e-Highway2050
WP2 - Grid Development for Long Term Planning
Second RGI Future Scenario Exchange Workshop
Thomas Anderski, Amprion
Climate target for 2050 as been set by the EC – only way towards it is blurry

- Climate Targets are fixed:
  80% - 95% reduction of greenhouse-gas emissions (1990), and:
  - Security of supply
  - Affordable energy supply
  - Internal European market

- Renewables are expected to contribute main part

→ How does a transmission system, to support this targets, look like?
e-Highway 2050 assesses and complements grid development plans in long term context

- NEP & TYNDP contain detailed grid expansion planning on national and European level
- e-Highway 2050 evaluates and amends detailed planning within the context of a long term system change – towards a CO2-neutral energy supply

* Ten Year Network Development Plan (ENTSO-e)
** Netz-Entwicklungsplan (Germany)
Objectives of grid architecture development in e-Highway 2050 is to provide operable structures

Goal is to define energy scenarios and grid architectures that lead to an achievement of the EU Climate targets in 2050

Analyzes to be based on:
► Ten Years Network Development Plan (ENTSO-e) (which includes the NEP)

Requirements towards expected outcomes:
► Only provide complete architectures
  • “Parts” are not independent and not exchangeable

► Definition of main transmission requirements in Europe

► Identification of “no-regret” grid reinforcements
Development of grid architectures in e-Highway 2050 follows a four step approach

- **Scenario definition**
- **European grid model**
- **Scenarios quantification**
- **Grid development & Operational Validation**

Based on Grid 2014 + TYNDP '14

Inst. capacities per Scenario

- 180 GW
- 90 GW
- 0 GW

Grid 2014 and TYNDP '14

**Scenarios**
- 100% RES
- Large Scale RES
- Big & Market RES
- Fossil & Nuclear
- Small & Local

**Grid Development & Operational Validation**

**European grid model**

**Scenarios quantification**
What is the starting point for analyses?
- What is the status of available transmission system at the beginning?

Deliverable 2.2 - European Grid Model
Target of infrastructure development is to define required bulk power transmission corridors

Objectives of work in e-Highway were, to consider

- high variety of possibilities for grid development
- main transmission requirements in Europe
- identify the “no-regret” grid reinforcements

→ European grid model

- cluster are used as smallest units for system modeling
- cluster modeled as single market node ("copperplate")
- installed capacities and demand defined on this level

- transmission equivalents represented by:
  - transmission capacity (TC) and
  - grid component (GC)

TC + GC
Cluster-model, as geographical basis, has been defined and consulted among TSO community.

- Consultation of TSOs to apply knowledge about particular systems
- Improvement of clusters (incl. justification of changes)

106 Clusters → 95 Clusters
2030 system has been applied to clustering - major grid reinforcement already included

Based on the data collection for TYNDP 2014 significant grid reinforcements have already been considered in the starting grid

- Starting Grid TYNDP 2014 already assumes projects which significantly increase transport capacity in the European Grid
  - Inter and Intra Country connections
  - Further interconnector projects
  - DC cable links

- Several „local“ reinforcements
What are the energy scenarios?
- How do energy mix and installed capacities look like?

Deliverable 2.1 - Data sets of scenarios for 2050
Scenario building methodology based on combination of *futures* & corresponding *strategies*

What will the situation be like in 2050?

Uncertainties (examples)

- Technical uncertainties
  - …

- Economic/financial uncertainties
  - …

- Political/social/environmental uncertainties
  - …

- Research, Development & Deployment uncertainties
  - …

What can we do to achieve the climate targets?

Options (examples)

- Technical options
  - …

- Economic/financial options
  - …

- Political/social/environmental options
  - …

- Research, Development & Deployment options
  - …

Which are relevant for Grid Development Planning?
Focus on scenarios that pose new challenges for the planned transmission grid

Three main Influences define the need for grid reinforcements

► **Effects on Demand**
  - GDP Increase
  - New Uses / Demand Shift
  - Efficiency

► **Effects on Generation Mix**
  - Share of Fossil Fuel
  - Share of Nuclear
  - Renewables
  - *Centralized Storage*

► **Effects on Energy Exchanges**
  - EU internal
  - EU external
Five „extreme but realistic“ development paths have been identified for Europe in 2050.
Different aspects were considered to forecast the yearly demand per scenario

► For each scenario, assumptions on country level about:
  • GDP and population growth
  • New uses of electricity
  • Energy efficiency

European demand (TWh)

- New Uses for Heating
- New Uses for Transport
- Trend demand (GDP and population)
- Final demand including energy efficiency
- Reduction due to Energy efficiency
Changes in load-patterns have been forecasted for each scenario individually.

Contrary effects by GDP/Population and Energy Efficiency.

Increase of demand by new uses of electricity.

Enhanced methodology changes level of consumption and hourly pattern.

(Example: Demand Germany in week 6)
Challenge of capacity quantification is to merge top-down approach and national legislation.

E-Highway
Scenario definition:
- Energy Mix
- Energy Exchanges

Determination installed Capacities on Macro-Area Level

National Policies and Regulation:
- Nuclear policy
- Renewable action plans

Determination installed Capacities on Country-Level

Determination installed Capacities on Cluster

Consideration of security of supply on EU-Level
distribution of generation and exchanges in accordance with the scenario definition

- **Renewable generation capacities are distributed by:**
  - profitability in the different areas
  - distribution of demand

- Depending on scenario the factors are weighted differently

- But: Installed capacities respect a maximal level of net import/export over the year in each country

<table>
<thead>
<tr>
<th></th>
<th>Large RES</th>
<th>100% RES</th>
<th>Big &amp; Market</th>
<th>Large CCS &amp; nuclear</th>
<th>Small &amp; Local</th>
<th>2014*</th>
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<tr>
<td>Maximal annual energy Balance (% of the national demand)</td>
<td>± 80%</td>
<td>± 80%</td>
<td>± 30%</td>
<td>± 30%</td>
<td>± 10%</td>
<td>± ~10%</td>
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</table>

*average value in Europe – data by ENSTO-e
Final energy mixes and installed capacities in the five e-Highway 2050 scenarios

- **Large scale RES**: 5% Hydro, 16% Wind, 20% Solar, 14% Biomass, 6% Nuclear, 40% Fossil
- **100% RES**: 9% Hydro, 21% Wind, 24% Solar, 52% Biomass
- **Big & market**: 18% Hydro, 13% Wind, 32% Solar, 19% Biomass, 8% Nuclear, 10% Fossil
- **Fossil & nuclear**: 33% Hydro, 12% Wind, 17% Solar, 7% Biomass, 5% Nuclear, 25% Fossil
- **Small & local**: 10% Hydro, 18% Wind, 23% Solar, 19% Biomass, 18% Nuclear, 3% Fossil

Graph showing the installed capacities (GW) for each energy source in the five scenarios.
North-Sea offshore grid is considered – realization by interconnected offshore-wind-parks (OPW)

- Offshore clusters are considered and can be connected in the grid development process
  - Installed capacity is different in each scenario
  - Initial transmission capacity between OWPs and mainland is initially half of installed capacity
  - Each OWP can be connected to its neighbors
  - Capacities are reinforced during grid development process – if it is beneficial
Which additional transmission grid is needed by 2050?

- Which transmission requirements are needed to solve constraints in the starting Grid

Deliverable 2.3 - Grid Development for 2050
Optimum for grid development is in between “copper plate” and starting grid situation.

- **Starting Grid** (no additional reinforcements)
  - Best case in terms of:
    - Investment costs (annually)
    - Public Acceptance
    - Maintenance Costs

- **Copper Plate** (infinity transmission capacity)
  - Best case in terms of:
    - Operation Costs
    - System Adequacy
    - RES-integration (Dump-Energy)
Decision for grid reinforcements based on analyses of key-indicators to determine benefits

- Identification of the “in-efficiencies” resulting from grid constraints:
  - Energy not served
  - Dump-Energy/ Renewable Spillage
  - Increase of expensive generation
  - Decrease of cheap generation

- Reinforcements increase exchange capacities and decrease “in-efficiencies”

- Benefits are assessed over 99 weather-years and compared to investment cost (Result of a Monte-Carlo Simulation)

SC: Focus is on major reinforcements, some smaller could be profitable as well
Iterative assessment process to consider mutual impact of integrated reinforcement

Example

Constraints analysis
(Identification of Key-Indicators in European Clusters)

Proposal of reinforcements
(Introduction of additional transmission capacities)

Annual benefit assessment
(Comparison of benefits and annual investment costs)

Analysis of the remaining constraints
(Sufficient security of supply & system costs reached?)

Final grid proposal for the scenario
(Set of transmission capacities to be realized)
Scenario X-7 - 100% RES: High imbalances and high need for exchanges

European energy shares

- High demand: 4500 TWh
- High share of non-dispatchable generation
- Renewables are dominated by wind
- Maximum of exploitable Pump-Storage
- Consideration of units included (DSM)
Grid development process – Start
High annual benefits by initial grid reinforcements

NB: other weeks and parameters are also studied
Grid Development Process – Final Step
Benefits of grid reinforcements decrease continuously

NB: other weeks and parameters are also studied
Overall drivers for grid reinforcements is inclusion of renewables and security of supply.

Changes in System (per year):
- 51 TWh of ENS avoided
- 465 TWh of spillage avoided
- 39 b€ of savings in operating costs

Total investment cost: 245 to 345* b€

NB: only some of the key factors are displayed

*depending on available technologies
Comparison of the final architectures

Large scale RES

100% RES

Big & market

Fossil & nuclear

Small & local
Common reinforcements that appear in two or more scenarios

- Displayed are all lines reinforced throughout two or more scenarios
  - Colors according to number of appearances in scenarios

- Reinforcement of high interest are driven by RES implementation and increase exchange capacities
  - North Sea for wind integration
  - Scandinavia to central Europe develop wind and storage potential
  - Connection Great Britain ↔ France ↔ Spain to distribute renewables (PV vs. Wind)

→ Need to transport energy from renewable sources from and to “European Border Countries”
Reinforcements in 2030 and beyond proof to be sustainable for EU-climate targets 2050

Investment in grid infrastructure is a very beneficial way to reach the EU energy targets

► **Main advantages of the Grid:**
  - Possibility to allocate renewables in more (/ most) profitable areas
  - Utilization of “balancing-effects” in RES-production due to geographical distribution

► **No higher transmission layer required: „Evolution, no Revolution“**

► **Need for transmission capacity correlates with share of renewables in energy mix**
  - And(!) even the decentralized “Small & Local” scenario requires further grid reinforcements

► **Interconnection capacities between countries should be among the top priorities**
  - Allowing higher exchanges between countries (utilized both ways)

► **Planned reinforcements in TYNDP sustainable in perspective of EU 2050 climate targets**
Results of e-Highway 2050 are taken up in ENTSO-e activities – especially the TYNDP ’18

Based on the results of e-Highway 2050 processes and methodologies have been included in the TYNDP framework

► Consideration of a long term scenario to define transmission system needs
   As the sustainability of grid investments can be evaluated in context of the long term targets a new time frame for assessment – 2040 – has been integrated in the TYNDP.

► TYNDP provides complement of e-Highway 2050 grid structures on regional level
   As e-Highway 2050 focuses on large scale transmission corridors the TYNDP takes up this corridors and specifies individual projects to realize them.

► Communication approach for stakeholder discussions
   Methods for the communication of results are used also for the TYNDP ‘16 and ‘18

► Commonly available Database with e-Highway 2050 results
   All data, methodologies and results of the study are available to ENTSO-e members
For more details see deliverables:

D2.1: Data sets of scenarios for 2050

D2.2: European cluster model of the Pan-European transmission grid

D2.3: System simulations analysis and overlay-grid development

D2.4: Contingency Analyses for Candidate grid architectures for 2050

on www.e-highway2050.eu
Thank you for your attention!

Contact: info@e-highway2050.eu
Web: www.e-highway2050.eu
Follow us on Twitter: @e_Highway2050
Summary of the main assumptions for grid development

► Only the inter-clusters transmission requirements are assessed

► Focus is on the major ones, some smaller could be profitable as well

► The 2030 grid from TYNDP2014 is the starting point, major projects like HVDC in Germany are thus already assumed

► The detailed routes and connection points are unknown

► Each transmission requirement could be realized through many parallel reinforcements

► For each scenario, a complete set of reinforcements for Europe is suggested, the reinforcements are not assessed independently.

► The time horizon is 2050: the profitability of the reinforcements is not proven before.
Deviations between E-Highway Starting Grid and ENTSO-e’s final TYNDP 2014 (based on received Feedback)

Consultation among ENTSO-e TSOs to reveal differences between E-Highway 2050 starting Grid and final TYNDP 2014.

- **France to UK:**
  Final TYNDP includes further DC-projects with a total capacity of 3.4 GW

- **France (internal):**
  Reinforcement along western part of additional 1 GW

- **France to Spain:**
  Final TYNDP plans an additional 1 GW

- **France to Germany**
Elaboration of Clustering criteria to split Europe into homogeneous clusters

Definition of criteria for clustering (measureable and non-measureable)

Allocation of measureable criteria to NUTS-3 regions inside each country

Mathematical optimization to identify homogeneous clusters inside countries (first step)
Methodology for setup of e-Highway2050 scenarios

- A detailed **bottom-up approach** is necessary to ensure transparency and efficient communication of scenario boundaries to the other WP's in e-Highway2050.

- Scenarios are constructed as a combination of **Uncertainties** (that cannot be controlled by the decision maker) and **Options** that can be chosen by the decision maker.

- A combination of **Uncertainties** create a unique **Future**

- One or more **Options** combined gives a **Strategy**

- A combination of a **Strategy** used within a **Future** is a **Scenario**

**Note:** The e-Highway2050 scenarios are **neither predictions nor forecasts** about the future. We do not conclude that one scenario will be more likely to happen than another, nor that one scenario is more preferred or "better" than another. Rather, each e-Highway2050 scenario is **one alternative image** of how the future of European Electricity Highways (EHS) could unfold.
# Five possible Futures

<table>
<thead>
<tr>
<th>Main Uncertainty</th>
<th>Possible Values</th>
<th>Future 1 Green Globe</th>
<th>Future 2 Green EU</th>
<th>Future 3 EU-Market</th>
<th>Future 4 Big is beautiful</th>
<th>Future 5 Small things matter</th>
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<td>Storage technology maturity</td>
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<td>All tech mature</td>
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<td>All</td>
<td>All</td>
<td>Large scale (commercial, industry&amp;freight)</td>
<td>Residential (Homes, person vehicles)</td>
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<td>Growth</td>
<td>Migration only</td>
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<td>GDP growth in EU</td>
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<td>Public perceptions to RES</td>
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# Six relevant Strategies

<table>
<thead>
<tr>
<th>Main Options</th>
<th>Strategy 1 MARKET LED</th>
<th>Strategy 2 LARGE SCALE RES</th>
<th>Strategy 3 LOCAL SOLUTIONS</th>
<th>Strategy 4 100% RES</th>
<th>Strategy 5 CARBON FREE CCS &amp; NUCLEAR</th>
<th>Strategy 6 NO NUCLEAR</th>
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<tr>
<td>Deployment of centralized RES</td>
<td>Medium</td>
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<td>Low</td>
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<td>Deployment of de-centralized RES (including CHP and Biomass)</td>
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<td>Deployment of centralized Storage</td>
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<td>Increase of energy efficiency (include DSM and flexibility)</td>
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<td>Heterogeneous framework at EU level</td>
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### The 5 final e-Highway2050 scenarios

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<td>35%</td>
<td>30%</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>Level of nuclear</td>
<td>20%</td>
<td>20%</td>
<td>0%</td>
<td>0%</td>
<td>20%</td>
<td>0%</td>
<td>20%</td>
<td>0%</td>
<td>20%</td>
<td>20%</td>
<td>0%</td>
<td>30%</td>
<td>0%</td>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td>Level of centralized storage</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
<td>High</td>
<td>No</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Enabling EU international exchanges</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>New use emerging (including DSM)</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New use</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population changes (demographic changes)</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth only</td>
<td>Growth</td>
<td>Growth only</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth</td>
<td>Growth only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDP increase</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
Anteil planbarer Erzeugung in Deutschland sinkt – bei steigender Spitzenlast*

*in X16: Small & Local annähernd konstant
In Langzeitszenarien ist Deutschland auf Import zur Versorgungssicherung angewiesen.

<table>
<thead>
<tr>
<th>Zeitpunkt</th>
<th>X-5: Large Scale RES</th>
<th>X-7: 100% RES</th>
<th>X-10: Big &amp; Market</th>
<th>X-13: Nuclear &amp; CCS</th>
<th>X-16: Small &amp; Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heute</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 GW</td>
<td>80 GW</td>
<td>100 GW</td>
<td>140 GW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Übersetzen

- Solar
- Wind
- Hydro
- Biofuels
- Oil
- Gas
- Hard coal
- Lignite
- Nuclear
- Nuclear & CCS
- Small & Local

Angenommene Verfügbarkeiten:
- Nuclear: 95%
- Lignite: 94%
- Hard Coal: 94%
- Gas: 98%
- Oil: 98%
- Hydro: 95%
- Wind-Onshore: 6%
- Wind-Offshore: 10%
- Biofuel: 94%
- PV: 0%

Gesicherte Leistung
Focus on Scenarios that pose a big Challenge for the existing Grid

Three main Influences define the need for grid reinforcements

- **Effects on Generation Mix**
  - Share of Fossil Fuel
  - Share of Nuclear
  - Renewables (centralized & decentralized)
  - Centralized Storage
- **Effects on Demand**
  - GDP Increase
  - New Uses / Demand Shift
  - Efficiency
- **Effects on Energy Exchanges**
  - EU internal
  - EU external
Load Forecasts considers socio-economical and technical developments towards 2050

- EuroHeat. Heat Roadmap Europe 2050

- Technical developments
- Alternative technologies

- European Commission Directorate-General for Energy
- European Environment Agency
Assessment of System Adequacy and need of extra capacities

Inputs: set of time series (11 wind and PV and 3 load)

- Wind time series
- PV time series
- Load time series

Installed capacities (GW)

- wind
- PV
- CSP
- nuclear
- biomass
- fossil

Hourly stochastic simulations at macro area level

Redistribution of the generation between macro areas

Adequacy OK? Energy mix OK? Imbalances OK?

Final installed capacities/final Imbalances
Incl. assessment of storage and Demand Side Management needs

<table>
<thead>
<tr>
<th>Range of Imbalances</th>
<th>Large RES</th>
<th>100% RES</th>
<th>Big &amp; market</th>
<th>Large fossil fuel</th>
<th>Small &amp; local</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+/- 80%</td>
<td>+/- 80%</td>
<td>+/- 30%</td>
<td>+/- 30%</td>
<td>+/- 10%</td>
</tr>
</tbody>
</table>
Assumptions for demand side management and storage

- Controllable load includes: a share of EV, a share of heating and a share of all the other appliances.

- Localization and power/energy ratio of storage follow typical Pumped Storage characteristics
Annual benefit assessment

New system simulation (99 MC years x 8760 hours) with the chosen reinforcements are performed to assess their impact

- The cost of the tested set of reinforcements is assessed to compare it with the benefits

- Some reinforcements can be modified if they are inefficient/over-sized (flows<<capacity, very small remaining MCV)
Analysis of the remaining constraints

- Iterations to solve the remaining constraints

- End of the iterations when no more significant issues (small and spread volumes of ENS/ Spillage/ Redispatch)
Scenario *Large Scale RES*
Presentation of the scenario Large Scale RES

- Highest demand: 5200TWh
- High participation of large scale RES, especially wind in North Sea (~105GW) and Solar in North Africa (~150GW)
- Dispatchable generation is dominated by nuclear

Installed capacities (GW)

European energy shares

*Imbalances in copper-plate simulation
Level of constraints in the Starting Grid

- Unsupplied energy:
  - Germany (44%)
  - Poland (19%)
  - Spain (17%)

- Spilled energy:
  - North sea (35%)
  - North Africa (23%)
  - Norway (13%)
  - Sweden (5%)

- Gas generation:
  - Italy (24%)
  - Spain (14%)
  - Netherlands (14%)

- Nuclear generation:
  - France (26%)

Unsupplied energy:
- Germany (44%)
- Poland (19%)
- Spain (17%)

Spilled energy:
- North sea (35%)
- North Africa (23%)
- Norway (13%)
- Sweden (5%)

Gas generation:
- Italy (24%)
- Spain (14%)
- Netherlands (14%)

Nuclear generation:
- France (26%)

Large scale RES

- +23 TWh
- +570 TWh
- +565 TWh
- -90 TWh

Operating costs ENS costs

- +320 Billion €
- +320 Billion €

* 10,000 €/MWh & sensitivity with 1000 €/MWh
**Final architecture for scenario Large scale RES**

- **Annual benefits**: 309 b€ *

*Assuming a cost of unsupplied energy equal to 10 k€/MWh. With 1k€/MWh 102b€

### ENS (TWh)

<table>
<thead>
<tr>
<th>Copper plate</th>
<th>Starting grid</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>23</td>
<td>0</td>
<td>-23</td>
<td>230 b€</td>
</tr>
</tbody>
</table>

### Spillage (TWh)

<table>
<thead>
<tr>
<th>Operating cost (b€)</th>
<th>ENS (TWh)</th>
<th>Spillage (TWh)</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>38</td>
<td>609</td>
<td>88</td>
<td>-521</td>
<td>***</td>
</tr>
</tbody>
</table>

### Operating cost (b€)

<table>
<thead>
<tr>
<th>Operating cost (b€)</th>
<th>ENS (TWh)</th>
<th>Spillage (TWh)</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>38</td>
<td>609</td>
<td>88</td>
<td>-521</td>
<td>***</td>
</tr>
</tbody>
</table>

### CO₂ (Mt)

<table>
<thead>
<tr>
<th>Operating cost (b€)</th>
<th>ENS (TWh)</th>
<th>Spillage (TWh)</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>-23</td>
<td>230 b€</td>
</tr>
</tbody>
</table>

Connections to North Africa are assumption of the scenario not incl. in starting Grid
Final architecture for scenario Large scale RES

Annual benefits: 549 b€ *

*Assuming a cost of unsupplied energy equal to 10 k€/MWh. With 1k€/MWh 90b€
Scenario *Big & Market*
Presentation of the scenario *Big & Market*

- Medium demand: 4300 TWh
- Nuclear and fossil energies are significant
- Renewables are dominated by wind especially North Sea (~ 71 GW)

*European energy shares*

*Installed capacities (GW)*

*Imbalances* in copper-plate simulation
Final architecture for scenario *Big & market*

Connections to North Africa are assumption of the scenario not incl. in starting Grid

**Annual benefits**: 132 b€

*Assuming a cost of unsupplied energy equal to 10 k€/MWh. With 1k€/MWh 33b€

<table>
<thead>
<tr>
<th></th>
<th>Copper plate</th>
<th>Starting grid</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENS (TWh)</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>-11</td>
<td>110 b€</td>
</tr>
<tr>
<td>Spillage (TWh)</td>
<td>3</td>
<td>205</td>
<td>22</td>
<td>-182</td>
<td>***</td>
</tr>
<tr>
<td>Operating cost (b€)</td>
<td>56</td>
<td>82</td>
<td>60</td>
<td>-22</td>
<td>22 b€</td>
</tr>
<tr>
<td>CO₂ (Mt)</td>
<td>39</td>
<td>101</td>
<td>47</td>
<td>-54</td>
<td>***</td>
</tr>
</tbody>
</table>
Distribution of wind and solar capacities

- **Wind capacities (GW):**
  - 0-1
  - 1-5
  - 5-20
  - >20

- **PV capacities (GW):**
  - 0-2
  - 1-5
  - 15-20
  - >35

(Imagery shows a map of Europe with color-coded regions indicating wind and solar capacities.)
Scenario Fossil & nuclear
Presentation of the scenario **Fossil & nuclear**

- After X-5, second highest annual European demand: 4854 TWh
- Lowest shares of RES among all scenarios
- Nuclear and fossil fuel plants with CCS as main production
- No exchanges with North-Africa

**European energy shares**
Final architecture for scenario **Fossil & nuclear**

- **Copper plate**
- **Starting grid**
- **Final grid**
- **Savings**
- **Financial Benefit**

<table>
<thead>
<tr>
<th></th>
<th>Copper plate</th>
<th>Starting grid</th>
<th>Final grid</th>
<th>Savings</th>
<th>Financial Benefit</th>
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</thead>
<tbody>
<tr>
<td>ENS (TWh)</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>-7</td>
<td>70 b€</td>
</tr>
<tr>
<td>Spillage (TWh)</td>
<td>0</td>
<td>42</td>
<td>1</td>
<td>-41</td>
<td>***</td>
</tr>
<tr>
<td>Operating cost (b€)</td>
<td>92</td>
<td>103</td>
<td>92</td>
<td>-11</td>
<td>11 b€</td>
</tr>
<tr>
<td>CO₂ (Mt)</td>
<td>40</td>
<td>78</td>
<td>42</td>
<td>-35</td>
<td>***</td>
</tr>
</tbody>
</table>

**Annual benefits**: 81 b€ *

*Assuming a cost of unsupplied energy equal to 10 k€/MWh. With 1k€/MWh 18b€
Scenario Small & local
Presentation of the scenario Small & local

- Lowest demand: 3278 TWh
- Focus on local solutions: generation close to demand
- 85% of energy is generated from RES (mainly decentralized)

![European energy shares](chart.png)

**Installed capacities (GW)**

*imbalances in copper-plate simulation*
Final architecture for scenario Small & local

---

**Annual benefits**: 60 b€ *

*S*Assuming a cost of unsupplied energy equal to 10 k€/MWh. With 1k€/MWh 15b€
Results - Big & market

Per year:
✓ 11 TWh of ENS avoided
✓ 182 TWh of spillage avoided
✓ 22 b€ of savings in operating costs

Total investment cost: 138-216** b€

NB: only some of the key factors are displayed

* Depending on the cost of ENS: 1k€/MWh or 10k€/MWh
* *Depending on the acceptance of over-head lines
Results – Small & local

Per year:
✓ 5 TWh of ENS avoided
✓ 47 TWh of spillage avoided
✓ 10 b€ of savings in operating costs

Total investment cost: 110-190** b€

* Depending on the cost of ENS: 1k€/MWh or 10k€/MWh
* *Depending on the acceptance of over-head lines

NB: only some of the key factors are displayed
Common reinforcements
Average Capacity of all reinforcements

- Displayed are all lines reinforced throughout all five scenarios
- Widths according to average reinforcement capacity
  \[ \frac{\text{Cap (X5)} + \text{Cap (X7)} + \ldots + \text{Cap (X16)}}{5} \]
  → National borders are first object for reinforcements
- Single corridors are very valuable in single scenarios
European annual benefits for the 5 scenarios

Benefits of the architectures are significant in all the scenarios:
- At least 10 b€ of savings on the operating cost, and up to 80b€ per year
- At least 40 TWh of spilled RES avoided, and up to 500 TWh
3 strategies to identify costs of possible realization

- The costs of a possible realization are dependent on implemented technologies
- Available technologies are influenced by the public acceptance of new lines
  -> Three “strategies” to encompass levels of acceptability

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Social assumption</th>
<th>Technical description</th>
<th>Cables</th>
<th>Up-grade of OHL’s</th>
<th>New OHL</th>
<th>New OHL on non existing corridors</th>
</tr>
</thead>
<tbody>
<tr>
<td>New grid acceptance</td>
<td>Public acceptance for new OH Lines.</td>
<td>The most efficient (cost &amp; technical) solution is selected.</td>
<td>x</td>
<td>(x)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Re-use of corridors</td>
<td>Public acceptance for new lines in existing infrastructure corridors.</td>
<td>Re-use of existing infrastructure corridors or construction of underground cable otherwise</td>
<td>x</td>
<td>(x)</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Status Quo</td>
<td>No public acceptance for new OH Lines.</td>
<td>Only up-grade of existing lines with same visual impact, or construction of underground cables otherwise</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

→ The cost of the full architecture is calculated for each strategy
Costs of the architectures

**Investment costs (b€)**

- OHL accepted
- Only DC cables

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Investment costs (b€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large scale RES</td>
<td>OHL accepted</td>
</tr>
<tr>
<td>100% RES</td>
<td>Only DC cables</td>
</tr>
<tr>
<td>Big &amp; market</td>
<td></td>
</tr>
<tr>
<td>Fossil &amp; Nuclear</td>
<td></td>
</tr>
<tr>
<td>Small &amp; local</td>
<td></td>
</tr>
</tbody>
</table>

**Annual benefits (b€)**

- Large scale RES
- 100% RES
- Big & market
- Fossil & Nuclear
- Small & local

→ Investment costs range from 100 to 400 b€, they are compensated by the benefits.

→ Scenarios Large Scale RES and 100% RES need twice more reinforcements, but those reinforcements are extremely profitable.