poweE[R] 2030:
A European Grid for $\frac{3}{4}$ Renewable Electricity by 2030

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Background of the powE[R] 2030 study:

1. Report builds on two earlier analysis from 2009 and 2011 “[r]enewables 24/7” consulting company ENERGYNAUTICS and GREENPEACE INTERNATIONAL developed a European Grid Model

2. Grid Analysis “powE[R] 2030 compares 3 different cases to study:
   - requirements for grid integration of renewable power
   - requirements for grid expansion for 75% RE power by 2030

3. Challenge the current ENTSO-E Ten Year Development Plan (TYNDP)
Simulation of 3 cases:

1. **The Reference Case** is based on the ‘business as usual’ scenario of:
   - IEA Current Policies scenarios (WEO 2011)
   - power plant capacities for 2020 + 2030 are equal to ENTSO-E TYNDP

   - 75% renewable electricity by 2030
   - broken down to 30 countries (28 EU member states +Norway, Switzerland)

3. **The Conflict Case**
   - France, Czech Republic and Poland keep inflexible coal/lignite/nuclear power
   - E[R] case for all other European countries
Methodology: Installed capacity by case for Europe (EU 28 + 2)

| Table 1.4: Installed capacities for reference, conflict and energy [r]evolution case (in GW) |
|---------------------------------|----------------|----------------|
| **EUROPE** | **REFERENCE 2030** | **CONFLICT 2030** | **E[R] 2030** |
| Coal | 113,515 | 49,106 | 39,123 |
| Lignite | 45,004 | 18,758 | 15,119 |
| Gas | 282,090 | 230,163 | 239,363 |
| Oil + Diesel | 25,167 | 7,815 | 8,732 |
| Nuclear | 106,120 | 75,424 | 11,668 |
| **RENEWABLE TOTAL** | **619,865** | **989,714** | **1,169,515** |
| Wind - Offshore | 47,566 | 111,195 | 144,811 |
| Wind - Onshore | 227,630 | 292,409 | 348,797 |
| Photovoltaic | 125,322 | 302,189 | 369,878 |
| Geothermal | 2,365 | 10,852 | 12,896 |
| Bioenergy | 36,399 | 45,222 | 49,022 |
| CSP | 11,011 | 75,188 | 75,175 |
| Hydro | 169,572 | 152,659 | 168,936 |
| Hydro Pump Storage | 64,669 | 64,669 | 64,669 |


RE electricity share: 37%  59%  77%
Methodology:
Renewable Electricity Share by Country:
Methodology:

The network model:
• 200+ nodes representing major load and generation sites in ENTSO-E area

• 400+ AC lines for major transmission corridors with capacities [in MVA]

• All existing HVDC lines with capacities [in MW]

• ENTSO-E’s Ten Year Network Development Plan (TYNDP) from 2012 split into mid- and long-term projects

• Network model built in DlgSILENT PowerFactory
Methodology:

Inputs:

• Initial network topology
  - for High Voltage Alternating Current (HVAC)
  - and High Voltage Direct Current (HVDC)
  - with line capacities [MW] aggregated EU grid model

• Installed capacities
  - for all power plant technologies in Giga-Watt [GW]
  - yearly electrical load in Terawatt hours per year [TWh/a] for all European countries according to Greenpeace and/or IEA scenarios

• Energynautics’ distribution key for how the technologies are distributed in each country
  - Wind and PV according to potential,
  - conventional generation sources according to existing capacity

• Time series for the weather year of 2011 to calculate the feed-in
  - for variable renewables, including wind and solar insolation;
  - the load profile for 2011 per country taken from ENTSO-E published profiles
Methodology:

Outputs:

• The necessary network extensions and costs

• Dispatch per node of technologies, including:
  - curtailment for variable renewables
  - load factors for controllable generators

• Network flows for AC and DC lines
Methodology: Costs taken from ENTSO-E

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>LENGTH (KM)</th>
<th>ASSUMED CAPACITY (MVA)</th>
<th>TVAKM</th>
<th>COST (BILLION €)</th>
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<tbody>
<tr>
<td>DC subsea</td>
<td>9,000</td>
<td>2,000</td>
<td>18</td>
<td>19,800</td>
</tr>
<tr>
<td>DC underground</td>
<td>1,490</td>
<td>2,000</td>
<td>2.98</td>
<td>3,725</td>
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<td>DC OHL</td>
<td>2,100</td>
<td>2,000</td>
<td>4.2</td>
<td>1,680</td>
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<tr>
<td>AC</td>
<td>36,700</td>
<td>1,500</td>
<td>55.05</td>
<td>24,497</td>
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<td>AC cable</td>
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<td>1,500</td>
<td>0.63</td>
<td>788</td>
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<tr>
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<td>660</td>
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<tr>
<td>Number of converter pairs</td>
<td>TW</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Converters for DC projects</td>
<td>22</td>
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<td>0.044</td>
<td>6,600</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>50,110</strong></td>
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<td><strong>57,750</strong></td>
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# Methodology: Technologies Assumptions

<table>
<thead>
<tr>
<th>MODEL TYPE</th>
<th>TECHNOLOGIES</th>
<th>MODELLING PROPERTIES</th>
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<tbody>
<tr>
<td>Variable renewables</td>
<td>Wind onshore and offshore, PV</td>
<td>Weather dependent availability, curtailable to % of nominal power</td>
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<tr>
<td>Flexible controllables</td>
<td>Biomass, Hydro, Gas, Oil, Geothermal, CSP</td>
<td>Flexibly dispatchable</td>
</tr>
<tr>
<td>Inflexible controllables</td>
<td>Nuclear, lignite, coal</td>
<td>Can be inflexibly modelled</td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>Pumped Hydro</td>
<td>Storage flexibly dispatchable</td>
</tr>
<tr>
<td>PV batteries</td>
<td>PV batteries</td>
<td>Must-run profiles according to local self-consumption</td>
</tr>
</tbody>
</table>

**Source:** ENERGYNAUTICS/GREENPEACE/ITESK 2014 - POWE[R] 2030.
Methodology: Assumption for inflexible generation (coal and nuclear)

*figure 1.8: example limited flexibility band (in pink) for two weeks in France in July*

- Allows for exports, since band higher than residual load
- Covers most of range of residual load

Methodology: Assumption for flexible generation e.g. solar photovoltaics
Example: Cross Border System Conflict in the Grid - France versus Germany in the Summer

- Inflexible controllables running flat out at 90% of nominal power the whole year - flexibility band 20%

*figure 2.7: generation in France plotted with variables in Germany shows a system conflict: inflexible generation in France causes curtailment in Germany*
Results: Capacity factor of conventional generation in selected countries in three scenarios

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>COAL</th>
<th>LIGNITE</th>
<th>GAS</th>
<th>NUCLEAR</th>
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<td>34%</td>
<td>0%</td>
<td>8%</td>
<td>70%</td>
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<tr>
<td>France - Conflict 2030</td>
<td>43%</td>
<td>0%</td>
<td>9%</td>
<td>75%</td>
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<tr>
<td>France - E[R] 2020</td>
<td>0%</td>
<td>0%</td>
<td>90%</td>
<td>18%</td>
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<tr>
<td>France - E[R] 2030</td>
<td>0%</td>
<td>0%</td>
<td>85%</td>
<td>0%</td>
</tr>
<tr>
<td>Poland - Conflict 2020</td>
<td>71%</td>
<td>0%</td>
<td>8%</td>
<td>90%</td>
</tr>
<tr>
<td>Poland - Conflict 2030</td>
<td>80%</td>
<td>11%</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>Poland - E[R] 2020</td>
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<td>1%</td>
<td>90%</td>
<td>0%</td>
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<tr>
<td>Poland - E[R] 2030</td>
<td>0%</td>
<td>0%</td>
<td>59%</td>
<td>0%</td>
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<tr>
<td>Czech Rep. - Conflict 2020</td>
<td>85%</td>
<td>67%</td>
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<td>86%</td>
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<td>Czech Rep. - Conflict 2030</td>
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<td>68%</td>
<td>33%</td>
<td>82%</td>
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<td>Czech Rep. - E[R] 2020</td>
<td>4%</td>
<td>2%</td>
<td>90%</td>
<td>14%</td>
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<td>0%</td>
<td>79%</td>
<td>0%</td>
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<tr>
<td>Germany - Conflict 2020</td>
<td>90%</td>
<td>80%</td>
<td>15%</td>
<td>89%</td>
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<tr>
<td>Germany - Conflict 2030</td>
<td>90%</td>
<td>83%</td>
<td>25%</td>
<td>0%</td>
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<tr>
<td>Germany - E[R] 2020</td>
<td>9%</td>
<td>3%</td>
<td>73%</td>
<td>14%</td>
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<tr>
<td>Germany - E[R] 2030</td>
<td>0%</td>
<td>0%</td>
<td>43%</td>
<td>0%</td>
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Results: Load coverage + load factors factor by technology/Imports in 2030 under the energy [r]evolution

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>IMPORTS</th>
<th>VARIABLE DISPATCH</th>
<th>FLEXIBLE CONTROLLABLE</th>
<th>RENEWABLE</th>
<th>NON-RENEWABLE</th>
<th>GAS LOAD FACTOR</th>
<th>CURTAILMENT</th>
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<td>52.9</td>
<td>47.3</td>
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<td>-3.3</td>
<td>60.6</td>
<td>42.9</td>
<td>84.2</td>
<td>19.2</td>
<td>84.8</td>
<td>1.4</td>
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<td>57.3</td>
<td>75.6</td>
<td>39.1</td>
<td>58.7</td>
<td>3.7</td>
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<td>7.2</td>
<td>30.8</td>
<td>62.2</td>
<td>64.9</td>
<td>27.9</td>
<td>79.4</td>
<td>1.2</td>
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<td>Germany</td>
<td>6.2</td>
<td>52.7</td>
<td>41.4</td>
<td>65.5</td>
<td>28.3</td>
<td>43.1</td>
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<td>9.0</td>
<td>47.2</td>
<td>44.0</td>
<td>54.4</td>
<td>36.6</td>
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<td>Italy</td>
<td>12.6</td>
<td>32.6</td>
<td>55.0</td>
<td>57.3</td>
<td>30.1</td>
<td>33.4</td>
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<td>-9.3</td>
<td>71.0</td>
<td>38.7</td>
<td>106.1</td>
<td>3.2</td>
<td>7.0</td>
<td>2.0</td>
</tr>
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</table>

Main Expansion:

• AC inter-connection between countries

• Switzerland – key for power exchange in the very centre of Europe

• DC over-lay
  - East-West
  - North-South
Switzerland in 2030:
100% renewables
+ ≈ 10% conventional
>> EXPORT COUNTRY
Curtailment rates of wind + solar by country and scenario for 2030
<table>
<thead>
<tr>
<th>CASE</th>
<th>TECHNOLOGY</th>
<th>NETWORK EXTENSION (MVA)</th>
<th>LENGTH (KM)</th>
<th>EXTENSION IN (MVAkm)</th>
<th>TRANSMISSION LINES (KM)</th>
<th>NETWORK EXTENSION COSTS (MILLION €)</th>
</tr>
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<tbody>
<tr>
<td>Reference 2020</td>
<td>AC</td>
<td>1,500</td>
<td>343</td>
<td>514,500</td>
<td>343</td>
<td>229</td>
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<tr>
<td></td>
<td>DC</td>
<td>5,000</td>
<td>1,727</td>
<td>1,682,910</td>
<td>1,370</td>
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<td>AC+DC</td>
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<td>2,070</td>
<td>2,197,410</td>
<td>1,713</td>
<td>2,197</td>
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<td>Reference 2030</td>
<td>AC</td>
<td>3,000</td>
<td>562</td>
<td>842,489</td>
<td>562</td>
<td>375</td>
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<tr>
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<td>DC</td>
<td>20,000</td>
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<td>8,145,934</td>
<td>3,101</td>
<td>7,773</td>
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<tr>
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<td>AC+DC</td>
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<td>2,985</td>
<td>8,988,423</td>
<td>3,663</td>
<td>8,148</td>
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<td>Conflict 2020</td>
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<td>731</td>
<td>1,095,796</td>
<td>731</td>
<td>530</td>
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<tr>
<td></td>
<td>DC</td>
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<td>2,895</td>
<td>7,909,550</td>
<td>2,895</td>
<td>6,702</td>
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<td>AC+DC</td>
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<td>8,006,346</td>
<td>3,626</td>
<td>7,232</td>
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<td>AC</td>
<td>84,700</td>
<td>8,224</td>
<td>15,188,762</td>
<td>8,779</td>
<td>7,089</td>
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<td>7,055</td>
<td>39,110,736</td>
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<td>33,563</td>
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<tr>
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<td>15,279</td>
<td>54,299,498</td>
<td>18,781</td>
<td>40,652</td>
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<tr>
<td>Energy [R]evolution In 2020</td>
<td>AC</td>
<td>4,500</td>
<td>731</td>
<td>1,096,796</td>
<td>731</td>
<td>530</td>
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<td></td>
<td>DC</td>
<td>15,000</td>
<td>2,634</td>
<td>7,648,550</td>
<td>2,634</td>
<td>6,254</td>
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<td>AC+DC</td>
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<td>3,365</td>
<td>8,745,346</td>
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<td>81,460,000</td>
<td>50,110</td>
<td>81,460</td>
<td>51,150</td>
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Notes:
- MVA = SUM OF CAPACITY EXTENSION IN MVA FOR EACH LINE.
- MVAkm = CAPACITY EXTENSION IN MVA MULTIPLIED WITH THE LENGTH IN KM OF EACH LINE.
- LENGTH IN KM = LENGTH OF LINE AFFECTED.
- TRANSMISSION LINE LENGTH IN KM = LENGTH OF NEW BUILD TRANSMISSION LINES.

Energy [R]evolution: Two times more RE with half the transmission and line expansion.
Thank you very much!

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