e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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Document information

General purpose

This deliverable summarizes the activities carried by WP6 in Task 6.7 “Cost-benefit analysis of grid architectures and modular plan 2030-2050” and it shows the application of the WP6 BCA methodology and the WP6 toolbox in order to evaluate cost and the benefits related to the envisaged network reinforcement plans at the target years 2050 and 2040.

Change status

Revision	Date	Changes description	Authors
V1.0	16.11.2015	First draft	F. Careri (RSE)
V2.0	02.12.2015	Revision after public consultation	F. Careri (RSE)

EXECUTIVE SUMMARY

This deliverable shows the results achieved in Task 6.7 "Cost-benefit analysis of grid architectures and modular plan 2030-2050" of the Work Package 6 "Socio economic profitability" in the e-Highway2050 research project: in particular, this document shows the application of the WP6 BCA methodology and the WP6 toolbox – for evaluating monetized benefits and costs – to the envisaged network reinforcement plans at the target years 2050 and 2040.

The WP6 BCA methodology has been applied for the following analyses taking into account the average over the Monte Carlo years provided as output by WP2 and WP4 simulations performed with ANTARES tool: it is assumed that the *without case* is represented by the "starting grid" ANTARES case, while the *with case* is represented by the last available "reinforcement step".

Taking into account the project approach, the aforementioned evaluations have been performed in coherence with the assumptions provided by the involved work packages (in particular, WP2 and WP4 for 2050 and 2040 target years, respectively). This has led to a set of simplification to the approach proposed in [1]: the most impacting assumptions are summarized below:

- for each Scenario, one reinforced grid architecture (described in terms of transmission corridors to be reinforced and reinforced transmission capacity) has been simulated by means of ANTARES, while the different technological solutions consequent to the public acceptance of new transmission assets (three Strategies) has been determined *ex-post* to those simulations.
    - **Strategy 1** – *New grid acceptance*. The public opinion accepts new OHL and also the development of new corridors. DC cables are also possible but OHL are preferred when possible due to their lower costs;
    - **Strategy 2** – *Re-Use of Corridors*. The public opinion accepts new OHL as long as they are close to existing lines. Therefore new AC or DC Overhead-lines can be implemented when they are in the existing corridors;
    - **Strategy 3** – *Status quo*. The public opposition against new infrastructure prevents any new OHLs. Only refurbishment of existing lines or new DC cables can be implemented.

  This is the reason why core and non-core indicators provided as output from WP6 toolbox and linked to ANTARES inputs and outputs have similar values in all the three Strategies;
- regarding life cycle costs, only CAPEX have been considered;
- CO2 emission ta value is assumed equal to 270 €/t and 189 €/t at 2050 and 2040, respectively;

- due to the limited impact, the reduction of market power (in terms of bidding strategies on generation cost curves) achievable thanks to network reinforcements has not been assessed;
- due to the modelling approach of AC transmission network reinforcements in ANTARES, the additional RES installed capacities achievable thanks to transmission network development have not been calculated;

Given those assumptions, the 2050 and 2040 evaluations have been performed for the five project Scenarios:

- **Scenario X-5** – *Large scale RES and low emissions*
- **Scenario X-7** – *100% RES*
- **Scenario X-10** – *Big and Market*
- **Scenario X-13** – *Large fossil fuel with CCS and nuclear*
- **Scenario X-16** – *Small and local*

for a total of ten cases (five scenarios times two target years). Each case is described in terms of:

- monetized core benefit indicators (increase of Social Welfare, reduction of CO2 emissions, reduction of Energy Not Served – ENS – costs);
- monetized core cost indicators (life cycle costs);
- sensitivity on F&R aspects on life cycle costs;
- sensitivity on S&E aspects on life cycle costs;
- non-core indicators;
- synthetic profitability indicators (Profitability Index[1], PI, and Net Present Value, NPV);
- GIS-based maps on ENS reduction (at cluster level), Social Welfare variation (at cluster level) and life cycle costs (at corridor level).

[1] The PI is defined as ratio between annual gross benefit and annual life cycle costs.

The main findings of those analyses are reported below:

- **the envisaged reinforcement plans at 2050 and 2040 are always profitable in each e-Highway2050 Scenario, also considering any public acceptance approach to new transmission network assets**. It is straightforward analysing the PI values in the table below;

	2050			2040		
	Strategy 1	**Strategy 2**	**Strategy 3**	**Strategy 1**	**Strategy 2**	**Strategy 3**
X-5	21.51	20.7	13.96	28.75	27.82	18.62
X-7	38.61	38.29	26.9	29.21	28.26	18.92
X-10	17.48	17.00	10.92	6.34	6.13	4.10
X-13	11.42	10.98	6.4	8.51	8.23	5.51
X-16	8.3	7.14	4.88	2.76	2.67	1.79

- the extra costs that arise between Strategy 2 and Strategy 1 is little respect the gross benefit; however Strategy 3 is between 40 and 70% more expensive than Strategy 1.
- **on those Scenarios where RES penetration is higher** (i.e. "X-5" and "X-7"), **the profitability of the envisaged network reinforcement plan is usually higher**: this shows that investments in transmission network reinforcements are an indispensable option to reach to desirable decarbonisation benefits for the future European power system;
- **core benefit and cost indicators have proven to be robust in order to measure the impact of transmission network reinforcement plans in very long term time horizons**;
- due to the simplification assumptions as well as the lack of compete and reliable data, non-core indicators (e.g. the reduction of investment in distribution network, the impact of S&E aspects on life cycle costs) have proved to have a small impact on the profitability of the envisaged transmission network reinforcement plans;
- there is an almost linear relationship between discount rate and annual life cycle cost;
- **the main impacting indicator on the total benefit is represented by the reduction of ENS costs**: clearly, there is a strong relationship between this aspect and the economic unitary value assumed for monetizing this benefit (the Value Of Lost Load, VOLL) assumed equal to 10000 €/MWh.

  Ad hoc sensitivity analyses for all the Scenarios at the target year 2050 have been conducted, in order to compare the cost in reducing the ENS by means of network reinforcements instead of installing new peak generation units (Open Cycle Gas Turbines, OCGT). These sensitivity analyses have shown that, for a range of CO2 emission tax value from 150 €/t to 270 €/t, **choosing to invest in transmission network reinforcements is the most resilient and cost-effective way to cover ENS in all the project Scenarios**.

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INTRODUCTION

The aim of this deliverable is to summarize the activities carried by WP6 in Task 6.7 "Cost-benefit analysis of grid architectures and modular plan 2030-2050" and to show the application of the WP6 BCA methodology [1] and the WP6 toolbox [2] in the evaluation of benefits and costs related to the envisaged network reinforcement plan at the target years 2050 and 2040.

The report is structured as follows:

- Chapter 1 shows the hypotheses assumed for the BCA evaluation at the target years 2050 and 2040.

- Chapter 2 shows the results in the application of the WP6 BCA methodology and WP6 toolbox in the BCA evaluations, providing synthetic indicators such as
  - annual gross benefit for all Scenarios and reinforcement Strategies;
  - annual life cycle costs for all Scenarios and reinforcement Strategies;
  - annual net benefits for all Scenarios and reinforcement Strategies;
  - Profitability Indicator values (PI): this indicator is defined as ratio between annual gross benefit and annual life cycle costs.

  Results are provided in terms of tables, graphs and GIS maps.

  Moreover, for the target year 2050, sensitivity analyses have been carried out in order to assess:
  - the impact of social and environmental aspects on life cycle costs;
  - the impact of financial and regulatory aspects on life cycle costs;
  - the comparison between investment in generation expansion instead of transmission network expansion in order to overcome energy not served at the target year.

- Chapter 3 provides a general overview on the results.

1. General assumptions on the application of WP6 BCA methodology in evaluating 2050 Grid Architectures

1.1. 2050 and 2040 BCA hypotheses

In order to evaluate the e-Highway2050 Grid Architectures at the target years 2050 and 2040 for all the project Scenarios, the analyses described in this document – performed by means of the WP6 Toolbox that exploits the WP6 BCA methodology – have been carried out considering the assumptions reported in this chapter.

Since the BCA methodology described in [1] accounts a deterministic approach, it has been applied for the following analyses taking into account the average over the Monte Carlo years provided as output by WP2 and WP4 simulations performed with ANTARES tool [3].For the evaluation of the benefits for all the Scenarios, it is assumed that the *without case* is represented by the "starting grid" ANTARES case, while the *with case* is represented by the last available "step" identified by WP2/WP4 approach, described in [4].

As general rule, most of the calculated indicators are expressed in terms of annual cost/benefit (M€/a or G€/a): for the other that are to be intended as Present Value values (e.g. reduction of investment costs in distribution networks, present value of gross benefit, etc.), they are converted assuming the same annuity factor between Present Value LCC and annual LCC.

In Table 1 a synthetic description of how the WP6 BCA methodology and the WP6 toolbox have been applied in this document.

Table 1 – Application of WP6 BCA methodology and WP6 toolbox for 2050 and 2040 evaluations

BCA indicator from [1]	Implemented in WP6 toolbox [2]		Not implemented in WP6 toolbox (explanation)	Is it applied in 2050 and 2040 evaluations? (explanation)
	Core indicator	Extra indicator		
Total increase of Social Welfare (excluding CO2 emissions)	X			YES
Total reduction of CO2 emissions	X			YES
Sensitivity of CO2 price		X		YES
Total increase of Social Welfare (excluding CO2 emissions) due to market power	X			NO (no possible exercise of market power arises at 2050 and 2040)
Total reduction of CO2 emissions due to market power	X			NO (no possible exercise of market power arises at 2050 and 2040)
Additional installed RES		X		NO (modeling limitation in system simulations)
Reduction of investment costs in distribution networks		X		YES (limited impact due to topological limitation and simplified approach)
Social Welfare split		X		YES
Life cycle costs - AUTEX		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Life cycle costs - CAPEX = ASSEX + INSTEX	X			YES
Life cycle costs - OPEX		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Life cycle costs - DECOMMEX		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Life cycle costs - DISPEX		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Reduction of inter-zonal transmission losses	X			NO (unavailability of pertinent data)
Reduction of intra-zonal transmission losses		X	X (topological limitation and simplified approach)	NO (topological limitation and simplified approach)
Social and environmental aspects - Impact on land use - ROW compensation costs		X		YES (limited impact due to topological limitation and simplified approach)
Social and environmental aspects - Impact on biodiversity and landscape		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Social and environmental aspects - Public attitudes and actions		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Social and environmental aspects - Time delays		X		NO (the temporal coherence of a case cannot be retained)
Impact of innovative transmission technologies - Controllability		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Impact of innovative transmission technologies - Adaptability/relocatability		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)
Impact of innovative transmission technologies - Enhanced observability		X	X (unavailability of pertinent data)	NO (unavailability of pertinent data)

Security of supply - Reduction of reliability costs (ENS) - European VOLL	X			**YES** (VOLL = 10000 €/MWh)
Security of supply - Reduction of reliability costs (ENS) - Zonal VOLL		X		**NO** (unavailability of trustworthy zonal VOLL values)
Security of supply - Reduction of reliability costs (ENS) - General methodology		X		**NO** (unavailability of pertinent data)
Security of supply - Reduction of resilience costs - General methodology		X		**NO** (unavailability of pertinent data)
Security of supply - Reduction of DSM costs - General methodology		X		**NO** (unavailability of pertinent data)
Security of supply - Reduction of RES curtailment - General methodology		X		**NO** (unavailability of pertinent data)
Financial and regulatory aspects - Common discount rate	X			**YES**
Financial and regulatory aspects - Common asset beta		X		**YES**
Financial and regulatory aspects - Investment specific asset beta		X		**YES**
Financial and regulatory aspects - General methodology		X		**NO** (unavailability of pertinent data)
Scenario flexibility		X	X (methodological limitation)	**NO** (methodological limitation)
BCA indicators weighting to EU policy pillars		X	X (methodological limitation)	**NO** (methodological limitation)

1.1.1. On Social Welfare

For each generation technology, the marginal cost of generation (including CO2 emission costs) assumed for the estimation of benefits at the target years 2050 and 2040 have been provided by WP2 and WP4, respectively: for sake of clarity, they are synthetically reported, for the five project Scenarios, in Table 2.

Table 2 – Generation cost assumptions at 2050 and 2040 (*NA* = not available technology for the pertinent Scenario)

[€/MWh]	Large scale RES		100% RES		Big & market		Fossil & nuclear		Small & local	
year	2050	2040	2050	2040	2050	2040	2050	2040	2050	2040
OCGT	189	157	203	168	172	160	172	160	203	168
CCGT without CCS	131	110	*NA*	117	117	88	118	88	141	117
CCGT with CCS	*NA*	68	*NA*	78	46	40	46	40	*NA*	78
Coal without CCS	180	139	*NA*	144	*NA*	139	*NA*	139	196	144
Coal with CCS	*NA*	41	*NA*	47	47	41	47	41	*NA*	47
Lignite without CCS	180	156	*NA*	156	*NA*	156	*NA*	156	200	156
Lignite with CCS	*NA*	25	*NA*	25	29	25	29	25	*NA*	25
Nuclear	14	14	*NA*	20	14	14	14	14	14	14
Biomass1	20	20	10	10	20	20	20	20	10	10
Biomass2	135	135	20	20	135	135	135	135	20	20

The *Social Welfare variation* split is described in terms of:

- sum of variation of Consumers and Producers Surpluses;
- variation of Merchandise Surplus/Congestion Rent.

1.1.2. On life cycle costs

For the evaluation of life cycle costs (LCC) for all the Scenarios, the three different implementation Strategies (evaluated ex-post to ANTARES simulations) have been considered, taking into account the WP2 approach described in [4]: according to the hypotheses from WP2, only CAPEX have been considered. The assumed investment cost figures for 2050 are shown in Figure 1 and Figure 2.

For 2040 analyses, specific WP3 unitary costs figures have been applied, if available: however, it can be noted how 2040 cost figures are very close to 2050 ones:

- on AC transformers and AC/DC stations: the deviation is lower than 1% with respect 2050 cost figures;
- on kilometric transmission technologies: the highest deviation with respect 2050 cost figures is lower than 5%, while the average one is lower than 4%.

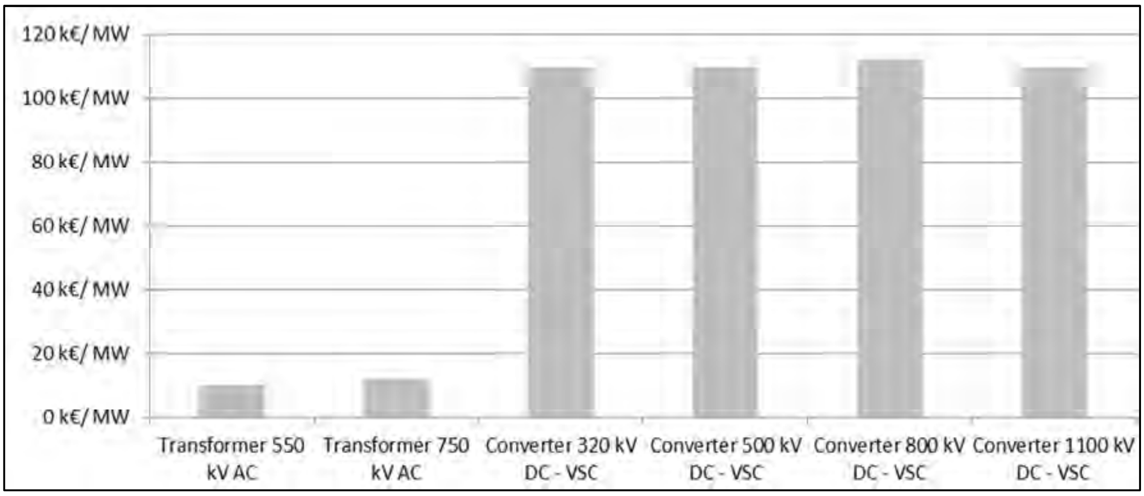

Figure 1 – 2050 investment costs – AC transformers and AC/DC converter stations

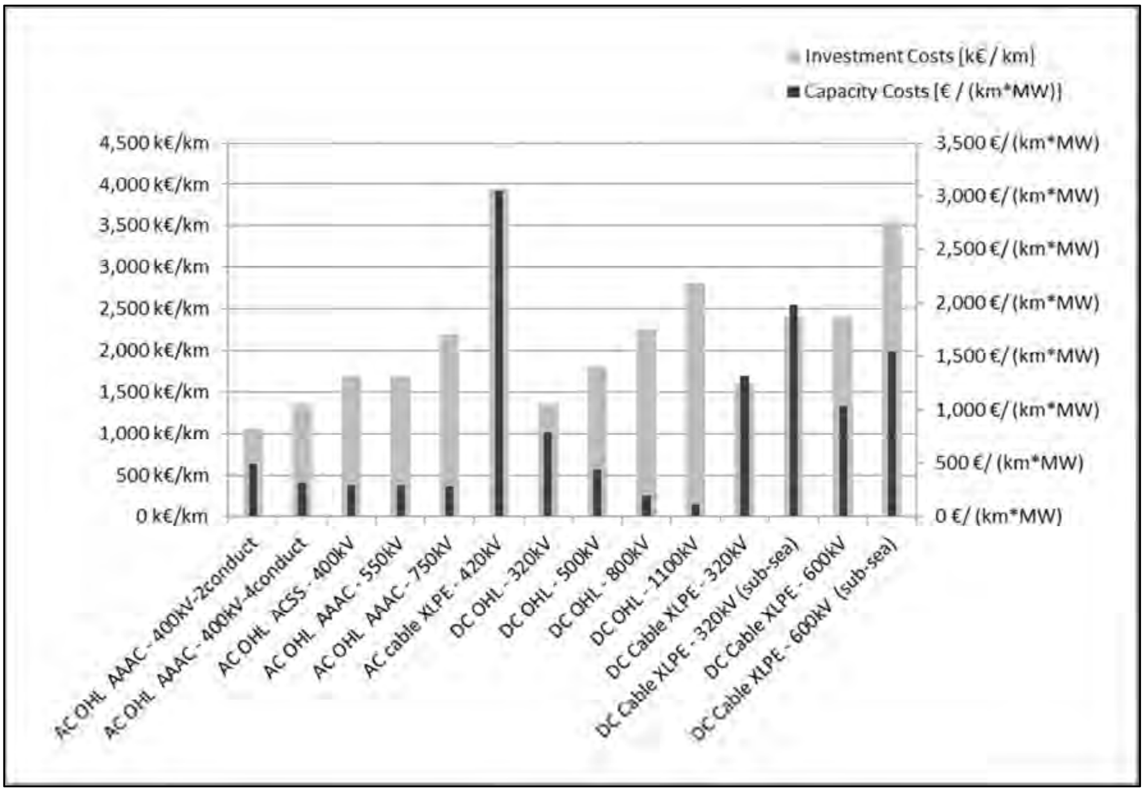

Figure 2 – 2050 investment costs – Kilometric transmission technologies

Benefits have been assessed through simulations supposing DC connections. As is not guaranteed that AC connections could provide the same results, 20% extra-cost was assumed for all AC lines to take account of possible extra-investments to “imitate” the DC behaviour (e.g. PST).

The present value of LCC has been calculated assuming, according with WP2 and WP3:

- a 40 year operative life for HVAC/HVDC cables, converter and substations;
- a 100 year operative life for overhead HVAC and HVDC lines.

Moreover, it is assumed that the amortization period is equal to operative life, so no residual value is present at the end of the operative life of an asset.

1.1.3. On CO2 emission tax values

In agreement with WP2 and WP4 assumptions, *the economic effect of CO2 emission is internalized in generation cost curves*. Moreover, calculations have been performed considering a *CO2 emission tax value* of 270 €/t for all the analysed Scenarios in 2050 and 189 €/t in 2040: however, sensitivity analyses have been carried out in order to identify the range of CO2 prices within the generation merit order holds.

The identification of this range is important because:

- if the merit order holds, the dispatching of generation units remains valid (even if the overall generation cost changes);
- if net injections (generation - consumption) hold, then also power flows and then transmission network reinforcements remain valid.

Therefore, this range of CO2 emission tax values identify a resilience range for the highlighted network reinforcement solutions.

The result of these analyses is described in the pertinent paragraphs.

1.1.4. On impact of market power on Social Welfare

For 2050, for what regards the effect of *possible exercise of market power* on the Social Welfare, the calculation of the relationship between Lerner Index and Residual Supply Index (described in [1]) has been performed externally with respect to the WP6 Toolbox thanks to a proper MATLAB calculation routine.

This calculation highlighted that in only one Scenario ("X-13") and only in one cluster ("56_IT"), possible market power could be exercised by local generation for about the 7% of one year.

Nevertheless, after running ANTARES simulations taking into account those bid-ups, no difference in terms of Social Welfare has been found with respect the cases encompassing marginal cost of generation. Therefore, no further mention on market power effect is reported in the following 2050 analyses and, for consistency reasons, neither for 2040 ones.

1.1.5. On additional RES installed capacity

As stated in paragraph 1.1.2, network developments in reinforced cases have been considered in ANTARES by means of DC links: therefore, for all the simulations, the structure of the HVAC system is constant and coincident with the starting grid HVAC layout, while the differentiation in terms of development Strategies has been taken into account ex-post simulations, according to WP2 pre-CBA.

Due to this peculiarity, the *additional RES installed capacity* indicator has been not calculated due to the approach defined in [1] (considering the amount of RES installed capacity that can be inserted into the system without violating any transmission constraint on the HVAC system).

1.1.6. On the reduction of investment costs in distribution networks

The *reduction of investment costs in distribution networks*, due to the unavailability of proper data, has been evaluated taking into account data obtained from WP6 elaboration: the adopted approach is described in detail in Annex 1.

1.1.7. On financial and regulatory aspects

The effect of *Financial and Regulatory* (*F&R*) *aspects* is internalized in LCC: for all the 2050 Scenarios, analyses have been performed taking into account different methodologies to calculate discount rate:

- common discount rate (5%), in agreement in WP2 hypotheses[2];
- common asset beta, assuming a risk free rate equal to 3.76% (2006 value, in order to not take into account the effect of 2008 financial crisis), a market premium risk equal to 5% and performing a sensitivity analysis on the common asset beta value:
    - 0.3;
    - 0.6;
    - 0.9;
    - 0.238: this average value has been calculated starting from levered beta values included in [6]. Levered beta values have been transformed in asset beta values assuming a (Debt / (Debt + Equity)) ratio equal to 0.65;
- investment specific asset betas, assuming a risk free rate equal to 3.76%, a market premium risk equal to 5% and considering the levered beta values included in [6]. Levered beta values have been transformed in asset beta values assuming a (Debt / (Debt + Equity)) ratio equal to 0.65.

For what regards 2040 analyses, they have been performed considering only the **reference case** (see paragraph 1.2).

[2] It must be pointed out these discount rate values are annual: therefore, they have to be interpreted as percentage values for each year ("%/a"). However, since this indicator is usually expressed in percentage, in the rest of this document the more widespread notation is used ("%").

1.1.8. On social and environmental aspects

The economic effect of *Social and Environmental (S&E) aspects* has been internalized in LCC: due to the unavailability of proper data, only the costs of purchasing rights of ways (RoW) have been considered, taking into account a brownfield approach and assuming land use percentages and costs described in the Annex 1 of [2]. However, sensitivity analyses in order to assess the impact of these aspect have been carried out (see paragraph 1.2).
Instead, the effect of *time delays* is not taken into account in LCC in order to maintain homogeneity with WP2 and WP4 approaches: this does not allow to retain the delay effect on 2050 and 2040 grid architectures: time delays are evaluated by the WP6 toolbox but they do not have any effect on the profitability of the proposed network reinforcements.

1.1.9. On reliability costs

In the *reduction of reliability costs*, the reduced ENS has been monetized considering an unique European level of VoLL equal to 10000 €/MWh;

1.1.10. On the reduction of inter-zonal transmission losses

The *reduction of inter-zonal transmission losses* has not been quantified due to the unavailability of losses parameters.

1.2. Description of sensitivity cases

In this paragraph, a synthetic description on the different cases analysed in order to perform sensitivity analyses is shown:

- **Case 1 (Reference case)**. This case takes into account the following assumptions:
    - common interest rate equal to 5%;
    - social environmental aspects (costs of RoW) have been considered.

- **Case 2 (Sensitivity on S&E aspects)**. This case takes into account the following assumptions:
    - common interest rate equal to 5%;
    - social environmental aspects (costs of RoW) have not been considered in LCC.

- **Case 3 (Sensitivity on F&R aspects)**. This case takes into account the following assumptions:
    - common asset beta (0.238), risk free rate (3.76%); market premium risk (5%). This lead to a common discount rate equal to 4.95%;
    - social environmental aspects (costs of RoW) have been considered.

- **Case 4 (Sensitivity on F&R aspects)**. This case takes into account the following assumptions:
    - common asset beta (0.3), risk free rate (3.76%); market premium risk (5%). This lead to a common discount rate equal to 5.26%;
    - social environmental aspects (costs of RoW) have been considered.

- **Case 5 (Sensitivity on F&R aspects)**. This case takes into account the following assumptions:
    - common asset beta (0.6), risk free rate (3.76%); market premium risk (5%). This lead to a common discount rate equal to 6.76%;
    - social environmental aspects (costs of RoW) have been considered.

- **Case 6 (Sensitivity on F&R aspects)**. This case takes into account the following assumptions:

- common asset beta (0.9), risk free rate (3.76%); market premium risk (5%). This lead to a common discount rate equal to 8.26%;
- social environmental aspects (costs of RoW) have been considered.

- **Case 7 (Sensitivity on F&R aspects)**. This case takes into account the following assumptions:
  - investment specific asset beta values, risk free rate (3.76%); market premium risk (5%);
  - social environmental aspects (costs of RoW) have been considered.

2. Evaluation of 2050 and 2040 Grid Architectures

This chapter describes the analyses carried out in WP6 in order to evaluate the envisaged reinforcement strategies at the target years 2050 and 2040, according to the following five project Scenarios [4]-[5]:

- **Scenario X-5** – *Large scale RES and low emissions*;
- **Scenario X-7** – *100% RES;*
- **Scenario X-10** – *Big and Market;*
- **Scenario X-13** – *Large fossil fuel with CCS and nuclear*;
- **Scenario X-16** – *Small and local.*

In coherence with WP2 and WP4, three approaches for reinforcement strategies – related to public acceptance of new transmission network assets – has been considered:

- **Strategy 1** – *New grid acceptance*. The public opinion accepts new OHL and also the development of new corridors. DC cables are also possible but OHL are preferred when possible due to their lower costs;
- **Strategy 2** – *Re-Use of Corridors*. The public opinion accepts new OHL as long as they are close to existing lines. Therefore new AC or DC Overhead-lines can be implemented when they are in the existing corridors;
- **Strategy 3** – *Status quo*. The public opposition against new infrastructure prevents any new OHLs. Only refurbishment of existing lines or new DC cables can be implemented.

These three strategies are only used to have extreme and simplified assessment of costs, they do not represent necessarily the best technological solution. The best solution could include other technological options than those considered and would for sure be a mixture of different strategies, depending on the local constraints (it is very unlikely that all the reinforcements in Europe are built following the same strategy).

It must be pointed out that since the aforementioned reinforcement Strategies have been evaluated *ex-post* to common ANTARES system simulations, the core and non-core indicators that are given – for each project Scenario – as output from those simulations (e.g., increase of Social Welfare, reduction of CO2 emissions, reduction of reliability costs, etc.) are the same for all the proposed Strategies: this is straightforward observing the indicator values in the following sub-paragraphs.

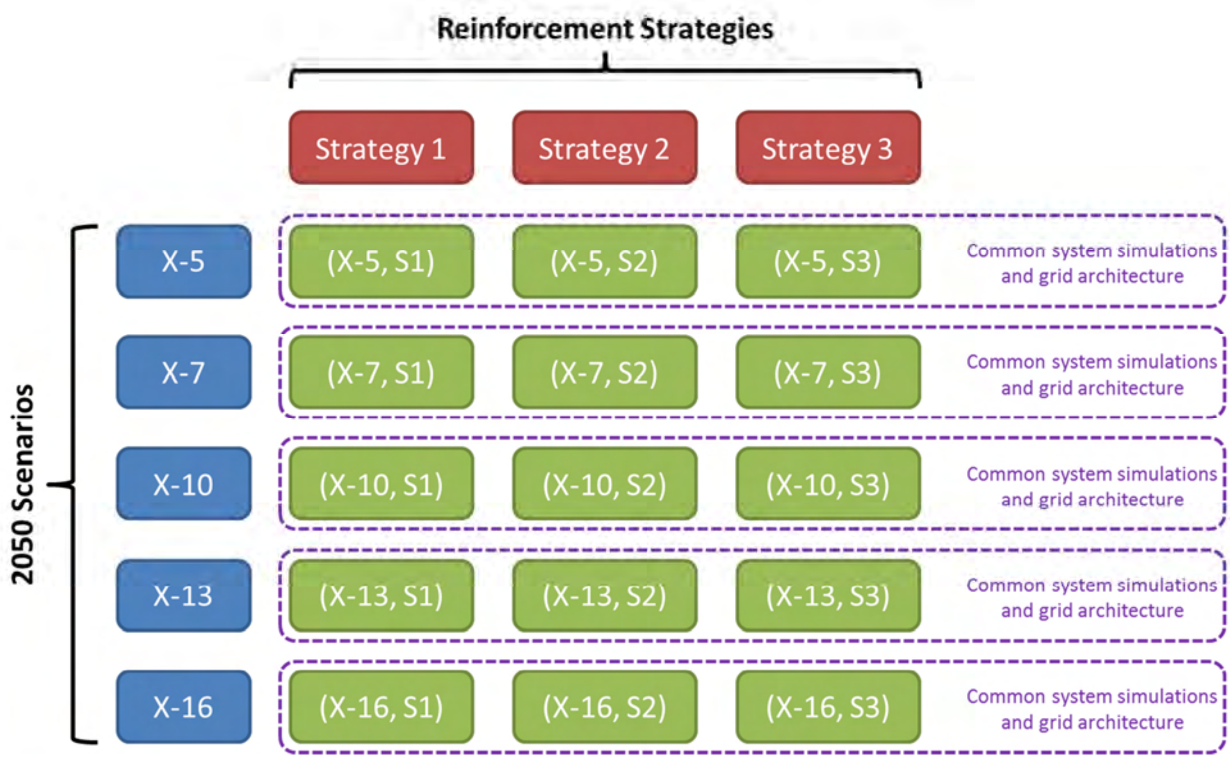

Figure 3 – Evaluation of 2050 cases

Figure 3 gives a schematic representation of the WP6 approach rationale behind 2050 evaluations:

- ANTARES system simulation for both starting grid and reinforced grid architecture cases have been provided by WP2 for all the project Scenarios (blue boxes in Figure 3). These simulations are not influenced by the technological implementation of a reinforced transmission corridor;
- for each Scenario, the reinforced grid architecture is obtained by the starting grid and by a pertinent reinforcement plan (in terms of topology and transmission capacities). This information has been provided by WP2;
- the three reinforcement approaches (red boxes in Figure 3) are described in terms of technological implementation of a grid architecture, in terms of one reinforced case for each Scenario and for each reinforcement approach;
- WP6 toolbox has been applied in order to evaluate the resulting 15 cases obtained by the combinations Scenario x Reinforcement Strategies (green boxes in in Figure 3).

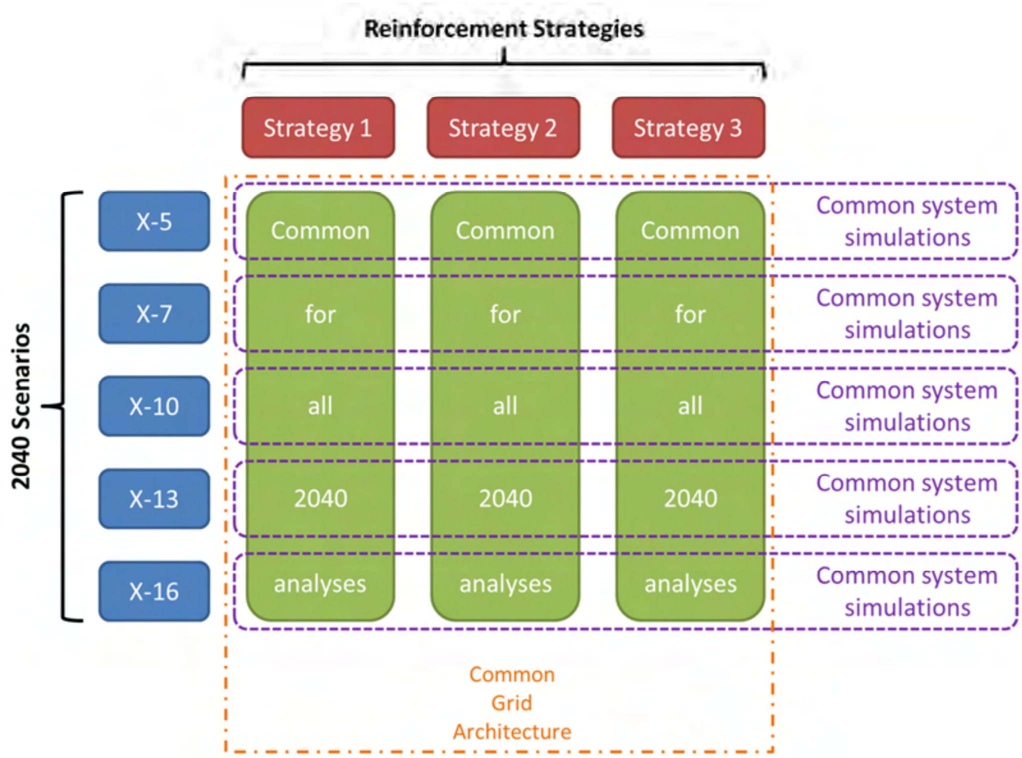

Figure 4 – Evaluation of 2040 cases

Figure 4 gives a schematic representation of the WP6 approach rationale behind 2040 evaluations:

- ANTARES system simulation for both starting grid and reinforced grid architecture cases have been provided by WP4 for all the project Scenarios (blue boxes in Figure 4). These simulations are not influenced by the technological implementation of a reinforced transmission corridor;
- for all Scenario, a reinforced grid architecture is obtained by the starting grid and by a pertinent reinforcement plan (in terms of topology and transmission capacities). For 2040, this grid architecture is common to all the scenarios. This information has been provided by WP4;
- the three reinforcement approaches (red boxes in Figure 4) are described in terms of technological implementation of a grid architecture, in terms of one reinforced case for reinforcement approach;
- WP6 toolbox has been applied in order to evaluate the resulting 15 cases obtained by the combinations Scenario x Reinforcement Strategies (green boxes in in Figure 4).

2.1. Scenario X-5 - Large scale RES and low emissions

2.1.1. 2050 analyses

2.1.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 3 shows the annual values of core benefit indicators for this Scenario.

Table 3 – X-5 Scenario – 2050 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 - Strategy 2 - Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	27
Reduction of CO2 emissions [G€/a]	52
Reduction of reliability costs [G€/a]	234
Benefit core indicators – Grand total [G€/a]	313

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 27 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 52 G€/a.

In any case, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 234 G€/a: since this value is directly related to the adopted VOLL (10000 €/MWh), this aspect is examined in detail in paragraph 2.1.1.7.

According to that, the annual benefit provided by core benefit indicators is about 313 G€/a.

2.1.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 4 and Figure 5 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (slightly lower than 15 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;
- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.92% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.05% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 4 – X-5 Scenario – 2050 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	14.6	15.1	22.4
Cost core indicators - Grand total [G€/a]	**14.6**	**15.1**	**22.4**

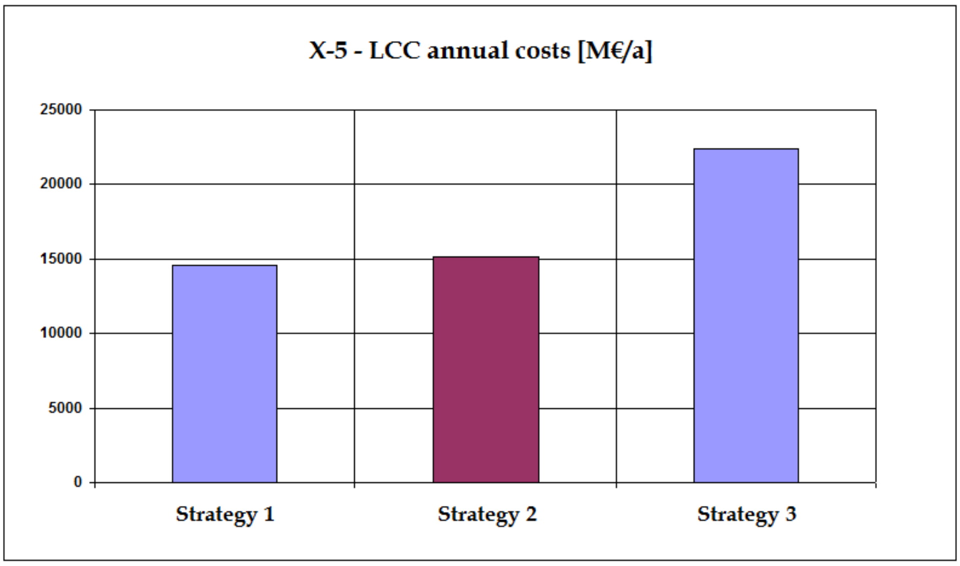

Figure 5 – X-5 Scenario – 2050 – LCC annual costs

2.1.1.2.1. LCC assessment – Sensitivity of S&E aspects

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the impact of Social and Environmental aspects on the LCC in the three different reinforcement Strategies at the target year 2050. Table 5 shows the results of this sensitivity analysis.

As can be easily pointed out, the monetary impact of S&E aspects (acquisition of rights of way) is very low (under than 1%).

The outcome of this analysis does not clearly imply that S&E aspects are a secondary item in transmission planning: in fact, those values find their justification in the adopted approach:

- considering only the rights of way acquisition do not allow to consider the full range of social and environmental externalities connected to transmission network planning;
- the cluster level of detail cannot allow to consider the very local peculiarities of crossed lands;
- the brownfield approach does not make feasible to extend the calculation to new transmission corridors.

Table 5 – X-5 Scenario – 2050 – Sensitivity on S&E aspects

LCC annual costs	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a] – Case 1 - S&E included	14.5	15.1	22.4
LCC - Annual costs [G€/a] – Case 2 - S&E not included	14.4	15.0	22.4
(Case 2 – Case 1)/Case 1 [%]	-0.72%	-0.67%	-0.20%

Therefore, in order to fully appraise the economic impact of S&E aspects in transmission network planning, different analyses with more precise approaches are needed.

2.1.1.2.2. LCC assessment – Sensitivity of F&R aspects

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the impact of Financial and Regulatory aspects on the annual LCC in the three different reinforcement Strategies at the target year 2050.

As shown in Table 6 and Figure 6, there is an exponential relationship between annual LCC and discount rate. In fact:

$$PV_{LCC} = \sum_{t=0}^{T_{ol}} A_{LCC} \cdot \left(\frac{1}{1+DR} \right)^t \Rightarrow A_{LCC} = PV_{LCC} \cdot \frac{(1+DR)^{T_{ol}} \cdot DR}{(1+DR)^{T_{ol}+1} - 1}$$

where:

- PV_{LCC} is the Present Value of life cycle costs [G€];
- T_{ol} is the operative life duration [a];
- A_{LCC} is the annual life cycle cost [G€/a];
- DR is the discount rate [%].

However, in the normal range of values assumed by discount rate, there is a very good approximation with an increasing line.

Table 6 – X-5 Scenario – 2050 – Sensitivity on F&R aspects – Common asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 3	14.4	15.0	22.3	4.95
LCC - Annual costs [G€/a] – Case 1	14.6	15.1	22.4	5.00
LCC - Annual costs [G€/a] – Case 4	15.1	15.7	23.2	5.26
LCC - Annual costs [G€/a] – Case 5	18.4	19.1	28.1	6.76
LCC - Annual costs [G€/a] – Case 6	21.9	22.7	33.2	8.26

This result is not surprising: in an investor perspective, if the money cost increases, the annual amortization of the asset increases as well. Moreover:

- with reference with Strategy 1 and Strategy 2, the lines are very close and practically parallel;
- the slope of Strategy 3 line is higher than the ones with of Strategy 1 and Strategy 2: this is due to the fact that Strategy 3 heavily exploits cables (40 years of operative life). This is due to the fact that the difference in asset operative life implies an increase in annual LCC, and this difference grows faster if the discount rate is higher.

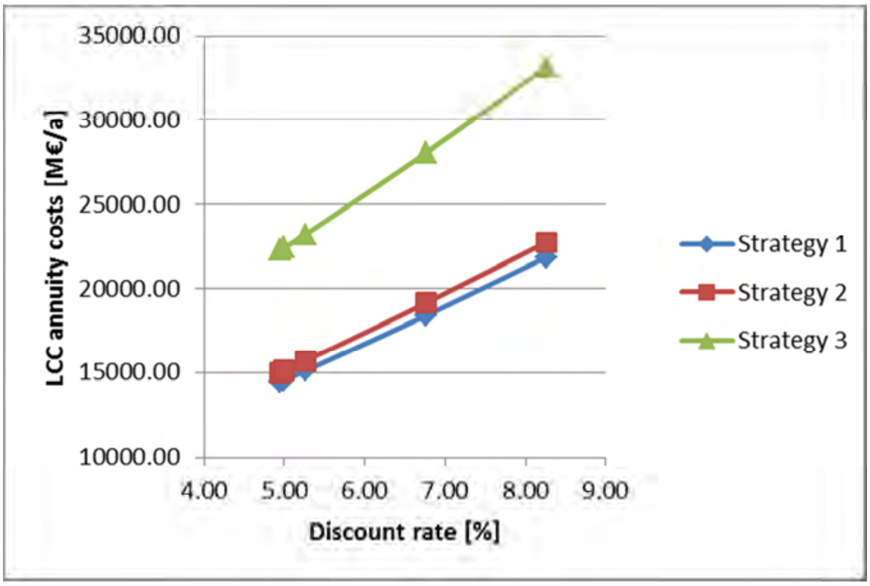

Figure 6 - X-5 Scenario – 2050 – Sensitivity on F&R aspects

Table 7 shows the result of the sensitivity analysis on F&R aspects, taking into account investment specific asset beta values: it can be noted how different values of asset beta do not bring to sensible changes (increases are lower than 0.5%) in the annual LCC. Moreover, it can be noted how resulting average discount rates are very close (5% in Case 1, 4.98% in Case 7).

Table 7 - X-5 Scenario – 2050 – Sensitivity on F&R aspects – Investment specific asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 1	14.6	15.1	22.4	5.00
LCC - Annual costs [G€/a] – Case 7	14.6	15.2	22.5	4.98
(Case 7 – Case 1)/Case 7 [%]	0.43%	0.41%	0.40%	-

2.1.1.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 8 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO2 emission tax between 250 and 300 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO2 emission tax value included in the interval (250, 300) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 1.4 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 85 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 79 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -910 G€/a) and Producers + Consumer Surpluses (about +989 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 8 – X-5 Scenario – 2050 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	300
Sensitivity on CO2 price - Lower bound [€/t]	250
Reduction of investment costs in distribution networks [G€]	1.4
Social Welfare variation (CO2 emissions are accounted) [G€/a]	79
Merchandise Surplus variation [G€/a]	-910
Producers + Consumers Surplus variation [G€/a]	989

2.1.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-5 Scenario is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 9. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 74% on total gross annual gross benefit).

Table 9 - X-5 Scenario – 2050 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	313
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	16.55
% Social Welfare increase [%]	8.62
% Reduction of distribution network investments [%]	0.03
% Reduction of reliability costs [%]	74.81

2.1.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-5 Scenario at the target year 2050 are shown in Table 10. Annual and present values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 10 - X-5 Scenario – 2050 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	313.0	313.0	313.0
Annual LCC cost [G€/a]	14.6	15.1	22.4
Annual net benefit [G€/a]	298.4	297.8	290.5
Present Value of gross benefit [G€]	5511.8	5522.8	5376.6
Present Value of LCC cost [G€]	256.3	266.9	385.1
Present Value of net benefit [G€]	5255.6	5256.0	4991.4
PI [adim]	**21.51**	**20.70**	**13.96**

In order to evaluate the present value of gross benefit, the same annuity ratio between annual and present LCC is shown: this allows to maintain the same PI between annual and present value indicators.

It can be observed how the Present Value of net benefit in Strategy 2 (NPV_2) is slightly higher than the one in Strategy 1 (NPV_1): this finds its justification in the high values assumed by the Profitability Index in Strategy 2. In fact, taking into account the link between NPV, PI and the present value of LCC cost (PV_{LCC}):

$$NPV_2 > NPV_1 \rightarrow (PI_2 - 1) \cdot PV_{LCC,2} > (PI_1 - 1) \cdot PV_{LCC,1} \rightarrow \frac{(PI_2 - 1)}{(PI_1 - 1)} > \frac{PV_{LCC,1}}{PV_{LCC,2}}$$

Therefore, NPV_2 is higher than NPV_1 when the increase of the present value of LCC cost in Strategy 2 is lower than the reduction the $PI_2 - 1$ respect $PI_1 - 1$.

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 21.51 in Strategy 1 to 13.96 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.1.1.6. GIS maps

Figure 7 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2050. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Balkan peninsula, Portugal, Norway, Sweden or Finland), in general many regions experience a significant reduction of reliability costs (in Germany, Spain, Poland).

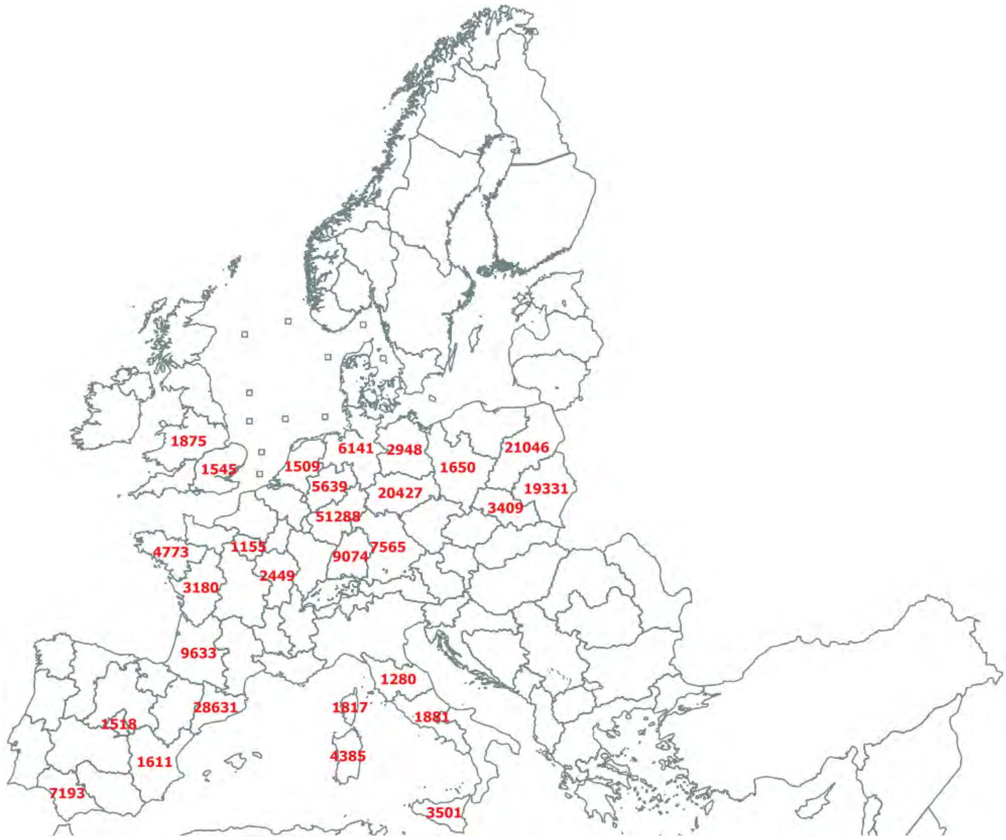

Figure 7 - X-5 Scenario – 2050 – Reduction of ENS costs [M€/a]

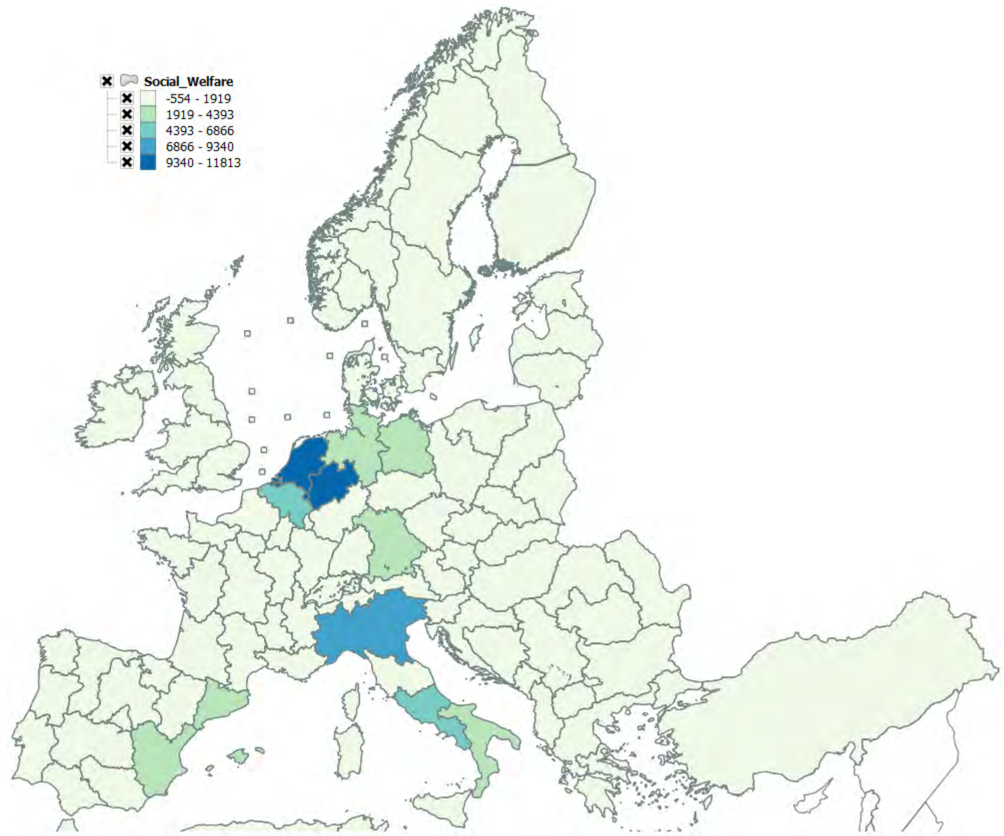

Figure 8 - X-5 Scenario – 2050 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 8.

As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 79 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 11.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators are far lower than 1% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, the transmission network reinforcement plan gives a (slight) negative sums: as shown in Table 12, the lowest negative value is reached in Sweden (-282 M€/a). The Ireland situation is emblematic because the local benefit provided by the reduction of ENS costs (449 M€/a) overshadows the local reduction of Social Welfare (-300 M€/a).

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 11 - X-5 Scenario – 2050 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	**-107**	Latvia	**-224**
Austria	925	Lithuania	**-68**
Belgium	921	Luxembourg	**-5**
Bosnia & Herzog.	74	Macedonia	938
Bulgaria	0	Montenegro	319
Croatia	324	Netherlands	6600
Czech Republic	1886	Norway	293
Denmark	1415	Poland	1987
Estonia	0	Portugal	2420
Finland	**-138**	Romania	618
France	2392	Serbia	9
Germany	29636	Slovakia	348
Great Britain	974	Slovenia	3157
Greece	183	Spain	5924
Hungary	52	Sweden	**-309**
Ireland	**-300**	Switzerland	702
Italy	15572	Ukraine	489

Table 12 - X-5 Scenario – 2050 – Country level SW vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Albania	-107	0	-107
Finland	-138	15	-123
Ireland	-300	449	149
Latvia	-224	9	-215
Lithuania	-68	5	-63
Luxembourg	-5	732	727
Sweden	-309	27	-282

Figure 23-Figure 25 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

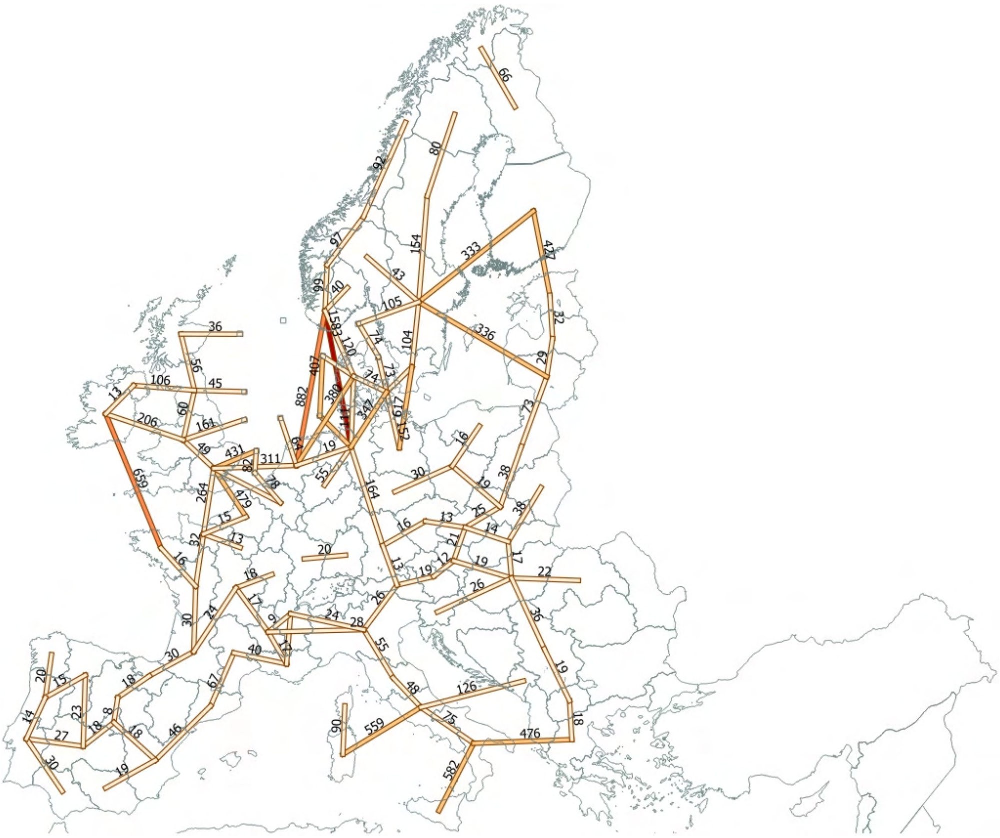

Figure 9 - X-5 Scenario – 2050 – Annual LCC – Strategy 1 [M€/a]

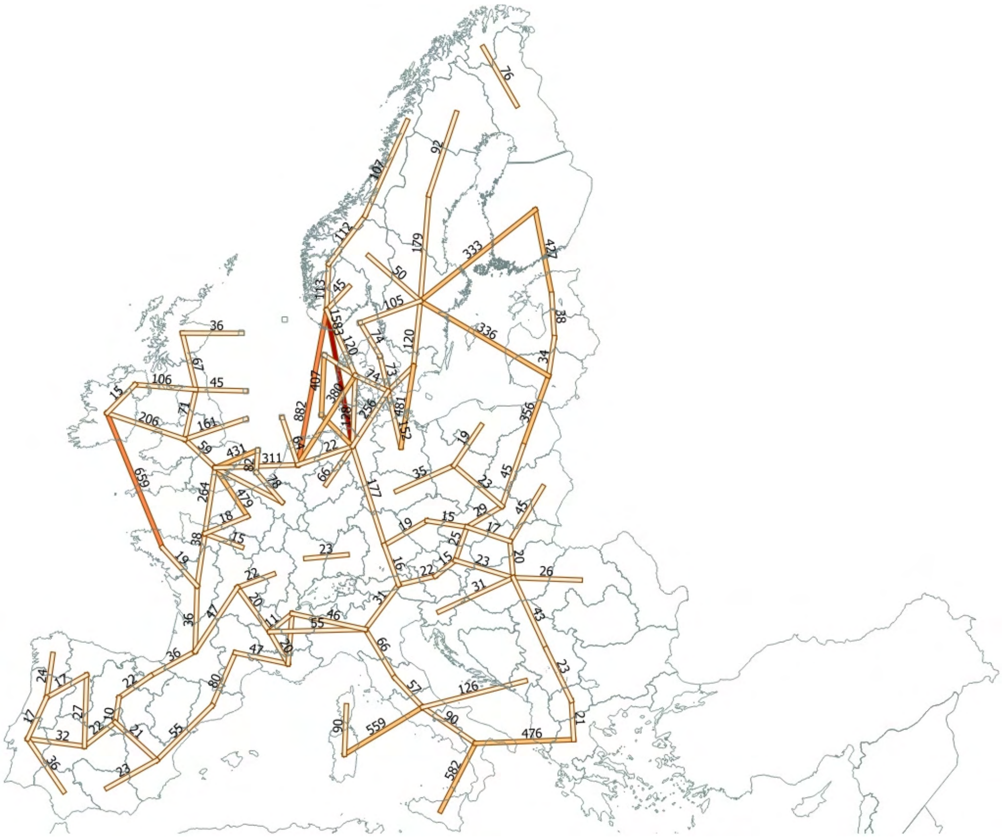

Figure 10 - X-5 Scenario – 2050 – Annual LCC – Strategy 2 [M€/a]

Figure 11 - X-5 Scenario – 2050 – Annual LCC – Strategy 3 [M€/a]

2.1.1.7. Investment sensitivity analysis: network vs. generation to cover ENS

This paragraph show the results of a sensitivity analysis performed at the target year 2050 in order to compare the cost in overcoming the same amount of ENS by means of:

- *option 1*: investment in grid reinforcements;
- *option 2*: investment in peak generation (in particular, Open Cycle Gas Turbine, OCGT, power plants).

The aim of this analysis is to check if, in order to cover ENS, investment in transmission network are (or are not) more profitable than investment in fossil-fuel peak generation, independently by the assumed VoLL.

Regarding option 2, calculation hypotheses (from WP2 and WP3) are reported below:

- fixed investment cost (CAPEX) in OCGT equal to 0.7 G€/MW;
- fuel and CO2 operation cost (OPEX) in OCGT equal to 189 €/MWh;
- maximum amount hourly saved ENS (without – with case) equal to 112 GW: this information is needed in order to properly rate the amount of additional OCGT installed capacity;
- saved ENS (without – with case) equal to 23.41 TWh/a: this information is needed in order to properly rate the production by additional OCGT power plants;
- annuity factor for investment in OCGT equal to 0.0745;

Taking into account both CAPEX and OPEX in new OCGT power plants, the annual TOTEX = CAPEX + OPEX in new OCGT power plants to cover ENS is equal to 10 G€/a.

However, option 2 implies a loss in other benefits achievable by transmission network reinforcements: therefore, this arises as opportunity costs in terms of increase of Social Welfare and reduction of CO2 emissions:

- opportunity cost due to the increase of Social Welfare: about 27 G€/a;
- opportunity cost due to the reduction of CO2 emissions:
  - about 29 G€/a assuming a CO2 tax value equal to 150 €/t;
  - about 52 G€/a assuming a CO2 tax value equal to 270 €/t.

As shown in Figure 12, according to the different implementation Strategy, the cost in option 1 spans from about 15 to about 22 G€/a: by contrast, according to the different CO2 emission tax value, the cost of option 2 spans from about 66 G€/a to 89 G€/a.

According to that, the ratio between:

- the annual investment cost in generation expansion to cover ENS (option 2);
- the annual investment cost in transmission expansion to cover ENS (option 1)

spans from 2.95 to 6.12. Therefore, it can be concluded that, at the target year, investing in transmission network is always the most cost-effective way to cover ENS.

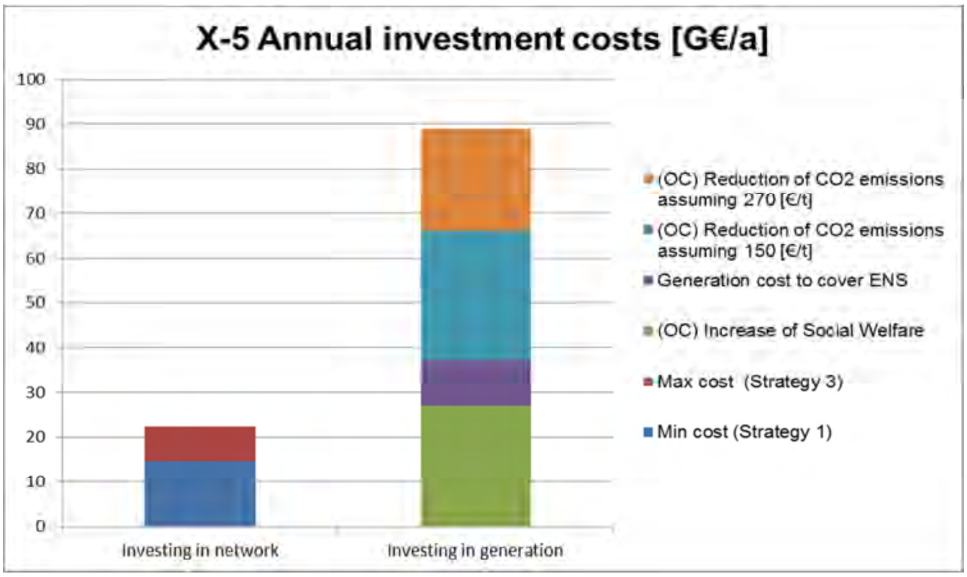

Figure 12 - X-5 Scenario – 2050 – Investment sensitivity analysis

2.1.2. 2040 analyses

2.1.2.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 13 shows the annual values of core benefit indicators for this Scenario.

Table 13 – X-5 Scenario – 2040 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	7
Reduction of CO2 emissions [G€/a]	12
Reduction of reliability costs [G€/a]	84
Benefit core indicators – Grand total [G€/a]	**102**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 7 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 12 G€/a.

In any case, and in coherence with the 2050 evaluation, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 84 G€/a.

According to that, the annual benefit provided by core benefit indicators is more than 102 G€/a.

2.1.2.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 14 and Figure 13 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (about 3.5 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;

- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.34% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.40% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 14 – X-5 Scenario – 2040 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	3.6	3.7	5.5
Cost core indicators - Grand total [G€/a]	**3.6**	**3.7**	**5.5**

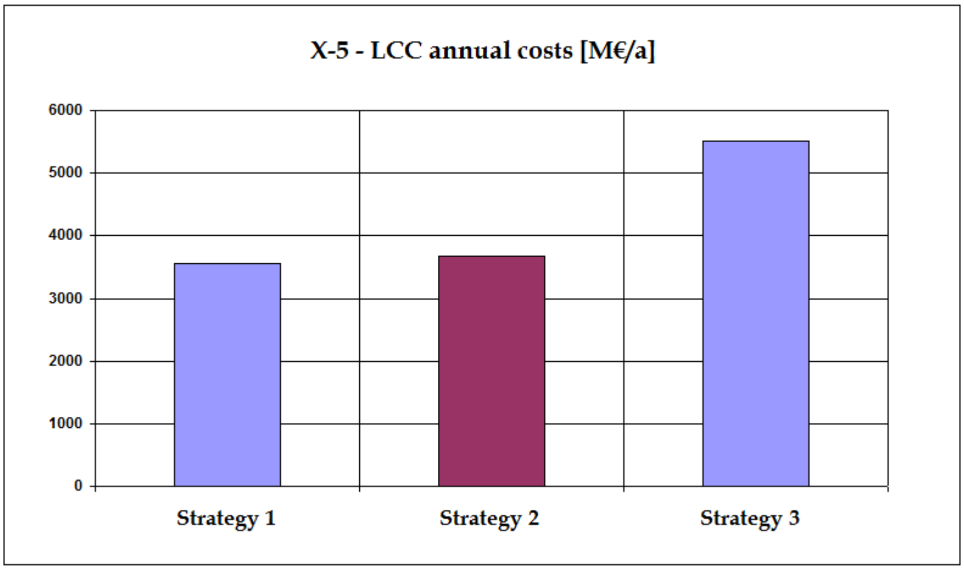

Figure 13 – X-5 Scenario – 2040 – LCC annual costs

2.1.2.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-5 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 15 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO2 emission tax between 169 and 259 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO2 emission tax value included in the interval (169, 259) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.2 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value slightly higher than 11 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO_2 emissions) equal to about 18 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -294 G€/a) and Producers + Consumer Surpluses (about +312 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 15 – X-5 Scenario – 2040 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	259
Sensitivity on CO2 price - Lower bound [€/t]	169
Reduction of investment costs in distribution networks [G€]	0.2
Social Welfare variation (CO2 emissions are accounted) [G€/a]	18
Merchandise Surplus variation [G€/a]	-294
Producers + Consumers Surplus variation [G€/a]	312

2.1.2.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-5 Scenario at the target year 2040 is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 16. As previously stated, the most impacting indicator on the total gross benefit is

represented by the reduction of reliability costs (more than 82% on total gross annual gross benefit).

Table 16 - X-5 Scenario – 2040 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	102.5
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	11.29
% Social Welfare increase [%]	6.61
% Reduction of distribution network investments [%]	0.01
% Reduction of reliability costs [%]	82.09

2.1.2.5. Profitability indicators – Reference case

The main profitability indicators for the X-5 Scenario at the target year 2040 are shown in Table 17. Annual values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 17 - X-5 Scenario – 2040 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	102.5	102.5	102.5
Annual LCC cost [G€/a]	3.6	3.7	5.5
Annual net benefit [G€/a]	98.9	98.8	97.0
PI [adim]	**28.75**	**27.82**	**18.62**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 28.75 in Strategy 1 to 18.62 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.1.2.6. GIS maps

Figure 14 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2040. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Balkan peninsula, Scandinavia peninsula and Italy), in general many regions experience a significant reduction of reliability costs (in Catalonia, Poland and Germany).

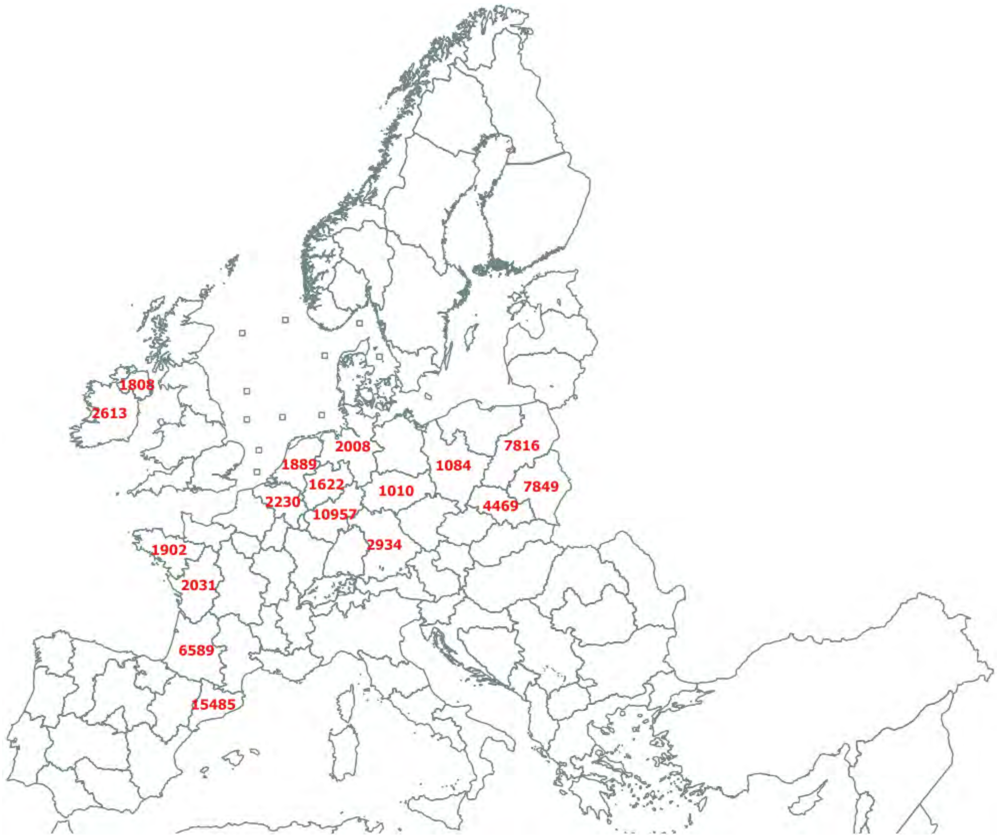

Figure 14 - X-5 Scenario – 2040 – Reduction of ENS costs [M€/a]

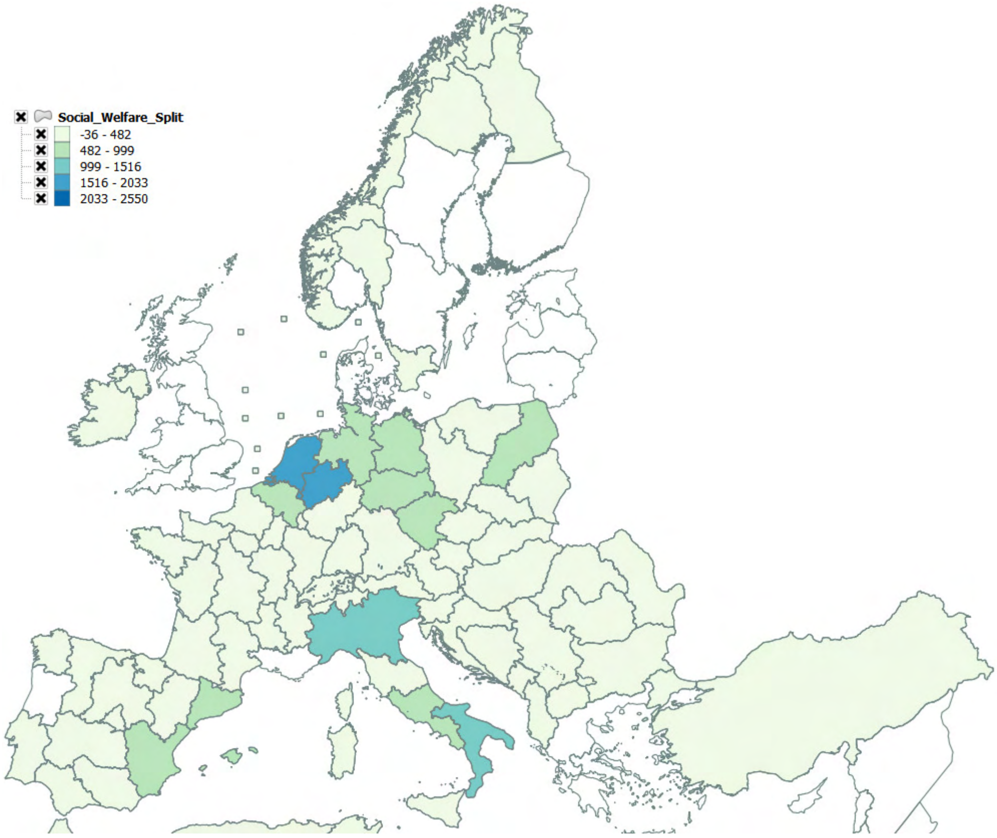

Figure 15 - X-5 Scenario – 2040 – Variation of Social Welfare (CO_2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 15.

As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 18 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 18.

Table 18 - X-5 Scenario – 2040 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	0	Latvia	**-132**
Austria	181	Lithuania	**-157**
Belgium	912	Luxembourg	74
Bosnia & Herzog.	133	Macedonia	49
Bulgaria	87	Montenegro	0
Croatia	177	Netherlands	1670
Czech Republic	629	Norway	**-56**
Denmark	**-159**	Poland	1664
Estonia	**-63**	Portugal	171
Finland	**-300**	Romania	208
France	425	Serbia	438
Germany	5480	Slovakia	**-8**
Great Britain	**-750**	Slovenia	23
Greece	**-230**	Spain	3667
Hungary	64	Sweden	**-279**
Ireland	347	Switzerland	211
Italy	3499	Ukraine	362

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute values of these negative indicators are about 4% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, the transmission network reinforcement plan gives a reduced negative impact at local level: as shown in Table 19, the lowest negative value is reached in Finland (-298 M€/a). The Great Britain situation is emblematic because the local benefit provided by the reduction of ENS costs (2987 M€/a) overshadows the local reduction of Social Welfare (-750 M€/a).

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 19 - X-5 Scenario – 2040 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Denmark	-159	68	-91
Estonia	-63	0	-63
Finland	-300	2	-298
Great Britain	-750	2987	2237
Greece	-230	1	-229
Latvia	-132	0	-132
Lithuania	-157	0	-157
Norway	-56	49	-7
Sweden	-279	23	-256

Figure 16-Figure 18 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

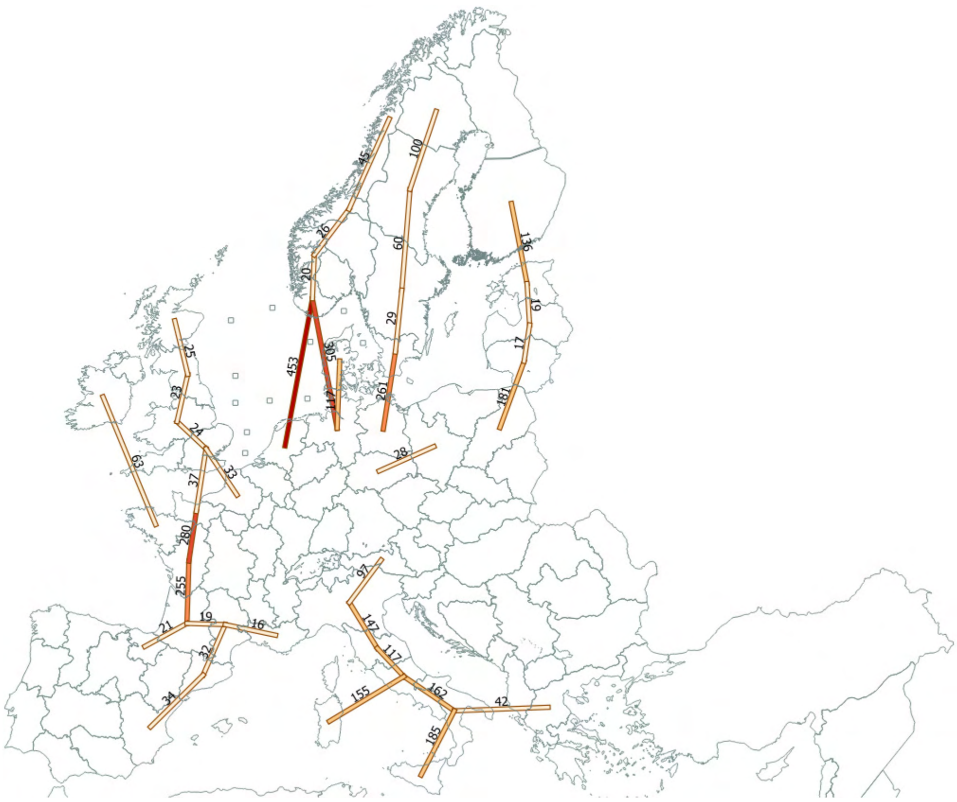

Figure 16 - X-5 Scenario – 2040 – Annual LCC – Strategy 1 [M€/a]

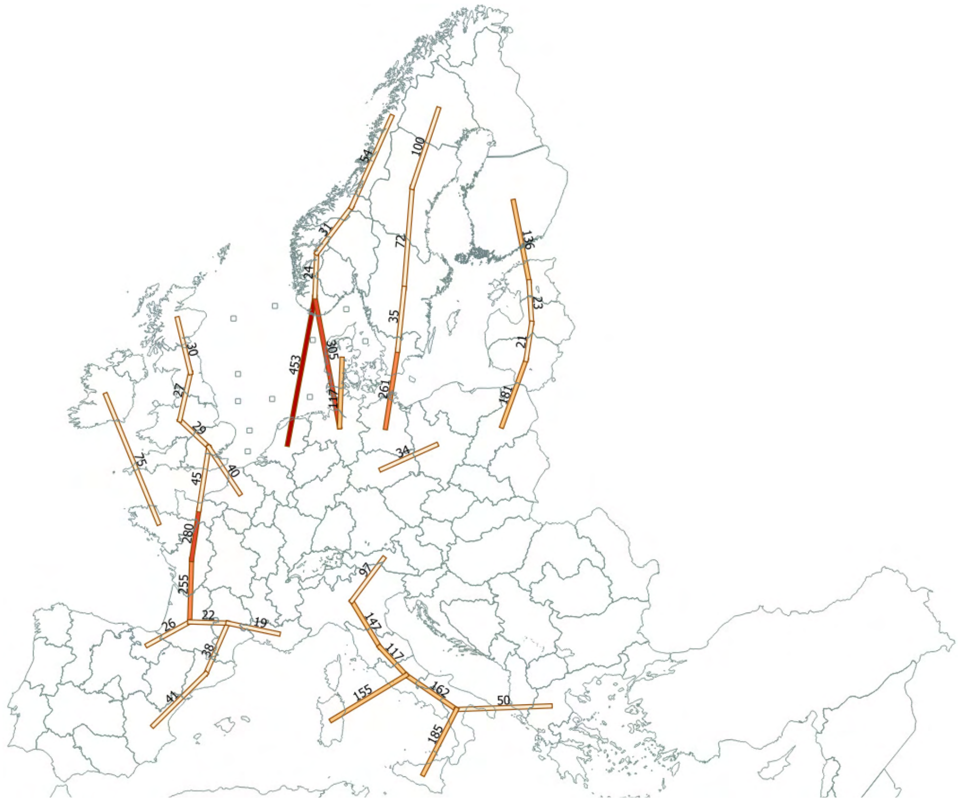

Figure 17 - X-5 Scenario – 2040 – Annual LCC – Strategy 2 [M€/a]

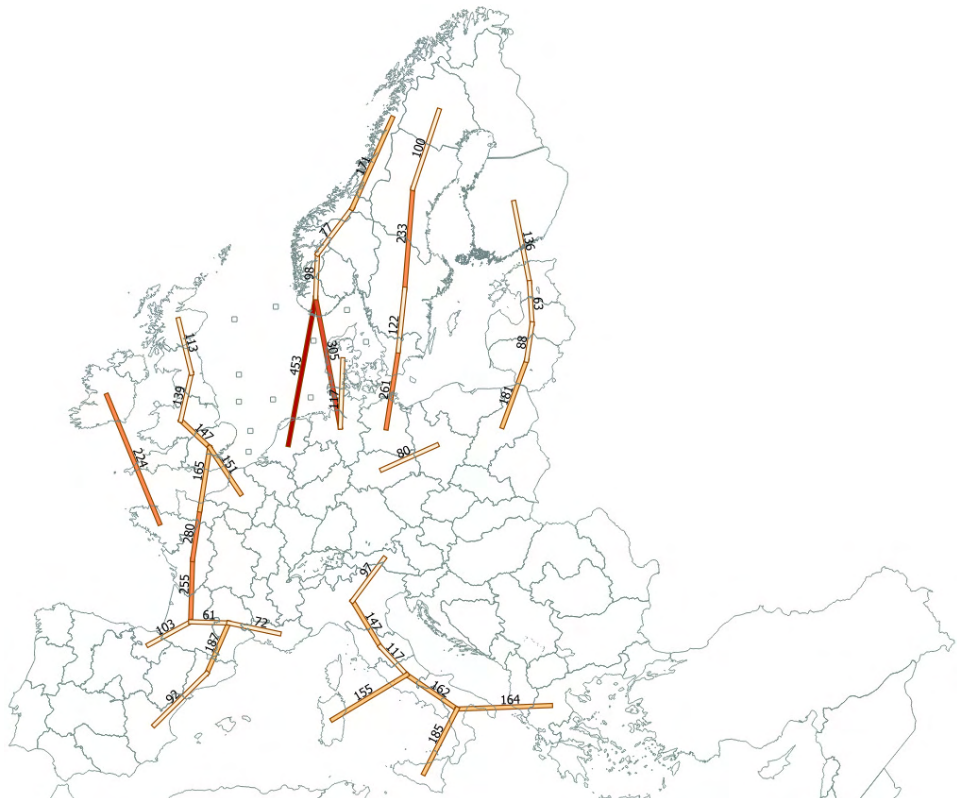

Figure 18 - X-5 Scenario – 2040 – Annual LCC – Strategy 3 [M€/a]

2.2. Scenario X-7 - 100% RES

2.2.1. 2050 analyses

2.2.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 20 shows the annual values of core benefit indicators for this Scenario.

Table 20 – X-7 Scenario – 2050 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	18
Reduction of CO2 emissions [G€/a]	22
Reduction of reliability costs [G€/a]	502
Benefit core indicators – Grand total [G€/a]	**541**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 18 G€/a, while the economic value correspondent to the reduction of CO2 emission is higher than 21 G€/a.

In any case, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 502 G€/a. Since this value is directly related to the adopted VOLL (10000 €/MWh), this aspect is examined in detail in paragraph 2.2.1.7.

According to that, the annual benefit provided by core benefit indicators exceeds 541 G€/a.

2.2.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 21 and Figure 19 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (about 14 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;
- Strategy 2 is slightly more expensive than Strategy 1 (+ 0.83% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 43.53% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 21 – X-7 Scenario – 2050 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	14.0	14.1	20.1
Cost core indicators - Grand total [G€/a]	**14.0**	**14.1**	**20.1**

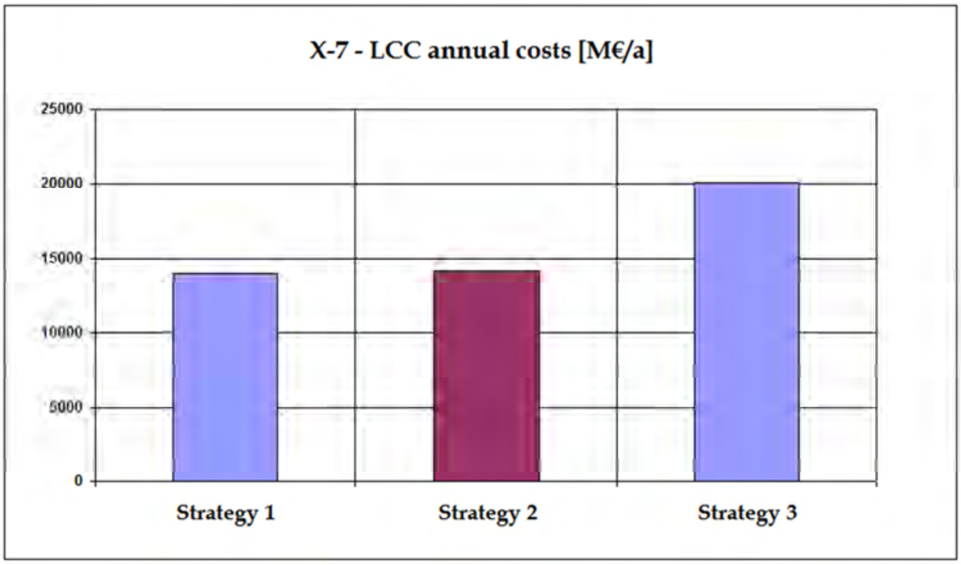

Figure 19 – X-7 Scenario – 2050 – LCC annual costs

2.2.1.2.1. LCC assessment – Sensitivity of S&E aspects

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the impact of Social and Environmental aspects on the LCC in the three different reinforcement Strategies at the target year 2050. Table 22 shows the results of this sensitivity analysis.

As can be easily pointed out, the monetary impact of S&E aspects (acquisition of rights of way) is very low (under than 1%).

The outcome of this analysis does not clearly imply that S&E aspects are a secondary item in transmission planning: in fact, those values find their justification in the adopted approach:

- considering only the rights of way acquisition do not allow to consider the full range of social and environmental externalities connected to transmission network planning;
- the cluster level of detail cannot allow to consider the very local peculiarities of crossed lands;
- the brownfield approach does not make feasible to extend the calculation to new transmission corridors.

Table 22 – X-7 Scenario – 2050 – Sensitivity on S&E aspects

LCC annual costs	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a] – Case 1 - S&E included	14.01	14.14	20.12
LCC - Annual costs [G€/a] – Case 2 - S&E not included	13.96	14.07	20.10
(Case 2 – Case 1)/Case 1 [%]	-0.45%	-0.45%	-0.14%

Therefore, in order to fully appraise the economic impact of S&E aspects in transmission network planning, different analyses with more precise approaches are needed.

2.2.1.2.2. LCC assessment – Sensitivity of F&R aspects

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the impact of Financial and Regulatory aspects on the annual LCC in the three different reinforcement Strategies at the target year 2050.

As shown in Table 23 and Figure 20, there is an exponential relationship between annual LCC and discount rate. In fact:

$$PV_{LCC} = \sum_{t=0}^{T_{ol}} A_{LCC} \cdot \left(\frac{1}{1+DR}\right)^t \Rightarrow A_{LCC} = PV_{LCC} \cdot \frac{(1+DR)^{T_{ol}} \cdot DR}{(1+DR)^{T_{ol}+1} - 1}$$

where:

- PV_{LCC} is the Present Value of life cycle costs [G€];
- T_{ol} is the operative life duration [a];
- A_{LCC} is the annual life cycle cost [G€/a];
- DR is the discount rate [%].

However, in the normal range of values assumed by discount rate, there is a very good approximation with an increasing line.

Table 23 – X-7 Scenario – 2050 – Sensitivity on F&R aspects – Common asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 3	13.9	14.0	20.0	4.95
LCC - Annual costs [G€/a] – Case 1	14.0	14.1	20.1	5.00
LCC - Annual costs [G€/a] – Case 4	14.5	14.7	20.8	5.26
LCC - Annual costs [G€/a] – Case 5	17.7	17.9	25.2	6.76
LCC - Annual costs [G€/a] – Case 6	21.0	21.2	29.8	8.26

This result is not surprising: in an investor perspective, if the money cost increases, the annual amortization of the asset increases as well. Moreover:

- with reference with Strategy 1 and Strategy 2, the lines are practically coincident;
- the slope of Strategy 3 line is higher than the ones with of Strategy 1 and Strategy 2: this is due to the fact that Strategy 3 heavily exploits cables (40 years of operative life). This is due to the fact that the difference in asset operative life implies an increase in annual LCC, and this difference grows faster if the discount rate is higher.

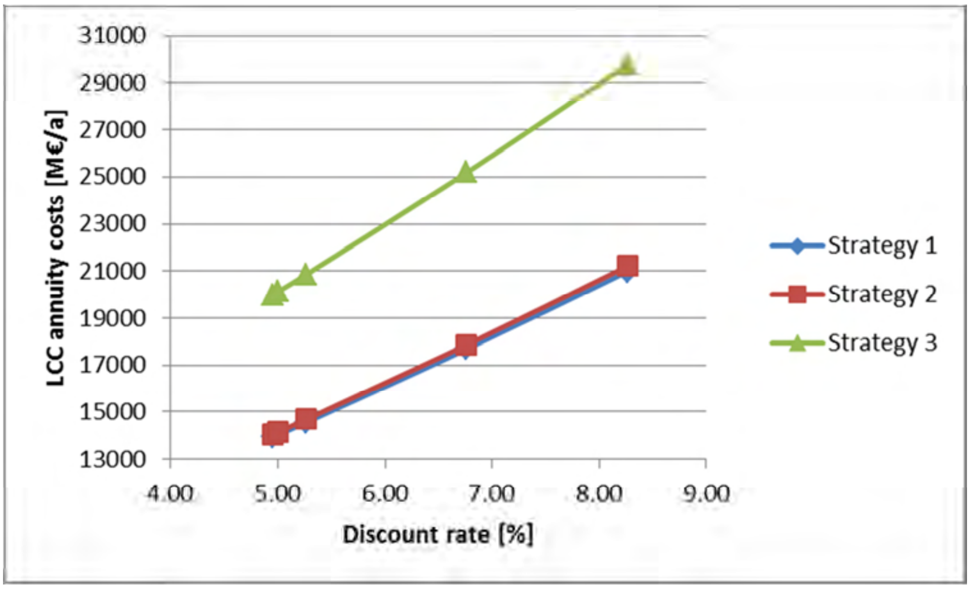

Figure 20 - X-7 Scenario – 2050 – Sensitivity on F&R aspects

Table 24 shows the result of the sensitivity analysis on F&R aspects, taking into account investment specific asset beta values: it can be noted how different values of asset beta do not bring to sensible changes (increases are lower than 0.5%) in the annual LCC.

Moreover, it can be noted how resulting average discount rates are very close (5% in Case 1, 4.99% in Case 7).

Table 24 - X-7 Scenario – 2050 – Sensitivity on F&R aspects – Investment specific asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 1	14.01	14.1	20.1	5.00
LCC - Annual costs [G€/a] – Case 7	14.09	14.2	20.2	4.99
(Case 7 – Case 1)/Case 7 [%]	0.47%	0.40%	0.20%	-

2.2.1.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 25 shows the values of non-core indicators for this Scenario.

Table 25 – X-7 Scenario – 2050 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	+ ∞
Sensitivity on CO2 price - Lower bound [€/t]	0
Reduction of investment costs in distribution networks [G€]	1.3
Social Welfare variation (CO2 emissions are accounted) [G€/a]	39
Merchandise Surplus variation [G€/a]	-1349
Producers + Consumers Surplus variation [G€/a]	1388

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any feasible variation of CO_2 emission tax does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO_2 emission tax value included in the interval (0, + ∞) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 1.40 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 70 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 39 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -1350 G€/a) and Producers + Consumer Surpluses (about +1388 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

2.2.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-7 Scenario at the target year 2050 is performed. The set of benefits that have been taken into account are:

- reduction of CO2 emissions;
- increase of Social Welfare (not including CO2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 26. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 90% on total gross annual gross benefit).

Table 26 - X-7 Scenario – 2050 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	541
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	3.99
% Social Welfare increase [%]	3.17
% Reduction of distribution network investments [%]	0.01
% Reduction of reliability costs [%]	92.82

2.2.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-7 Scenario at the target year 2050 are shown in Table 27. Annual and present values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

In order to evaluate the present value of gross benefit, the same annuity ratio between annual and present LCC is shown: this allows to maintain the same PI between annual and present value indicators.

Table 27 - X-7 Scenario – 2050 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	541.3	541.3	541.3
Annual LCC cost [G€/a]	14.0	14.1	20.1
Annual net benefit [G€/a]	527.3	527.2	532.2
Present Value of gross benefit [G€]	9471.4	9504.1	9393.9
Present Value of LCC cost [G€]	245.3	248.2	345.5
Present Value of net benefit [G€]	9226.1	9255.9	8948.4
PI [adim]	**38.61**	**38.29**	**26.90**

It can be observed how the Present Value of net benefit in Strategy 2 (NPV_2) is slightly higher than the one in Strategy 1 (NPV_1): this finds its justification in the high values assumed by the Profitability Index in Strategy 2. In fact, taking into account the link between NPV, PI and the present value of LCC cost (PV_{LCC}):

$$NPV_2 > NPV_1 \rightarrow (PI_2 - 1) \cdot PV_{LCC,2} > (PI_1 - 1) \cdot PV_{LCC,1} \rightarrow \frac{(PI_2 - 1)}{(PI_1 - 1)} > \frac{PV_{LCC,1}}{PV_{LCC,2}}$$

Therefore, NPV_2 is higher than NPV_1 when the increase of the present value of LCC cost in Strategy 2 is lower than the reduction the $PI_2 - 1$ respect $PI_1 - 1$.

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 38.61 in Strategy 1 to 26.90 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.2.1.6. <u>GIS maps</u>

Figure 21 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2050. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Denmark, Greece, Norway, Portugal or Sweden), in general many regions experience a significant reduction of reliability costs (in Germany, Belgium, France, Netherlands and Spain).

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO_2 emissions) is shown in a colored map in Figure 22.

Figure 21 - X-7 Scenario – 2050 – Reduction of ENS costs [M€/a]

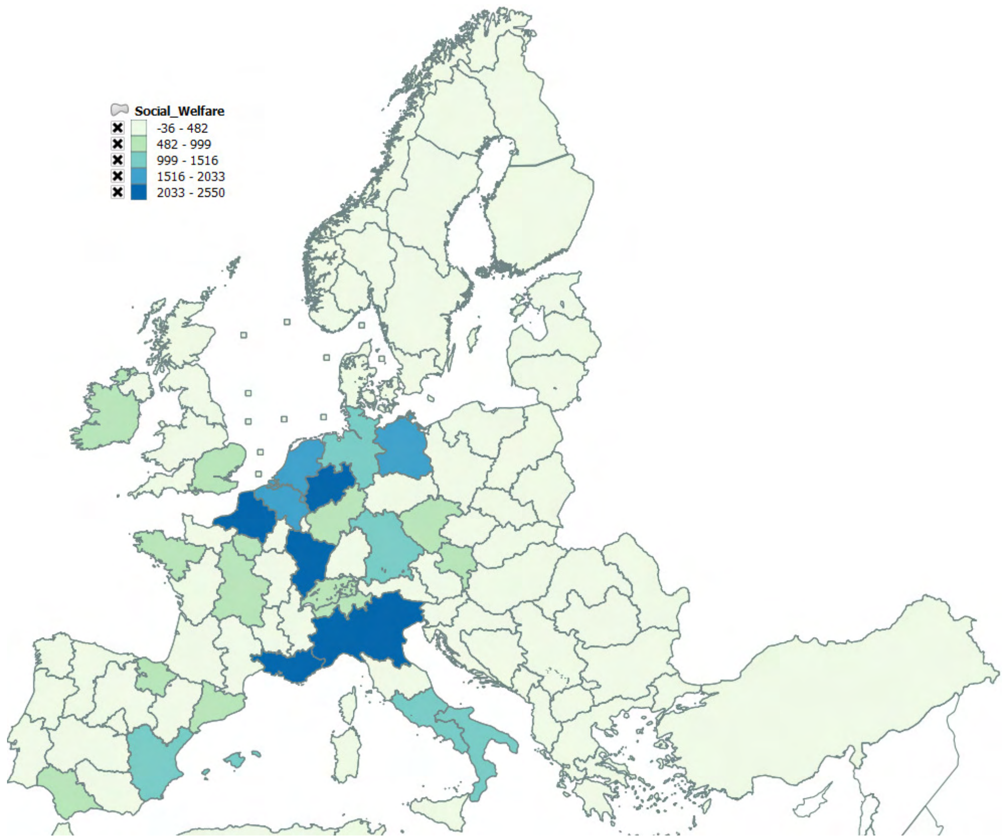

Figure 22 - X-7 Scenario – 2050 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 39 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 28.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators are far lower than 1% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, as shown in Table 29 the transmission network reinforcement plan gives a (slight) negative sum only in Greece (-6 M€/a) and Norway (-13 M€/a).

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 28 - X-7 Scenario – 2050 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	0	Latvia	41
Austria	838	Lithuania	34
Belgium	1744	Luxembourg	146
Bosnia & Herzog.	1	Macedonia	0
Bulgaria	12	Montenegro	0
Croatia	0	Netherlands	1941
Czech Republic	955	Norway	**-13**
Denmark	**-1**	Poland	937
Estonia	16	Portugal	**-13**
Finland	40	Romania	82
France	9157	Serbia	10
Germany	8090	Slovakia	232
Great Britain	1415	Slovenia	168
Greece	**-59**	Spain	4.668
Hungary	150	Sweden	**-60**
Ireland	807	Switzerland	1.269
Italy	5296	Ukraine	898

Table 29 - X-7 Scenario – 2050 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Denmark	-1	20	19
Greece	-59	53	-6
Norway	-13	0	-13
Portugal	-13	463	450
Sweden	-60	65	5

Figure 23-Figure 25 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

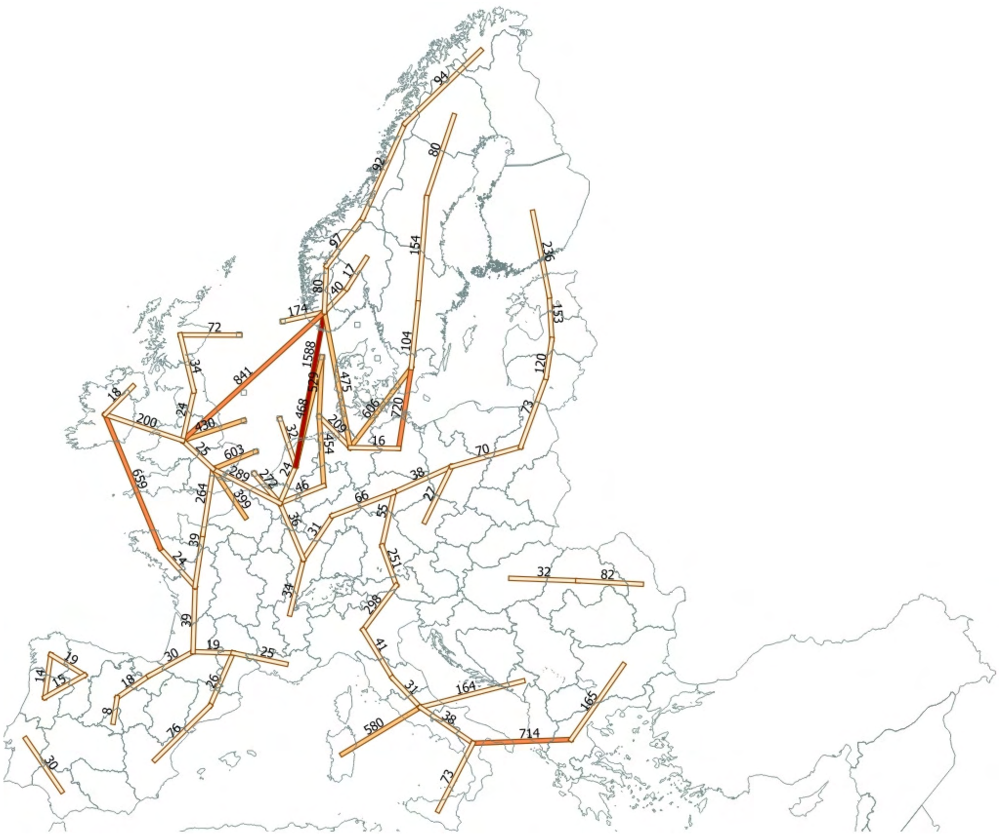

Figure 23 - X-7 Scenario – 2050 – Annual LCC – Strategy 1 [M€/a]

Figure 24 - X-7 Scenario – 2050 – Annual LCC – Strategy 2 [M€/a]

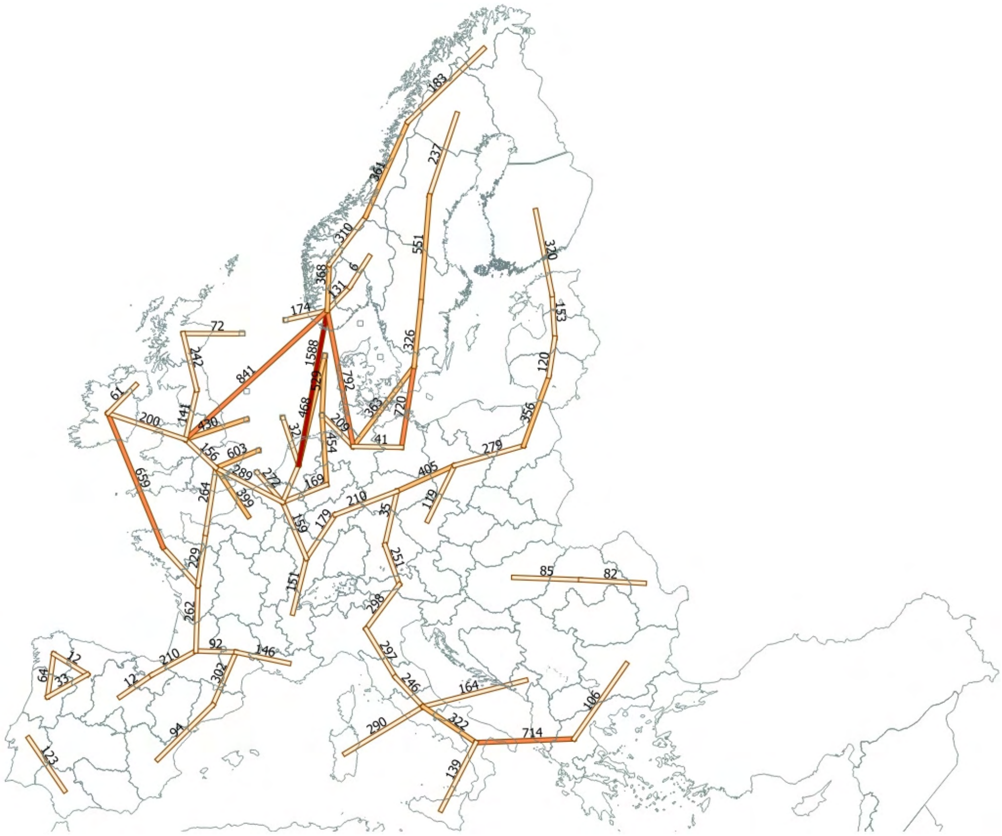

Figure 25 - X-7 Scenario – 2050 – Annual LCC – Strategy 3 [M€/a]

2.2.1.7. Investment sensitivity analysis: network vs. generation to cover ENS

This paragraph show the results of a sensitivity analysis performed at the target year 2050 in order to compare the cost in overcoming the same amount of ENS by means of:

- *option 1*: investment in grid reinforcements;
- *option 2*: investment in peak generation (in particular, Open Cycle Gas Turbine, OCGT, power plants).

The aim of this analysis is to check if, in order to cover ENS, investment in transmission network are (or are not) more profitable than investment in fossil-fuel peak generation, independently by the assumed VoLL.

Regarding option 2, calculation hypotheses (from WP2 and WP3) are reported below:

- fixed investment cost (CAPEX) in OCGT equal to 0.7 G€/MW;
- fuel and CO2 operation cost (OPEX) in OCGT equal to 203 €/MWh;
- maximum amount hourly saved ENS (without – with case) equal to 137 GW: this information is needed in order to properly rate the amount of additional OCGT installed capacity;
- saved ENS (without – with case) equal to 50.25 TWh/a: this information is needed in order to properly rate the production by additional OCGT power plants;
- annuity factor for investment in OCGT equal to 0.0745;

Taking into account both CAPEX and OPEX in new OCGT power plants, the annual TOTEX = CAPEX + OPEX in new OCGT power plants to cover ENS is equal to 17 G€/a.

However, option 2 implies a loss in other benefits achievable by transmission network reinforcements: therefore, this arises as opportunity costs in terms of increase of Social Welfare and reduction of CO2 emissions:

- opportunity cost due to the increase of Social Welfare: about 17 G€/a;
- opportunity cost due to the reduction of CO2 emissions:
    - about 12 G€/a assuming a CO2 tax value equal to 150 €/t;
    - about 22 G€/a assuming a CO2 tax value equal to 270 €/t.

As shown in Figure 26, according to the different implementation Strategy, the cost in option 1 spans from about 14 to about 20 G€/a: by contrast, according to the different CO2 emission tax value, the cost of option 2 spans from about 47 G€/a to 56 G€/a.

According to that, the ratio between:

- the annual investment cost in generation expansion to cover ENS (option 2);
- the annual investment cost in transmission expansion to cover ENS (option 1)

spans from 2.31 to 4.01. Therefore, it can be concluded that, at the target year, investing in transmission network is always the most cost-effective way to cover ENS.

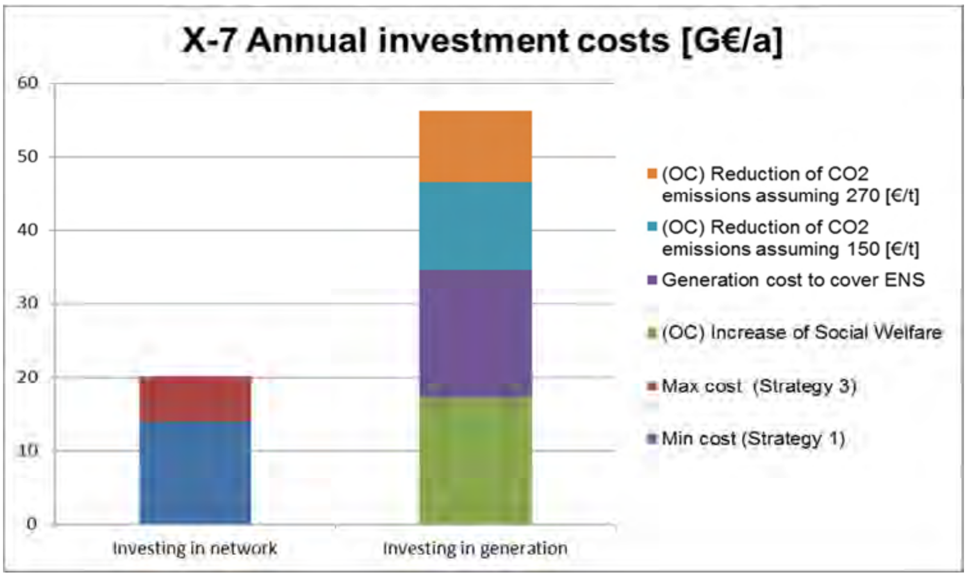

Figure 26 - X-7 Scenario – 2050 – Investment sensitivity analysis

2.2.1. 2040 analyses

2.2.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 30 shows the annual values of core benefit indicators for this Scenario.

Table 30 – X-7 Scenario – 2040 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	5
Reduction of CO2 emissions [G€/a]	8
Reduction of reliability costs [G€/a]	92
Benefit core indicators – Grand total [G€/a]	**104**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 5 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 8 G€/a.

In any case, and in coherence with the 2050 evaluation, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for about 92 G€/a.

According to that, the annual benefit provided by core benefit indicators is about 104 G€/a.

2.2.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 31 and Figure 27 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (slightly lower than 3.6 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;

- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.34% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.40% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 31 – X-7 Scenario – 2040 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	3.6	3.7	5.5
Cost core indicators - Grand total [G€/a]	**3.6**	**3.7**	**5.5**

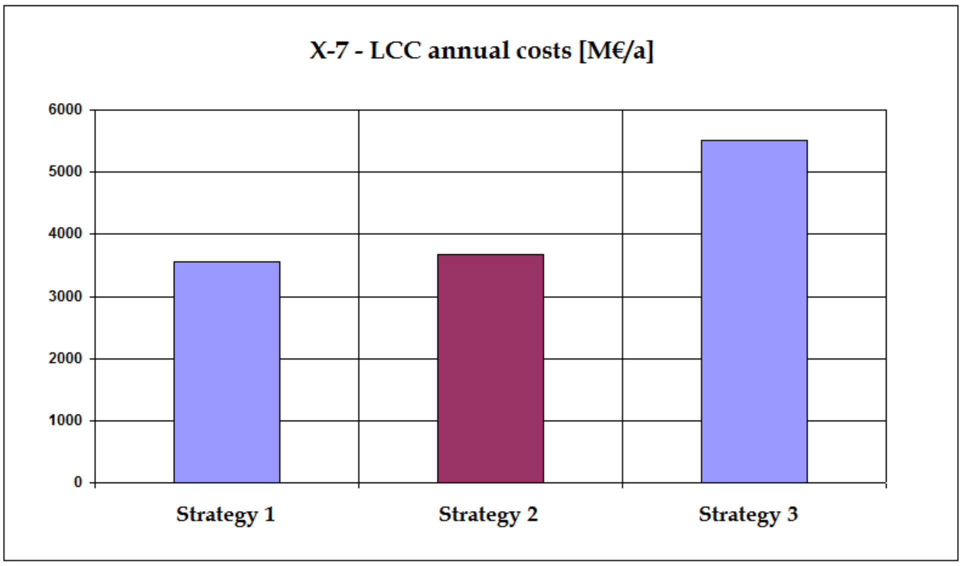

Figure 27 – X-7 Scenario – 2040 – LCC annual costs

2.2.1.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-7 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 32 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any CO_2 emission tax value higher than 89 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO_2 emission tax value included in the interval (89, + ∞) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.2 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 11 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 12 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -304 G€/a) and Producers + Consumer Surpluses (about +316 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 32 – X-7 Scenario – 2040 – Non-core indicators

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	+ ∞
Sensitivity on CO2 price - Lower bound [€/t]	89
Reduction of investment costs in distribution networks [G€]	0.2
Social Welfare variation (CO2 emissions are accounted) [G€/a]	12
Merchandise Surplus variation [G€/a]	-304
Producers + Consumers Surplus variation [G€/a]	316

2.2.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-7 Scenario at the target year 2040 is performed. The set of benefits that have been taken into account are:

- reduction of CO2 emissions;
- increase of Social Welfare (not including CO2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 33. As previously stated, the most impacting indicator on the total gross benefit is

represented by the reduction of reliability costs (more than 88% on total gross annual gross benefit).

Table 33 - X-7 Scenario – 2040 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	104.1
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	7.36
% Social Welfare increase [%]	4.50
% Reduction of distribution network investments [%]	0.01
% Reduction of reliability costs [%]	88.13

2.2.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-7 Scenario at the target year 2040 are shown in Table 34. Annual values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 34 - X-7 Scenario – 2040 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	104.1	104.1	104.1
Annual LCC cost [G€/a]	3.6	3.7	5.5
Annual net benefit [G€/a]	100.5	100.4	98.6
PI [adim]	**29.21**	**28.26**	**18.92**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 29.21 in Strategy 1 to 18.92 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.2.1.6. GIS maps

Figure 28 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2040. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Scandinavian peninsula, Balkan peninsula and Italy), in general many regions experience a significant reduction of reliability costs (in Catalonia, Poland, France, and Germany).

Figure 28 - X-7 Scenario – 2040 – Reduction of ENS costs [M€/a]

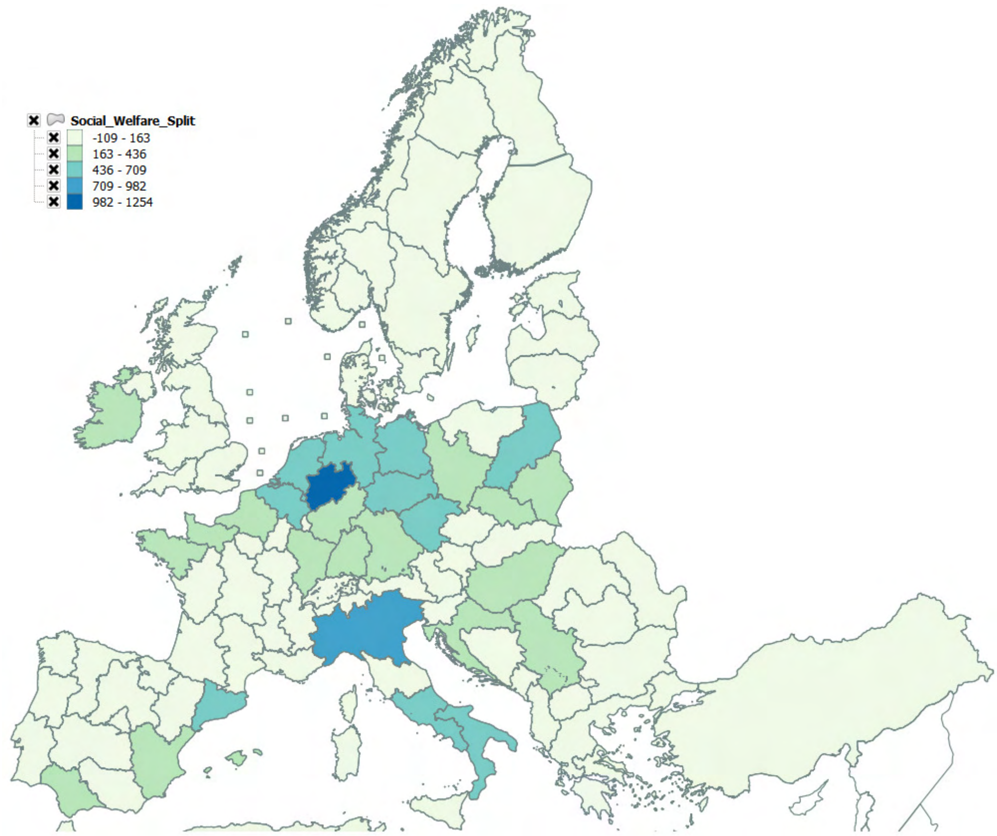

Figure 29 - X-7 Scenario – 2040 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 29.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 12 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 35.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators are far lower than 1% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, as shown in Table 36 the transmission network reinforcement plan gives (slight) negative sums: the lowest negative value is reached in Greece (-153 M€/a). The Great Britain situation is emblematic because the local benefit provided by the reduction of ENS costs (6484 M€/a) overshadows the local reduction (-279 M€/a) of Social Welfare.

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 35 - X-7 Scenario – 2040 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	0	Latvia	**-38**
Austria	190	Lithuania	**-44**
Belgium	458	Luxembourg	42
Bosnia & Herzog.	93	Macedonia	33
Bulgaria	31	Montenegro	0
Croatia	191	Netherlands	637
Czech Republic	465	Norway	**-7**
Denmark	**-99**	Poland	1287
Estonia	**-18**	Portugal	84
Finland	**-103**	Romania	114
France	1065	Serbia	190
Germany	3957	Slovakia	25
Great Britain	**-279**	Slovenia	162
Greece	**-153**	Spain	1461
Hungary	168	Sweden	**-151**
Ireland	239	Switzerland	16
Italy	1975	Ukraine	357

Table 36 - X-7 Scenario – 2040 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Denmark	-99	55	-44
Estonia	-18	0	-18
Finland	-103	15	-88
Great Britain	-279	6484	6205
Greece	-153	0	-153
Latvia	-38	0	-38
Lithuania	-44	0	-44
Norway	-7	11	4
Sweden	-151	127	-24

Figure 30-Figure 32 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

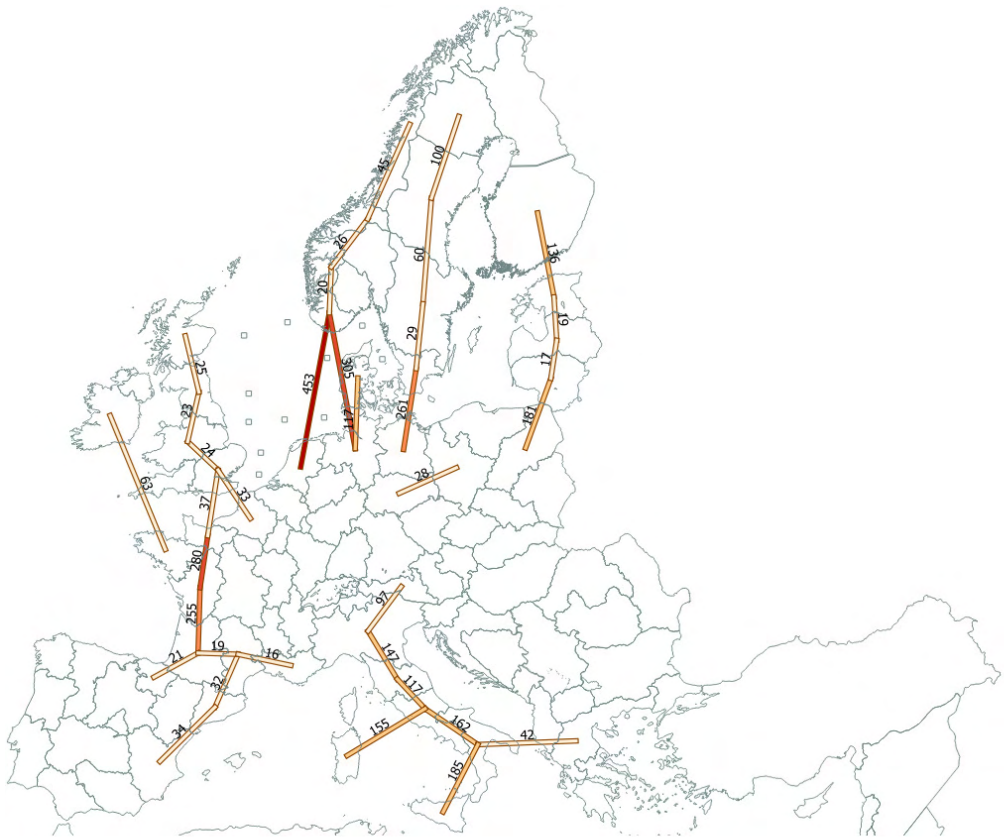

Figure 30 - X-7 Scenario – 2040 – Annual LCC – Strategy 1 [M€/a]

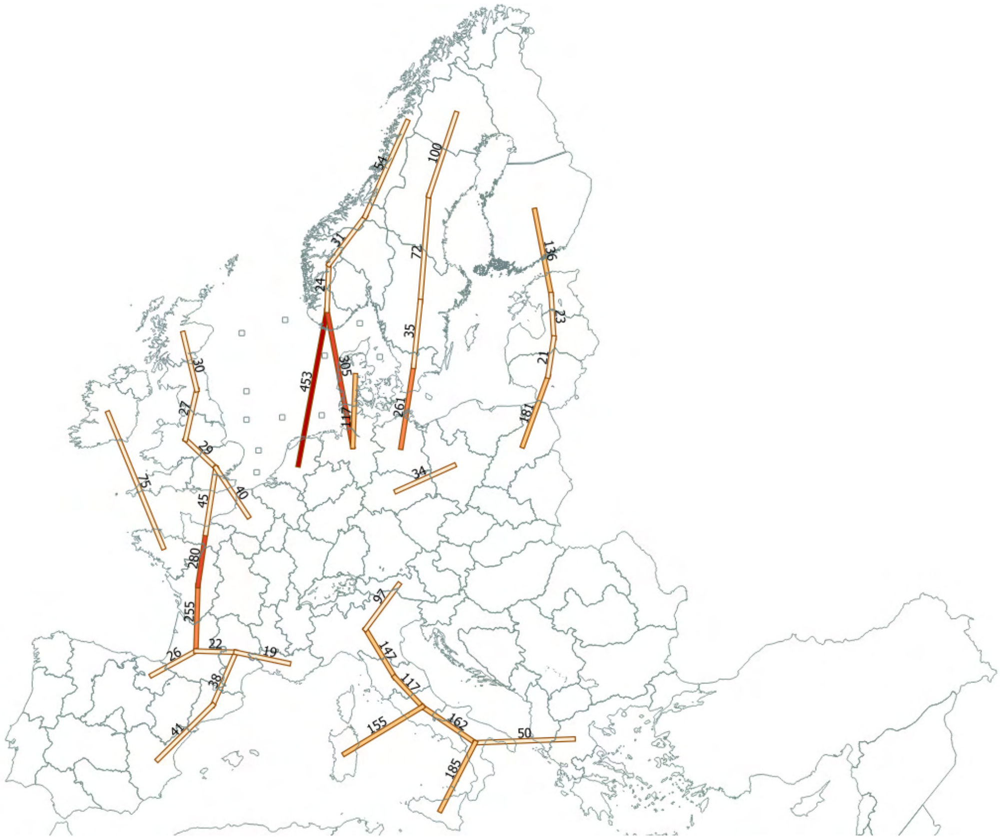

Figure 31 - X-7 Scenario – 2040 – Annual LCC – Strategy 2 [M€/a]

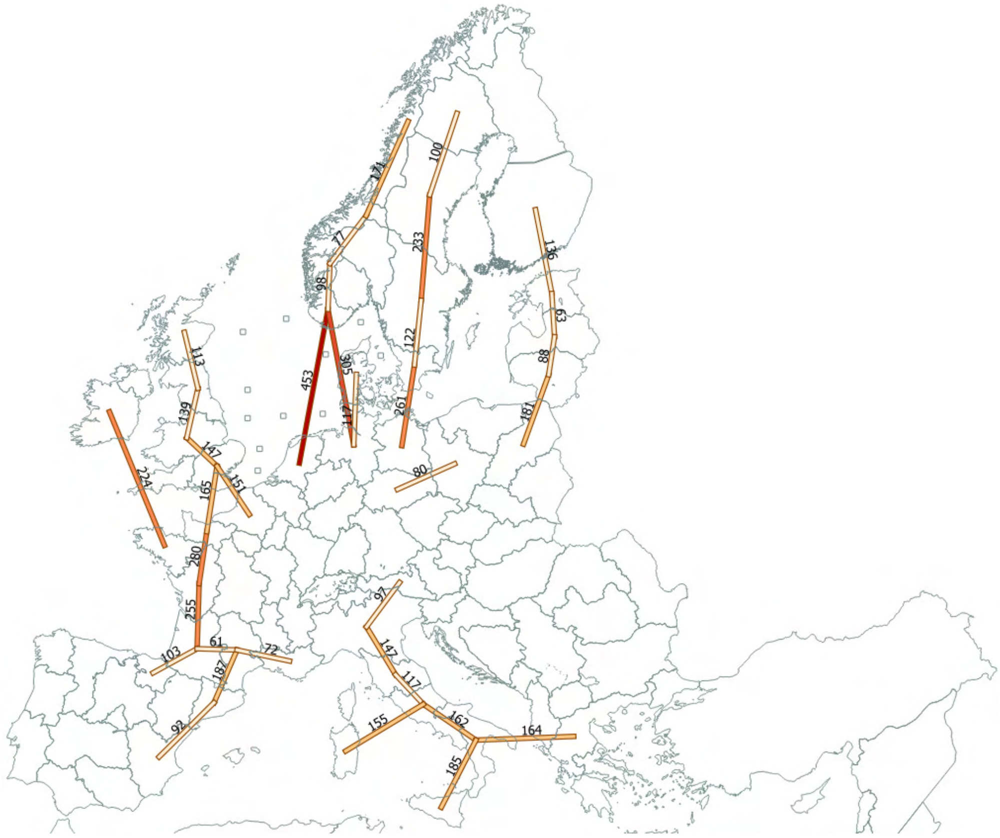

Figure 32 - X-7 Scenario – 2040 – Annual LCC – Strategy 3 [M€/a]

2.3. Scenario X-10 - Big and Market

2.3.1. 2050 analyses

2.3.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 37 shows the annual values of core benefit indicators for this Scenario.

Table 37 – X-10 Scenario – 2050 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	8
Reduction of CO2 emissions [G€/a]	15
Reduction of reliability costs [G€/a]	115
Benefit core indicators – Grand total [G€/a]	138

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 8 G€/a, while the economic value correspondent to the reduction of CO2 emission is slightly higher than 14 G€/a.

In any case, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for about 115 G€/a. Since this value is directly related to the adopted VOLL (10000 €/MWh), this aspect is examined in detail in paragraph 2.3.1.7.

According to that, the annual benefit provided by core benefit indicators in about 138 G€/a.

2.3.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 38 and Figure 33 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (about 7.9 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;
- Strategy 2 is slightly more expensive than Strategy 1 (+ 2.80% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 60.06% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 38 – X-10 Scenario – 2050 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	7.9	8.1	12.6
Cost core indicators - Grand total [G€/a]	**7.9**	**8.1**	**12.6**

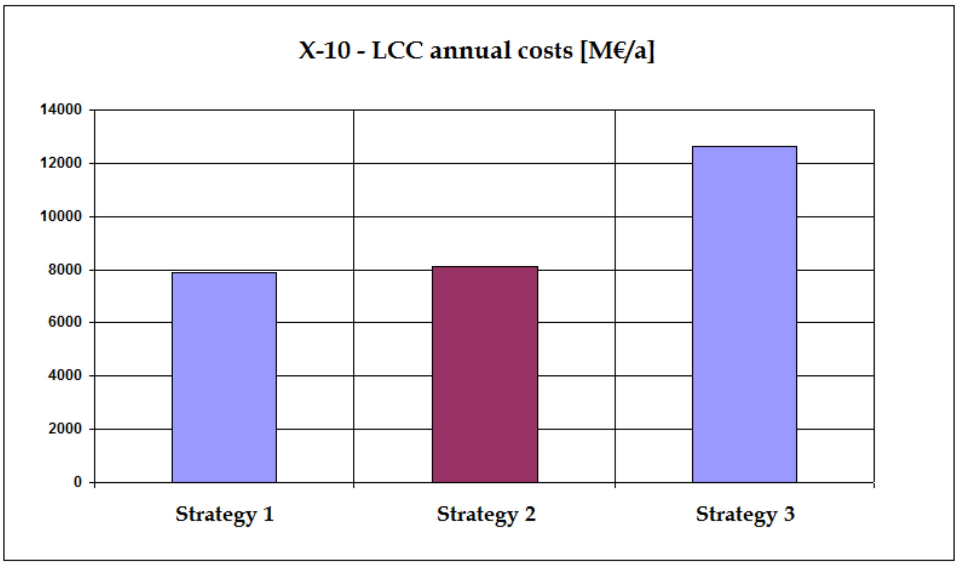

Figure 33 – X-10 Scenario – 2050 – LCC annual costs

2.3.1.2.1. LCC assessment – Sensitivity of S&E aspects

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the impact of Social and Environmental aspects on the LCC in the three different reinforcement Strategies at the target year 2050. Table 39 shows the results of this sensitivity analysis.

As can be easily pointed out, the monetary impact of S&E aspects (acquisition of rights of way) is very low (under than 1%).

The outcome of this analysis does not clearly imply that S&E aspects are a secondary item in transmission planning: in fact, those values find their justification in the adopted approach:

- considering only the rights of way acquisition do not allow to consider the full range of social and environmental externalities connected to transmission network planning;
- the cluster level of detail cannot allow to consider the very local peculiarities of crossed lands;
- the brownfield approach does not make feasible to extend the calculation to new transmission corridors.

Table 39 – X-10 Scenario – 2050 – Sensitivity on S&E aspects

LCC annual costs	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a] – Case 1 - S&E included	7.98	8.1	12.61
LCC - Annual costs [G€/a] – Case 2 - S&E not included	7.85	8.08	12.60
(Case 2 – Case 1)/Case 1 [%]	-0.29%	-0.28%	-0.09%

Therefore, in order to fully appraise the economic impact of S&E aspects in transmission network planning, different analyses with more precise approaches are needed.

2.3.1.2.2. LCC assessment – Sensitivity of F&R aspects

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the impact of Financial and Regulatory aspects on the annual LCC in the three different reinforcement Strategies at the target year 2050.

As shown in Table 40 and Figure 34, there is an exponential relationship between annual LCC and discount rate. In fact:

$$PV_{LCC} = \sum_{t=0}^{T_{ol}} A_{LCC} \cdot \left(\frac{1}{1+DR}\right)^{t} \Rightarrow A_{LCC} = PV_{LCC} \cdot \frac{(1+DR)^{T_{ol}} \cdot DR}{(1+DR)^{T_{ol}+1} - 1}$$

where:

- PV_{LCC} is the Present Value of life cycle costs [G€];
- T_{ol} is the operative life duration [a];
- A_{LCC} is the annual life cycle cost [G€/a];
- DR is the discount rate [%].

However, in the normal range of values assumed by discount rate, there is a very good approximation with an increasing line.

Table 40 – X-10 Scenario – 2050 – Sensitivity on F&R aspects – Common asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 3	7.8	8.0	12.5	4.95
LCC - Annual costs [G€/a] – Case 1	7.9	8.1	12.6	5.00
LCC - Annual costs [G€/a] – Case 4	8.2	8.4	13.1	5.26
LCC - Annual costs [G€/a] – Case 5	10.0	10.3	15.8	6.76
LCC - Annual costs [G€/a] – Case 6	11.8	12.2	18.7	8.26

This result is not surprising: in an investor perspective, if the money cost increases, the annual amortization of the asset increases as well. Moreover:

- with reference with Strategy 1 and Strategy 2, the lines are very close and practically parallel;
- the slope of Strategy 3 line is higher than the ones with of Strategy 1 and Strategy 2: this is due to the fact that Strategy 3 heavily exploits cables (40 years of operative life). This is due to the fact that the difference in asset operative life implies an increase in annual LCC, and this difference grows faster if the discount rate is higher.

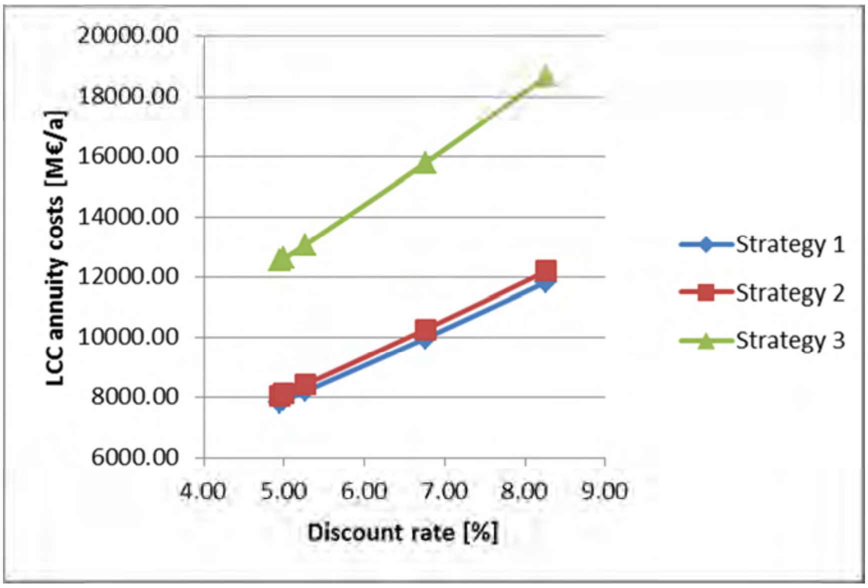

Figure 34 - X-10 Scenario – 2050 – Sensitivity on F&R aspects

Table 24 shows the result of the sensitivity analysis on F&R aspects, taking into account investment specific asset beta values: it can be noted how different values of asset beta do not bring to sensible changes (increases are lower than 0.5%) in the annual LCC. Moreover, it can be noted how resulting average discount rates are very close (5% in Case 1, 5.01% in Case 7).

Table 41 - X-10 Scenario – 2050 – Sensitivity on F&R aspects – Investment specific asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 1	7.88	8.10	12.61	5.00
LCC - Annual costs [G€/a] – Case 7	7.93	8.15	12.69	5.01
(Case 7 – Case 1)/Case 7 [%]	0.68%	0.67%	0.65%	-

2.3.1.3. Non-core indicator assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 42 shows the values of non-core indicators for this Scenario.

Table 42 – X-10 Scenario – 2050 – Non-core indicators

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	320
Sensitivity on CO2 price - Lower bound [€/t]	240
Reduction of investment costs in distribution networks [G€]	0.5
Social Welfare variation (CO2 emissions are accounted) [G€/a]	23
Merchandise Surplus variation [G€/a]	-281
Producers + Consumers Surplus variation [G€/a]	304

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO_2 emission tax between 320 €/t and 240 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO_2 emission tax value included in the interval (240, 320) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.5 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 27 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO_2 emissions) equal to about 23 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -281 G€/a) and Producers + Consumer Surpluses (about +304 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

2.3.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-10 Scenario at the target year 2050 is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 43. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 80% on total gross annual gross benefit).

Table 43 - X-10 Scenario – 2050 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	137.7
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	10.64
% Social Welfare increase [%]	5.86
% Reduction of distribution network investments [%]	0.02
% Reduction of reliability costs [%]	83.48

2.3.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-10 Scenario at the target year 2050 are shown in Table 44. Annual and present values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 44 - X-10 Scenario – 2050 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	137.7	137.7	137.7
Annual LCC cost [G€/a]	7.9	8.1	12.6
Annual net benefit [G€/a]	129.8	129.6	125.1
Present Value of gross benefit [G€]	2415.3	2423.9	2363.6
Present Value of LCC cost [G€]	138.2	142.57	216.5
Present Value of net benefit [G€]	2277.1	2281.4	2147.2
PI [adim]	**17.48**	**17.00**	**10.92**

In order to evaluate the present value of gross benefit, the same annuity ratio between annual and present LCC is shown: this allows to maintain the same PI between annual and present value indicators.

It can be observed how the Present Value of net benefit in Strategy 2 (NPV_2) is slightly higher than the one in Strategy 1 (NPV_1): this finds its justification in the high values assumed by the Profitability Index in Strategy 2. In fact, taking into account the link between NPV, PI and the present value of LCC cost (PV_{LCC}):

$$NPV_2 > NPV_1 \rightarrow (PI_2 - 1) \cdot PV_{LCC,2} > (PI_1 - 1) \cdot PV_{LCC,1} \rightarrow \frac{(PI_2 - 1)}{(PI_1 - 1)} > \frac{PV_{LCC,1}}{PV_{LCC,2}}$$

Therefore, NPV_2 is higher than NPV_1 when the increase of the present value of LCC cost in Strategy 2 is lower than the reduction the $PI_2 - 1$ respect $PI_1 - 1$.

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 17.48 in Strategy 1 to 10.92 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.3.1.6. GIS maps

Figure 35 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2050. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Baltic region, Balkan peninsula, etc.), in general many regions experience a significant reduction of reliability costs (in Spain, Ireland and France).

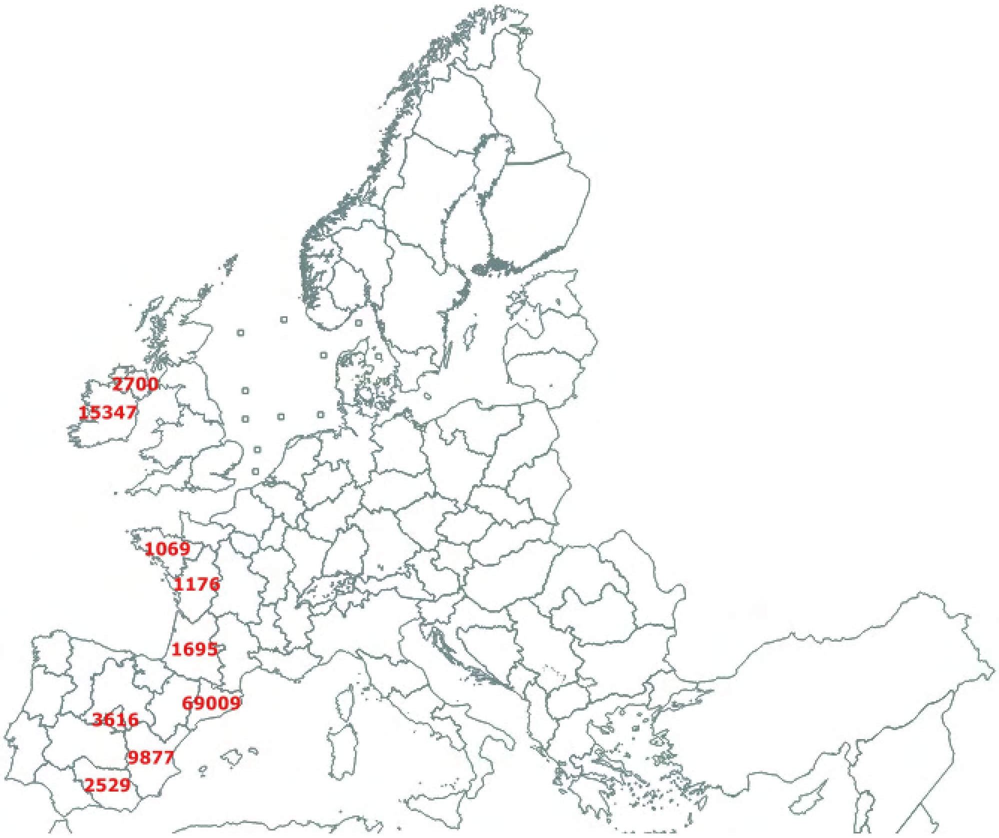

Figure 35 - X-10 Scenario – 2050 – Reduction of ENS costs [M€/a]

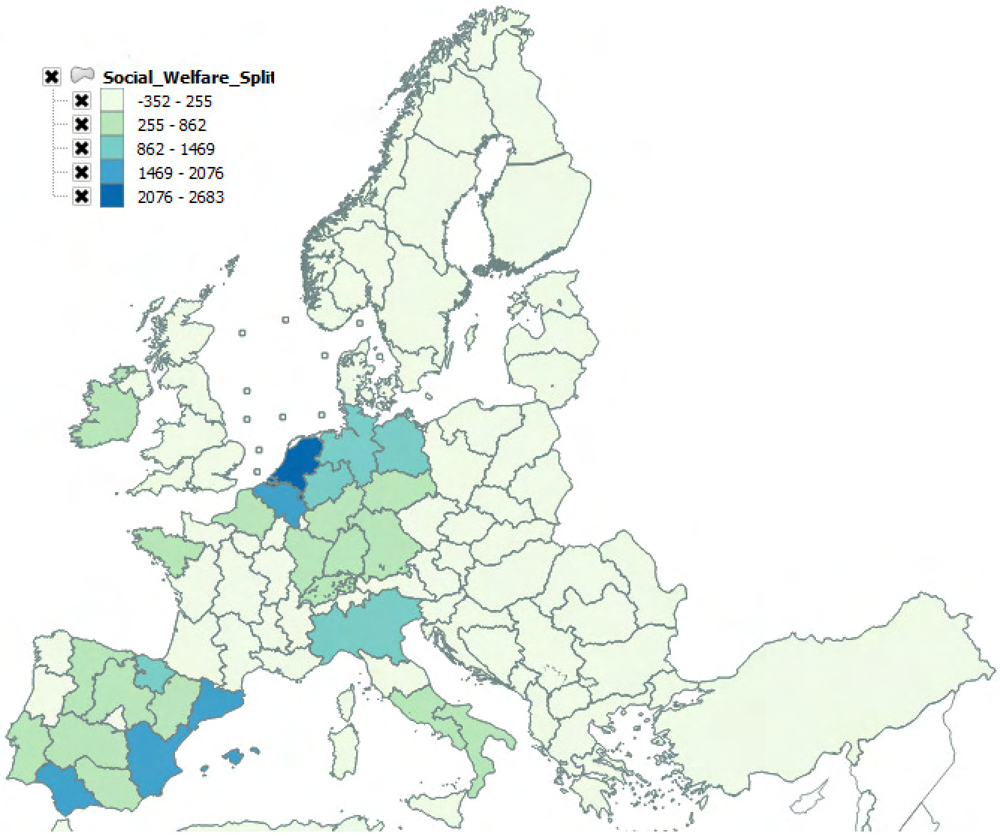

Figure 36 - X-10 Scenario – 2050 – Variation of Social Welfare (CO_2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 36.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 23 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 45.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators are far lower than 1% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, the transmission network reinforcement plan gives a (slight) negative sums: as shown in Table 46, the lowest negative value is reached in Finland (-385 M€/a). The Great Britain situation is emblematic because the local benefit provided by the reduction of ENS costs (4133 M€/a) overshadows the local reduction (-997 M€/a) of Social Welfare.

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 45 - X-10 Scenario – 2050 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	47	Latvia	**-99**
Austria	193	Lithuania	**-161**
Belgium	1538	Luxembourg	73
Bosnia & Herzog.	54	Macedonia	48
Bulgaria	55	Montenegro	45
Croatia	128	Netherlands	2683
Czech Republic	58	Norway	**-59**
Denmark	**-74**	Poland	615
Estonia	**-27**	Portugal	582
Finland	**-385**	Romania	166
France	1233	Serbia	49
Germany	5623	Slovakia	34
Great Britain	**-997**	Slovenia	49
Greece	70	Spain	8635
Hungary	112	Sweden	**-329**
Ireland	276	Switzerland	393
Italy	2003	Ukraine	77

Table 46 - X-10 Scenario – 2050 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Denmark	-74	3	-71
Estonia	-27	0	-27
Finland	-385	0	-385
Great Britain	-997	4133	3136
Latvia	-99	0	-99
Lithuania	-161	0	-161
Norway	-59	68	9
Sweden	-329	31	298

Figure 37-Figure 39 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

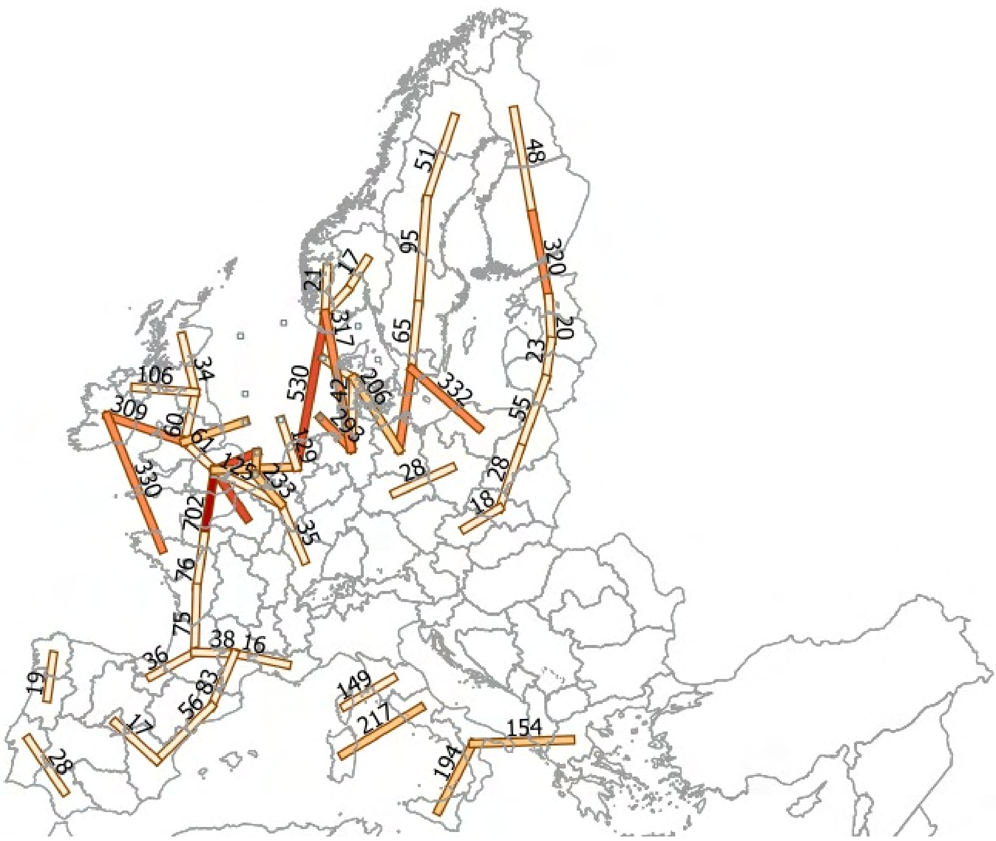

Figure 37 - X-10 Scenario – 2050 – Annual LCC – Strategy 1 [M€/a]

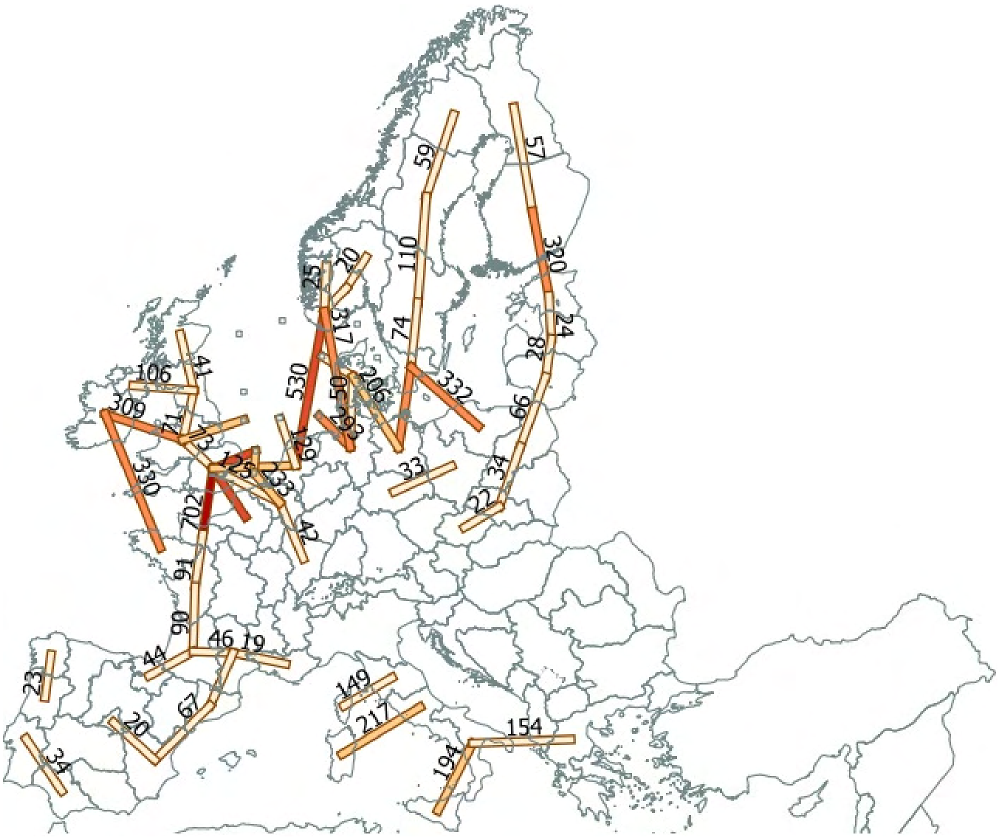

Figure 38 - X-10 Scenario – 2050 – Annual LCC – Strategy 2 [M€/a]

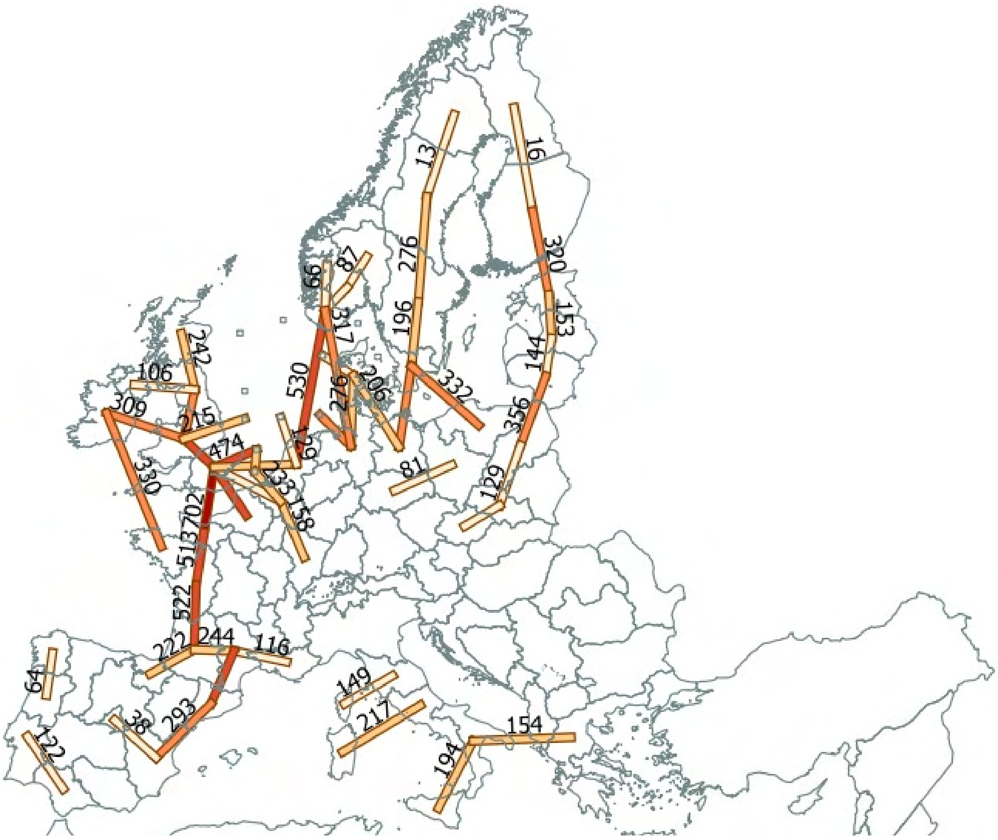

Figure 39 - X-10 Scenario – 2050 – Annual LCC – Strategy 3 [M€/a]

2.3.1.7. Investment sensitivity analysis: network vs. generation to cover ENS

This paragraph show the results of a sensitivity analysis performed at the target year 2050 in order to compare the cost in overcoming the same amount of ENS by means of:

- *option 1*: investment in grid reinforcements;
- *option 2*: investment in peak generation (in particular, Open Cycle Gas Turbine, OCGT, power plants).

The aim of this analysis is to check if, in order to cover ENS, investment in transmission network are (or are not) more profitable than investment in fossil-fuel peak generation, independently by the assumed VoLL.

Regarding option 2, calculation hypotheses (from WP2 and WP3) are reported below:

- fixed investment cost (CAPEX) in OCGT equal to 0.7 G€/MW;
- fuel and CO2 operation cost (OPEX) in OCGT equal to 172 €/MWh;
- maximum amount hourly saved ENS (without – with case) equal to 78 GW: this information is needed in order to properly rate the amount of additional OCGT installed capacity;
- saved ENS (without – with case) equal to 11.49 TWh/a: this information is needed in order to properly rate the production by additional OCGT power plants;
- annuity factor for investment in OCGT equal to 0.0745;

Taking into account both CAPEX and OPEX in new OCGT power plants, the annual TOTEX = CAPEX + OPEX in new OCGT power plants to cover ENS is equal to 6 G€/a.

However, option 2 implies a loss in other benefits achievable by transmission network reinforcements: therefore, this arises as opportunity costs in terms of increase of Social Welfare and reduction of CO2 emissions:

- opportunity cost due to the increase of Social Welfare: about 8 G€/a;
- opportunity cost due to the reduction of CO2 emissions:
  - about 8 G€/a assuming a CO2 tax value equal to 150 €/t;
  - about 15 G€/a assuming a CO2 tax value equal to 270 €/t.

As shown in Figure 40, according to the different implementation Strategy, the cost in option 1 spans from about 8 to about 13 G€/a: by contrast, according to the different CO2 emission tax value, the cost of option 2 spans from about 22 G€/a to 29 G€/a.

According to that, the ratio between

- the annual investment cost in generation expansion to cover ENS (option 2);
- the annual investment cost in transmission expansion to cover ENS (option 1)

spans from 1.76 to 3.65. Therefore, it can be concluded that, at the target year, investing in transmission network is always the most cost-effective way to cover ENS.

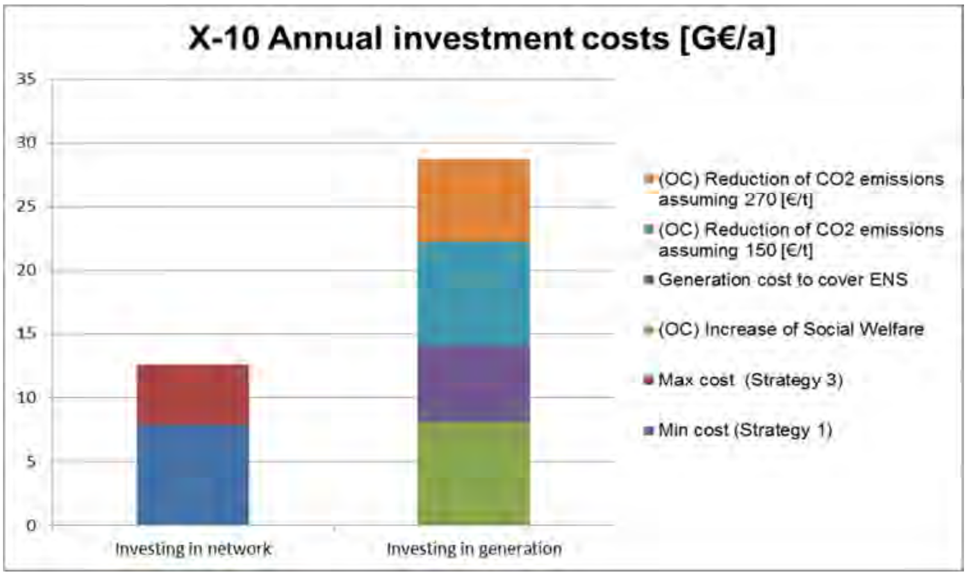

Figure 40 - X-10 Scenario – 2050 – Investment sensitivity analysis

2.3.2. 2040 analyses

2.3.2.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 47 shows the annual values of core benefit indicators for this Scenario.

Table 47 – X-10 Scenario – 2040 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	1
Reduction of CO2 emissions [G€/a]	5
Reduction of reliability costs [G€/a]	17
Benefit core indicators – Grand total [G€/a]	23

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 1 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 5 G€/a.

In any case, and in coherence with the 2050 evaluation, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 17 G€/a.

According to that, the annual benefit provided by core benefit indicators is about 23 G€/a.

2.3.2.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 48 and Figure 41 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (slightly lower than 3.6 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;

- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.34% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.40% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 48 – X-10 Scenario – 2040 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	3.6	3.7	5.5
Cost core indicators - Grand total [G€/a]	**3.6**	**3.7**	**5.5**

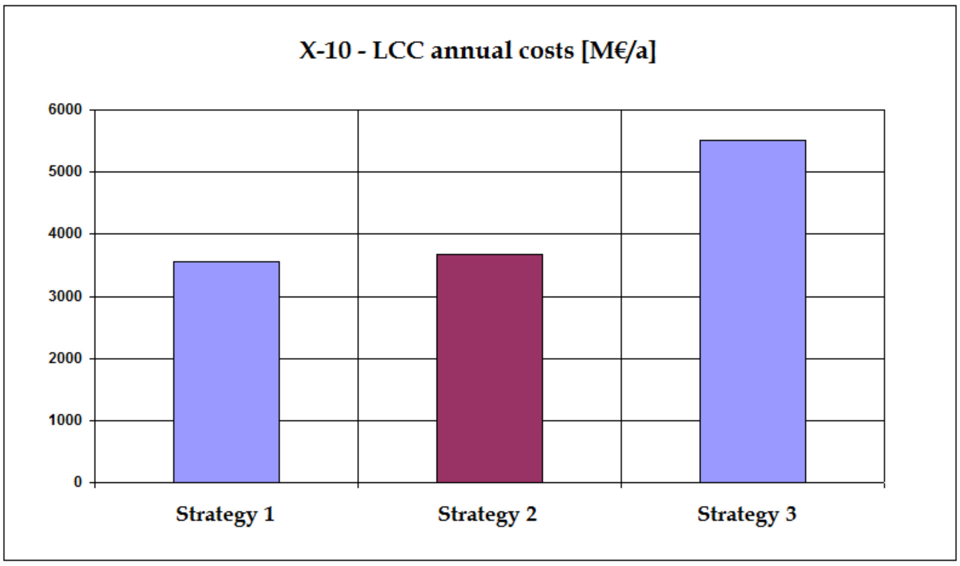

Figure 41 – X-10 Scenario – 2040 – LCC annual costs

2.3.2.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-10 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 49 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO_2 emission tax between 169 and 329 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO_2 emission tax value included in the interval (169, 329) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.1 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 6 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 5 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -80 G€/a) and Producers + Consumer Surpluses (about +86 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 49 – X-10 Scenario – 2040 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 3 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	329
Sensitivity on CO2 price - Lower bound [€/t]	169
Reduction of investment costs in distribution networks [G€]	0.1
Social Welfare variation (CO2 emissions are accounted) [G€/a]	5
Merchandise Surplus variation [G€/a]	-80
Producers + Consumers Surplus variation [G€/a]	86

2.3.2.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-10 Scenario at the target year 2040 is performed. The set of benefits that have been taken into account are:

- reduction of CO2 emissions;
- increase of Social Welfare (not including CO2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in

Table 50. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 76% on total gross annual gross benefit).

Table 50 - X-10 Scenario – 2040 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	22.6
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	20.26
% Social Welfare increase [%]	2.97
% Reduction of distribution network investments [%]	0.03
% Reduction of reliability costs [%]	76.75

2.3.2.5. Profitability indicators – Reference case

The main profitability indicators for the X-10 Scenario at the target year 2040 are shown in Table 51. Annual values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 51 - X-10 Scenario – 2040 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	22.6	22.6	22.6
Annual LCC cost [G€/a]	3.6	3.7	5.5
Annual net benefit [G€/a]	19.0	18.9	17.1
PI [adim]	**6.34**	**6.13**	**4.10**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 6.34 in Strategy 1 to 4.10 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.3.2.6. GIS maps

Figure 42 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2040. The map displays the regions where the annual benefit is greater than 1 G€/a.

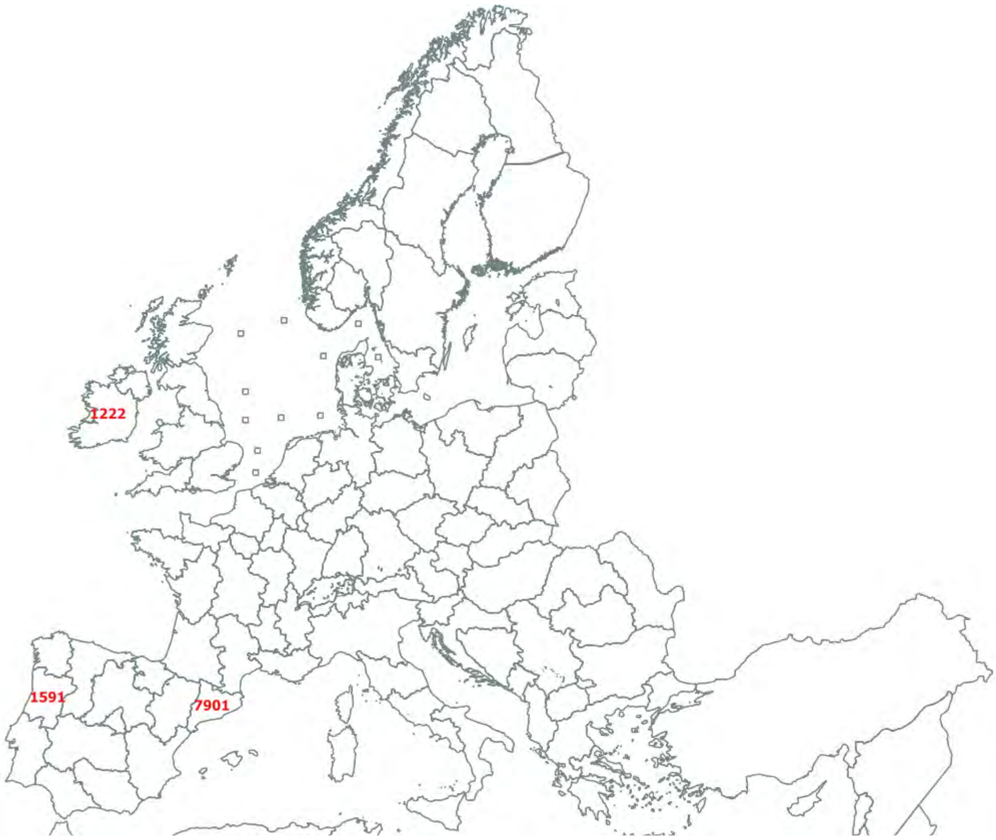

Figure 42 - X-10 Scenario – 2040 – Reduction of ENS costs [M€/a]

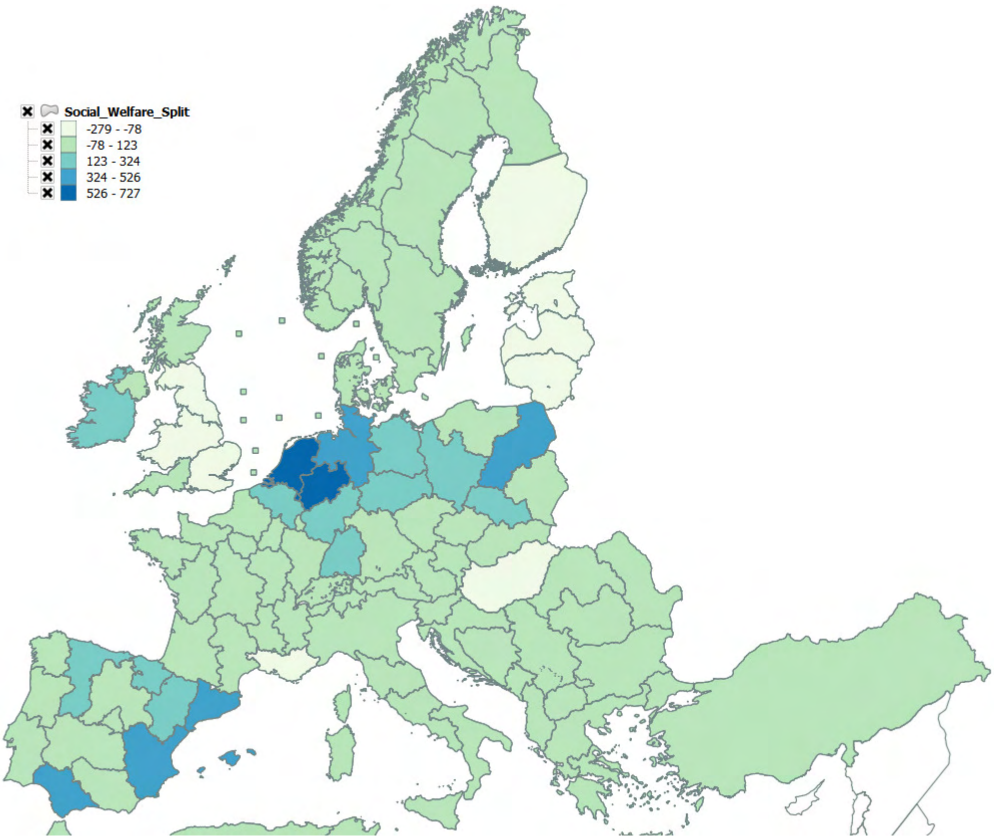

Figure 43 - X-10 Scenario – 2040 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 43.

It can be seen that, even if there are some clusters with a lower benefit (e.g. most of Europe), in general many regions experience a significant reduction of reliability costs (in Catalonia, Portugal and Ireland).

As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 5 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in

Table 52.

Table 52 - X-10 Scenario – 2040 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	**-6**	Latvia	**-210**
Austria	36	Lithuania	**-213**
Belgium	283	Luxembourg	24
Bosnia & Herzog.	6	Macedonia	**-5**
Bulgaria	**-9**	Montenegro	**-2**
Croatia	12	Netherlands	639
Czech Republic	109	Norway	**-9**
Denmark	**-69**	Poland	919
Estonia	**-81**	Portugal	158
Finland	**-169**	Romania	**-125**
France	**-47**	Serbia	16
Germany	2054	Slovakia	**-22**
Great Britain	**-729**	Slovenia	3
Greece	**-26**	Spain	2295
Hungary	**-102**	Sweden	**-133**
Ireland	262	Switzerland	27
Italy	244	Ukraine	118

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators lower than 10% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, as shown in Table 53, the transmission network reinforcement plan gives (slight) negative sums: the

lowest negative value is reached in Lithuania (-213 M€/a). The Norway situation is emblematic because the local benefit provided by the reduction of ENS costs (1234 M€/a) overshadows the local reduction (-9 M€/a) of Social Welfare.

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 53 - X-10 Scenario – 2040 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Albania	-6	0	-6
Bulgaria	-9	0	-9
Denmark	-69	18	-51
Estonia	-81	0	-81
Finland	-169	102	-67
France	-47	666	619
Great Britain	-729	737	8
Greece	-26	14	-12
Hungary	-102	51	-51
Latvia	-210	0	-210
Lithuania	-213	0	-213
Macedonia	-5	0	-5
Montenegro	-2	0	-2
Norway	-9	1234	1225
Romania	-125	0	-125
Slovakia	-22	8	-16
Sweden	-133	420	287

Figure 44-Figure 46 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

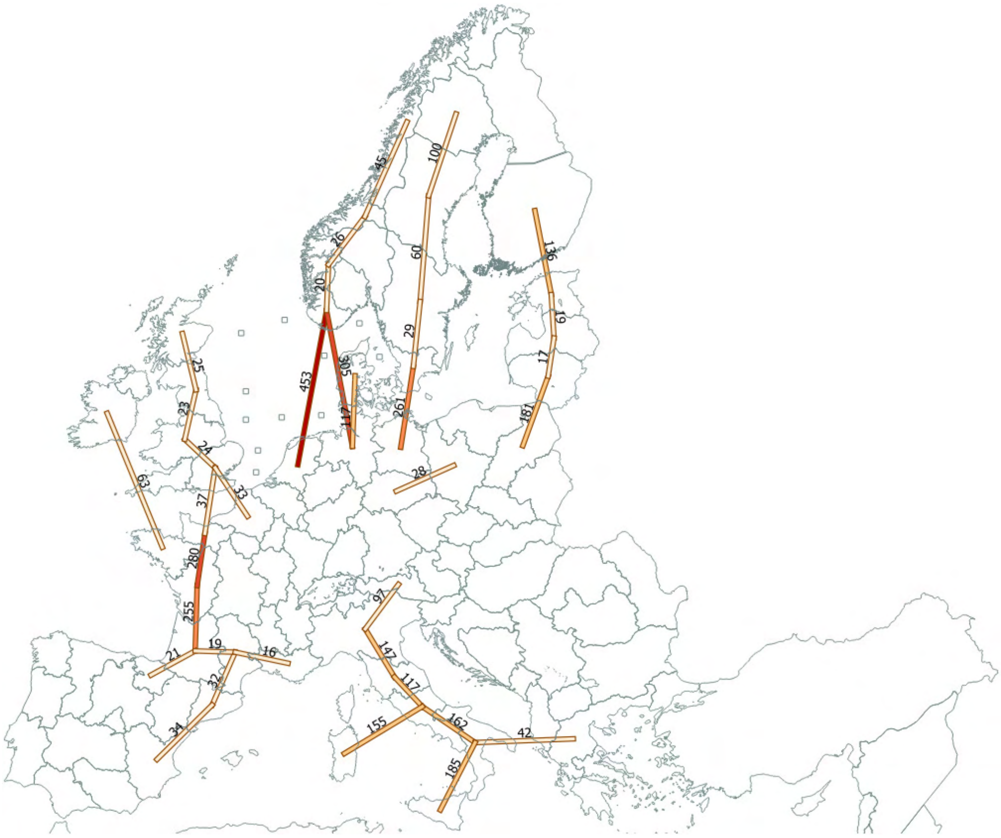

Figure 44 - X-10 Scenario – 2040 – Annual LCC – Strategy 1 [M€/a]

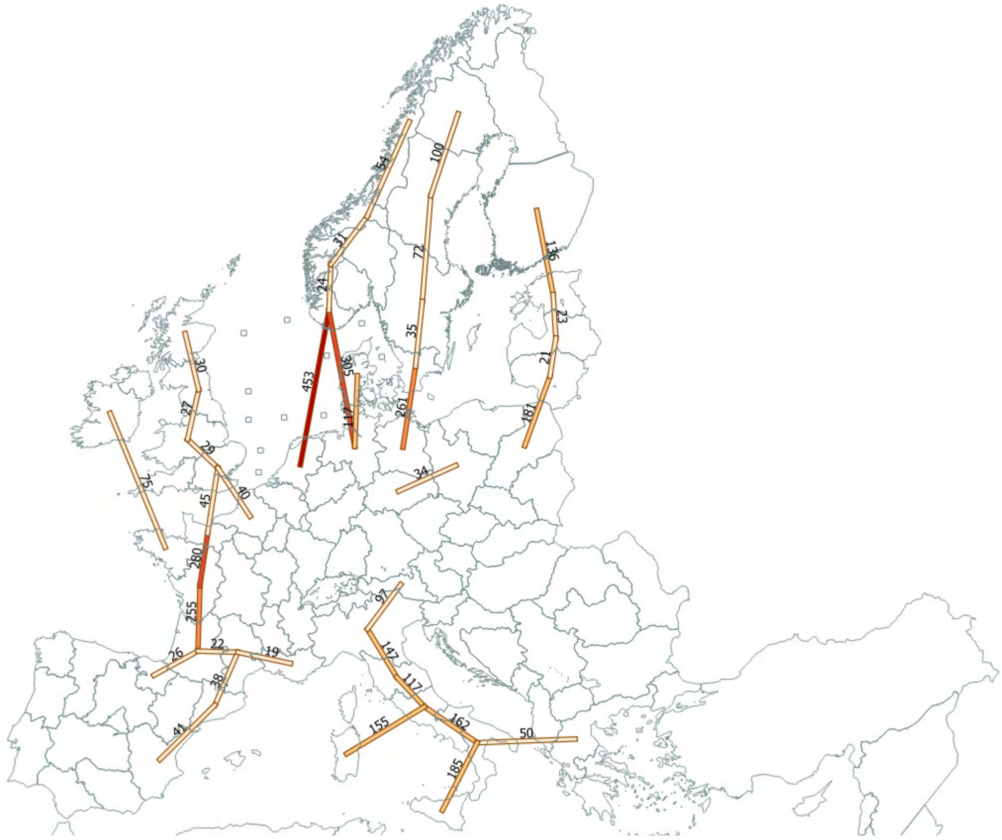

Figure 45 - X-10 Scenario – 2040 – Annual LCC – Strategy 2 [M€/a]

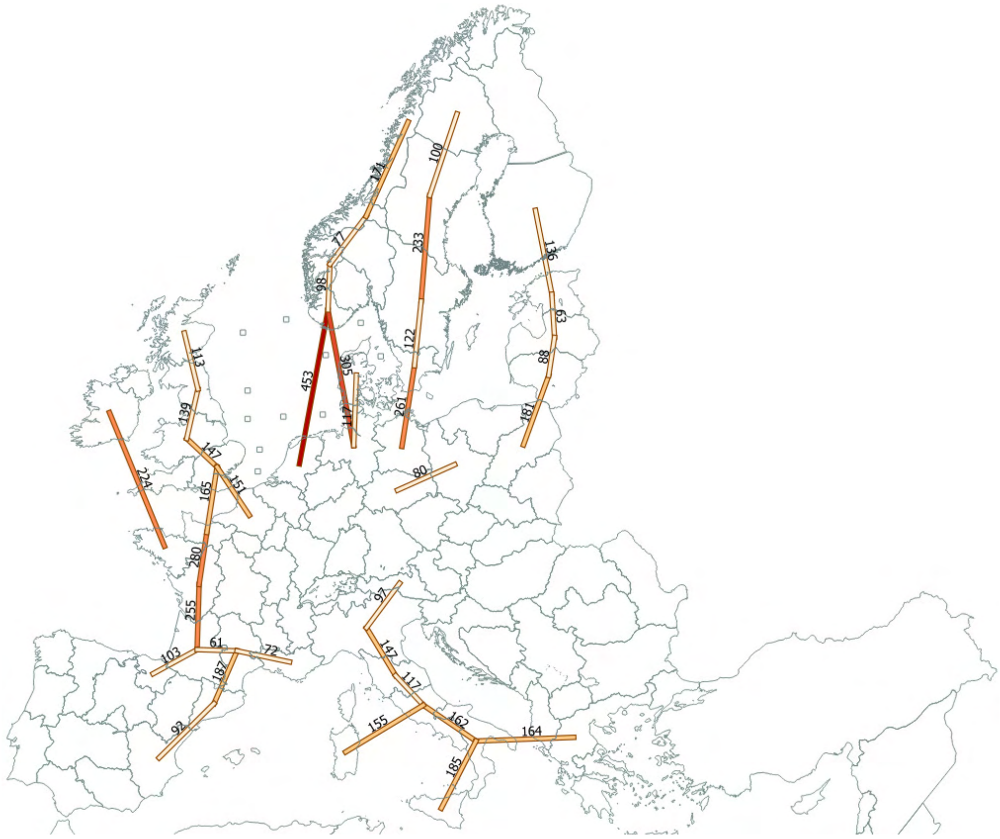

Figure 46 - X-10 Scenario – 2040 – Annual LCC – Strategy 3 [M€/a]

2.4. Scenario X-13 - Large fossil fuel with CCS and nuclear

2.4.1. 2050 analyses

2.4.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 54 shows the annual values of core benefit indicators for this Scenario.

Table 54 – X-13 Scenario – 2050 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	2
Reduction of CO2 emissions [G€/a]	9
Reduction of reliability costs [G€/a]	68
Benefit core indicators – Grand total [G€/a]	**79**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 2 G€/a, while the economic value correspondent to the reduction of CO2 emission is 9 G€/a.

In any case, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for about 68 G€/a. Since this value is directly related to the adopted VOLL (10000 €/MWh), this aspect is examined in detail in paragraph 2.4.1.7.

According to that, the annual benefit provided by core benefit indicators in slightly lower than 79 G€/a.

2.4.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 55 and Figure 47 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (about 6.9 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;
- Strategy 2 is slightly more expensive than Strategy 1 (+ 4.00 % respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 78.28% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 55 – X-13 Scenario – 2050 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	6.9	7.2	12.3
Cost core indicators - Grand total [G€/a]	**6.9**	**7.2**	**12.3**

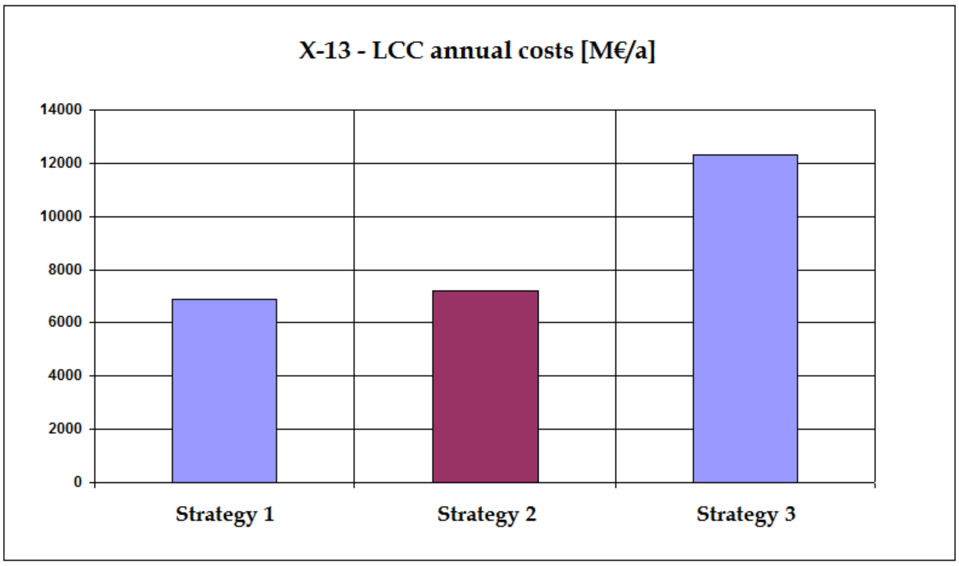

Figure 47 – X-13 Scenario – 2050 – LCC annual costs

2.4.1.2.1. LCC assessment – Sensitivity of S&E aspects

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the impact of Social and Environmental aspects on the LCC in the three different reinforcement Strategies at the target year 2050. Table 56 shows the results of this sensitivity analysis.

As can be easily pointed out, the monetary impact of S&E aspects (acquisition of rights of way) is very low (under than 1%).

The outcome of this analysis does not clearly imply that S&E aspects are a secondary item in transmission planning: in fact, those values find their justification in the adopted approach:

- considering only the rights of way acquisition do not allow to consider the full range of social and environmental externalities connected to transmission network planning;
- the cluster level of detail cannot allow to consider the very local peculiarities of crossed lands;
- the brownfield approach does not make feasible to extend the calculation to new transmission corridors.

Table 56 – X-13 Scenario – 2050 – Sensitivity on S&E aspects

LCC annual costs	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a] – Case 1 - S&E included	6.9	7.2	12.3
LCC - Annual costs [G€/a] – Case 2 - S&E not included	6.8	7.1	12.2
(Case 2 – Case 1)/Case 1 [%]	-0.90%	-0.86%	-0.21%

Therefore, in order to fully appraise the economic impact of S&E aspects in transmission network planning, different analyses with more precise approaches are needed.

2.4.1.2.2. LCC assessment – Sensitivity of F&R aspects

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the impact of Financial and Regulatory aspects on the annual LCC in the three different reinforcement Strategies at the target year 2050.

As shown in Table 57 and Figure 48, there is an exponential relationship between annual LCC and discount rate. In fact:

$$PV_{LCC} = \sum_{t=0}^{T_{ol}} A_{LCC} \cdot \left(\frac{1}{1+DR} \right)^t \Rightarrow A_{LCC} = PV_{LCC} \cdot \frac{(1+DR)^{T_{ol}} \cdot DR}{(1+DR)^{T_{ol}+1} - 1}$$

where:

- PV_{LCC} is the Present Value of life cycle costs [G€];
- T_{ol} is the operative life duration [a];
- A_{LCC} is the annual life cycle cost [G€/a];
- DR is the discount rate [%].

However, in the normal range of values assumed by discount rate, there is a very good approximation with an increasing line.

Table 57 – X-13 Scenario – 2050 – Sensitivity on F&R aspects – Common asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 3	6.9	7.1	12.2	4.95
LCC - Annual costs [G€/a] – Case 1	6.9	7.2	12.3	5.00
LCC - Annual costs [G€/a] – Case 4	7.2	7.5	12.8	5.26
LCC - Annual costs [G€/a] – Case 5	8.8	9.2	15.4	6.76
LCC - Annual costs [G€/a] – Case 6	10.4	10.9	18.2	8.26

This result is not surprising: in an investor perspective, if the money cost increases, the annual amortization of the asset increases as well. Moreover:

- with reference with Strategy 1 and Strategy 2, the lines are very close and practically parallel;
- the slope of Strategy 3 line is higher than the ones with of Strategy 1 and Strategy 2: this is due to the fact that Strategy 3 heavily exploits cables (40 years of operative life). This is due to the fact that the difference in asset operative life implies an increase in annual LCC, and this difference grows faster if the discount rate is higher.

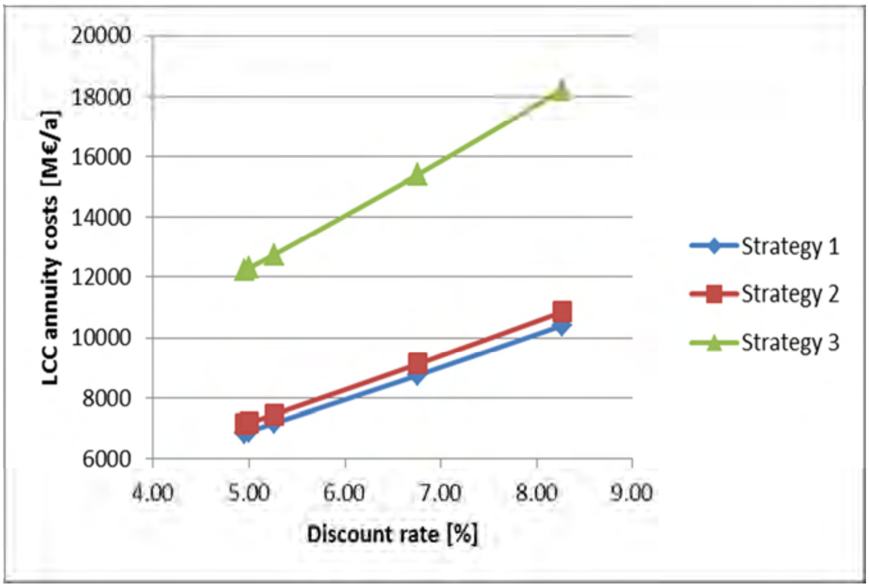

Figure 48 - X-13 Scenario – 2050 – Sensitivity on F&R aspects

Table 58 shows the result of the sensitivity analysis on F&R aspects, taking into account investment specific asset beta values: it can be noted how different values of asset beta do not bring to sensible changes (increases are lower than 0.3%) in the annual LCC. Moreover, it can be noted how resulting average discount rates are practically coincident (5% both in Case 1 and Case 7).

Table 58 - X-13 Scenario – 2050 – Sensitivity on F&R aspects – Investment specific asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 1	6.91	7.18	12.31	5.00
LCC - Annual costs [G€/a] – Case 7	6.92	7.20	12.35	5.00
(Case 7 – Case 1)/Case 7 [%]	0.23	0.23	0.29	-

2.4.1.3. Non-core indicator assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 59 shows the values of non-core indicators for this Scenario.

Table 59 – X-13 Scenario – 2050 – Non-core indicators

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	320
Sensitivity on CO2 price - Lower bound [€/t]	240
Reduction of investment costs in distribution networks [G€]	0.2
Social Welfare variation (CO2 emissions are accounted) [G€/a]	11
Merchandise Surplus variation [G€/a]	-189
Producers + Consumers Surplus variation [G€/a]	200

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO2 emission tax between 320 €/t and 240 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO2 emission tax value included in the interval (240, 320) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.2 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 14 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO_2 emissions) equal to about 11 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -189 G€/a) and Producers + Consumer Surpluses (about +200 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

2.4.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-13 Scenario at the target year 2050 is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 60. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 85% on total gross annual gross benefit).

Table 60 - X-13 Scenario – 2050 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy2 – Strategy 3
Annual gross benefit [G€/a]	79
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	11.92
% Social Welfare increase [%]	2.13
% Reduction of distribution network investments [%]	0.02
% Reduction of reliability costs [%]	85.93

2.4.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-13 Scenario at the target year 2050 are shown in Table 61. Annual and present values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

In order to evaluate the present value of gross benefit, the same annuity ratio between annual and present LCC is shown: this allows to maintain the same PI between annual and present value indicators.

Table 61 - X-13 Scenario – 2050 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	78.9	78.9	78.9
Annual LCC cost [G€/a]	6.9	7.2	12.3
Annual net benefit [G€/a]	71.9	71.7	66.5
Present Value of gross benefit [G€]	1397	1404	1354
Present Value of LCC cost [G€]	122	127.9	211
Present Value of net benefit [G€]	1275	1275.8	1143
PI [adim]	**11.42**	**10.98**	**6.40**

It can be observed how the Present Value of net benefit in Strategy 2 (NPV_2) is slightly higher than the one in Strategy 1 (NPV_1): this finds its justification in the high values assumed by the Profitability Index in Strategy 2. In fact, taking into account the link between NPV, PI and the present value of LCC cost (PV_{LCC}):

$$NPV_2 > NPV_1 \rightarrow (PI_2 - 1)\cdot PV_{LCC,2} > (PI_1 - 1)\cdot PV_{LCC,1} \rightarrow \frac{(PI_2 - 1)}{(PI_1 - 1)} > \frac{PV_{LCC,1}}{PV_{LCC,2}}$$

Therefore, NPV_2 is higher than NPV_1 when the increase of the present value of LCC cost in Strategy 2 is lower than the reduction the $PI_2 - 1$ respect $PI_1 - 1$.

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 11.42 in Strategy 1 to 6.40 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.4.1.6. GIS maps

Figure 49 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2050. The map displays the regions where the annual benefit is greater than 1 G€/a.

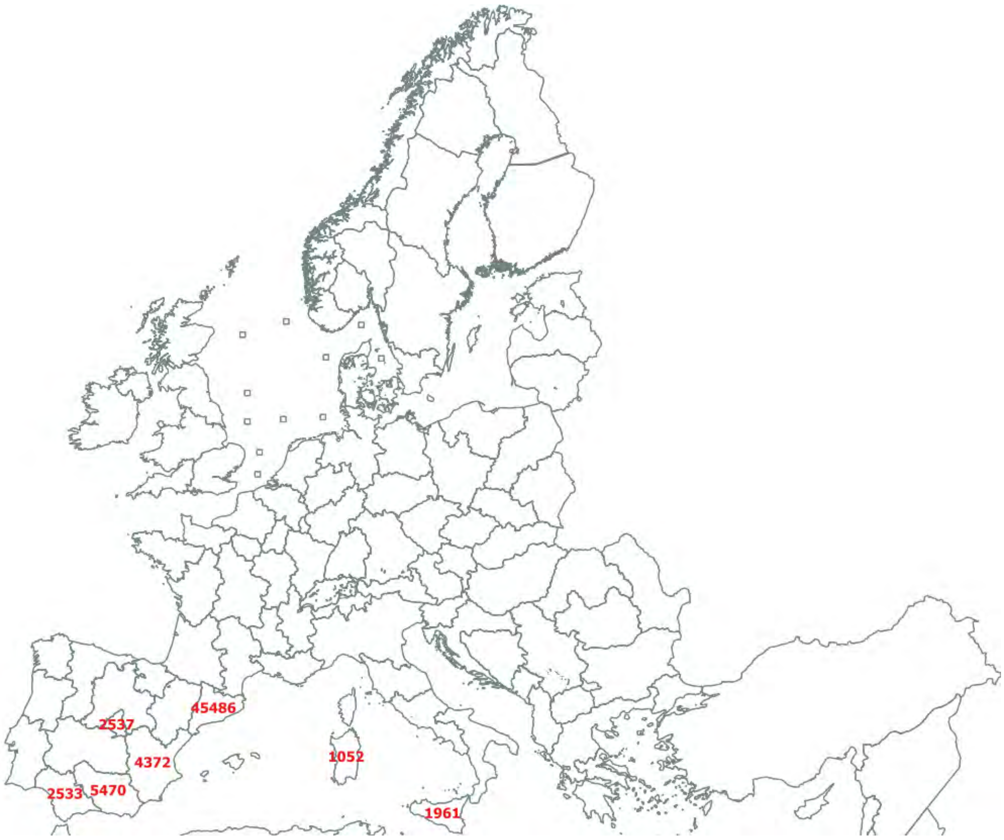

Figure 49 - X-13 Scenario – 2050 – Reduction of ENS costs [M€/a]

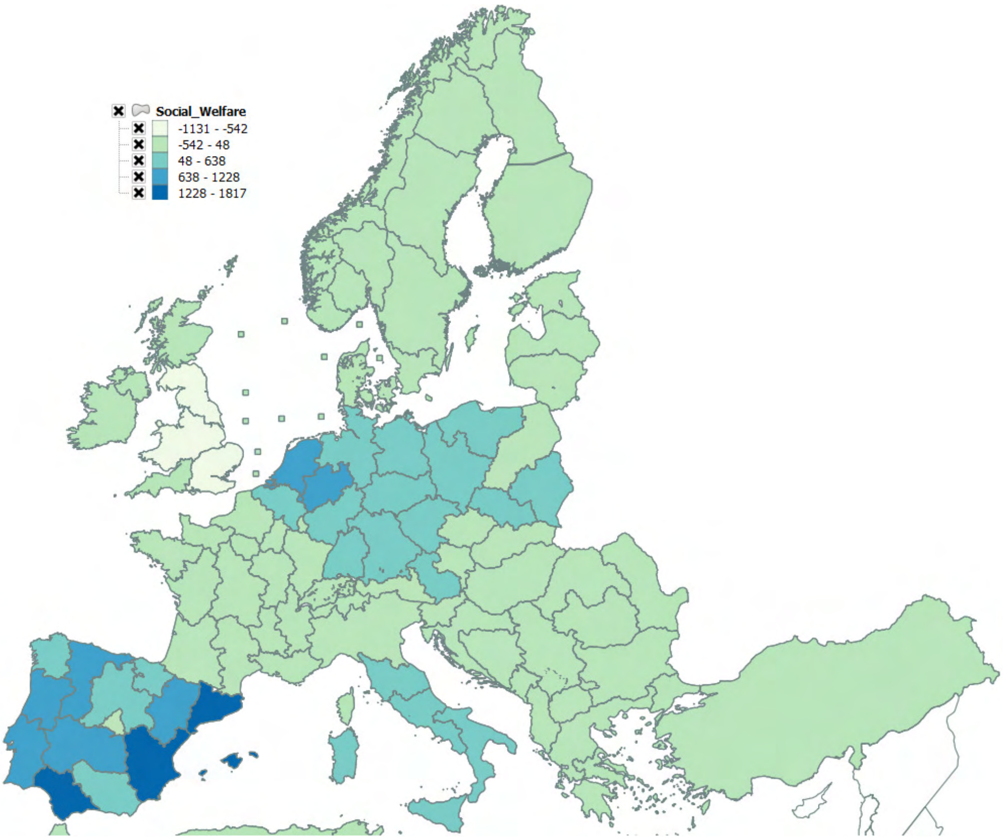

Figure 50 - X-13 Scenario – 2050 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Baltic region, Balkan peninsula, etc.), in general many regions experience a significant reduction of reliability costs (in Spain and insular Italy).

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 50.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 11 G€/a, even if there are some countries that could experience a reduction of their Social Welfare. These countries are highlighted in Table 62.

Table 62 - X-13 Scenario – 2050 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	**-13**	Latvia	**-3**
Austria	70	Lithuania	17
Belgium	323	Luxembourg	13
Bosnia & Herzog.	7	Macedonia	0
Bulgaria	**-20**	Montenegro	0
Croatia	43	Netherlands	1199
Czech Republic	56	Norway	**-34**
Denmark	**-86**	Poland	318
Estonia	13	Portugal	1970
Finland	**-273**	Romania	**-79**
France	**-800**	Serbia	17
Germany	2795	Slovakia	**-65**
Great Britain	**-3360**	Slovenia	**-7**
Greece	**-101**	Spain	8824
Hungary	**-215**	Sweden	**-200**
Ireland	**-41**	Switzerland	**-261**
Italy	903	Ukraine	13

However, it can be pointed out that:

- in most countries, the Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries;
- taking into account the reduction of reliability costs, the transmission network reinforcement plan gives the lowest negative value in Great Britain (-3111 M€/a), as shown in Table 63.

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension: this is particular relevant for the Great Britain case.

Table 63 - X-13 Scenario – 2050 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Albania	-13	0	-13
Bulgaria	-20	12	-8
Denmark	-86	1	-85
Finland	-273	0	-273
France	-800	1593	793
Great Britain	-3360	249	-3111
Greece	-101	146	45
Hungary	-215	55	-160
Ireland	-41	487	446
Latvia	-3	0	-3
Norway	-34	0	-34
Romania	-79	0	-79
Slovakia	-65	23	-42
Slovenia	-7	0	-7
Sweden	-200	0	-200
Switzerland	-261	1	-260

Figure 51-Figure 53 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

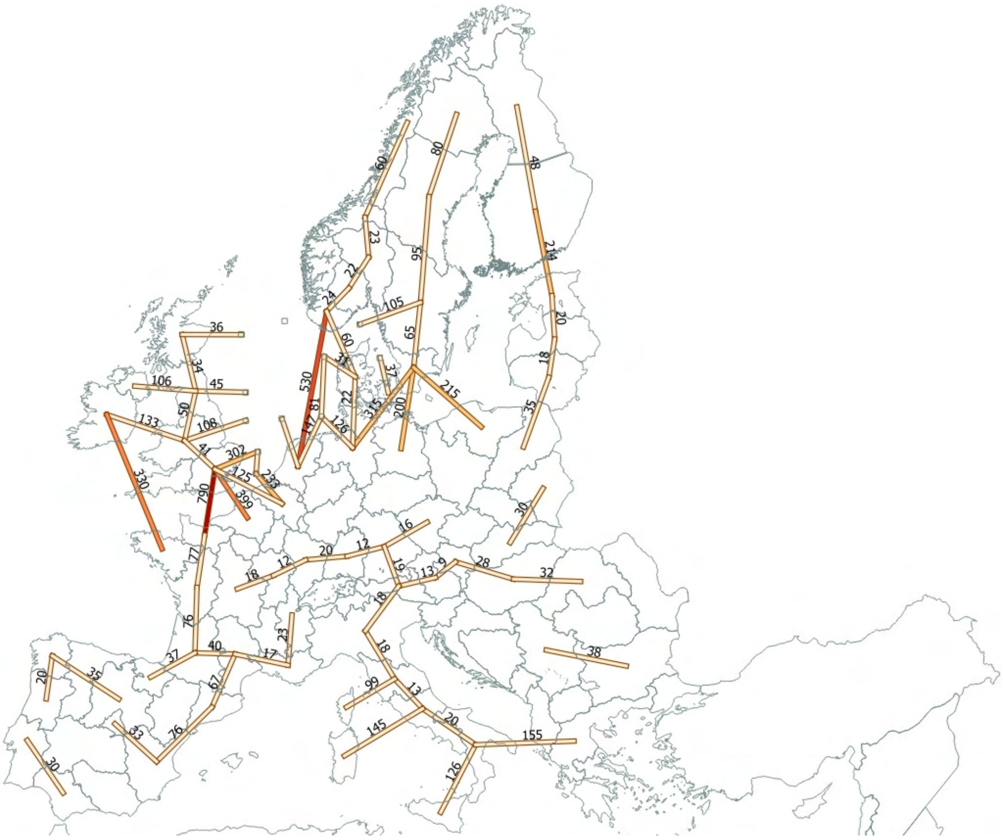

Figure 51 - X-13 Scenario – 2050 – Annual LCC – Strategy 1 [M€/a]

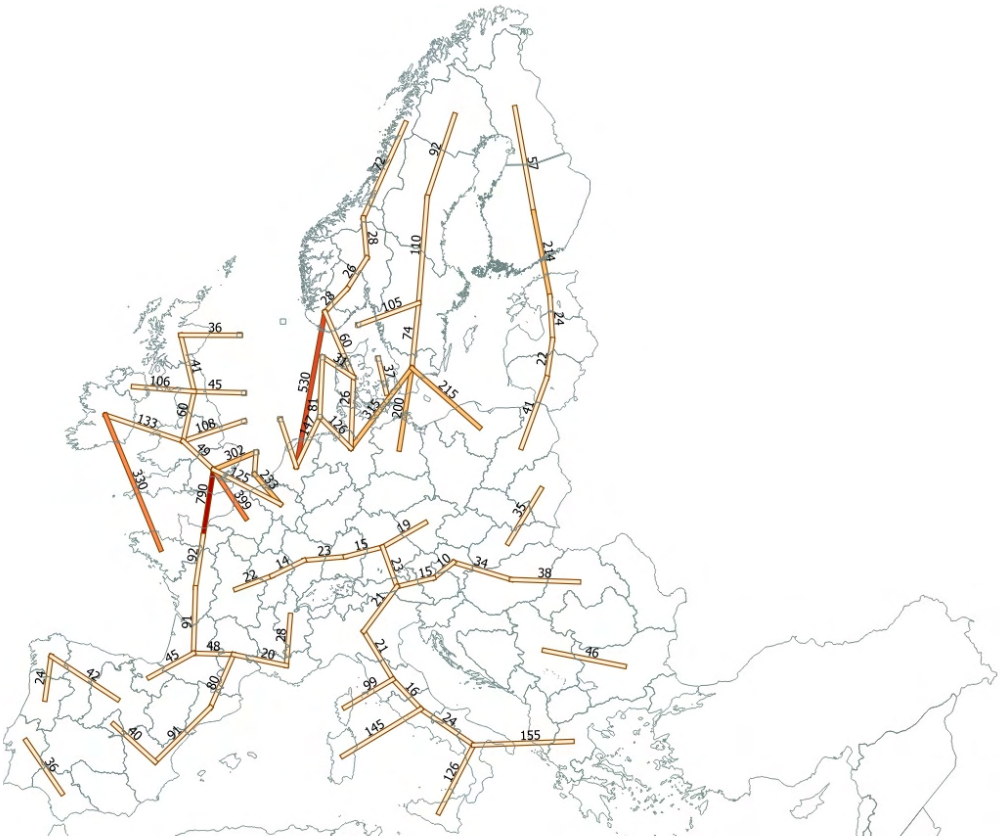

Figure 52 - X-13 Scenario – 2050 – Annual LCC – Strategy 2 [M€/a]

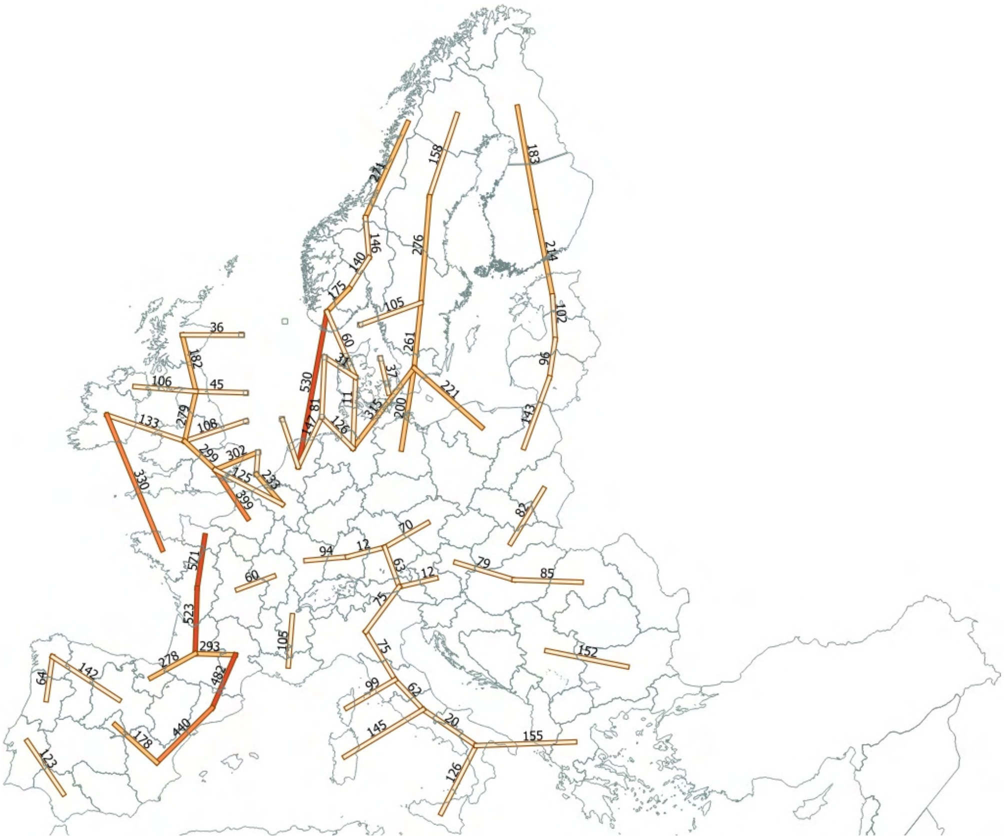

Figure 53 - X-13 Scenario – 2050 – Annual LCC – Strategy 3 [M€/a]

2.4.1.7. Investment sensitivity analysis: network vs. generation to cover ENS

This paragraph show the results of a sensitivity analysis performed at the target year 2050 in order to compare the cost in overcoming the same amount of ENS by means of:

- *option 1*: investment in grid reinforcements;
- *option 2*: investment in peak generation (in particular, Open Cycle Gas Turbine, OCGT, power plants).

The aim of this analysis is to check if, in order to cover ENS, investment in transmission network are (or are not) more profitable than investment in fossil-fuel peak generation, independently by the assumed VoLL.

Regarding option 2, calculation hypotheses (from WP2 and WP3) are reported below:

- fixed investment cost (CAPEX) in OCGT equal to 0.7 G€/MW;
- fuel and CO2 operation cost (OPEX) in OCGT equal to 172 €/MWh;
- maximum amount hourly saved ENS (without – with case) equal to 77 GW: this information is needed in order to properly rate the amount of additional OCGT installed capacity;
- saved ENS (without – with case) equal to 6.78 TWh/a: this information is needed in order to properly rate the production by additional OCGT power plants;

- annuity factor for investment in OCGT equal to 0.0745;

Taking into account both CAPEX and OPEX in new OCGT power plants, the annual TOTEX = CAPEX + OPEX in new OCGT power plants to cover ENS is equal to 5 G€/a.

However, option 2 implies a loss in other benefits achievable by transmission network reinforcements: therefore, this arises as opportunity costs in terms of increase of Social Welfare and reduction of CO2 emissions:

- opportunity cost due to the increase of Social Welfare: about 2 G€/a;
- opportunity cost due to the reduction of CO2 emissions:
  - about 5 G€/a assuming a CO2 tax value equal to 150 €/t;
  - about 9 G€/a assuming a CO2 tax value equal to 270 €/t.

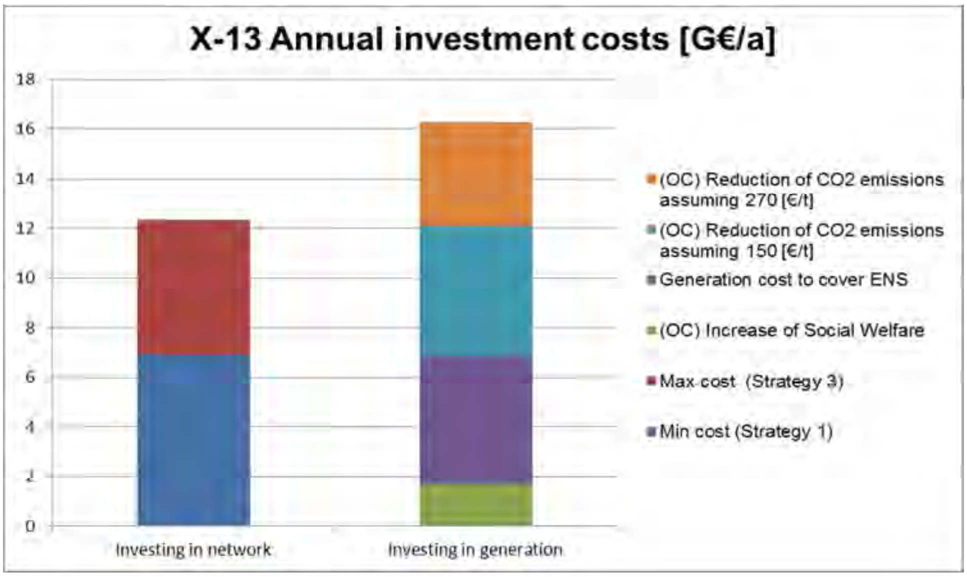

Figure 54 - X-13 Scenario – 2050 – Investment sensitivity analysis

As shown in Figure 54, according to the different implementation Strategy, the cost in option 1 spans from about 7 to about 12 G€/a: by contrast, according to the different CO2 emission tax value, the cost of option 2 spans from about 12 G€/a to 16 G€/a.

According to that, the ratio between

- the annual investment cost in generation expansion to cover ENS (option 2)
- the annual investment cost in transmission expansion to cover ENS (option 1)

spans from 0.98 to 2.36. However, the modest value of the difference (+2%), respect to the broad interval that CO2 emission tax can assume suggests that investing in transmission network is the most resilient and cost-effective way to cover ENS.

2.4.2. 2040 analyses

2.4.2.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 64 shows the annual values of core benefit indicators for this Scenario.

Table 64 – X-13 Scenario – 2040 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	0
Reduction of CO2 emissions [G€/a]	5
Reduction of reliability costs [G€/a]	26
Benefit core indicators – Grand total [G€/a]	30

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (reduction of fuel costs) is negligible, while the economic value correspondent to the reduction of CO2 emission is about 5 G€/a. It can be noted how the aforementioned steadiness of Social is coherent with a system optimization that maximize the whole Social Welfare (including also CO2 emission costs).

In any case, and in coherence with the 2050 evaluation, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for about 26 G€/a.

According to that, the annual benefit provided by core benefit indicators is about 30 G€/a.

2.4.2.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 65 and Figure 55 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (slightly lower than 3.6 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;

- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.34% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.40% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 65 – X-13 Scenario – 2040 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	3.56	3.68	5.50
Cost core indicators - Grand total [G€/a]	**3.56**	**3.68**	**5.50**

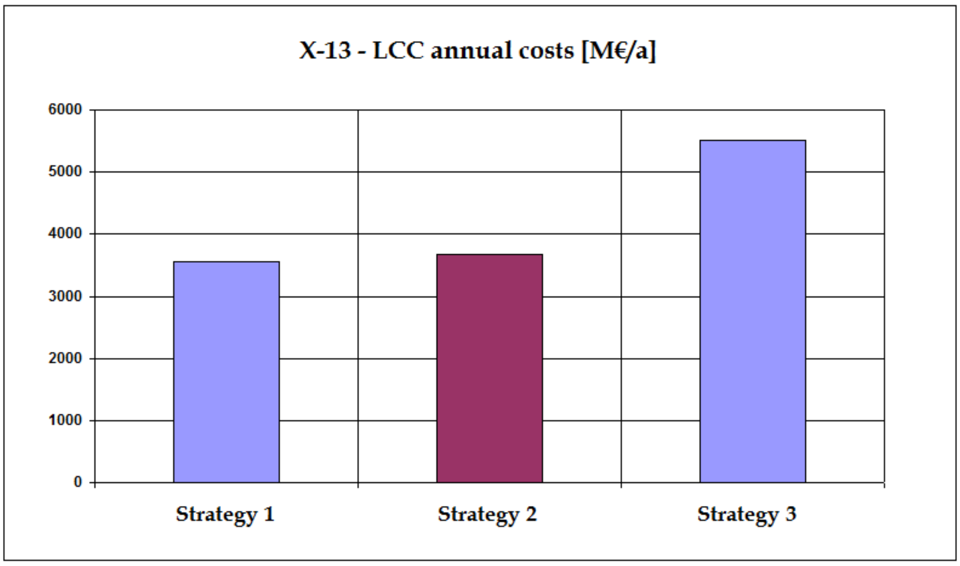

Figure 55 – X-13 Scenario – 2040 – LCC annual costs

2.4.2.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-13 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 66 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO_2 emission tax between 169 and 329 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO_2 emission tax value included in the interval (169, 329) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.1 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value lower than 7 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO_2 emissions) equal to about 5 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -96 G€/a) and Producers + Consumer Surpluses (about +100 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 66 – X-13 Scenario – 2040 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	329
Sensitivity on CO2 price - Lower bound [€/t]	169
Reduction of investment costs in distribution networks [G€]	0.1
Social Welfare variation (CO2 emissions are accounted) [G€/a]	5
Merchandise Surplus variation [G€/a]	-96
Producers + Consumers Surplus variation [G€/a]	100

2.4.2.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-13 Scenario at the target year 2040 is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 67. As previously stated, the most impacting indicator on the total gross benefit is

represented by the reduction of reliability costs (more than 84% on total gross annual gross benefit).

Table 67 - X-13 Scenario – 2040 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	30.3
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	15.18
% Social Welfare increase [%]	-0.06
% Reduction of distribution network investments [%]	0.02
% Reduction of reliability costs [%]	84.85

2.4.2.5. Profitability indicators – Reference case

The main profitability indicators for the X-13 Scenario at the target year 2040 are shown in Table 68. Annual values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 68 - X-13 Scenario – 2040 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	30.3	30.3	30.3
Annual LCC cost [G€/a]	3.6	3.7	5.5
Annual net benefit [G€/a]	26.8	26.6	24.8
PI [adim]	**8.51**	**8.23**	**5.51**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 8.51 in Strategy 1 to 5.51 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.4.2.6. GIS maps

Figure 56 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2040. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. most of Europe), in general many regions experience a significant reduction of reliability costs (in Catalonia, Portugal and Sicily).

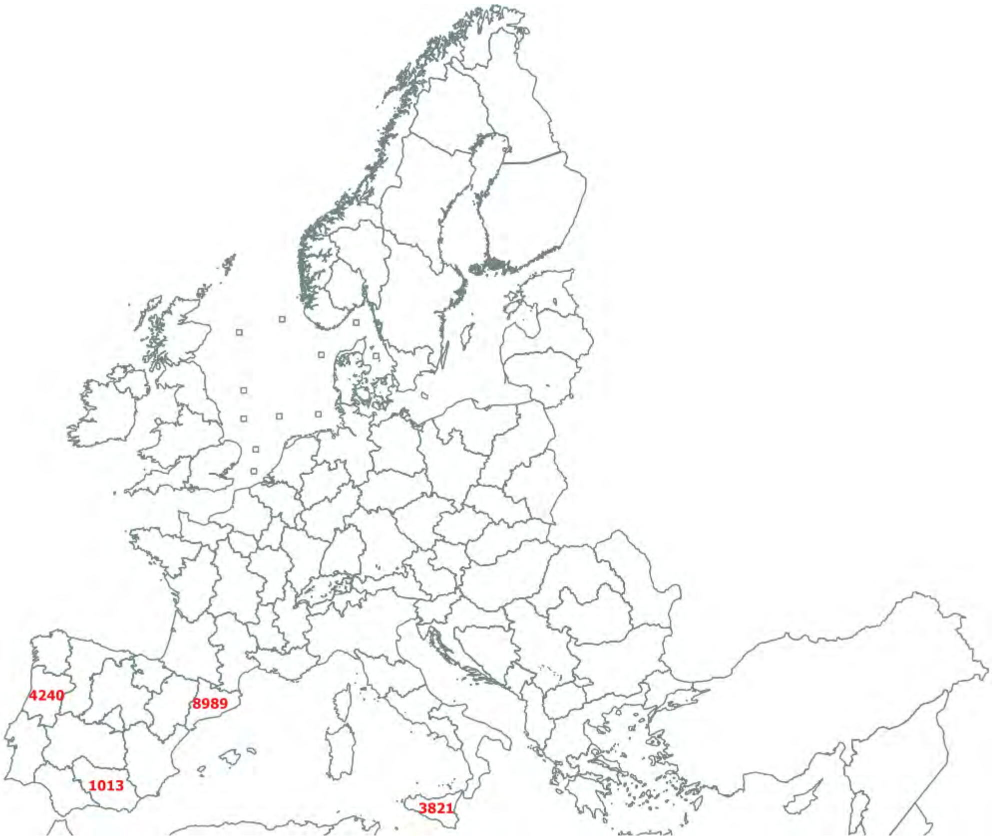

Figure 56 - X-13 Scenario – 2040 – Reduction of ENS costs [M€/a]

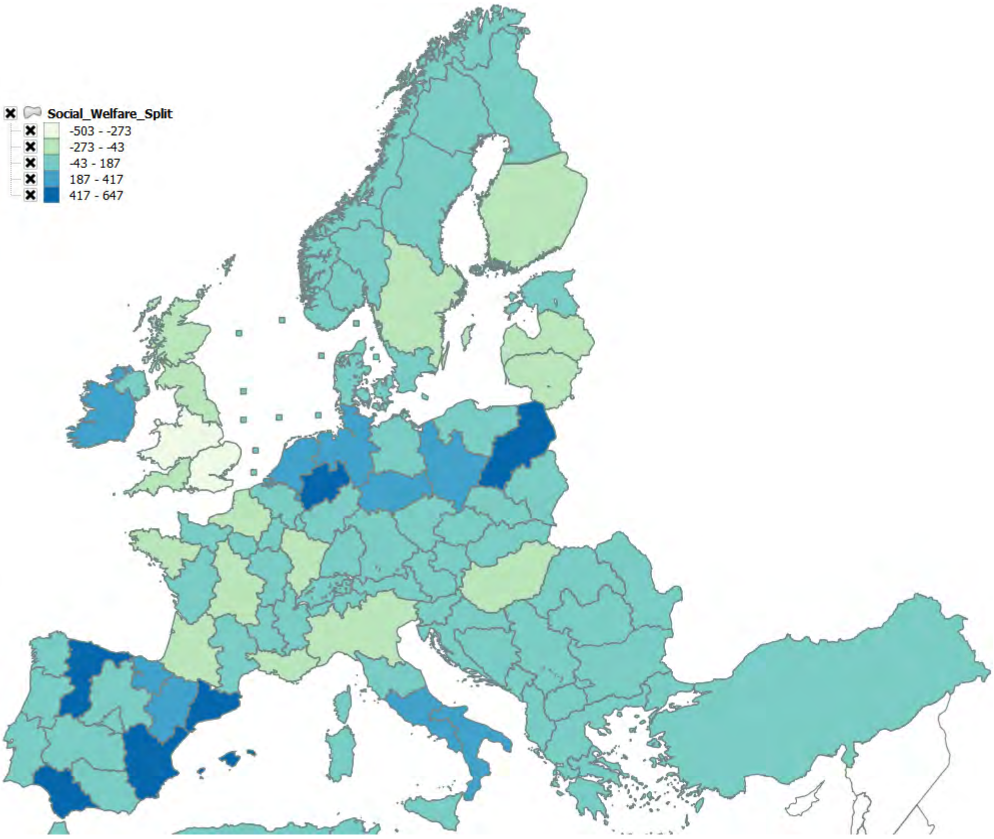

Figure 57 - X-13 Scenario – 2040 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 57.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 5 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 69.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators lower than 30% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, as shown in
- Table 70, the transmission network reinforcement plan gives (slight) negative sums: the lowest negative value is reached in Great Britain (-1129 M€/a).

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension: this is particular relevant for the Great Britain case.

Table 69 - X-13 Scenario – 2040 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	0	Latvia	-81
Austria	23	Lithuania	-80
Belgium	96	Luxembourg	1
Bosnia & Herzog.	12	Macedonia	2
Bulgaria	12	Montenegro	0
Croatia	9	Netherlands	273
Czech Republic	118	Norway	-6
Denmark	-29	Poland	946
Estonia	-28	Portugal	206
Finland	-189	Romania	-73
France	-603	Serbia	35
Germany	1345	Slovakia	-31
Great Britain	-1275	Slovenia	-4
Greece	-8	Spain	3255
Hungary	-100	Sweden	-97
Ireland	202	Switzerland	-38
Italy	541	Ukraine	153

Table 70 - X-13 Scenario – 2040 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Denmark	-29	44	15
Estonia	-28	0	-28
Finland	-189	39	-150
France	-603	524	-79
Great Britain	-1275	146	-1129
Greece	-8	-8	0
Hungary	-100	121	21
Latvia	-81	0	-81
Lithuania	-80	0	-80
Norway	-6	894	888
Romania	-73	0	-73
Slovakia	-31	17	-14
Slovenia	-4	0	-4
Sweden	-97	146	49
Switzerland	-38	40	2

Figure 58-Figure 60 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

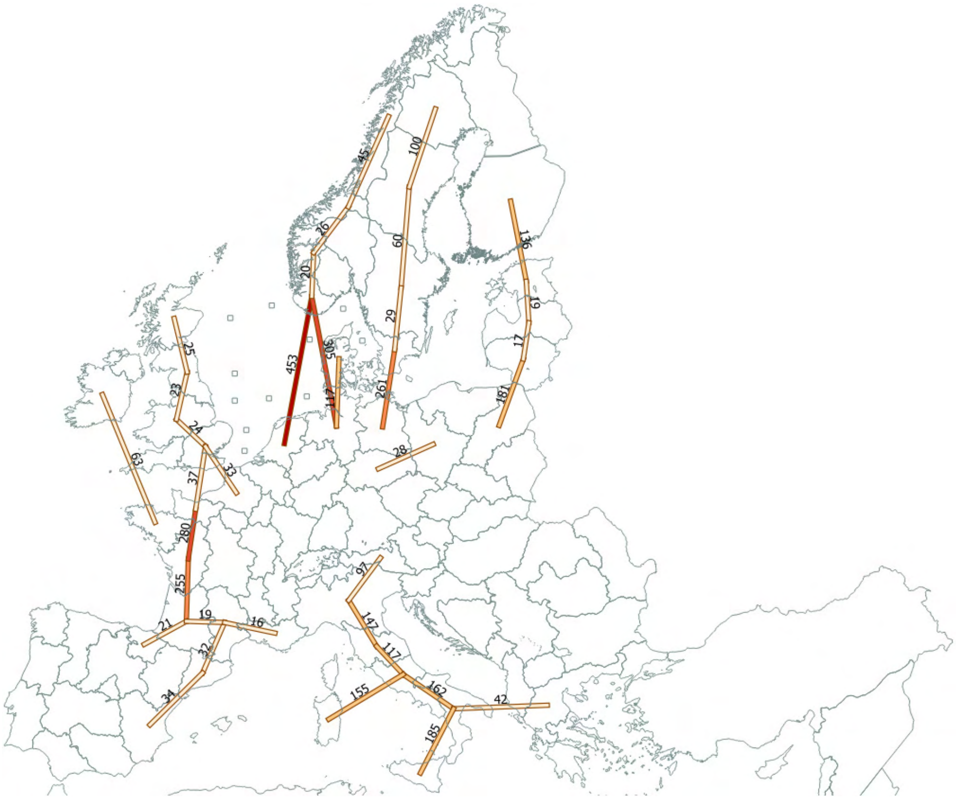

Figure 58 - X-13 Scenario – 2040 – Annual LCC – Strategy 1 [M€/a]

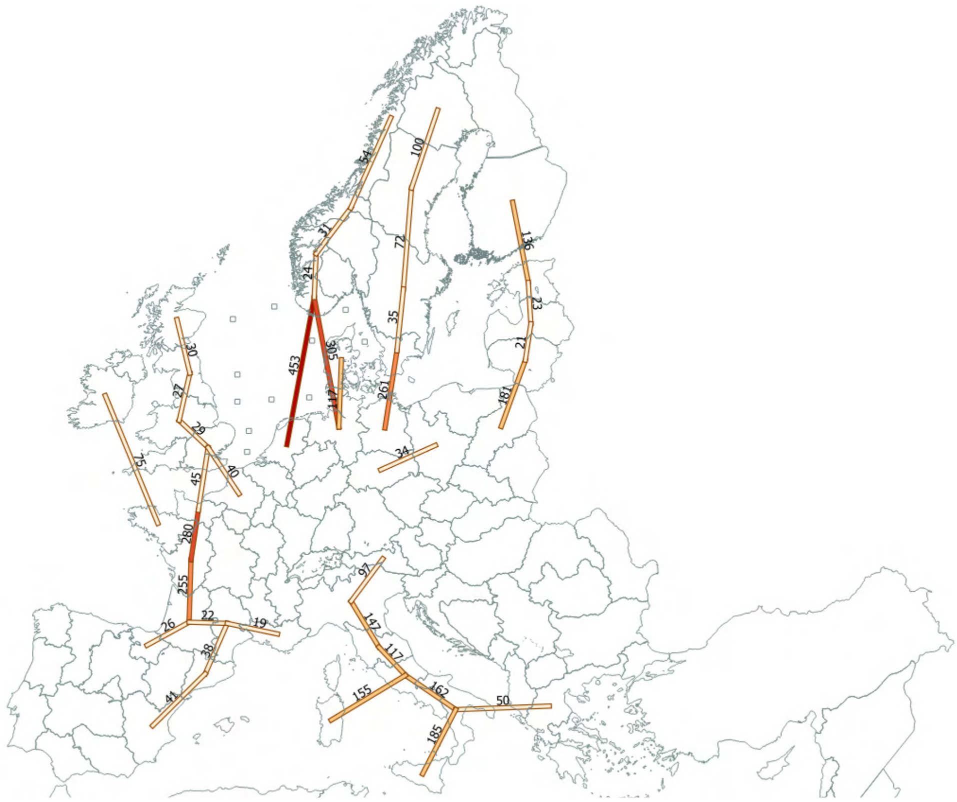

Figure 59 - X-13 Scenario – 2040 – Annual LCC – Strategy 2 [M€/a]

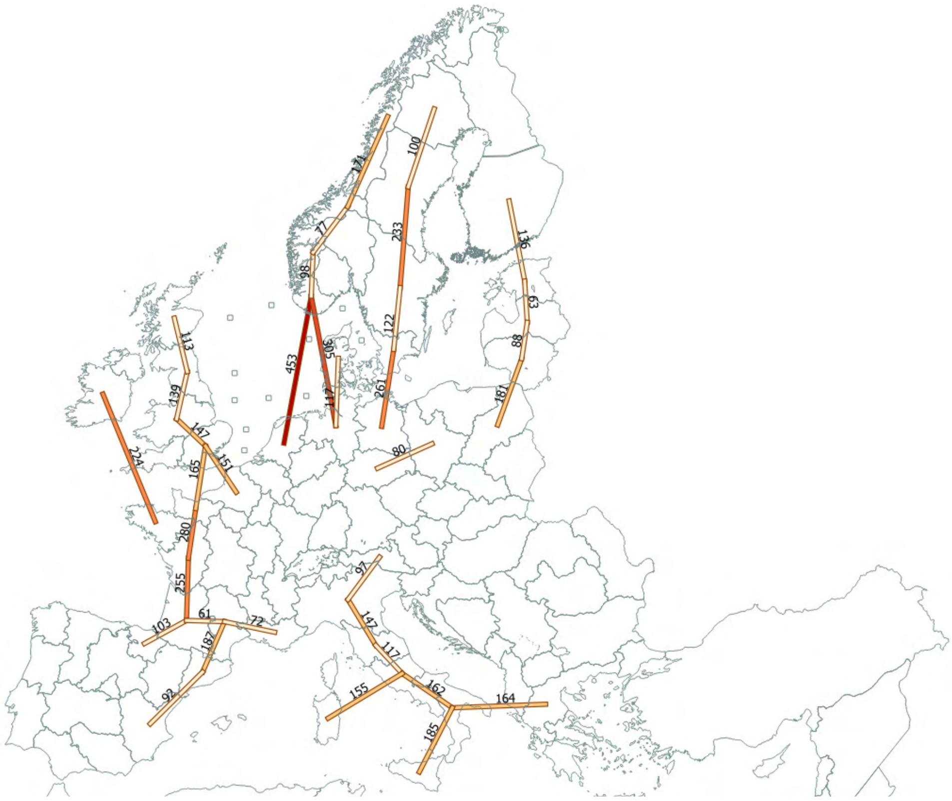

Figure 60 - X-13 Scenario – 2040 – Annual LCC – Strategy 3 [M€/a]

2.5. Scenario X-16 - Small and local

2.5.1. 2050 analyses

2.5.1.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 71 shows the annual values of core benefit indicators for this Scenario.

Table 71 – X-16 Scenario – 2050 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	3
Reduction of CO2 emissions [G€/a]	6
Reduction of reliability costs [G€/a]	45
Benefit core indicators – Grand total [G€/a]	**55**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 3 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 6 G€/a.

In any case, it can be noted how the most impacting core benefit indicator is the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 45 G€/a. Since this value is directly related to the adopted VOLL (10000 €/MWh), this aspect is examined in detail in paragraph 2.5.1.7.

According to that, the annual benefit provided by core benefit indicators in slightly higher than 55 G€/a.

2.5.1.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 72 and Figure 61 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (about 6.6 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;
- Strategy 2 is slightly more expensive than Strategy 1 (+ 16.00 % respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 69.90% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 72 – X-16 Scenario – 2050 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	6.6	7.7	11.3
Cost core indicators - Grand total [G€/a]	**6.6**	**7.7**	**11.3**

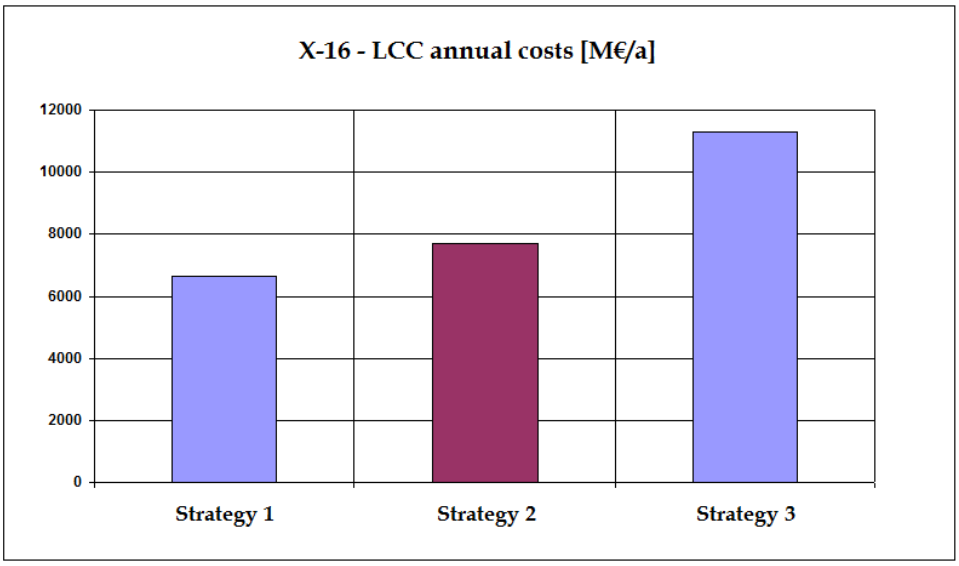

Figure 61 – X-16 Scenario – 2050 – LCC annual costs

2.5.1.2.1. LCC assessment – Sensitivity of S&E aspects

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the impact of Social and Environmental aspects on the LCC in the three different reinforcement Strategies at the target year 2050. Table 73 shows the results of this sensitivity analysis.

As can be easily pointed out, the monetary impact of S&E aspects (acquisition of rights of way) is very low (under than 1%).

The outcome of this analysis does not clearly imply that S&E aspects are a secondary item in transmission planning: in fact, those values find their justification in the adopted approach:

- considering only the rights of way acquisition do not allow to consider the full range of social and environmental externalities connected to transmission network planning;
- the cluster level of detail cannot allow to consider the very local peculiarities of crossed lands;
- the brownfield approach does not make feasible to extend the calculation to new transmission corridors.

Table 73 – X-16 Scenario – 2050 – Sensitivity on S&E aspects – Rounded values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a] – Case 1 - S&E included	6.6	7.7	11.3
LCC - Annual costs [G€/a] – Case 2 - S&E not included	6.6	7.7	11.3
(Case 2 – Case 1)/Case 1 [%]	-0.64	-0.53	-0.16

Therefore, in order to fully appraise the economic impact of S&E aspects in transmission network planning, different analyses with more precise approaches are needed.

2.5.1.2.2. LCC assessment – Sensitivity of F&R aspects

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the impact of Financial and Regulatory aspects on the annual LCC in the three different reinforcement Strategies at the target year 2050.

As shown in Table 74 and Figure 62, there is an exponential relationship between annual LCC and discount rate. In fact:

$$PV_{LCC} = \sum_{t=0}^{T_{ol}} A_{LCC} \cdot \left(\frac{1}{1+DR}\right)^t \Rightarrow A_{LCC} = PV_{LCC} \cdot \frac{(1+DR)^{T_{ol}} \cdot DR}{(1+DR)^{T_{ol}+1} - 1}$$

where:

- PV_{LCC} is the Present Value of life cycle costs [G€];
- T_{ol} is the operative life duration [a];
- A_{LCC} is the annual life cycle cost [G€/a];
- DR is the discount rate [%].

However, in the normal range of values assumed by discount rate, there is a very good approximation with an increasing line.

Table 74 – X-16 Scenario – 2050 – Sensitivity on F&R aspects – Common asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 3	6.6	7.7	11.2	4.95
LCC - Annual costs [G€/a] – Case 1	6.6	7.7	11.3	5.00
LCC - Annual costs [G€/a] – Case 4	6.9	8.0	11.7	5.26
LCC - Annual costs [G€/a] – Case 5	8.4	9.8	14.1	6.76
LCC - Annual costs [G€/a] – Case 6	10.0	11.6	16.7	8.26

This result is not surprising: in an investor perspective, if the money cost increases, the annual amortization of the asset increases as well. Moreover:

- with reference with Strategy 1 and Strategy 2, the lines are practically parallel;
- the slope of Strategy 3 line is higher than the ones with of Strategy 1 and Strategy 2: this is due to the fact that Strategy 3 heavily exploits cables (40 years of operative life). This is due to the fact that the difference in asset operative life implies an increase in annual LCC, and this difference grows faster if the discount rate is higher.

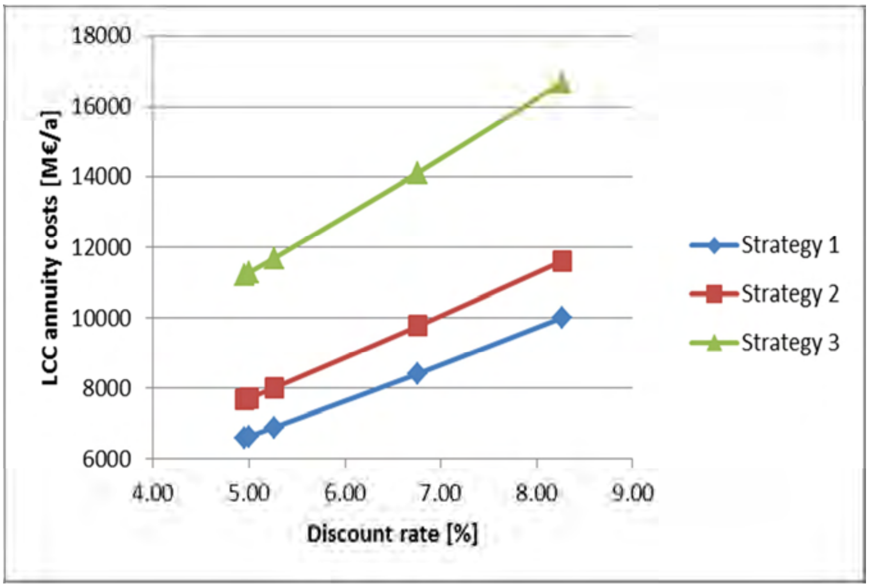

Figure 62 - X-16 Scenario – 2050 – Sensitivity on F&R aspects

Table 75 shows the result of the sensitivity analysis on F&R aspects, taking into account investment specific asset beta values: it can be noted how different values of asset beta do not bring to sensible changes (increases are lower than 1.2%) in the annual LCC. Moreover, it can be noted how resulting average discount rates are very close (5% in Case 1, 4.95% in Case 7).

Table 75 - X-16 Scenario – 2050 – Sensitivity on F&R aspects – Investment specific asset beta values

LCC annual costs	Strategy 1	Strategy 2	Strategy 3	Average discount rate [%]
LCC - Annual costs [G€/a] – Case 1	6.6	7.7	11.3	5.00
LCC - Annual costs [G€/a] – Case 7	6.7	7.8	11.3	4.95
(Case 7 – Case 1)/Case 7 [%]	**1.11**	**0.79**	**0.30**	**-**

2.5.1.3. Non-core indicator assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2050. Table 59 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any variation of CO2 emission tax between 280 €/t and 220 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO2 emission tax value included in the interval (220, 280) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.3 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value slightly higher than 14 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 10 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -218 G€/a) and Producers + Consumer Surpluses (about +228 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 76 – X-16 Scenario – 2050 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1 – Strategy 2 – Strategy 3
Sensitivity on CO2 price - Upper bound [€/t]	280
Sensitivity on CO2 price - Lower bound [€/t]	220
Reduction of investment costs in distribution networks [G€]	0.3
Social Welfare variation (CO2 emissions are accounted) [G€/a]	10
Merchandise Surplus variation [G€/a]	-219
Producers + Consumers Surplus variation [G€/a]	228

2.5.1.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-16 Scenario at the target year 2050 is performed. The set of benefits that have been taken into account are:

- reduction of CO_2 emissions;
- increase of Social Welfare (not including CO_2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 77. As previously stated, the most impacting indicator on the total gross benefit is represented by the reduction of reliability costs (more than 80% on total gross annual gross benefit).

Table 77 - X-16 Scenario – 2050 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	55.1
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	11.41
% Social Welfare increase [%]	6.24
% Reduction of distribution network investments [%]	0.03
% Reduction of reliability costs [%]	82.33

2.5.1.5. Profitability indicators – Reference case

The main profitability indicators for the X-16 Scenario at the target year 2050 are shown in Table 78. Annual and present values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

In order to evaluate the present value of gross benefit, the same annuity ratio between annual and present LCC is shown: this allows to maintain the same PI between annual and present value indicators.

Table 78 - X-16 Scenario – 2050 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	55.1	55.1	55.1
Annual LCC cost [G€/a]	6.6	7.7	12.3
Annual net benefit [G€/a]	48.4	47.4	43.8
Present Value of gross benefit [G€]	973.6	970.5	945.8
Present Value of LCC cost [G€]	117.4	136.0	193.7
Present Value of net benefit [G€]	856.2	834.5	752.1
PI [adim]	**8.30**	**7.14**	**4.88**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are very profitable for the whole society: in fact, the PI values vary from 8.30 in Strategy 1 to 4.88 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.5.1.6. GIS maps

Figure 63 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2050. The map displays the regions where the annual benefit is greater than 1 G€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. in Baltic region, Scandinavia, Balkan peninsula, Central-Eastern Europe, etc.), in general many regions experience a significant reduction of reliability costs (in Italy, France and Spain).

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO_2 emissions) is shown in a colored map in Figure 64.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 10 G€/a, even if there are some countries that could experience a reduction of their Social Welfare. These countries are highlighted in Table 79.

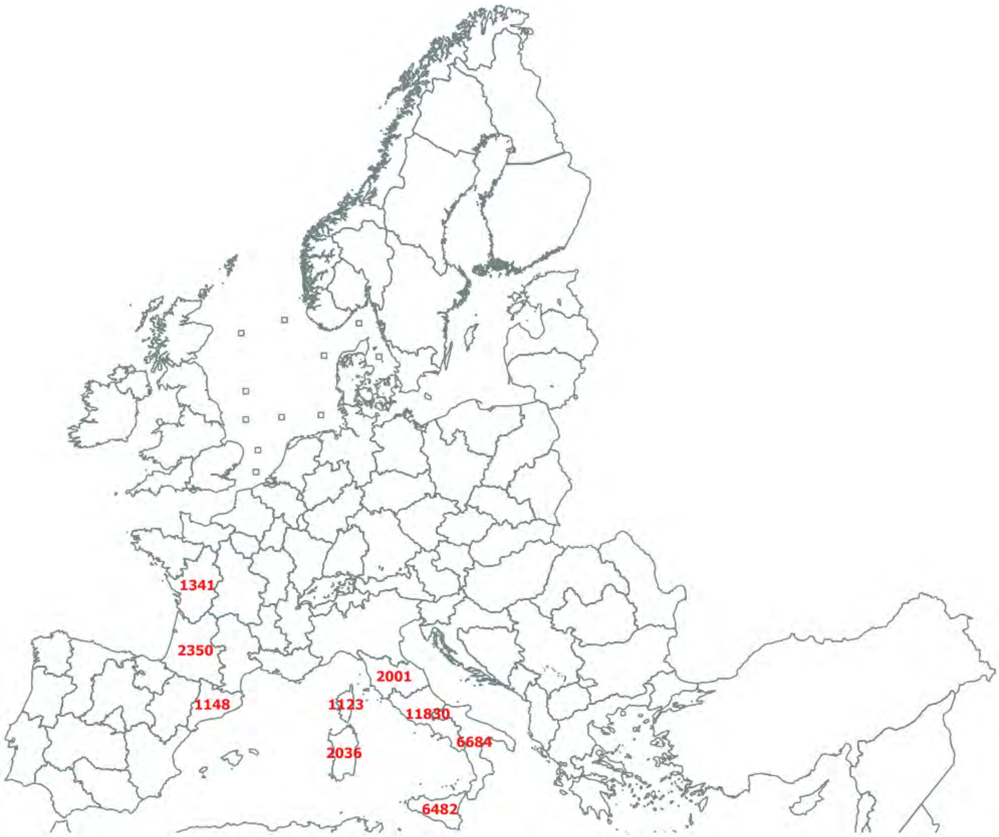

Figure 63 - X-16 Scenario – 2050 – Reduction of ENS costs [M€/a]

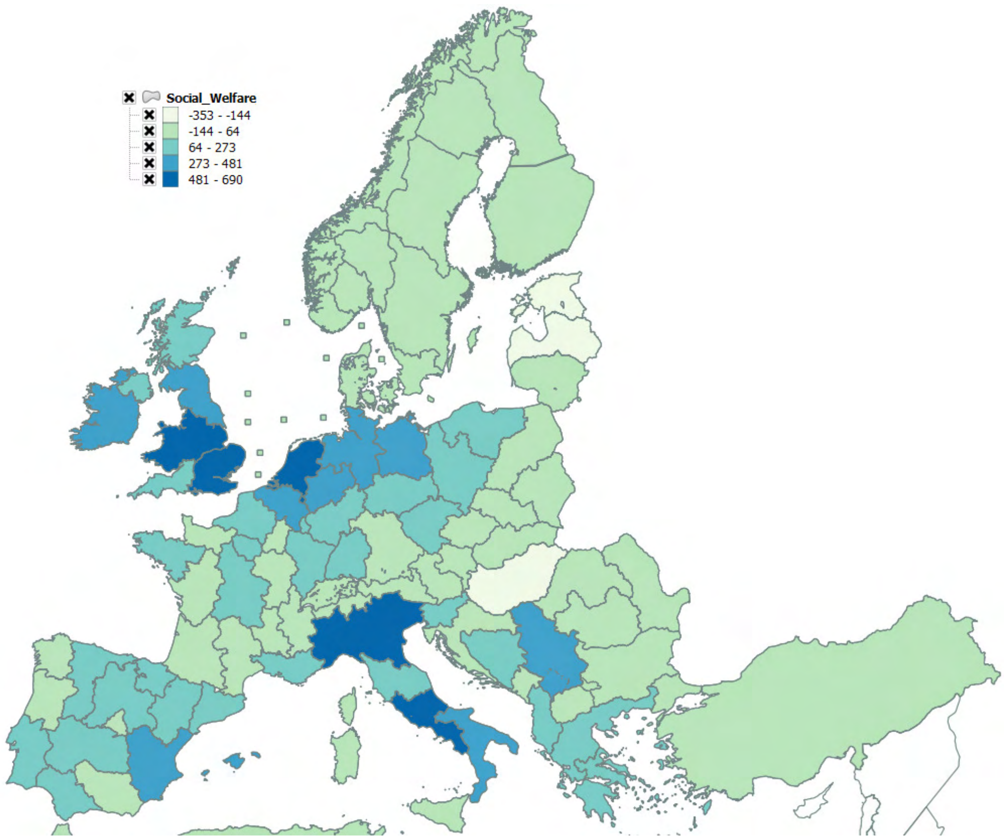

Figure 64 - X-16 Scenario – 2050 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

However, it can be pointed out that:

- in most countries, the Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries;
- taking into account the reduction of reliability costs, the transmission network reinforcement plan gives the lowest negative value in Hungary (-353 M€/a), as shown in Table 80.

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 79 - X-16 Scenario – 2050 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	**145**	Latvia	**-261**
Austria	**-19**	Lithuania	**-118**
Belgium	324	Luxembourg	84
Bosnia & Herzog.	82	Macedonia	0
Bulgaria	**-1**	Montenegro	0
Croatia	55	Netherlands	578
Czech Republic	289	Norway	**-16**
Denmark	68	Poland	234
Estonia	**-145**	Portugal	32
Finland	**-160**	Romania	**-6**
France	1030	Serbia	346
Germany	1389	Slovakia	**-59**
Great Britain	1962	Slovenia	101
Greece	208	Spain	1777
Hungary	**-353**	Sweden	**-129**
Ireland	362	Switzerland	45
Italy	1703	Ukraine	138

Table 80 - X-16 Scenario – 2050 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Austria	-19	165	146
Bulgaria	-1	0	-1
Estonia	-145	0	-145
Finland	-160	44	-116
Hungary	-353	0	-353
Latvia	-261	0	-261
Lithuania	-118	0	-118
Norway	-16	71	55
Romania	-6	0	-6
Slovakia	-59	3	-56
Sweden	-129	126	-3

Figure 65-Figure 67 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

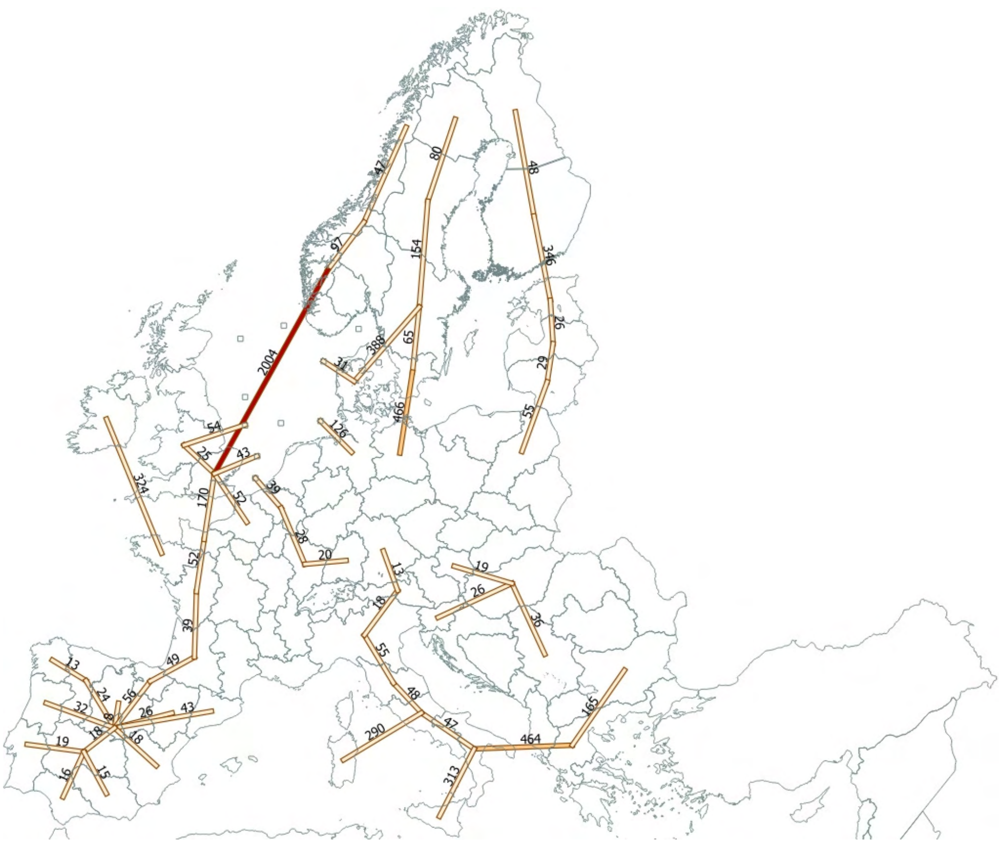

Figure 65 - X-16 Scenario – 2050 – Annual LCC – Strategy 1 [M€/a]

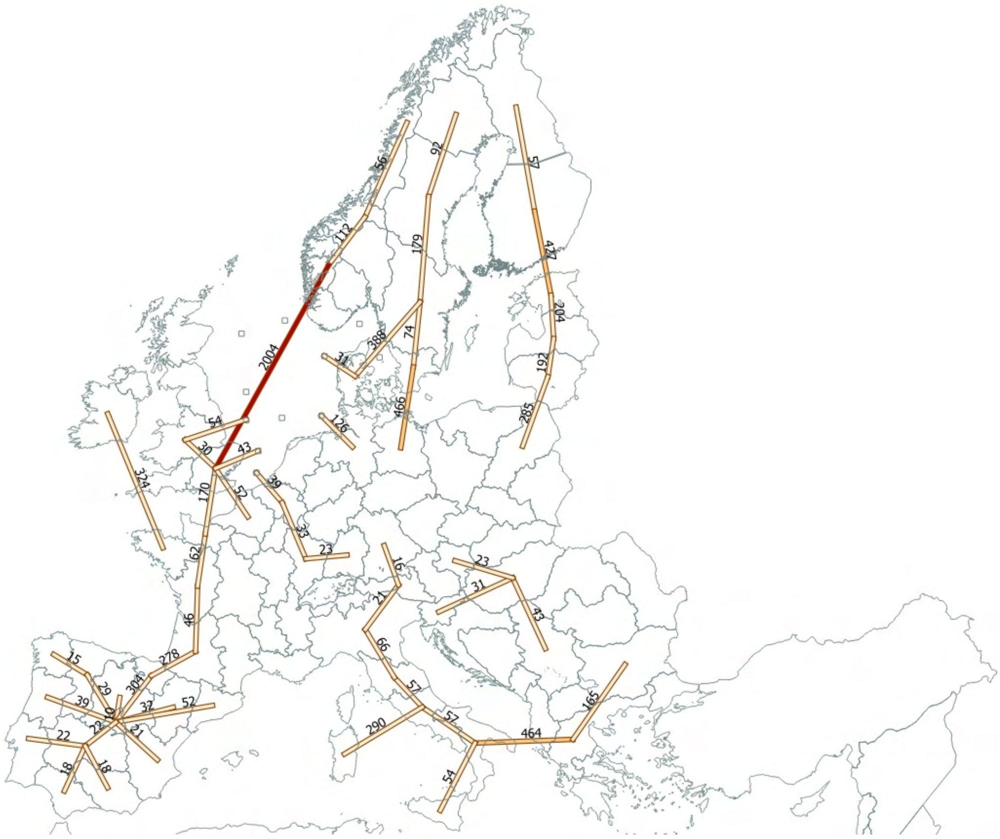

Figure 66 - X-16 Scenario – 2050 – Annual LCC – Strategy 2 [M€/a]

Figure 67 - X-16 Scenario – 2050 – Annual LCC – Strategy 3 [M€/a]

2.5.1.7. Investment sensitivity analysis: network vs. generation to cover ENS

This paragraph show the results of a sensitivity analysis performed at the target year 2050 in order to compare the cost in overcoming the same amount of ENS by means of:

- *option 1*: investment in grid reinforcements;
- *option 2*: investment in peak generation (in particular, Open Cycle Gas Turbine, OCGT, power plants).

The aim of this analysis is to check if, in order to cover ENS, investment in transmission network are (or are not) more profitable than investment in fossil-fuel peak generation, independently by the assumed VoLL.

Regarding option 2, calculation hypotheses (from WP2 and WP3) are reported below:

- fixed investment cost (CAPEX) in OCGT equal to 0.7 G€/MW;
- fuel and CO2 operation cost (OPEX) in OCGT equal to 203 €/MWh;
- maximum amount hourly saved ENS (without – with case) equal to 63 GW: this information is needed in order to properly rate the amount of additional OCGT installed capacity;
- saved ENS (without – with case) equal to 4.53 TWh/a: this information is needed in order to properly rate the production by additional OCGT power plants;
- annuity factor for investment in OCGT equal to 0.0745;

Taking into account both CAPEX and OPEX in new OCGT power plants, the annual TOTEX = CAPEX + OPEX in new OCGT power plants to cover ENS is equal to 4.2 G€/a.

However, option 2 implies a loss in other benefits achievable by transmission network reinforcements: therefore, this arises as opportunity costs in terms of increase of Social Welfare and reduction of CO2 emissions:

- opportunity cost due to the increase of Social Welfare: about 3.4 G€/a;
- opportunity cost due to the reduction of CO2 emissions:
    - about 3.5 G€/a assuming a CO2 tax value equal to 150 €/t;
    - about 6.3 G€/a assuming a CO2 tax value equal to 270 €/t.

As shown in Figure 68, according to the different implementation Strategy, the cost in option 1 spans from about 7 to about 12 G€/a: by contrast, according to the different CO2 emission tax value, the cost of option 2 spans from about 11 to about 14 G€/a.

According to that, the ratio between

- the annual investment cost in generation expansion to cover ENS (option 2)
- the annual investment cost in transmission expansion to cover ENS (option 1)

spans from 0.99 to 2.10. However, the modest value of the difference (+1%), respect to the broad interval that CO2 emission tax can assume suggests that investing in transmission network is the most resilient and cost-effective way to cover ENS.

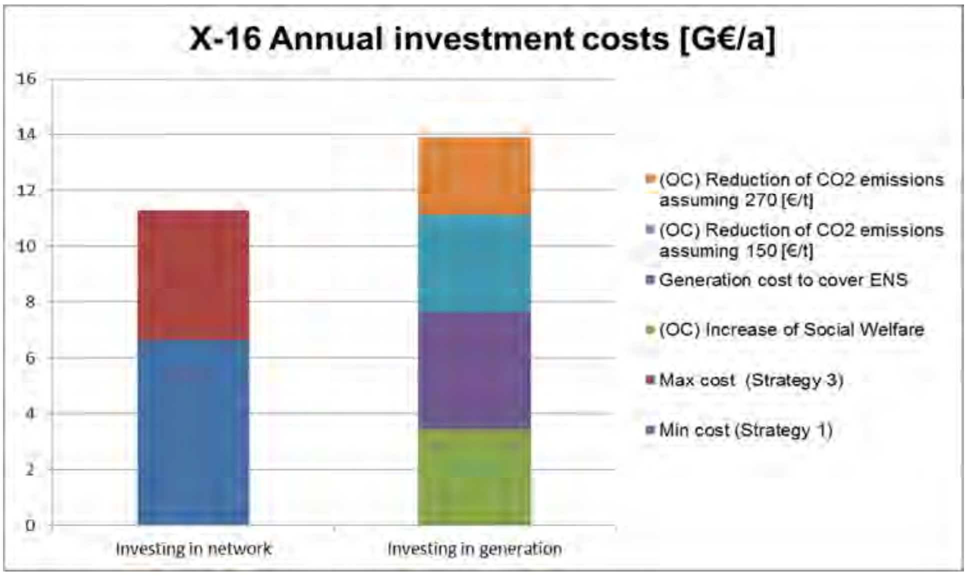

Figure 68 - X-16 Scenario – 2050 – Investment sensitivity analysis

2.5.2. 2040 analyses

2.5.2.1. Core benefits assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the benefits provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 81 shows the annual values of core benefit indicators for this Scenario.

Table 81 – X-16 Scenario – 2040 – Core benefit indicators – Rounded values

Core benefit indicators	Strategy 1 – Strategy 2 – Strategy 3
Increase of Social Welfare (no CO2 emissions accounted) [G€/a]	2
Reduction of CO2 emissions [G€/a]	4
Reduction of reliability costs [G€/a]	4
Benefit core indicators – Grand total [G€/a]	**10**

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

It can be noted how the reduction of variable costs of generation achievable thanks to transmission network reinforcement is important: in particular, the increase of Social Welfare (mainly reduction of fuel costs) is about 2 G€/a, while the economic value correspondent to the reduction of CO2 emission is about 4 G€/a.

In any case, it can be noted how an important core benefit indicator is represented by the reduction of reliability costs: transmission network reinforcements are able to cover ENS costs for more than 4 G€/a.

According to that, the annual benefit provided by core benefit indicators is about 10 G€/a.

2.5.2.2. LCC assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the cost provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 82 and Figure 69 show the annual core cost indicator (LCC) for this Scenario.

The difference between the three Strategies is noticeable and arises due to different technologies (e.g. use and acceptance of transmission lines) which are used for the different grid architectures:

- Strategy 1 is clearly the cheapest solution (slightly lower than 3.6 G€/a) since it encompasses a full acceptance of new overhead lines (OHL) at the target year, following the shortest path;

- Strategy 2 is slightly more expensive than Strategy 1 (+ 3.34% respect Strategy 1), since it is only allowed the re-use of existing OHL corridors, applying a +20% detour factor;
- Strategy 3 is the most expensive solution (+ 54.40% respect Strategy 1) since it assumes that no further OHL lines can be realised.

Table 82 – X-16 Scenario – 2040 – Core cost indicators

Core cost indicators	Strategy 1	Strategy 2	Strategy 3
LCC - Annual costs [G€/a]	3.6	3.7	5.5
Cost core indicators - Grand total [G€/a]	**3.6**	**3.7**	**5.5**

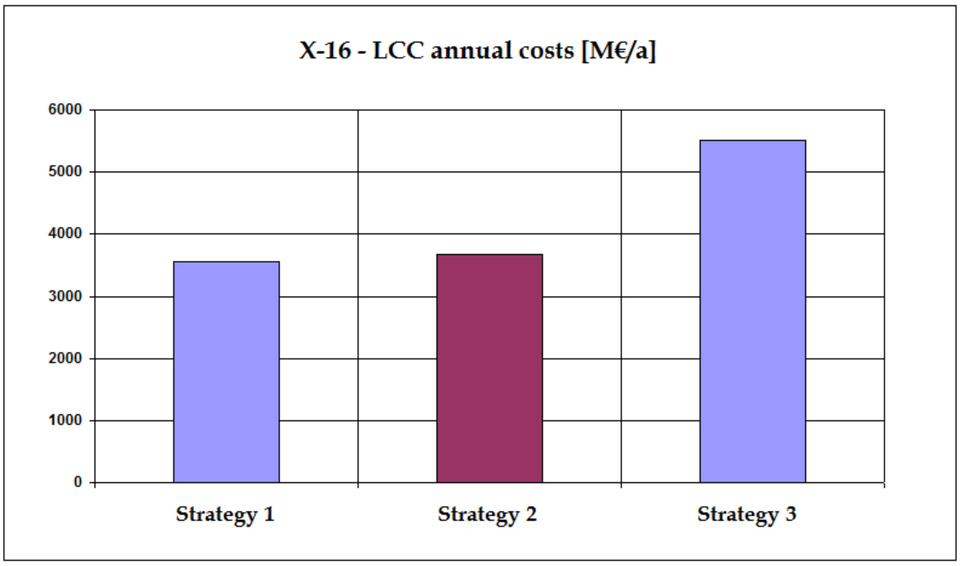

Figure 69 – X-16 Scenario – 2040 – LCC annual costs

2.5.2.3. Non-core indicators assessment – Reference case

The WP6 toolbox has been applied to the X-16 Scenario in order to appraise the non-core indicators provided by the realization of the three different reinforcement Strategies at the target year 2040. Table 83 shows the values of non-core indicators for this Scenario.

As can be easily pointed out, the values do not differ between the three Strategies: this is coherent with the hypotheses recalled in Section 1.1, since these indicators directly descend from ANTARES simulations results, while reinforcement Strategies have been identified ex-post to ANTARES system simulations.

Any CO2 emission tax value higher than 89 €/t does not bring to a change in the generation merit order: therefore, the annual dispatching plan of generation units is resilient for any CO2 emission tax value included in the interval (89, +∞) €/t.

The reduction of investment costs in distribution networks (Present Value) thanks to transmission network reinforcement reaches about 0.1 G€: in order to convert this value in an annual cost and assuming the same annuity factor between annual and Present Value LCC, the annual reduction of investment costs in distribution networks reaches a value slightly higher than 6 M€/a. The outcome of this analysis does not clearly imply that the impact of transmission network planning in distribution network planning and operation is a secondary item: in fact, the very low impact of this value finds its justification in the adopted approach: the cluster level of detail cannot allow to consider the very local peculiarities of distribution network planning and operation. Therefore, in order to fully appraise the economic impact of transmission network planning in distribution network investments, different analyses with more precise approaches are needed.

The annual Social Welfare variation (including also the value of CO2 emissions) equal to about 6 G€/a is reached thanks to the contextual variation of Merchandise Surplus (about -32 G€/a) and Producers + Consumer Surpluses (about +38 G€/a). Therefore, transmission network reinforcements allow to reach a more efficient operating point for the pan-European system:

- they reduce energy prices;
- they relieve congestions on transmission corridors;
- they increase the benefit for all the actors of the future European power system.

Table 83 – X-16 Scenario – 2040 – Non-core indicators – Rounded values

Non-core indicators	Strategy 1
Sensitivity on CO2 price - Upper bound [€/t]	+∞
Sensitivity on CO2 price - Lower bound [€/t]	89
Reduction of investment costs in distribution networks [G€]	0.1
Social Welfare variation (CO2 emissions are accounted) [G€/a]	6
Merchandise Surplus variation [G€/a]	-32
Producers + Consumers Surplus variation [G€/a]	38

2.5.2.4. Gross Benefit breakdown – Reference case

In this paragraph, a detailed decomposition of the benefits for the X-16 Scenario at the target year 2040 is performed. The set of benefits that have been taken into account are:

- reduction of CO2 emissions;
- increase of Social Welfare (not including CO2 emissions);
- annual reduction of investment costs in distribution networks;
- reduction of reliability costs.

The annual gross benefit, as well as the percentage of each indicator, are reported in Table 84. As previously stated, one of the most impacting indicator on the total gross benefit is

represented by the reduction of reliability costs (more than 43% on total gross annual gross benefit).

Table 84 - X-16 Scenario – 2040 – Gross benefit breakdown

Total gross benefit breakdown	Strategy 1 – Strategy 2 – Strategy 3
Annual gross benefit [G€/a]	9.9
Annual gross benefit [%]	100.00
% CO2 emission reduction [%]	41.31
% Social Welfare increase [%]	15.59
% Reduction of distribution network investments [%]	0.06
% Reduction of reliability costs [%]	43.04

2.5.2.5. Profitability indicators – Reference case

The main profitability indicators for the X-13 Scenario at the target year 2040 are shown in Table 85. Annual values of gross benefit, cost and net benefit are depicted. Moreover, the Profitability Index (PI) indicator, ratio between gross benefit and cost, is shown.

Table 85 - X-16 Scenario – 2040 – Profitability indicators

Profitability of core indicators	Strategy 1	Strategy 2	Strategy 3
Annual gross benefit [G€/a]	9.9	9.9	9.9
Annual LCC cost [G€/a]	3.6	3.7	5.5
Annual net benefit [G€/a]	6.3	6.2	4.3
PI [adim]	**2.76**	**2.67**	**1.79**

In general, it can be noted how transmission network investments, in all the three reinforcement Strategies, are profitable for the whole society: in fact, the PI values vary from 2.76 in Strategy 1 to 1.79 in Strategy 3. This condition implies that, at the target year, the envisaged reinforcement plans are inevitable.

2.5.2.6. GIS maps

Figure 70 gives a numerical and geographical representation of how the reduction of reliability costs (as shown, the most impacting benefit indicator) is spread in the pan-European system at the target year 2040. The map displays the regions where the annual benefit is greater than 200 M€/a.

It can be seen that, even if there are some clusters with a lower benefit (e.g. most of Europe), in general many regions experience a reduction of reliability costs (in Catalonia, South-Western France and Sicily).

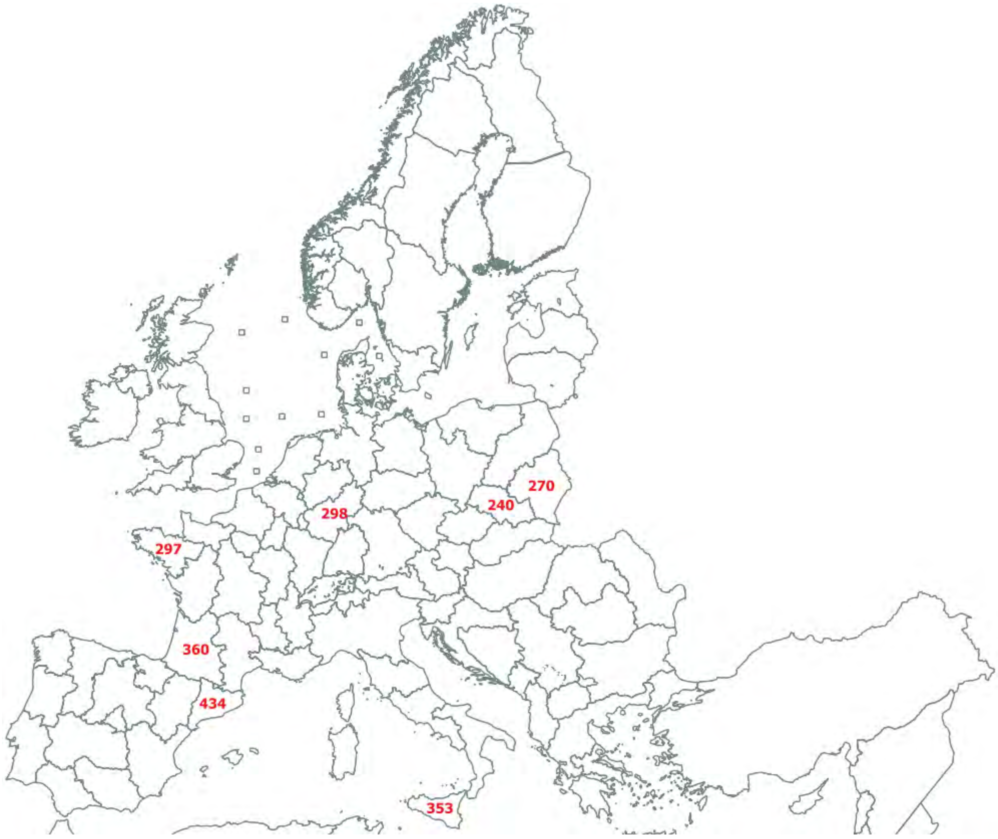

Figure 70 - X-16 Scenario – 2040 – Reduction of ENS costs [M€/a]

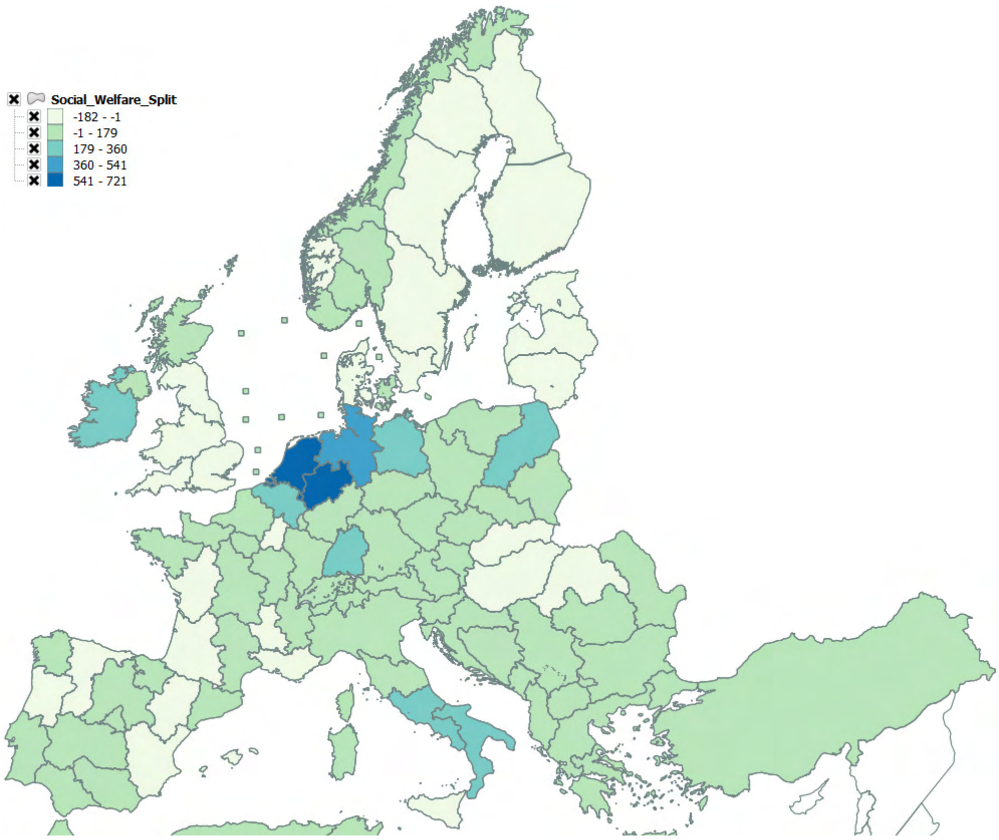

Figure 71 - X-16 Scenario – 2040 – Variation of Social Welfare (CO2 emissions are included) [M€/a]

The regional distribution of Social Welfare variation (inclusion also the component due to the reduction of CO2 emissions) is shown in a colored map in Figure 71.
As shown in the previous paragraphs, one of the main objective of transmission network reinforcement is to maximize the global Social Welfare for the future pan-European power system: this objective is reached (the annual Social Welfare increase is equal to about 6 G€/a, even if there are some countries that could experience a (slight) reduction of their Social Welfare. These countries are highlighted in Table 86.

However, it can be pointed out that:

- these negative Social Welfare variations do not appear to have a significant impact since they do not show a strong trend in worsening the power system operation of the reference countries (the absolute value of these negative indicators lower than 5% of the total Social Welfare variation);
- taking into account the reduction of reliability costs, as shown in Table 87, the transmission network reinforcement plan gives (slight) negative sums: the lowest negative value is reached in Great Britain (-191 M€/a).

This phenomenon demonstrates once again how investment decisions that are correctly carried out following the benefit maximization for a wide system (i.e. at pan-European level) should also have to take into account the local dimension.

Table 86 - X-16 Scenario – 2040 – Country level Social Welfare variation – Reference case

Country	SW variation [M€/a]	Country	SW variation [M€/a]
Albania	15	Latvia	**-182**
Austria	80	Lithuania	**-98**
Belgium	295	Luxembourg	42
Bosnia & Herzog.	27	Macedonia	12
Bulgaria	38	Montenegro	0
Croatia	55	Netherlands	649
Czech Republic	177	Norway	**-8**
Denmark	1	Poland	850
Estonia	**-87**	Portugal	19
Finland	**-115**	Romania	41
France	326	Serbia	111
Germany	2119	Slovakia	**-8**
Great Britain	**-40**	Slovenia	15
Greece	83	Spain	172
Hungary	**-28**	Sweden	**-128**
Ireland	262	Switzerland	1
Italy	836	Ukraine	74

Table 87 - X-16 Scenario – 2040 – Country level Social Welfare vs. Reduction of reliability costs – Reference case

Country	SW variation [M€/a]	Reduction of reliability costs [M€/a]	Algebraic sum [M€/a]
Estonia	-87	0	-87
Finland	-115	35	80
Great Britain	-40	231	-191
Hungary	-28	16	-12
Latvia	-182	0	-182
Lithuania	-98	0	-98
Norway	-8	106	98
Slovakia	-8	5	-3
Sweden	-128	36	-92

Figure 72-Figure 74 show the annual LCC cost for the three different reinforcement Strategies. It can be noted the impact of the different public acceptance approaches on the annual LCC costs of transmission network reinforcements.

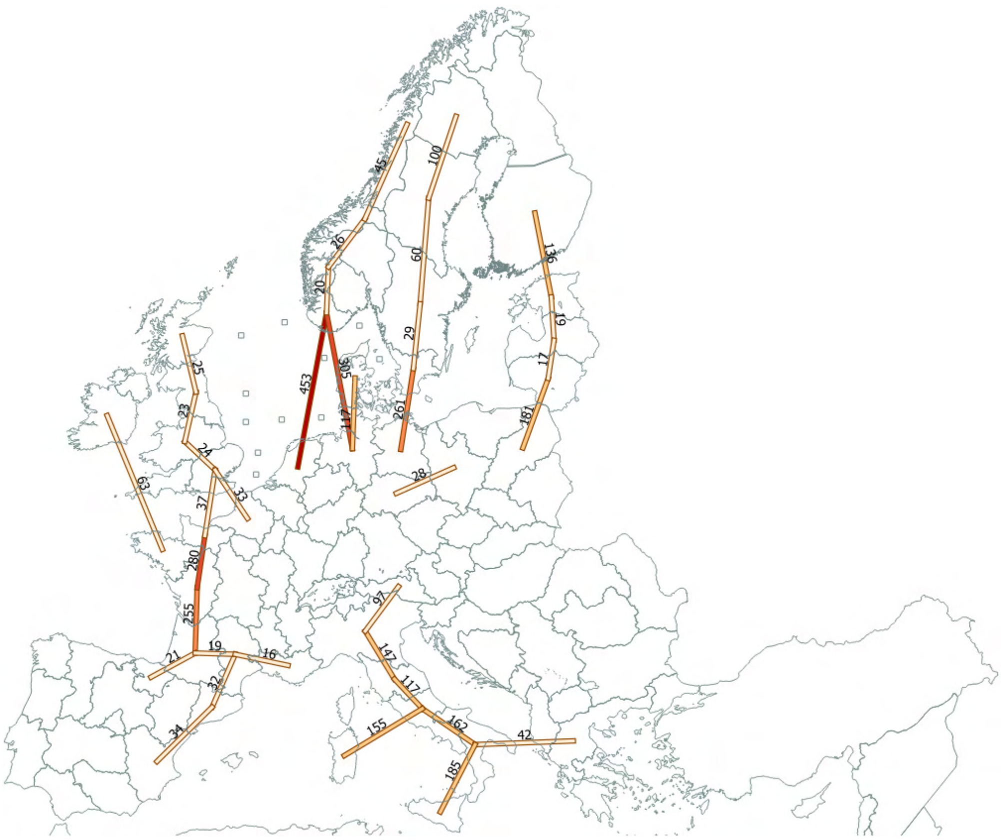

Figure 72 - X-16 Scenario – 2040 – Annual LCC – Strategy 1 [M€/a]

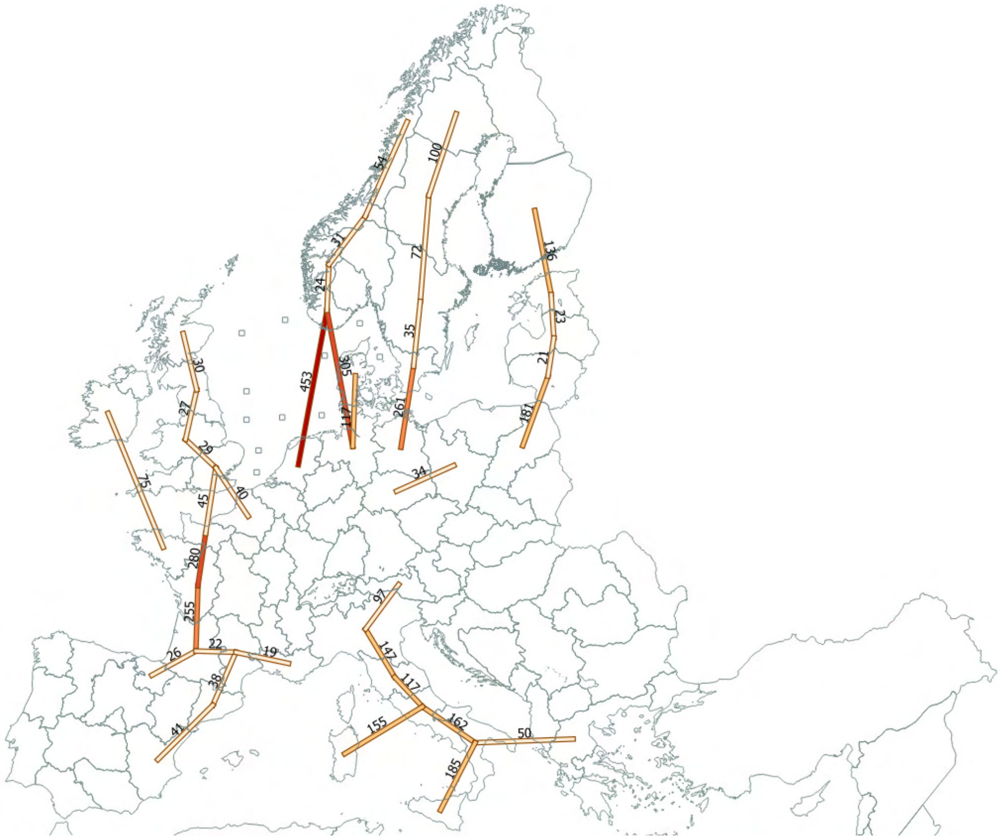

Figure 73 - X-16 Scenario – 2040 – Annual LCC – Strategy 2 [M€/a]

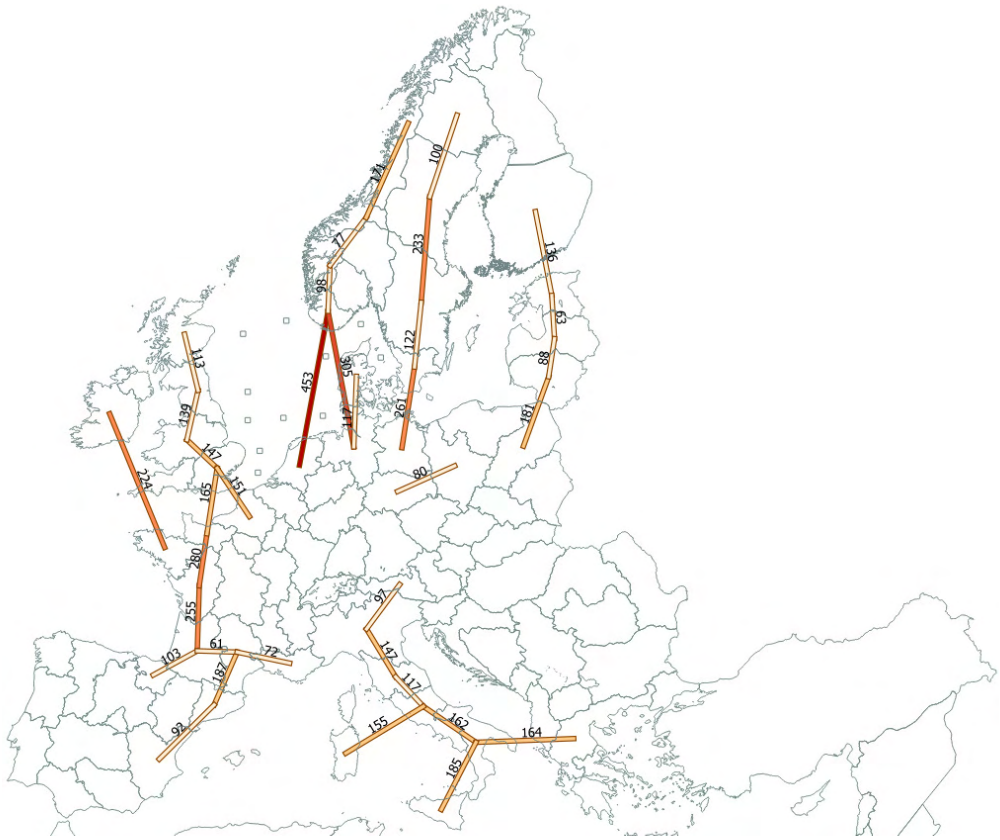

Figure 74 - X-16 Scenario – 2040 – Annual LCC – Strategy 3 [M€/a]

3. Conclusions

Figure 75 and Table 88 show the synthesis of the results exposed in chapter 2 in terms of gross benefit and LCC comparison: it can be easily noted how:

- the envisaged reinforcement plans at 2050 and 2040 are always profitable in each e-Highway2050 Scenario since, in most of the cases, annual gross benefit is one order of magnitude higher than annual cost: moreover, the different approaches for reinforcement strategies (connected to public acceptance to new transmission network assets) are all profitable;
- as shown in Figure 75, the extra costs that arise between Strategy 2 and Strategy 1 is little respect the gross benefit. However Strategy 3 is between 40 and 70% more expensive than Strategy 1;
- in proportional terms and for a given Scenario, investment at 2050 are usually more profitable (i.e the PI indicator is higher) than the pertinent investment at 2040. This is due to the fact than a 2050 Scenario is more constraining (in terms of load and RES development) than the relative 2040 one, therefore the benefits achievable by the system thanks to grid reinforcements are higher;
- or those Scenarios where RES penetration is higher (i.e. "X-5" and "X-7"), the profitability of the envisaged network reinforcement plan is usually higher: this shows that investments in transmission network reinforcements are an indispensable option to reach to desirable decarbonisation benefits for the future European power system;
- the proposed results are based on robust and widespread CBA indicators: the application of the WP6 BCA methodology for evaluating experimental indicators such as the impact of S&E aspects on LCC, the impact on Social Welfare of the possible exercise of market power or the reduction of extra costs in distribution networks has shown that a simplified approach is not able to catch the full dimension of these aspects in a very long term transmission planning;
- as described in chapter 2, most of the annual gross benefit is given by the reduction of ENS cost: however, sensitivity analyses – comparing, at 2050, the possibility to solve ENS by means of a generation expansion plan in OCGT instead of network investment – has been carried out. The result of these analyses has confirmed that, investment in transmission expansion is the most profitable way to solve ENS.

Table 88 - Synthesis of 2050 an 2040 evaluations – PI values

	2050			2040		
	Strategy 1	**Strategy 2**	**Strategy 3**	**Strategy 1**	**Strategy 2**	**Strategy 3**
X-5	21.51	20.7	13.96	28.75	27.82	18.62
X-7	38.61	38.29	26.9	29.21	28.26	18.92
X-10	17.48	17.00	10.92	6.34	6.13	4.10
X-13	11.42	10.98	6.4	8.51	8.23	5.51
X-16	8.3	7.14	4.88	2.76	2.67	1.79

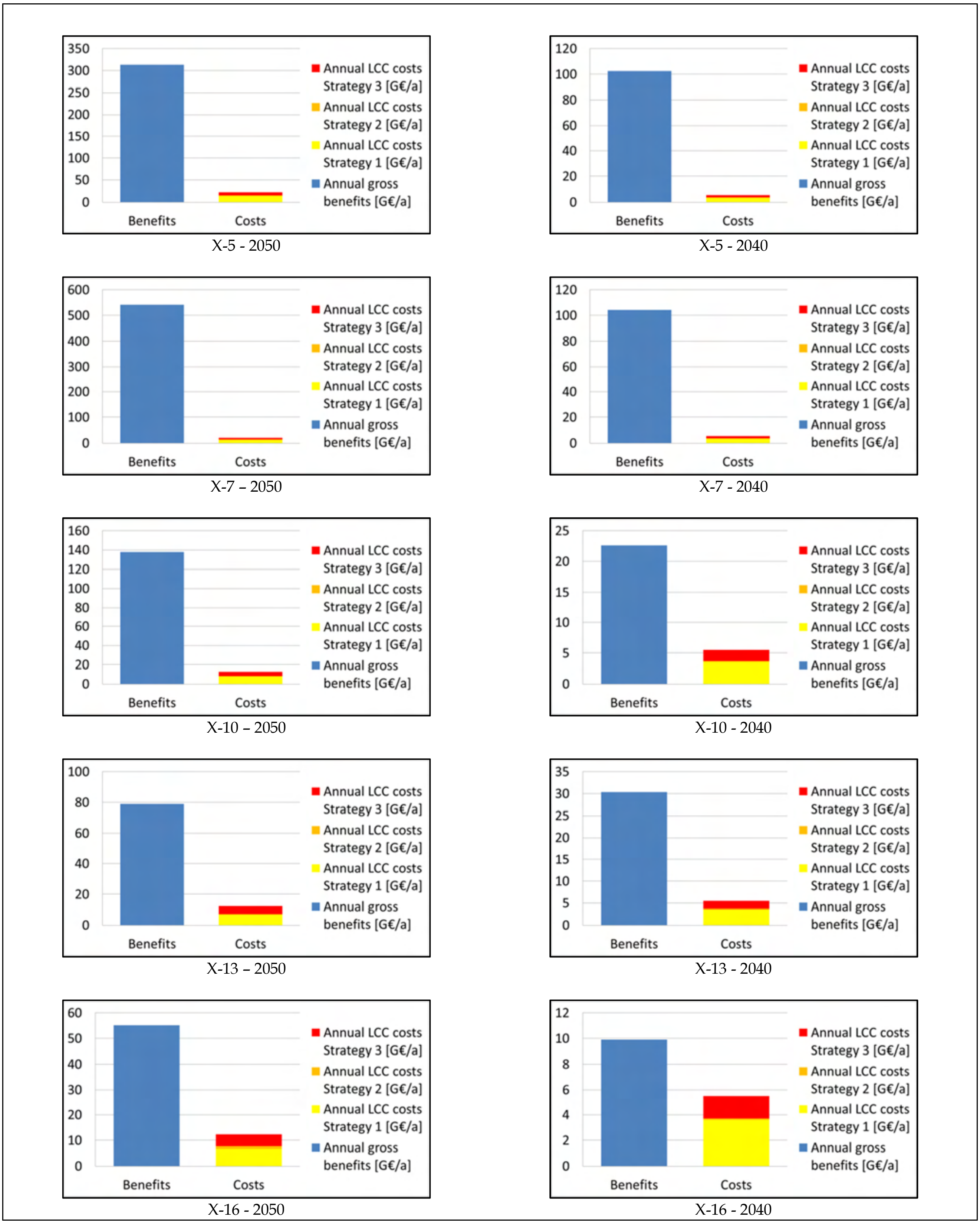

Figure 75 – Synthesis of 2050 an 2040 evaluations – Gross benefit vs. LCC costs [G€/a]

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ANNEX 1 – Evaluation of input data for calculating the reduction of investment in distribution networks

In order to evaluate the input files for calculating the reduction of investment cost in distribution network, average unitary figures have been estimated starting from Italian cost data, parameterized on population and network consistencies. These figures have been then applied for all Europe in the context of the e-Highway2050 project.

A1.1 – Population data

The WP2 clusterization has been taken into account starting from NUTS3 sets provided by Eurostat. Demographic tables have been then analysed considering total areas (km^2) and population.

A1.2 –Italian EHV-HV network consistency data

The following EHV-HV network consistency data have been obtained from Terna website (2013 data):

- 10746 km of 380 kV lines;
- 11149 km of 220 kV lines
- 46300.5 km of 132-150 kV lines.

According to that, the total kilometric consistencies at 2013 is equal to 68.196 km.

A1.3 – Italian medium voltage network consistency data

The following distribution network consistency data have been obtained from Enel Distribuzione website, the main Italian DSO:

- 13 km of HV lines;
- 350358 km of MV lines;
- 786390 km of LV lines.

Assuming that Enel Distribuzione assets cover the 85% of the total Italian distribution network (2014 data) and limiting the analysis to MV level, a 350358 km / 0.85 = 412.186 km of MV lines have been estimated from Italy.

A1.4 – Regulation annual revenues for Italian distribution network

Transmission, distribution and measurement network costs in tariff are reported in Table A1.1: these figures take into account, OPEX remuneration, cost of capital remuneration and investment remuneration.

Table A1.1 - Trasmissione, distribution and measurement Italian network tariffs [M€]
(Source: Elaboration of RSE, "Energia elettrica, anatomia dei costi" on Terna and Enel Distribuzione figures)

	2008	2009	2010	2011	2012	**2013**
Transmission	1.240	1.185	1.306	1.381	1.532	**1.644**
Distribution and measurements	5.765	5.473	5.789	6.037	6.080	**5.877**

For transmission network, the split in the three tariff component is the following:

- 49% on cost of capital remuneration;
- 29% on investment remuneration;
- 22% on OPEX remuneration.

Distribution network figures have been determined starting from Enel Distribuzione financial statement and AEEGSI (the Italian NRA) annual reports 15% is related to measurement expenses.

For distribution service, it is hard to quantify the different components but it can be reasonably assumed that the biggest component is represented by the cost of capital remuneration and, at the same time, OPEX remuneration has a higher impact respect transmission service.

This is the quantification of regulation annual revenues for transmission and distribution networks:

- EHV-HV transmission network:
  - 49% of 1644 M€ = **806** M€
- HV-MV distribution network:
  - 85% of 5.877 M€ = 4.995 M€ (subtracting a 15% for measurement services)
  - 40% of 4.995 M€ = 1.998 M€ (assuming a 40% cost of capital component)
  - 50% di 1.998 M€ = **999** M€ (LV consistencies are twice the MV ones, but LV unitary costs are assumed lower than MV ones)

A1.5 – Unitary values for e-Highway2050

Total Italian consistencies EHV-HV-MV:

- 10.746 + 11.149 + 46.301 + 412.186 = 480.381 km

Total Italian population (2013 data):

- 60788845 persons

Annual cost in tariff for transmission and distribution network assets

- 806 + 999 = 1805 M€/a

Line density (for projecting consistencies at European level)

- 480381 km / 60788845 inhabitants = **7.90 m/person**

Annual cost in tariff for transmission and distribution network assets for km o line

- 1805 M€/a / 480381 km = **3760 €/km/a**