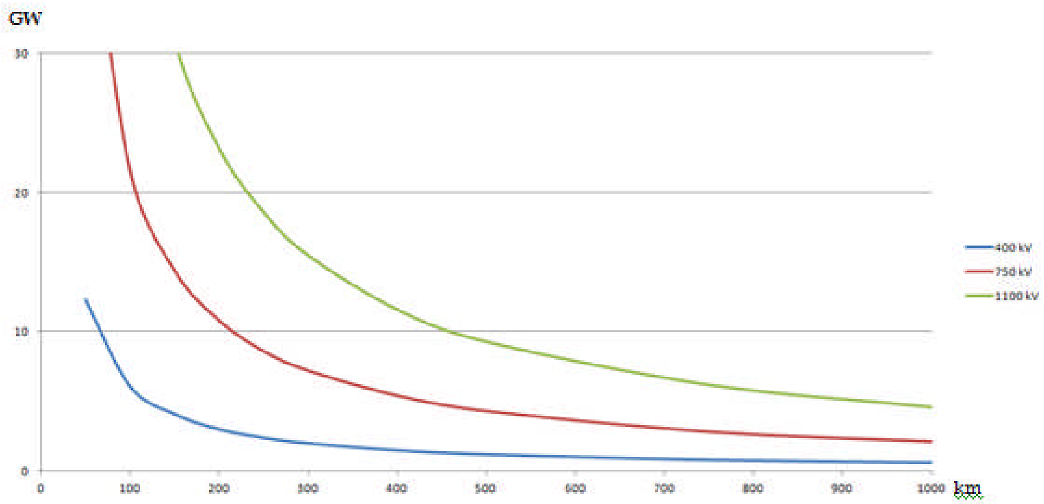



**Figure 5 : Maximum transmissible power for typical OHL**

# 6 Annex B: taxonomy of HVAC OHL systems and rationale for selection of the portfolio

**Taxonomy of HVAC OHL systems**

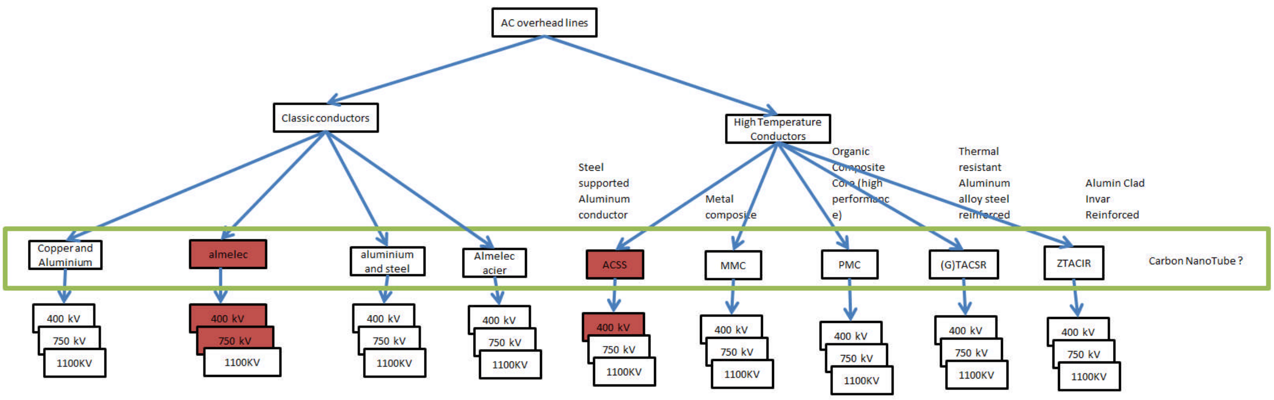
Overhead lines can be distinguished following four axes:

- the nature of material used for the conductor and the number of conductor per phase.
- the type of towers used to bear the weight of the conductors
- the design of foundations
- the level of voltage.

An overhead line (OHL) is a complex system where all these elements are chosen and optimized for each particular OHL project.

**Rationale for selection of HVAC OHL in the e-Highway2050 technology portfolio**

For the e-highway2050 project, it has been proposed to only consider two out of these four parameters, i.e. the level of voltage and the material used for the conductor (as well as the number of conductors). The other two dimensions (type of towers and foundations) are indeed project specific and impact only the cost of the system.




Number of circuits=2 Number of conductors per bundle=4

**Validation during the external workshop**

During the WP3 external workshop, April 15th 2014, session on overhead lines, the above approach as well as the "reasonable" architecture were presented to stakeholders attending the workshop by C. Counan, RTE.

A central question was then discussed during the Q/A session moderated by Mihai Paun, ENTSOE: *to which extent do you agree on the design choices selected by eHighway2050?*

**Discussion during the Q/A session[2]**

The discussion session included exchanges on operating such lines: voltage, AC/DC, acceptance issues. An important remark should be highlighted on the resulting reinforcement solutions. These solutions are under the responsibility of Work Package 2 through system simulations and they will

[2] Topics are beyond the scope of HVAC OHL but are reported here for consistency reasons

clearly depend on the type of constraints in the local context and of the scenario. The discussion reported below should be read in this context.

**Could we say that in the future a voltage of 750 kV will be feasible for transmission in Europe?**

One major point is that Europe is very densely populated. Thus when you build a line the acceptance question is very important. The EMF issue and the visual aspects are also key. It will be difficult to operate above 400kV but this parameter could be a parameter to study.

**What could be the benefits of increasing the voltage to such levels?**

The increased transmitted power would be the main benefit. In a line you have a reactance which creates a problem if you carry huge amounts of energy over a long distance. You will not be able to be above 3 or 4 GW and you will need some FACTS or service capacitors, in order to reduce the reactance which will increase the complexity in the grid. With higher voltage you can transport higher power without such problems.

**What about DC?**

It is a competition with DC, we do not have the same issue with distance but the grid is quite short in Europe, the lines will be rather short and this is a problem for DC.

A key issue is brought by ENTSOE: it is much easier to deal with reactance than with public acceptance issues.

**In addition to the development in conductors, which developments do you expect in terms of design?**

The question is that it is much more expensive to build an aesthetic line.

**In terms of efficiency, do you consider to monitor the temperature of the conductor?**

This should be an interesting information; but only if we can deliver the information to the dispatcher with a forecast (wind, temperature) at day-ahead. In the case of wind power production, there is an interesting conjunction, i.e. when there is wind the temperatures of the conductors are lower (forced convection), and this should allow to increase the load. This issue is currently under investigation.

**With regard to technical evolutions at 2050, how to describe the configuration of the grid in terms of lines and underground cables?**

From the point of view of TSOs, how the HVDC grid will expand is the most important issue. This will change the balance between lines and underground cables.

From cable manufacturers' point of view, underground cables will allow overcoming public acceptance constraints. This will have some system implications which will have to be looked at carefully.

**What about the approach for the selection of the transmission technologies in 2050?**

The aim of our work is to provide technology descriptions and assessments which will be used as inputs in order to select technologies for power system simulations. At the end of eHighway2050 project, we will be able to conclude on the chosen technologies. This is too early today.

# 7 Attached document to the Technology Assessment Report

Excel file including date 2013-2050 on the three configurations of the reference case: 400 kV HVAC OHL, 4 AAAC conductor bundle, 2 circuits, in rural plain area.