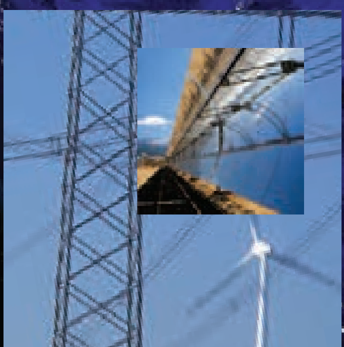
powE[R] 2030

A EUROPEAN GRID FOR 3/4 RENEWABLE ELECTRICITY BY 2030



GREENPEACE

report 2014

Greenpeace Germany

date March 2014

image OFFSHORE WIND PARK GUNFLEET SANDS IN THE NORTH SEA. GF 1 AND GF 2 AROUND 10 KM OF THE BRITISH NORTH SEA COAST ARE OPERATED BY DONG ENERGY. 48 WINDMILLS PRODUCE 172 MW IN TOTAL.

© GREENPEACE / LANGROCK

project manager
Dipl. Ing. Sven Teske

authors
Dipl. Ing. Sven Teske, Dr. Tom Brown, Dr. Eckehard Tröster, Peter-Philipp Schierhorn, Dr. Thomas Ackermann.

researchers
Dr. Tom Brown, Dr. Eckehard Tröster, Peter-Philipp Schierhorn, Dr. Thomas Ackermann.

energynautics GmbH,
Robert-Bosch-Straße 7,
64293 Darmstadt, Germany

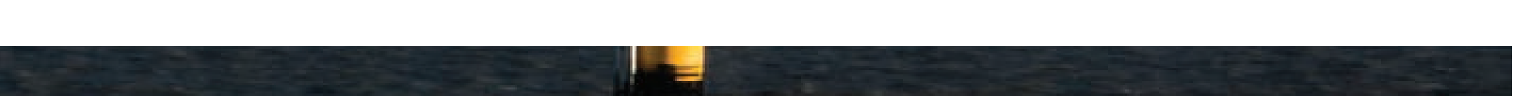
editor Alexandra Dawe

design & layout onehemisphere, Sweden, www.onehemisphere.se

contacts
sven.teske@greenpeace.org

further information about the global, regional and national scenarios please visit the energy [r]evolution website:

www.energyblueprint.info/



contents

image WIND FARM SINTFELDEN/PADERBORN IN GERMANY WITH 65 WINDMILLS MADE BY ENERCON, MICON AND VESTAS.

list of figures

list of tables

executive summary

"TWO TIMES MORE RENEWABLE ENERGY INTEGRATION WITH HALF THE TRANSMISSION LINE EXPANSION."

image HIGH VOLTAGE POWER LINES AND A WIND TURBINE IN RAGOW, GERMANY.

Europe's energy system is at a crossroads. It was built and designed to support large, polluting power plants that must be shut down and replaced by renewable energy if we are to have a truly sustainable energy system. At the same time, the agreement by European leaders on Europe's 2030 climate and energy targets will shape the future of Europe's energy system to 2030 and beyond. It will also determine if Europe can deliver on its promise to cut carbon emissions by 80-95% by 2050, in line with keeping global temperature rise below 2 degrees Celsius.

Europe's transition towards a sustainable energy system based on renewables is already underway. Renewable energy technologies delivered almost 15% of Europe's energy in 2012[1] and are on track to reach a 21% share by 2020, just ahead of the 20% target. These renewables have created jobs, cut fossil fuel imports and delivered almost half of Europe's carbon emission cuts.[2] However, the growth of renewables has slowed down recently as a result of increasing political uncertainty in Europe's renewable sector. In 2013, renewable energy investments in Europe fell by 41% to $ 57.8 billion.[3] This came on top of a 29% drop in investments the previous year. At the same time, renewables are suffering as they bump up against transmission bottlenecks and against conventional, dirty technologies like nuclear and coal. For example, 850 GWh of Spanish wind power worth an estimated €83 million was curtailed in the first three months of 2013 alone by the Spanish grid operator, REE.[4] These costs will only increase if Europe continues to try to support two incompatible energy systems.

A new report by Greenpeace based on modelling from Energynautics illustrates the extent of this clash across Europe, and the potentially enormous cost savings if Europe chooses to shift more quickly to a system based on renewables.

The ***powE[R] 2030*** report builds on two previous reports which were collaborations between energynautics and Greenpeace. For the first, published in 2009 *Renewable Energy 24/7*, energynautics developed a European grid model to investigate the required network upgrades for operating a power system with 90% renewable energy supply in Europe by 2050. This third report is based on the modeling work of 2009 and 2011 and focusses on possible conflicts of national power supply pathways

references

1 EUROBSERV'ER (2013): ESTIMATES OF THE RENEWABLE ENERGY SHARE IN GROSS FINAL ENERGY CONSUMPTION FOR THE YEAR 2012.
2 CDC CLIMAT (2013: CLIMATE AND ENERGY POLICIES IN THE EU: A MAJOR ROLE IN REDUCING CO_2 EMISSIONS FROM THE ENERGY AND INDUSTRY SECTORS.
3 BLOOMBERG NEW ENERGY FINANCE (2014): CLEAN ENERGY INVESTMENT FALLS FOR SECOND YEAR.
4 WIND POWER MONTHLY (2013): INTEGRATION SUCCESS LEADS TO EASY CURTAILMENT.

image PS10 SOLAR POWER TOWER, IN SANLUCAR LA MAYOR, NEAR SEVILLE, IS A 11 MW PLANT PRODUCES ELECTRICITY WITH 624 LARGE HELIOSTATS THAT CONCENTRATES THE SUN'S RAYS TO THE TOP OF A HIGH TOWER WHERE A SOLAR RECEIVER AND A STEAM TURBINE ARE LOCATED. THE TURBINE DRIVES A GENERATOR, PRODUCING ELECTRICITY.

and a new innovative "overlay-concept" or "super grid" which uses a network of a new generation of long distance transmission lines called *High Voltage Direct Current (HVDC)* instead of the currently used transmission lines (HVAC). All simulations have been calculated for 2020 and 2030.

a new renewable energy target for 2030

Europe is currently debating new targets for renewable energy for 2030, following the current legally binding renewable energy target of 20% by 2020. Greenpeace demands a target of at least 45% renewables by 2030 in order to reach the climate target of staying below 2°C temperature rise. Reaching the goal of 45% renewable energy by 2030 will require at least 65% to 70% renewable electricity, of which the majority will be variable solar and wind, due to economic reasons. The integration of such large amounts of renewables is challenging, and requires European-wide cooperation to get the best possible results. The optimization explores trajectories, by integrating grid investments, storage/DSM, the production mix and the geographical location of the production capacities. Three cases have been calculated:

1. **The Energy [R]evolution Case** is based on the new EU 27 Energy [R]evolution scenario, published in December 2012. The ambitious energy plan leads to around 70% renewable electricity by 2030 and over 95% by 2050 and has been broken down to 29 countries (27 EU member states plus Norway, Switzerland and Croatia).
2. **The Reference Case** is based on the 'business as usual' scenario of the Energy [R]evolution EU 27 report (see above) and the Current Policies scenarios published by the International Energy Agency (IEA) in World Energy Outlook 2011 (WEO 2011).[5] It only takes existing international energy and environmental policies into account. Its assumptions include, for example, continuing progress in electricity and gas market reforms, the liberalization of cross border energy trade and recent policies designed to combat environmental pollution. This does not include additional policies to reduce greenhouse gas (GHG) emissions and has taken as a base the capacities assumed in the 2012 ENTSO-E 10 year Network development plan.[6]
3. **The Conflict Case** illustrates what happens if inflexible coal/lignite/nuclear power plants are kept in the system in France, Czech Republic and Poland while flexible wind and solar capacities are added in all other EU member states plus Switzerland and Norway. The "Conflict" Case has a special focus on the bottleneck of the French inflexible electricity system and the growing system conflict between France and Germany as well as between Germany and its eastern neighbor countries Poland and Czech Republic with their aggressive coal and nuclear policy.

methodology

The European power system model used for this study was developed by energynautics, using the commercial simulation software *DIgSILENT PowerFactory*. The model uses grid nodes representing all major load and generation sites in the European power grid area covered by ENTSO-E. Starting from the current or future planned European high voltage transmission network and a given set of installed capacities for various generation technologies (e.g. wind, PV, gas, etc.), the dispatch of these technologies and their effect on network flows were optimized to reduce the network expansions necessary to accommodate these generation technologies while guaranteeing security of electricity supply.

Inputs:

- Initial network topology for High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) and line capacities in Mega-Volt-Ampere [MVA] or Mega-Watt [MW] and impedances from Energynautics' aggregated grid model for Europe
- Installed capacities for all power plant technologies in Giga-Watt [GW] and 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 is taken from ENTSO-E published profiles

Outputs:

- The necessary network extensions and costs
- Dispatch per node of technologies, including curtailment for variable renewables and load factors for controllable generators
- Network flows for AC and DC lines

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] and impedances
- 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 can be included as necessary
- Network model built in *DIgSILENT PowerFactory*

reference

5 INTERNATIONAL ENERGY AGENCY (IEA), 'WORLD ENERGY OUTLOOK 2011', OECD/IEA 2011.
6 https://www.entsoe.eu/about-entso-e/system-development/system-adequacy-and-market-modeling/soaf-2012-2030/

key results

The **Reference** case needs very little network expansion due to the fact that the entire power supply and demand structure will not change compared to the past decades. Countries with large shares of inflexibly operated coal or nuclear power plants such as Poland or France will continue to export electricity cross border . Therefore flexible gas power plants will have very poor load factor of 17% in the European average and renewable power generation will face high curtailment rates of around 6.2% as a result of the infexibility of coal and nuclear generation and transmission grid capacity shortages. Thus the business case for renewables will remain difficult and their electricity will only increase from currently 20% to 37% by 2030. The situation for countries with progressive renewable energy targets, such as Germany, is particularly bad. In Germany curtailment is extremely high as inflexible coal competes with wind and solar generation and causes high economic losses for them.

The reference case with its high share of inflexible coal and nuclear power generation forces gas power plants out of the market and keeps flexible renewable power generation on low market penetrations. A dynamic market growth for new flexible and renewable power generation is economically impossible with a base-load driven power plant fleet. The power market is locked in an inflexible system which does not allow any structural changes or forces further expansion to by-pass system conflicts.

The **Conflict** case illustrates what happens if inflexible coal, lignite and nuclear power plants are kept in the system while flexible wind and solar capacities are added across Europe except in France, Poland and Czech Republic which would continue business as usual, by keeping and extending less flexible coal and nuclear power plant fleets. The rest of Europe however would implement high levels of renewables combined with flexible controllable generation. An integrated European power market which develops two very different energy supply concepts – a flexible renewable energy and an inflexible coal and nuclear power based one – in parallel, will have significant problems especially along the borders of high RE and high coal/nuclear penetration. Curtailment can be reduced from 9.5% to 2.9% by increasing flexibility of coal and nuclear power plants.

Several cases have been calculated ranging from 0% flexibility which means that power plants will not ramp up and down at all in times of lower demand and higher renewable energy production to 100% flexibility leading to a direct response of power plants. While 0% flexibility leads to high capacity factors of conventional power plants and high curtailment rates for renewables, 100% flexibility reduces curtailment to a minimum but leads to very low – and uneconomic – capacity factors of coal and nuclear power plants. The results provided for the conflict scenario correspond to a 20% flexibility rate. Comparing the costs of curtailment over 40 years with curtailment costing €50 / MWh it is possible to see that inflexibility is associated with additional costs to operators from wind and solar generators. Even with 20% flexibility it costs €47.5 billion more over 40 years to compensate the curtailment than if the "inflexible" controllables were fully flexible.

As opposed to the reference and the conflict case, the **Energy [R]evolution** case has a high level of capacity from renewable energy. Flexible controllable generation technologies like gas ("flexible") come before inflexible expensive (assuming CO_2 costs) generators like coal and nuclear ("inflexible") in the merit order. All controllable generators assumed to be retro-fitted for flexibility. In addition, like in the other scenarios, variable renewables (wind and PV) may be curtailed to 60% of their nominal power in times of high feed-in and network bottle necks, but only when strictly necessary. All controllables are assumed to be available only 90% of the time, due to maintenance; however all load/capacity factors are quoted as percentages of the full nominal power. Several different assumptions have been calculated to find the ideal cost-effective combination of technologies for the Energy [R]evolution case:

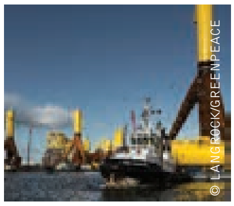
- PV batteries are added for 10% of the PV systems in 2030, operating in a "self-consumption-oriented" mode, which reduces sharp in-feed peaks from PV, therefore reducing network expansion
- Simulations are carried out without the TYNDP network extensions already built in, since this was found to significantly reduce the total network expansion and to a lesser extent the costs
- An overlay HVDC super grid was included to facilitate long-distance power transfers. The topology and dimensions of this overlay grid were optimised to reduce the total costs

Under the Energy [R]evolution case, Europe as a whole covers 53% of its load with wind and PV. Including hydro, biomass, geothermal and CSP – which are "renewable controllables" – the total load coverage by renewables increased to 77% by 2030 across Europe. Compared to the Reference and Conflict cases, France and Poland are covering a lot of their load by variable renewables under this scenario. Overall the import/export balances over the year are more even than in the Reference or Conflict cases, Germany also imports much less than in the Conflict case.

Key findings of the Energy [R]evolution case:

- PV batteries (with a nominal power 10% of installed PV capacity) have reduced the network extensions by around 10%, by capping PV peaks
- By starting with today's network instead of the TYNDP and using an optimised overlay HVDC grid, the total network extensions can be reduced by a further 40%
- By encouraging HVDC expansions over HVAC expansions in the Energy [R]evolution scenario the total network extensions have been further reduced by 19%
- The Energy [R]evolution scenario – with its focus on direct current transmission corridors – needs fewer lines because the power is transferred directly from one region to another and stops electricity from spreading out in the neighbouring network ("loop flows") which causes further stress of the AC network and requires more expansion as well.

image WESERWIND GMBH IN BREMERHAVEN, PRODUCING FOUNDATION STRUCTURES FOR OFFSHORE WIND PARKS. STRUCTURES FOR OFFSHORE WINDPARK GLOBAL TECH ONE AND NORDSEE OST 1 IN THE NORTH SEA READY FOR SHIPPING.



- As a side effect of the HVAC overlay-network, there is also lower curtailment, which has a big impact on the total system price. HVDC has lower thermal losses and no need for reactive power compensation along the line as well.

conclusions

A high level of renewables can be integrated into the European power system with only modest changes to the transmission network. With similar investment levels in network infrastructure to those already planned by network operators, Europe can cover up to 77% of its electrical load with RES, including up to 860 GW of wind and PV with low curtailment (2.8% of available energy).

By preferring an Overlay HVDC grid to continued extension of the HVAC transmission network, the total length of new transmission lines can be reduced by a third [from 39,000 km to 26,000 km, see variations of the Energy [R]evolution scenario and maps thereof]. This minimizes the impact on the landscape and therefore should facilitate public acceptance.

The inflexible operation of older nuclear and coal generation plant causes additional curtailment of variable renewables such as wind and PV. In the Conflict Scenario the inflexibility increases curtailment (and its associated costs) by 55% [2.9% curtailment to 4.5%] and could double or even triple curtailment levels if operators of conventional plant seek to improve their load factors [see Variations of the Conflict Scenario].

If policy in France, Poland and the Czech Republic continues to favor coal and nuclear, operating them inflexibly and early in the merit order, then it will cost more to integrate lower levels of RES in Europe than if every country follows the Energy [R]evolution scenario. The inflexibility causes additional curtailment, which outweighs the lower network costs. The Reference case showed clearly that a high level of coal and nuclear power capacity operated in base load mode will lead to very high curtailment rate for wind and solar by up to 9.8% in countries with progressive renewable targets.

However by focusing exclusively on renewable integration and allowing some curtailment, double the wind and PV levels can be integrated into the European power system for similar investment in network infrastructure, when compared with ENTSO-E's Ten Year Network Development Plan 2012.

table 0.1: key results + comparison with ENTSO-E

CASE	TECHNOLOGY	NETWORK EXTENSION (MVA)[a]	LENGTH (KM)[b]	EXTENSION IN (MVAkm)[c]	TRANSMISSION LINES (KM)[d]	NETWORK EXTENSION COSTS (MILLION €)
Reference 2020	AC	1,500	343	514,500	343	229
	DC	5,000	1,727	1,682,910	1,370	1,968
	AC+DC	6,500	2,070	2,197,410	1,713	2,197
Reference 2030	AC	3,000	562	842,489	562	375
	DC	20,000	2,425	8,145,934	3,101	7,773
	AC+DC	23,000	2,985	8,988,423	3,663	8,148
Conflict 2020	AC	4,500	731	1,095,796	731	530
	DC	16,000	2,895	7,909,550	2,895	6,702
	AC+DC	20,500	3,625	8,005,346	3,626	7,232
Conflict 2030	AC	84,700	8,224	15,188,762	8,779	7,089
	DC	91,000	7,055	39,110,736	10,002	33,563
	AC+DC	175,700	15,279	54,299,498	18,781	40,652
Energy [R]evolution in 2020	AC	4,500	731	1,096,796	731	530
	DC	15,000	2,634	7,648,550	2,634	6,254
	AC+DC	19,500	3,365	8,745,346	3,365	6,784
Energy [R]evolution in 2030	AC	112,200	22,489	22,168,854	11,719	10,314
	DC	148,000	10,738	52,390,238	14,556	50,859
	AC+DC	260,200	22,227	74,559,093	26,275	61,172
ENTSO-E TYNDP	AC		37,520	56,280,000	37,520	25,945
	DC		12,590	25,180,000	12,590	31,805
	AC+DC		50,110	81,460,000	50,110	57,750

notes
a MVA = SUM OF CAPACITY EXTENSION IN MVA FOR EACH LINE.
b MVAkm = CAPACITY EXTENSION IN MVA MULTIPLIED WITH THE LENGTH IN KM OF EACH LINE.
c LENGTH IN KM = LENGTH OF LINE AFFECTED.
d TRANSMISSION LINE LENGTH IN KM = LENGTH OF NEW BUILD TRANSMISSION LINES.

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

Two times more renewable energy integration with half the transmission line expansion

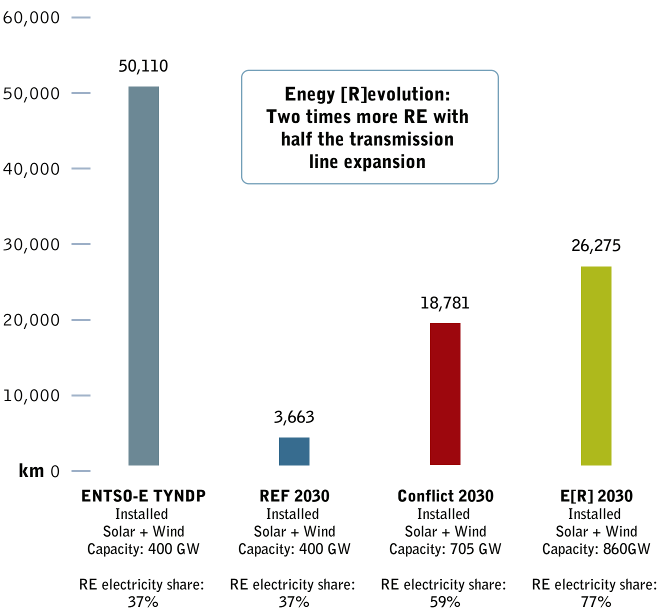
A clear result of this research has been that network expansion must be optimized towards the regional and technical power generation structure, as well as the integration of the latest transmission technologies. The TYNDP is inadequate to integrate high levels of renewables, since it is based on conservative RES targets and the continuance of existing power generation structures. This led to much higher system costs and potentially to an overcapacity of power generation. The *power 2030* concept outlined in this report is optimized for the highest share of renewables and a phase-out of coal and nuclear across Europe.

Besides the location of the specific network expansion, the chosen technologies for the transmission cables are of great importance. One of the major findings of this research is that a High Voltage Direct Current (HVDC) "Overlay-Network" avoids a significant amount of conventional transmission line expansion. This is particularly important as new power lines face huge public opposition and therefore many projects have delays of many years if not more than a decade.

An HVDC system transports renewable electricity from generation hubs to load-centers and – combined with smart-grids – can form a secure and economically viable infrastructure for renewable energies. Under the Energy [R]evolution case about 1,500 TWh per year solar and wind electricity will be produced by 2030. If an optimized grid concept reduces the required curtailment by 2% - from e.g. 4.6% down to 2.6% - the saved curtailment costs would add up to €60 billion, which is comparable with the network expansion costs in the Energy [R]evolution 2030 Scenario. Optimizing to a specific energy mix pays off. However if a network operator expands the network simply to minimize conflicts - which is the current approach – which is the current ENTSO-E approach – this would mean far higher network expansion costs and lead to many more overhead power lines, which as mentioned, face huge public opposition.

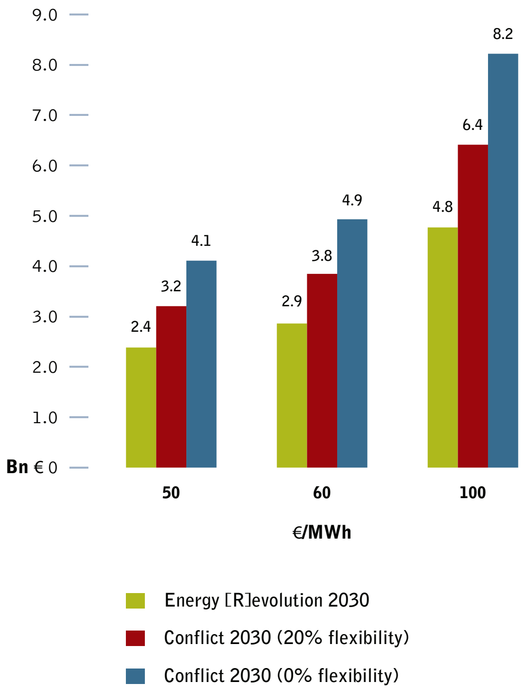
In the Conflict case, renewable energy levels would clash frequently with nuclear and coal "baseload" power, leading to the shutdown or curtailment of renewable sources. These clashes would increase the curtailment of renewables by 100% (2.9% in the Energy Revolution case rising to 5.8% in the Conflict case). Assuming an electricity cost of 60 €/MWh in 2030, the annual cost of this curtailment in such conflict case would raise to 4.9 billion €/year in 2030, or 2 billion €/year more than in the Energy Revolution scenario, as shown in figure 0.2.

figure 0.1: network expansion in km



source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

figure 0.2: curtailment costs



source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

image COAL POWER PLANT MEHRUM (OPERATED BY E.ON, STADTWERKE HANOVER AND BS ENERGY) AND WIND TURBINES. THE COAL-FIRED POWER PLANT DELIVERS 683 MEGAWATT OF ENERGY.

As a result the Energy[R]evolution case, with a share twice as high as in the reference case, turns out to be the most financially sound option. The curtailment costs are lowest and outweigh the additional grid extension costs – compared to the conflict case.

greenpeace recommendations

After decades of state subsidies to conventional energy sources, the entire electricity market and network have been developed to suit centralised nuclear and fossil production. Much of this system will have to change if Europe is to meet its long term climate and energy goals. European governments, grid operators and energy regulators must ensure the right policies are in place to help not hinder this transition:

- Governments should agree on an ambitious 2030 climate and energy framework that will set a clear direction for the future of Europe's energy system based on renewable energy and energy efficiency. Greenpeace supports a renewables target of 45%, an energy savings target of 40% (compared with 2005) and a climate target of at least 55% domestic greenhouse gas emission reductions (compared with 1990).
- Governments should ensure a stable and coherent approach to the development of renewables across Europe to avoid conflict between flexible and inflexible energy systems. Greenpeace supports the continuation of binding national renewable energy targets for 2030.
- Governments and grid operators should develop a strategic interconnection plan until 2050 which enables the development of a fully renewable electricity supply. Plans to build power lines to support existing and additional coal and nuclear plants must be scrapped.
- When assessing grid optimization options, grid operators should consider not only the costs of building new lines but the overall system costs, which include costs of renewable energy curtailment as well as cost for buying CO_2 pollution permits under the European Emission Trading System (ETS) or possible similar mechanisms in the future.
- European governments should ensure the implementation of the trans-European energy infrastructure regulation. These conditions are necessary to develop the most cost-effective grid connections to integrate renewable energy across Europe.
- European governments should secure full ownership unbundling of transmission and distribution system operations from power production and supply activities. This is the effective way to provide fair market access and overcome existing discriminatory practices against new market entrants, such as renewable energy producers.
- The role of Agency for the Cooperation of Energy Regulators (ACER) should be strengthened and the mandate of national energy regulators should be reviewed. Electricity market regulation should ensure that investments in balancing capacity and flexible power production facilitate the integration of renewable power sources, while phasing out inflexible "base load" power supply and preventing the introduction of supporting payments in the form of capacity payments.

table 0.2: key results system costs

CASE	TRANSMISSION LINES [KM]	NETWORK EXPANSION COSTS [BN €]	CURTAILMENT COSTS IN [BILLION €/a] - WITH DIFFERENT COSTS ASSUMPTIONS PER MWH			ADDITIONAL WIND + SOLAR CAPACITY INTEGRATION (BASIS 2013) [GW]
			50 MWh	60 MWh	100 MWh	
Conflict 2030	18,781	41	4.1	4.9	8.2	705
Energy [R]evolution 2030	26,275	61	2.4	2.9	4.8	860

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

introduction

"TRANSMISSION GRID OPERATORS SHOULD BE PARTNERS - NOT OPPONENTS FOR THE ENERGY TRANSITION."

image AERIAL PHOTO OF THE PS10 CONCENTRATING SOLAR THERMAL POWER PLANT. THE 11 MEGAWATT SOLAR POWER TOWER PRODUCES ELECTRICITY WITH 624 LARGE MOVABLE MIRRORS CALLED HELIOSTATS. THE SOLAR RADIATION, MIRROR DESIGN PLANT IS CAPABLE OF PRODUCING 23 GWH OF ELECTRICITY WHICH IS ENOUGH TO SUPPLY POWER TO A POPULATION OF 10,000.

Renewable energy has been growing spectacularly over recent years in Europe. In 2013, renewable energy technologies accounted for 72% of new electricity capacity connected to the grid. This strong growth of renewable electricity, especially wind energy and solar PV, has started to challenge the traditional electricity system in countries such as Spain, Italy and Germany.

However increasingly often wind turbines in certain regions are being switched off during periods of high wind, because the electricity cannot be absorbed safely by the grid. This is called 'curtailment'. The main cause of this problem is bottlenecks in the electricity grid. Currently renewable electricity surpluses cannot be transferred to other regions with a net demand or stored due to lack of required economic storage capacities.

For economic and ecological efficiency, it has become urgent that Europe upgrades and adapts its electricity system to optimize the integration of renewable energy sources. Greenpeace research (Greenpeace International, EREC, 2010) on the economic potentials for further growth of renewable electricity sources has demonstrated that by 2030, renewables could supply around 70% of all electricity and by almost 100% by 2050. Coal and nuclear power plants could almost be entirely phased out by 2030, with gas plants playing a role of bridging fuel towards an entirely renewable electricity sector by mid-century.

This report focuses on how the electricity system must be adapted (grids, production mix, storage, and demand management) to integrate the high levels of renewable energy production with specific targets for 2020 and 2030, while maintaining a high level of security of supply 24/7. Simply put this Energy [R]evolution concept could be achieved via an optimization process of grid extension, grid management, storage of energy, demand side management and allocation of specific power generation technologies in a specific region. All investments in grid extensions and storage would be kept to a minimum, avoiding situations where wind and solar PV are constrained, and an increase in non-renewable back-up production. This in turn would keep CO_2 emissions as low as possible. Two other scenarios have also been calculated - a reference case and a conflict case - which show the impact of unchanged grid policies if European member states follow different energy pathways.

image THE PELAMIS WAVE POWER MACHINE IN ORKNEY. IT ABSORBS THE ENERGY OF OCEAN WAVES AND CONVERTS IT INTO ELECTRICITY. THE MACHINE FLOATS SEMI-SUBMERGED ON THE SURFACE OF THE WATER AND IS MADE UP OF A NUMBER OF CYLINDRICAL SECTIONS JOINED TOGETHER BY HINGED JOINTS

This new research builds on an earlier work, in the form of two reports, from collaborations between energynautics and Greenpeace. For the first, published in 2009 Renewable Energy 24/7, energynautics developed a European grid model to investigate the required network upgrades for operating a power system with 90% renewable energy supply in Europe by 2050. That study however did not include the different possible pathways nor was the generation portfolio optimized.

A second collaborative published in 2011 European Grid Study 2030-2050 had three objectives:

- Determine the level of investment in grid infrastructure required to integrate 68% and 97% renewable electricity while ensuring security of supply.
- Determine the optimal generation mix of fossil fuel power stations considering a certain CO_2 ceiling from the electricity sector for 2030 and 2050.
- Determine the possible impact of storage (e.g., pump storage and electric cars), demand-side management, delayed phase-out of inflexible generation, and energy imports from North Africa on the required network upgrades and optimal generation mix.

This third report, is based on the modeling work of 2009 and 2011 and focusses on possible conflicts of national power supply pathways and a new innovative "overlay-concept" which uses a DC cable network instead of the currently the AC. All simulations have been calculated for 2020 and 2030.

Reaching the goal of 45% renewable energy by 2030 will require at least 65% to 70% renewable electricity, of which the majority will be variable solar and wind due to economic reasons. The integration of such amounts of renewables is challenging, and requires a European-wide cooperation to get the best possible results. The optimization explores trajectories, by integrating grid investments, storage/DSM, the production mix and the geographical location of the production capacities.

1. **The Energy [R]evolution Case** is based on the new EU 27 Energy [R]evolution scenario, published in December 2012. The ambitious energy plan leads to around 70% renewable electricity by 2030 and over 95% by 2050 and has been broken down to 29 countries (27 EU member states plus Norway and Switzerland).
2. **The Reference Case** is based on the 'business as usual' scenario of the Energy [R]evolution EU 27 report (see above) and the Current Policies scenarios published by the International Energy Agency (IEA) in World Energy Outlook 2011 (WEO 2011).[7] It only takes existing international energy and environmental policies into account. Its assumptions include, for example, continuing progress in electricity and gas market reforms, the liberalization of cross border energy trade and recent policies designed to combat environmental pollution. This does not include additional policies to reduce greenhouse gas (GHG) emissions and has taken as a base the capacities assumed in the 2012 ENTSO-E 10 year Network development plan.[8]
3. **The Conflict Case** illustrates what happens if inflexible coal/lignite/nuclear power plants are kept in the system in France, Czech Republic and Poland while flexible wind and solar capacities are added in all other EU member states plus Switzerland and Norway. The "Conflict" Case has a special focus on the bottleneck of the French inflexible electricity system and the growing system conflict between France and Germany as well as between Germany and its eastern neighbor countries Poland and Czech Republic with their aggressive coal and nuclear policy.

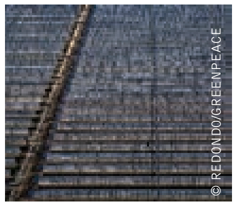
references

7 INTERNATIONAL ENERGY AGENCY (IEA), 'WORLD ENERGY OUTLOOK 2011', OECD/IEA 2011.
8 https://www.entsoe.eu/about-entso-e/system-development/system-adequacy-and-market-modeling/soaf-2012-2030/

methodology

image BORKUM RIFFGAT, ALSO KNOWN AS OWP RIFFGAT IS AN OFFSHORE WIND FARM UNDER CONSTRUCTION 15 KILOMETRES (9.3 MI) TO THE NORTH-WEST OF THE GERMAN ISLAND OF BORKUM. THE WIND TURBINES ARE BUILT ACROSS AN AREA OF 6 SQUARE KILOMETRES (2.3 SQ MI). IT WILL CONSIST OF 30 TURBINES WITH A TOTAL CAPACITY OF 108 MEGAWATT (MW), AND IS EXPECTED TO GENERATE ENOUGH ELECTRICITY FOR 112,000 HOUSEHOLDS.

image AERIAL PHOTO OF THE ANDASOL 1 SOLAR POWER STATION, EUROPE'S FIRST COMMERCIAL PARABOLIC TROUGH SOLAR POWER PLANT. ANDASOL 1 SUPPLIES UP TO 200,000 PEOPLE WITH CLIMATE-FRIENDLY ELECTRICITY AND SAVE ABOUT 149,000 TONS OF CARBON DIOXIDE PER YEAR COMPARED WITH A MODERN COAL POWER PLANT.



1.1 methodology

The European power system model used for this study was developed by energynautics, led by Dr. Thomas Ackermann, using the commercial simulation software *DIgSILENT PowerFactory*. The model uses grid nodes representing all major load and generation sites in the European power grid area ENTSO-E.

Starting from the current or future planned European high voltage transmission network and a given set of installed capacities for various generation technologies (e.g. wind, PV, gas, etc.), the dispatch of these technologies and their effect on network flows were optimized to reduce the network expansions necessary to accommodate these generation technologies while guaranteeing security of electricity supply.

Inputs:

- Initial network topology for High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) and line capacities in Mega-Volt-Ampere [MVA] or Mega-Watt [MW] and impedances from Energynautics' aggregated grid model for Europe
- Installed capacities for all power plant technologies in Giga-Watt [GW] and 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 is taken from ENTSO-E published profiles

Outputs:

- The necessary network extensions and costs
- Dispatch per node of technologies, including curtailment for variable renewables and load factors for controllable generators
- Network flows for AC and DC lines

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] and impedances
- 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 can be included as necessary
- Network model built in DIgSILENT PowerFactory

figure 1.1: basis grid node model (including planned international HVDC projects)

source ENERGYNAUTICS 2014 - POWE[R]2030.

image LOADING OF A SIEMENS WIND POWER TURBINE SWT 6.0 120 ON THE SPECIAL CARGO SHIP A2SEA INSTALLER. THE WIND TURBINE IS MADE FOR THE GUNFLEET SANDS GF III WIND PARK 10 KM OFF THE BRITISH COAST IN THE NORTH SEA.

1.2 overlay network

The optimization algorithm can build both AC lines and DC lines. In the scenarios with the overlay network, the algorithm has the option to build a long-distance HVDC overlay network, which connects major European load centers and nodes with a high share of renewable power generation. This overlay network consists of several connected HVDC lines; the algorithm can expand each line separately with difference capacities, or choose not to build the line at all.

After examining the flows in the Energy [R]evolution scenario, the following important corridors were identified for the HVDC overlay:

1. Scotland to southern England
2. Spain to France
3. Southern Italy to Northern Italy
4. French coast to Paris (for offshore wind)
5. Northern Germany to the Ruhr and/or Southern Germany (again for offshore wind)
6. France to Germany
7. Italy to Germany

1.3 the european ten year network development plan

This report uses the Ten Year Network Development Plan (TYNDP) published by the European Network of Transmission System Operators (TSO) for Electricity (ENTSO-E) from 2012 which outlines all planned projects for the coming period as the basis for its modeling.[9] The TYNDP started as a collection of the national TSOs plans, but it aims to strive towards transnational planning. The next version comes out at the end of 2014 after consultation in mid-2014.

The following two maps, from the 2012 TYNDP, geographically display all investments of Pan-European Significance. The first map (Figure 1.2) shows all mid-term commissioned projects, i.e. in the first five-year period of the TYNDP, from 2012 to 2016. The second map (Figure 1.3) shows all projects commissioned in the longer run, i.e. from 2017. The maps show basic information regarding location, routes and technology (AC or DC, voltage level). When the precise location of an investment is not yet known, the area where the investment is likely to occur is colored.

reference
9 https://www.entsoe.eu/major-projects/ten-year-network-development-plan/

figure 1.2: projects of pan-european significance mid-term (until 2016)

source ENTSO-E, 10-YEAR NETWORK DEVELOPMENT PLAN 2012.

image POWER LINES AT THE PREDEFINED INSTALLATION SITE FOR THE PLANNED NEW NUCLEAR POWER STATION GOESGEN, SWITZERLAND, ON THE OTHER SIDE OF THE RIVER OF THE EXISTING NUCLEAR POWER STATION.

figure 1.3: **projects of pan-european significance long-term (from 2017)**

source ENTSO-E, 10-YEAR NETWORK DEVELOPMENT PLAN 2012.

As displayed in Figure 1.4, projects of pan-European significance total about 52,300 km of new or refurbished Extra High Voltage routes, compared to the existing grid length of about 305,000 km. The expected commissioning dates are split rather equally between the two five year periods.

The TYNDP 2012[10] figures represent a 25% increase in projects, compared to TYNDP 2010, with especially individually long-distance new investments:

- + 3,000 km of subsea routes are envisaged, developing in total 10,000 km of offshore grid key-assets.
- + 7000 km of routes are considered inland, mostly to bring to load centers the power generated on the outskirts of the European territory.

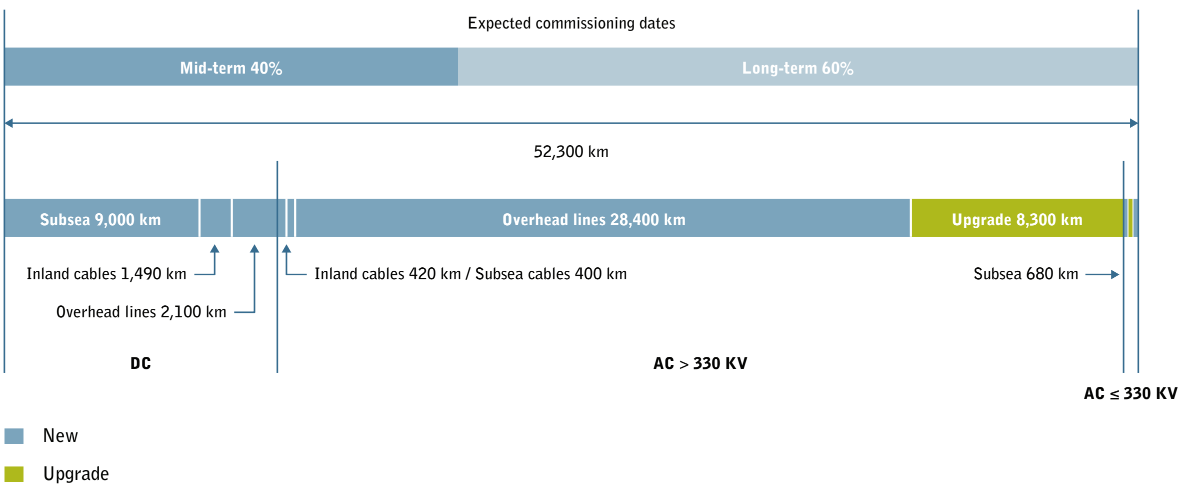
The vast majority of projects (around 39,000 km) use the common HVAC technology. This is the common technical standard in Europe for electricity transmission and is a well-established technology. In addition, about 12,600 km of HVDC links are planned. Most relate to subsea investments where AC technology is no option. Several HVDC interconnection projects are however considered inland with parallel operation with HVAC lines. 1,080 km of HVAC subsea cables, at 150 kV or 220 kV are also planned, mostly for offshore wind connection. Over 82% of the investments correspond to new equipment/routes and 18% to refurbishment or upgrade of existing assets.

1.4 cost estimations from ENTSO-E[11]

Project costs from 34 European countries and regions show a very wide range, corresponding to the diversity of the designs, from less than €50 million to more than €1 billion: 40% of the projects display costs lower than €300 million and 23 % greater than €1 billion. Total investments costs across Europe amount to €104 billion, of which €23 billion is for subsea cables. The figures are in line with the previous analysis of the TYNDP 2010 and of the overall €100 billion envisaged by the European Commission in their communication on Energy Infrastructure Package on 17th November 2011.

Total investment costs per country correlate relatively with land size and population. Still there are noticeable deviations. Ireland thus foresees as much as €4 billion (due mostly to HVDC long distance cables), an important effort compared to the population size. With big evolutions with respect to generation location on the German ground, Germany considers by far the highest investments, with €30.1 billion. The investment efforts are significant for TSOs financial means. It represents however about 1.5 – 2 €/ MWh of power consumption in Europe over the 10-year period, about 2% of the bulk power prices or less than 1% of the total electricity bill (Source ENTSO-E, TYNDP 2012, page 70).

figure 1.4: projects of pan-european significance – volumes



source TYNDP – ENTSO E 2012, PAGE 62.

references
10 https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/
11 https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/, p.70

image STOCKPILES OF COAL UNLOADED FROM BULK CARRIERS IN THE PORT OF GIJON.

1.5 renewable integration capacity assumed for the TYNDP 2012

Grid development requires long term anticipation and consideration. ENTSO-E developed four visions up to 2030 to examine the challenges and opportunities for TSOs development of longer-term scenarios. The development of the two different 2012 TYNDP scenarios, both take the European 20-20-20 strategy into account and are based on the binding EU National Renewable Energy Action Plans. Also the "SAF-B" scenario extrapolates information from market players' present investments perspectives in a bottom-up approach.[12]

The European 20-20-20 objectives are the following:

- Power demand evolution influenced by the present economic crisis, strong energy efficiency measures, and by the switch by end-uses from fossil fuel to electricity (heat pumps, electric vehicles) and the development of electronic devices
- Renewable energies continue to grow, mostly wind and photovoltaic, providing by 2020 38% of the electricity demand in Scenario EU 2020.
- Depending on the share of gas and coal-fired units in the mix in the coming ten years, CO_2 emissions of the power sector also decline from 26% to 57% in Scenario EU 2020.

ENTSO-E assumes 220 GW extra Wind and Solar Energy Capacity by 2022 (ten years after the report was published in 2012) and acknowledge that "80% of the identified 100 bottlenecks are related to the direct or indirect integration of renewable energy sources (RES)" and is comparable to the assumption of our Reference Scenario 2030.

In its report, ENTSO-E quotes a figure of €104 billion to implement all the projects, however the overview above totals €57.7 billion using the cost assumptions from this report, which we have done to enable a fair comparison with our scenarios. Our costs are lower because they do not include obtaining land rights and building permissions, which vary strongly from country to country and from project to project.

1.6 installed capacities and demand for this report

This research calculated the installed electricity capacity, and load per country and technology for 2020 and 2030 and split into "Reference" and "Energy [R]evolution" values, corresponding to "business as usual" and "Energy [R]evolution" cases.

Hourly time series for the year 2011 were inputted for:

- The load per country based on ENTSO-E data
- Wind data per node based on wind speeds from the NOAA Climate Prediction Center, converted to "per unit of nominal power of wind turbine" with power curves from the *Tradewind Study* (2009) and then gently non-linearly scaled to get average full load hours for each country [equivalent to adjusting the power curves for future modern turbines]
- Solar insolation data from HelioClim per node for PV feed-in, also gently non-linearly scaled to get average full load hours for each country.

table 1.1: calculation of costs for the ENTSO-E TYNDP

(WITH ESTIMATED COST ASSUMPTION USED FOR ALL CASES IN THIS REPORT)

COUNTRY	LENGTH (KM)	ASSUMED CAPACITY (MVA)	TVAKM	COST (BILLION €)
DC subsea	9,000	2,000	18	19,800
DC underground	1,490	2,000	2.98	3,725
DC OHL	2,100	2,000	4.2	1,680
AC	36,700	1,500	55.05	24,497
AC cable	420	1,500	0.63	788
AC subsea	400	1,500	0.6	660
	Number of converter pairs		TW	
Converters for DC projects	22	2,000	0.044	6,600
Total	**50,110**			**57,750**

source VALUES TAKE FROM SECTION 7.2 OF TYNDP 2012 AT https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/

reference
12 https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/, p.10

Figure 1.5 shows a time series for a node near Frankfurt, Germany for the last quarter of 2011, based on weather data. The yellow line represents the potential production of solar photovoltaic generators based on the amount of sunlight, while the blue line is the potential generation from wind turbines, based on the wind speeds. The black line is the overall demand (= load) for this particular location: The load drops at the weekends; PV generation was lowest in November and December while wind was particularly strong in December.

1.7 optimisation of dispatch to minimise network expansion[9]

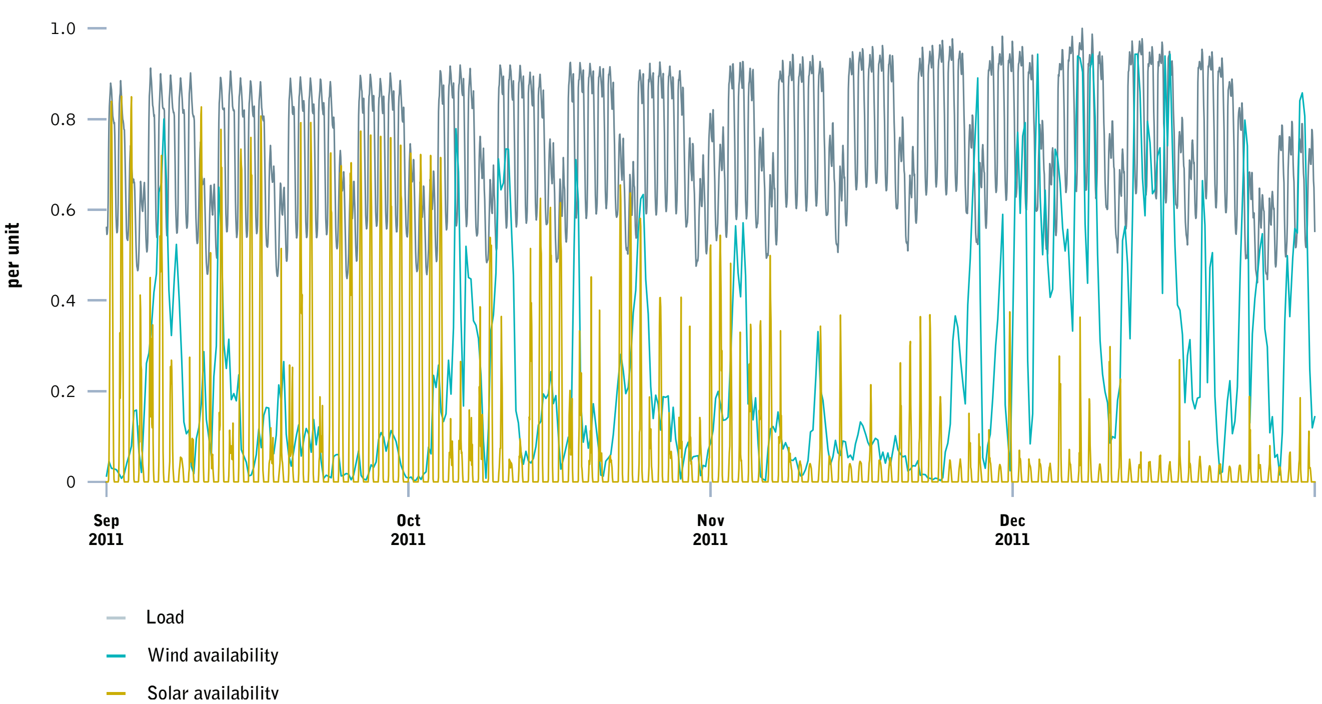
The various inputs (network, capacities, time series, etc.) are then fed into Energynautics' optimal power flow model, developed in-house in the Python computer language. This model has the following features:

- It performs a constrained linear optimisation using the open source GNU Linear Programming Kit (GLPK) to dispatch generation for each point in time
- It performs a linearized load flow for the AC network, respecting thermal limits of network assets (with a 70% safety margin to allow for n-1 security)
- HVDC is controllable
- Its optimisation priority is to minimise necessary network extensions of both HVAC and HVDC lines
- The 380 kV AC lines are built out in discrete 1500 MVA circuits; there is a "buffer" so if the lines are only slightly overloaded (e.g. 5%) then the expansion doesn't take place
- Once network extensions are minimised, it dispatches generation according to availability and price
- PV and wind ("variable renewables") have zero price; other generation assets are given a dummy price to set the merit order depending on the scenario
- The dispatch of some controllable generators (e.g. nuclear) can be made inflexible by limiting the allowed dispatch
- The model will curtail renewables as a last resort if there are network restrictions or restrictions from flexibility of other generators.

1.7.1 dispatch of variable renewables

Variable renewables means those generation technologies whose available power is weather-dependent, i.e. wind onshore, wind offshore and photovoltaic solar power (PV). Their available power for each hour for each node is given by the per node time series described above. Also when feed-in is very high at a node, and is causing stress in the network, the algorithm has the option to curtail the wind or PV down to 60% of its nominal power. 60% was chosen, since this causes very little loss of energy as a fraction of the available energy over the year (less than 5%/a). Curtailment is associated with a cost if the generation is replaced by gas power plants.

figure 1.5: DE23 per unit time series for load, wind and solar



source ENERGYNAUTICS 2014 - POWE[R]2030.

image WIND TURBINES (2 MEGAWATT) IN FRONT OF NUCLEAR POWER PLANT BRUNSBUETTEL, GERMANY.

1.7.2 dispatch of controllables

Controllables are generation technologies for which the dispatch can be freely changed within the limits of their installed capacities on an hourly basis. An availability of 90% is assumed due to down time for maintenance, etc. The merit order of different controllables can be controllable by giving the different generation technologies different prices, which determines where they come in the merit order.

To account for generation technologies (e.g. nuclear or lignite) which cannot ramp up and down quickly or may be restricted in their ability to shut down and then restart again, these are modelled separately.

1.7.3 dispatch of inflexible controllables (e.g. nuclear)

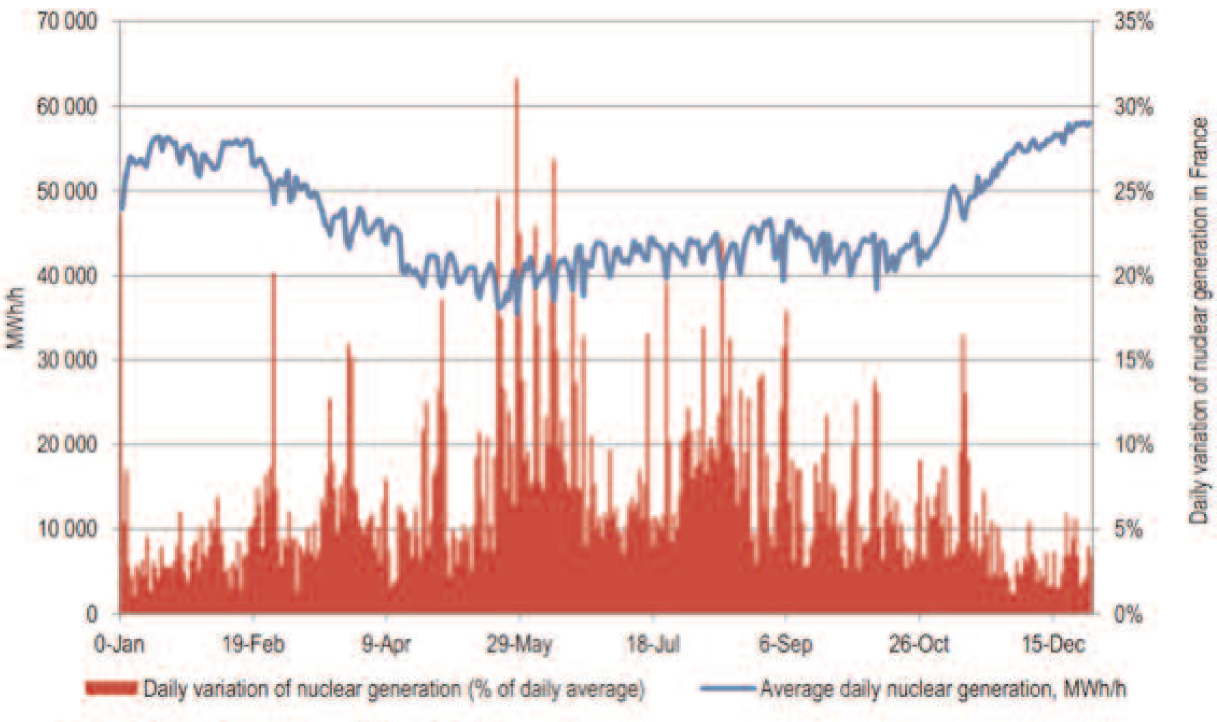
Nuclear and lignite generation is currently operated in a particularly inflexible way and therefore hinders the uptake of renewable energy resources. Most lignite and some nuclear units, like the British AGR and the Soviet/Russian VVER (which is used in the Czech Republic), were only ever envisaged and designed as "baseload units" with emphasis on a long operational lifespan and high efficiency. They have a very limited ability to ramp up and down and cannot stay at low generation levels for very long, because of neutron poisoning in nuclear and water content in the fuel for lignite units. Most large thermal power plants also take days to shut down and restart.

French and German nuclear power plants, equipped mostly with pressurized water reactors (PWR) from the second generation onwards were designed for load following operations and increased flexibility. Load following capability was needed for the high share of nuclear generation that was planned in both countries the 1970s, but only realized in France in the end. There are also a few more modern lignite fired power plants in Germany with ramping capabilities comparable to hard coal units. The operational inflexibility of nuclear and lignite generation in Germany and France is mainly down to economic reasons – nuclear and lignite plants have high fixed and low variable costs, which makes them most profitable with high full load hours. Also, ramping is severely limited during the last 20% of the nuclear fuel cycle in the CP class of reactors, which make up almost 50% of French nuclear generation.

Standard practice in French NPP operation is to have CP units run mainly as baseload plants or in "shallow load following mode" with slow ramp rates and high minimum output, and assign a few newer units (types P4, P'4, N4) to "special duty" with high ramp rates and partial load operation. This comes down to about 20-30% overall flexibility for French nuclear generation. German boiling water reactors (BWR) and most PWR are generally operated in baseload, some PWR units in the northern parts of Germany are occasionally used in shallow load following mode to level out wind generation.

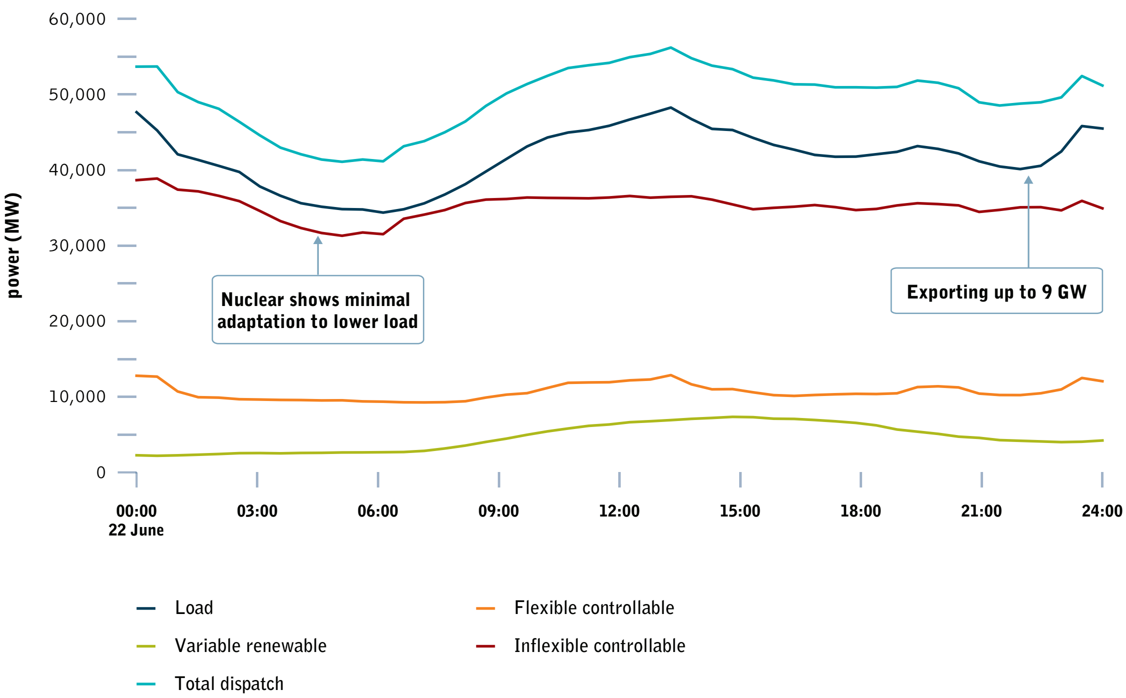
Figure 1.6 shows that shows the daily variation and change in nuclear generation over the year in France from RTE (the French network operator).

figure 1.6: average daily nuclear generation and daily variation of nuclear generation in france in 2010



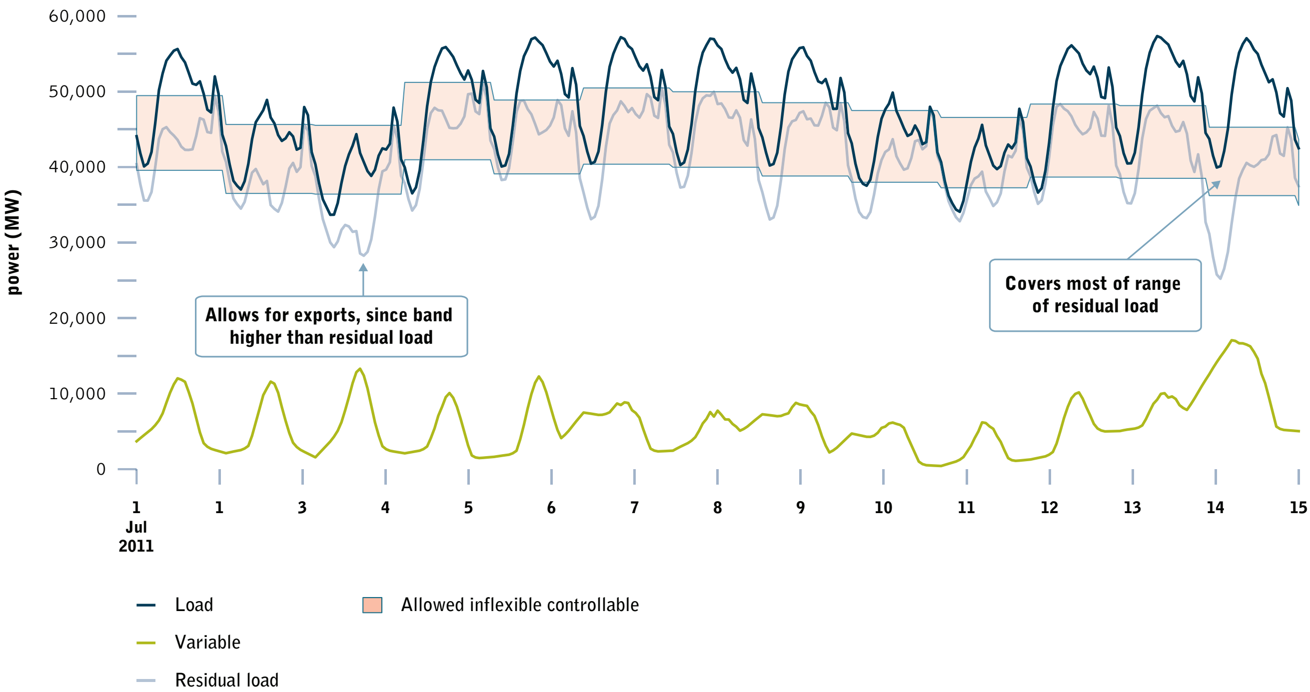
source RTE - RÉSEAU DE TRANSPORT D'ÉLECTRICITÉ (FRANCE), http://clients.rte-france.com/lang/fr/visiteurs/vie/telecharge.jsp

figure 1.7: example of nuclear power generation in france in summer (23.06.2013)



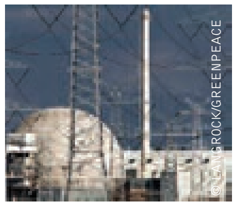
source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 1.8: example limited flexibility band (in pink) for two weeks in france in july



source ENERGYNAUTICS 2014 - POWE[R]2030.

image ELECTRICITY PYLON AND HIGH VOLTAGE LINE IN FRONT OF THE NUCLEAR POWER PLANT UNTERWESER, GERMANY. OPERATED BY E.ON KERNKRAFT GMBH.

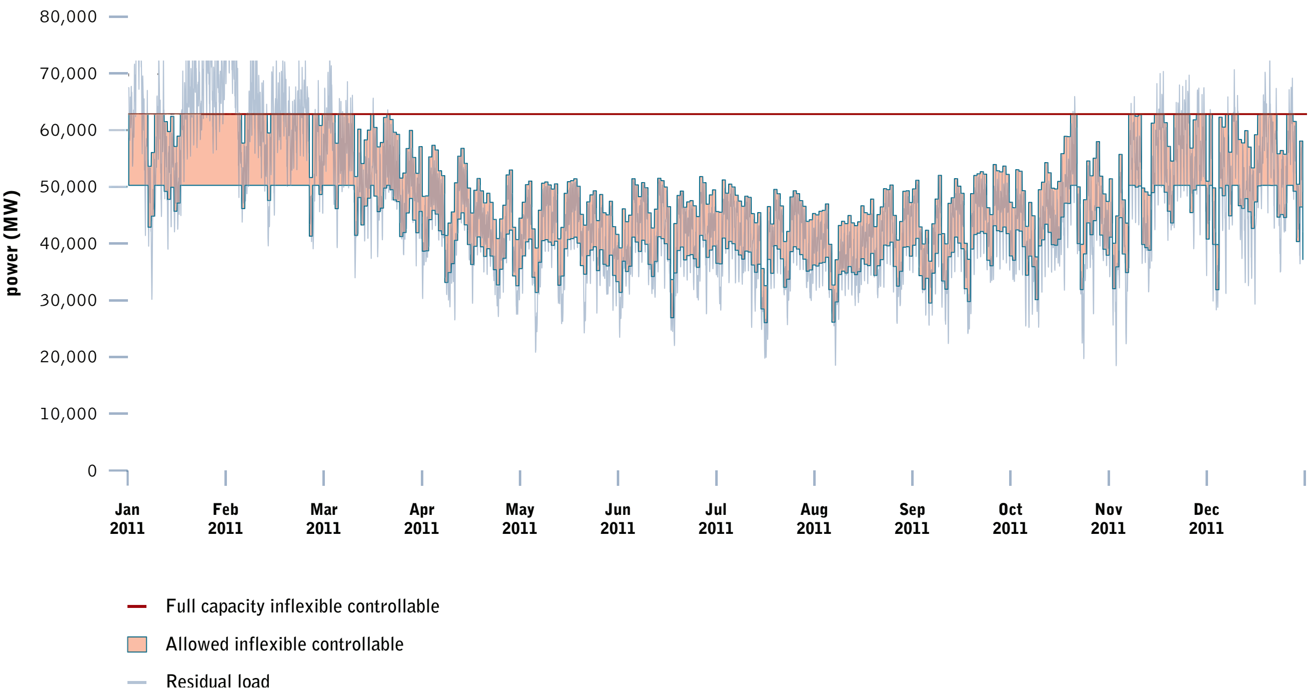


Nuclear power plants have very specific operational features. From these graphs we see that the total nuclear generation in France varies its output relatively little on a daily basis (up to by 20% a day). Seasonal changes can mean that some plants are taken off line entirely in the summer due to lower energy demand. However there is a preference export rather than ramping down nuclear in times of low demand.

To simulate this behavior a model was developed for this report. For each country a daily limit was set on the dispatch of inflexible controllables in advance (like a day-ahead market) according to predicted load and renewable feed-in, then restricted ramping was allowed. The maximum dispatch of inflexible controllables is set by the maximum of the residual load (load minus variable renewables); then they can then ramp down up to 20% from this upper limit, creating a limited allowed band of flexibility.

The dispatch of the infexible controllables can only be within the pink band. Over the year the research reproduces the characteristics and shape of the real graph from RTE.

figure 1.9: france allowed band for inflexible controllables determined from residual load



source ENERGYNAUTICS 2014 - POWE[R]2030.

1.7.4 dispatch of pumped hydro

Pumped hydro acts as storage, so that it can both store power and release it. It is assumed to have an efficiency of 75% for a round trip (storage and then release) and an energy storage capacity equal to 7 hours storing at nominal power.

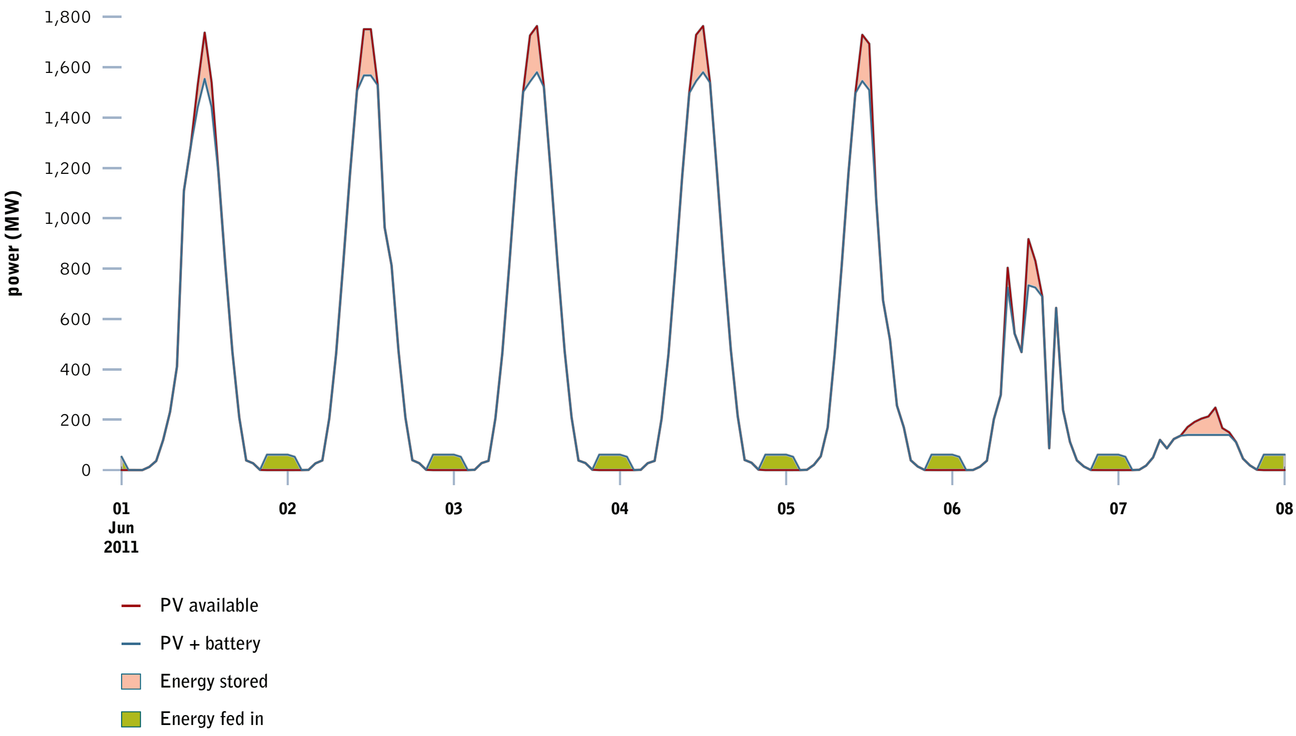
1.7.5 dispatch of PV batteries

In 2030 only will PV batteries be installed at each node with a nominal power corresponding to 10% of the total installed capacity of PV at the node. They have an energy storage capacity corresponding to two hours at nominal power (so a 1 kW battery can store 2 kWh).

They are operated to reduce the midday peak as much as possible and then feed in over six hours in the evening. They operate according to self-consumption, not to help reduce network extensions, although that may be a side-effect.

The below figure is an example dispatch from a German node for a week in June.

figure 1.10: PV peak capping by battery with consumer-orientated operation at node DE02



source ENERGYNAUTICS 2014 - POWE[R]2030.

image NORDEX LATTICE MAST WIND MILLS STANDING INBETWEEN HIGH VOLTAGE LINES IN BORNHEIM, GERMANY.

1.8 assignment of non/flexible/inflexible-controllables to particular generation technologies

The model used for this research delivers the dispatch per model type. This is then sub-divided into the separate generation technologies according to the following rules:

- Variable renewable dispatch is divided between wind and PV according to how much is available for that time point for each technology
- Controllable dispatch is divided between the technologies according to a merit order which prioritises renewables, i.e. hydro, biomass, CSP and geothermal come before gas
- Hydro and CSP generation per country in TWh/a is not allowed to exceed either the yearly generation today (in total around 500 TWh/a for hydro in Europe) or the total generation given in the countries for which there are country reports so that what is physically possible from hydro and CSP is not exceeded

1.8.1 network extension cost assumptions

Table 1.3 shows the different cost assumptions. In addition each line has a terrain factor that adds up to 50% to the line cost according to the difficulty of the terrain (e.g. mountainous terrain in the Alps has a high terrain factor). The model delivers the network extensions as a continuous number (e.g. 253.2 MVA for a line). As it is not possible to build fractions of line, there is a discrete unit size, e.g. 1500 MVA corresponding to a single AC circuit. There is a small buffer, so if the line is only slightly overloaded, it won't get built out.

For existing and planned HVDC lines the division between overhead line and cable is according to current available information; for the Overlay Grid we have assumed it is all overhead line. The high converter costs for DC, which corresponds to the equivalent of around 400 km of overhead line, makes DC generally more expensive. However HVDC can reduce curtailment, which is comparatively more expensive, and reduces thermal losses compared to HVAC.

table 1.3: network extension cost assumptions

TYPE	COST [IN €]	DISCRETE UNIT SIZE
HVAC (Overhead Line)	400 per MVA per km	1,500 MVA
HVAC Reactive power compensation	45 per MVA per km	1,500 MVA
HVDC (Overhead Line)	400 per MW per km	1,000 MW
HVDC (Underground Cable)	1,250 per MW per km	1,000 MW
HVDC (Sea Cable)	1,100 per MW per km	1,000 MW
HVDC VSC Converter Pair	150,000 per MW	1,000 MW

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

table 1.2: assignment of variable renewables and flexible/inflexible controllables to particular generation technologies

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

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

1.8.2 curtailment costs

To compare the costs of curtailment with the network extension costs, energynautics used the same costs assumptions as in the previous study, European Grid Study 2030-2050.[13] We assume for this report that curtailment is priced as the cost to replace generation by gas with an average generation cost of 50€ per Megawatt hour (MWh). If the transmission equipment is in service for 40 years, then the curtailment of 1 TWh/a over that period is:

40 TWh * 50 €/MWh = €20 billion

If there is wind and PV generation of 1500 TWh/a in all of Europe and the curtailment rate would be 2%, i.e. 30 TWh/a, this costs €60 billion, which is comparable with the network expansion costs in the Energy [R]evolution 2030 Scenario.

The curtailment costs for the scenarios are presented in the Section "Comparison between Scenarios".

1.8.3 network expansion in transmission line lengths

In the results the network extensions are given in

- MVA (i.e. the sum of capacity extension in MVA for each line)
- MVAkm (i.e. capacity extension in MVA multiplied with the length in km of each line)
- Length in km (i.e. the length of line affected)
- Transmission Line Length in km (i.e. the length of new transmission lines that would need to be built, assuming 3,000 MVA per transmission line for HVAC (corresponding to two AC circuits) and 6,000 MW per transmission line for HVDC (corresponding to building practice in China).

For example, if a 1,000 km AC line is built out 4,500 MVA (corresponding to three circuits), this is 4,500,000 MVAkm. It affects a length of 1,000 km and corresponds to 2,000 km of transmission lines (one two-circuit transmission line with 3,000 MVA capacity and one single circuit transmission line with 1,500 MVA capacity).

The Transmission Line Length measure works to the benefit of DC, since from a single set of masts you can transport more power (up to 6,000 MW) compare to AC (3,000 MVA for two circuits; some AC transmission lines with four circuits, i.e. 6,000 MVA do exist, but they are rare).

1.8.4 fuel cost savings and co_2 price

The fuel cost savings are calculated on the basis of power plant efficiencies and fuel costs for gas, coal and lignite for the 2020 and 2030 assumptions of the Energy [R]evolution for EU 27 report published in December 2012. According to those assumptions, fuel costs for the year 2030 result to 21.60 € per MWh for gas, 8.30 € per MWh for coal and 2.10 € per MWh for lignite. The CO_2 price under the European Emission Trading System (ETS) has been a subject to rapid and significant changes; therefore a range from 5 Euro per ton (price in February 2014), 20 Euro (price during the first half 2008) up to 40 Euro (Projection from Mantzos, Papandreou and Tasios 2008) has been calculated. Both – fuel cost savings and a price for carbon – are used with curtailment and network expansion costs to calculate system costs for specific power generation scenarios.

1.8.5 power sector scenarios for eu 27

As previously stated the energy scenarios used for this analysis are taken from Greenpeace's Energy Revolution report[14], adjusted to include Croatia which wasn't a member of the EU when the report was published in 2012. The Energy [R]evolution 2012 provides a consistent fundamental pathway for protecting our climate through investment in renewable energy. The development of the electricity supply market under the Energy [R]evolution scenario is characterized by a dynamically growing renewable energy market. This will compensate for the phasing out of nuclear energy and reduce the number of fossil fuel-fired power plants required for grid stabilization.

By 2050, 96% of the electricity produced in EU 27 will come from renewable energy sources. 'New' renewables – mainly wind, solar thermal energy and PV – will contribute 75% of electricity generation. The Energy [R]evolution scenario projects an immediate market development with high annual growth rates achieving a renewable electricity share of 44% already by 2020 and 67% by 2030. The installed capacity of renewables will reach 989 GW in 2030 and 1,480 GW by 2050.

Figure 1.11 (below) shows the comparative evolution of the different renewable technologies in the EU 27 over time. Up to 2020 hydro and wind will remain the main contributors of the growing market share. After 2020, the continuing growth of wind will be complemented by electricity from biomass, photovoltaic and solar thermal (CSP) energy. The Energy [R]evolution scenario will lead to a 40% share of fluctuating power generation sources (photovoltaic, wind and ocean) by 2030. Therefore the expansion of smart grids, demand side management (DSM) and storage capacity from the increased share of electric vehicles is needed for a better grid integration and power generation management.

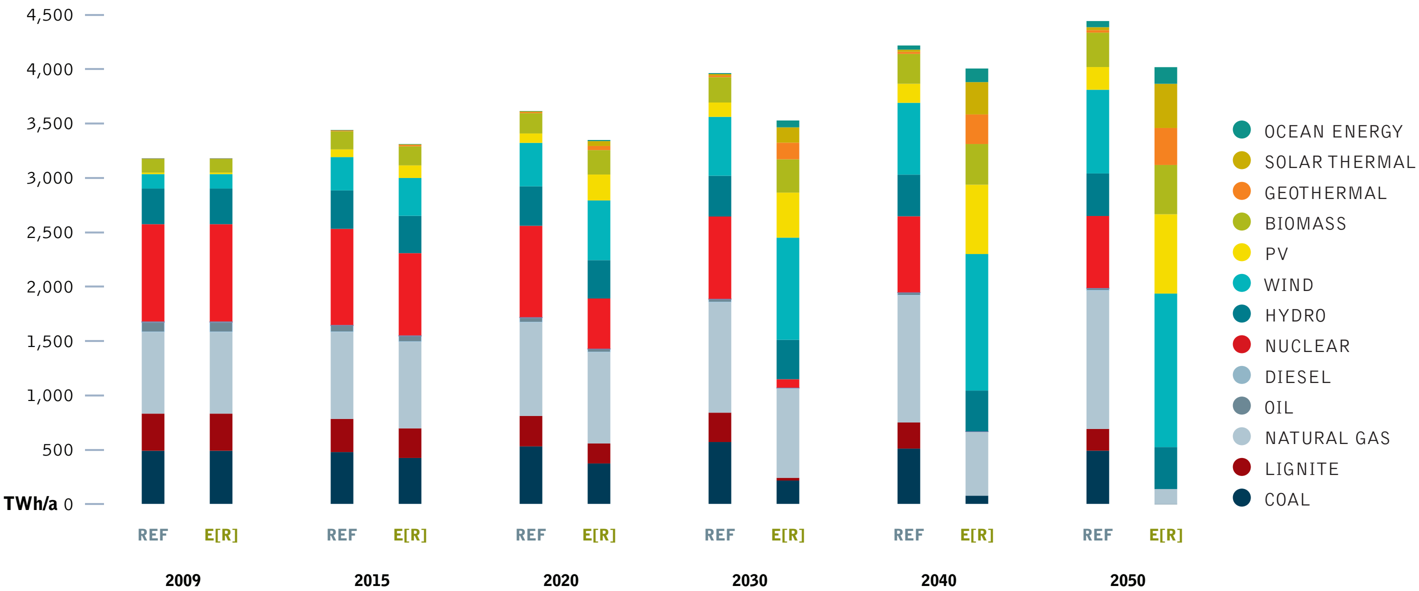
references

13 http://www.energynautics.com/downloads/competences/energynautics_EUROPEAN-GRID-STUDY-2030-2050.pdf

14 www.greenpeace.org/energyrevolution

image AVEDØRE POWER STATION IS A CHP (COMBINED HEAT AND POWER) PLANT IN HAMMERHOLMEN, HVIDOVRE. CHP IS THE PROCESS OF CAPTURING AND THEN UTILISING THE HEAT PRODUCED BY GENERATING ELECTRICITY.

figure 1.11: electricity generation structure under the reference scenario and the energy [r]evolution scenario (INCLUDING ELECTRICITY FOR ELECTROMOBILITY, HEAT PUMPS AND HYDROGEN GENERATION)



source ENERGY [R]EVOLUTION, A SUSTAINABLE EU 27 ENERGY OUTLOOK, GREENPEACE INTERNATIONAL, 2012.

The installed capacities in the Energy [R]evolution EU 27 published in 2012 have been modified for the purposes of this report as during the research phase, due to the needs for the distribution of accumulated capacities in the 30 countries (EU 27 plus Croatia, Switzerland and Norway considered).

table 1.4: installed capacities for reference, conflict and energy [r]evolution case (IN GW)

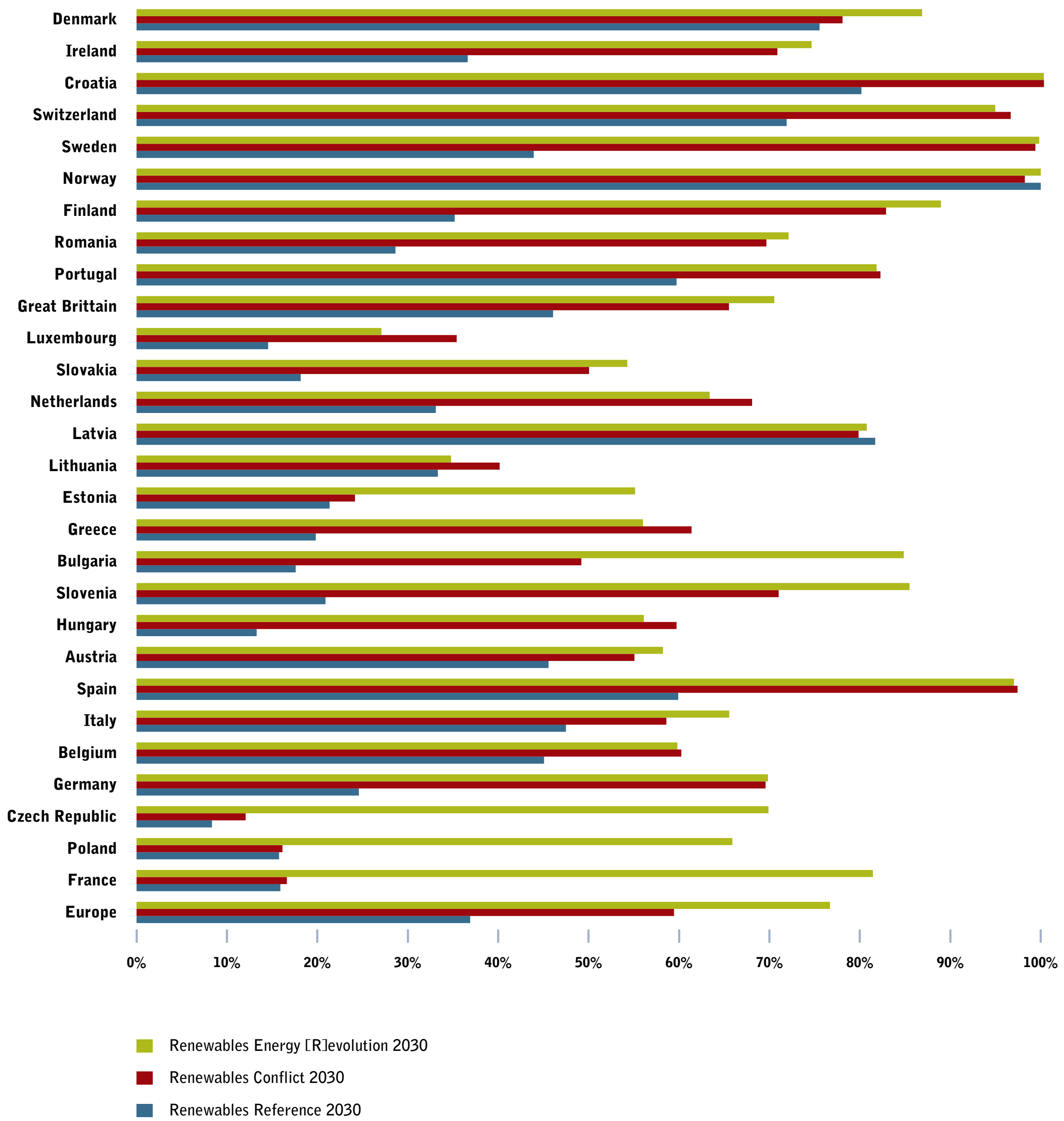
EUROPE	REF 2030	CONFLICT 2030	E[R] 2030
Coal	113,515	49,106	39,123
Lignite	45,004	18,758	15,119
Gas	282,090	230,163	239,363
Oil + Diesel	25,167	7,815	8,732
Nuclear	106,120	75,424	11,668
Renewable Total	**619,865**	**989,714**	**1,169,515**
Wind - Offshore	47,566	111,195	144,811
Wind - Onshore	227,630	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

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

Figure 1.12 shows the resulting renewable energy shares by country. In a few cases the renewable energy share in the conflict case is slightly higher than in the Energy [R]evolution case, this is due to the fact that the optimization process took place for the ER but not for the conflict case. Especially in small countries like Luxembourg high import electricity shares are currently normal, therefore future RE generation will also partly be imported. A regional optimization – independent from national borders – results in some cases in higher RE import shares to avoid a high curtailment and / or high storage or transmission line expansion.

Based on the methodology and assumptions documented in this first chapter, three scenarios with several variations have been calculated.

figure 1.12: renewable electricity shares by country and scenario in 2030



source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

grid modelling results

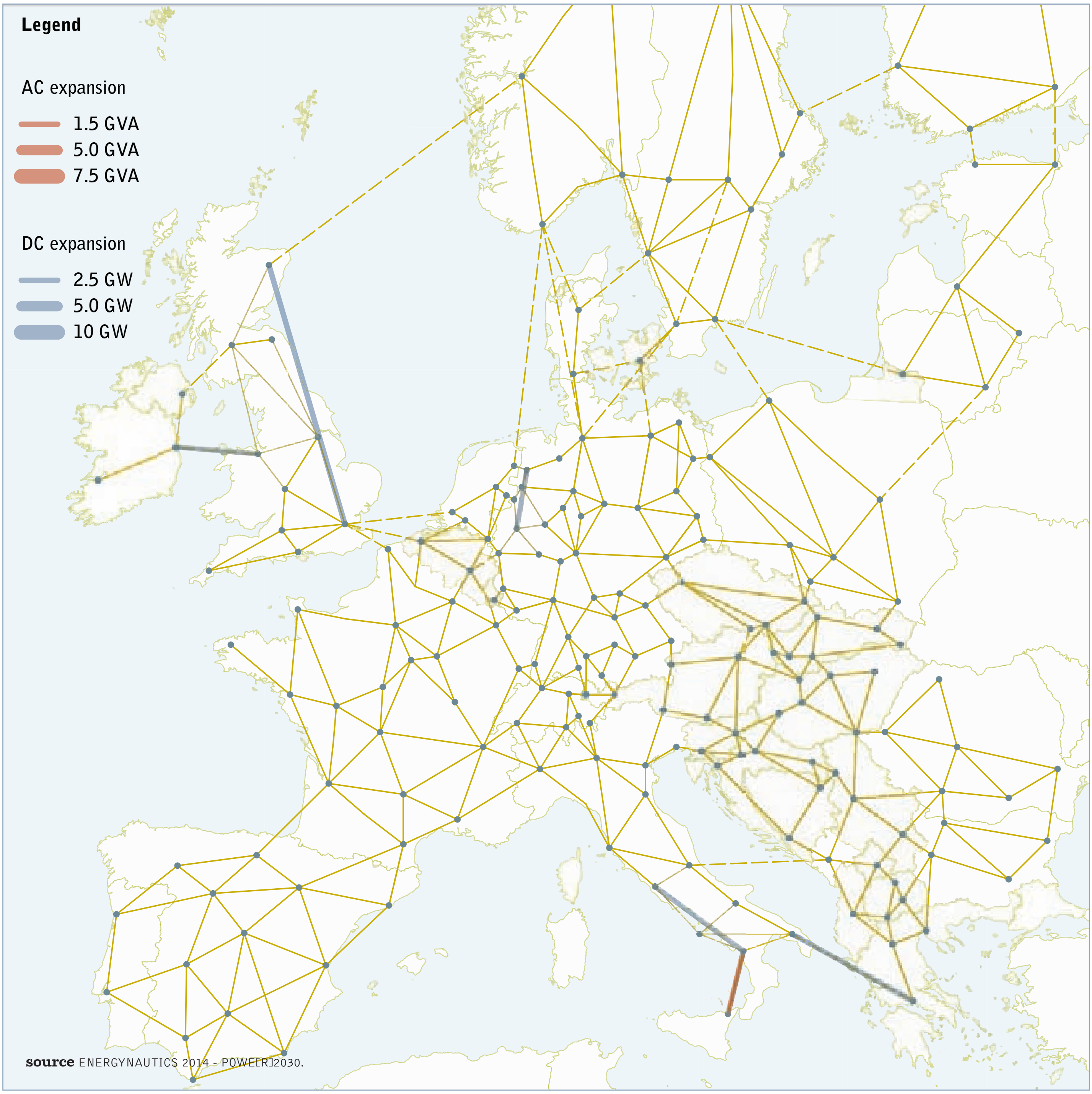
image PHOTOVOLTAIC/SOLAR ENERGY FACILITY AT THE EUREF CAMPUS OF TU (TECHNISCHE UNIVERSITAET) IN BERLIN, GERMANY. THE ENERGY SUPPLY CONCEPT IS BASED ON THE FUNDAMENTAL IDEA OF MAKING ENERGY GENERATION AND CONSUMPTION AS FAR AS POSSIBLE CO_2 NEUTRAL.

As previously stated this report focuses on how the electricity system must be adapted (grids, production mix, storage and demand management) to integrate the high levels of renewable energy production with specific targets for 2020 and 2030, while maintaining a high level of security of supply 24/7. To model this optimization process two scenarios have been calculated - a reference case and a conflict case - which show the impact of unchanged grid policies if European member states follow different energy pathways.

2.1 reference scenario

This scenario is a "business-as-usual" scenario with reference to capacities for all countries, where coal and nuclear have priority

figure 2.1: extension map for reference scenario 2020



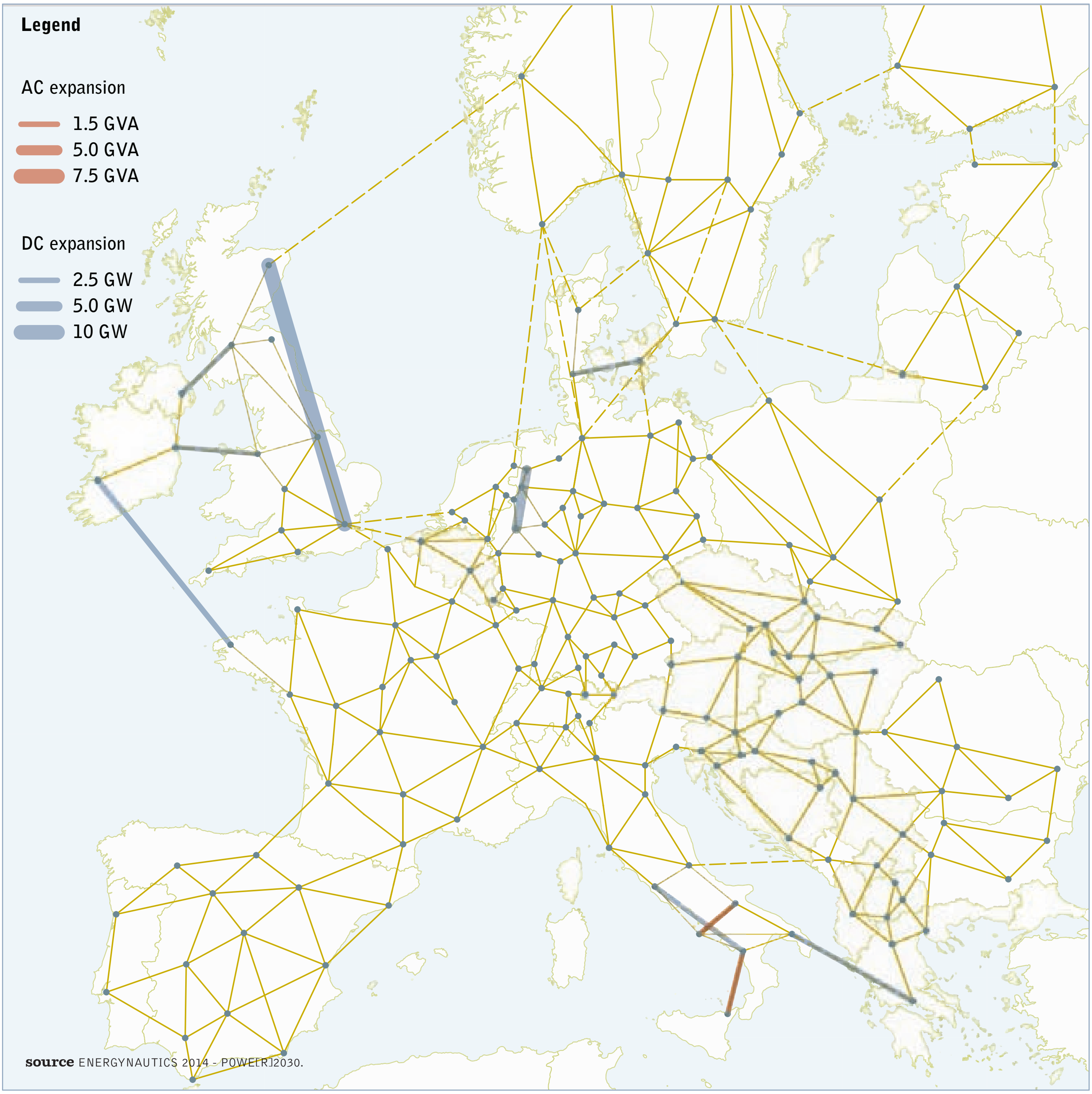
source ENERGYNAUTICS 2014 - POWE[R]2030.

image NUCLEAR POWER PLANT GRAFENRHEINFELD, GERMANY. THE PLANT IS OPERATED BY E.ON.

in merit order. Coal and nuclear is dispatched inflexibly according to residual load, with a 20% flexibility band. Network expansion was determined to reduce curtailment of renewables (network expansions are determined with an initial dummy run in which wind and PV may curtail down to 60% of their nominal power if necessary and controllables are fully flexible). PV batteries were assumed to be in 10% of all PV systems by 2030 and no TYNDP projects were assumed; expansion was determined from today's network.

Extension map for 2020: notable extensions being a Scotland-London HVDC and a North Sea – Ruhr HVDC in Germany. The HVDC between Ireland, England and France were encouraged to reduce curtailment in Ireland, which as an island can only export via HVDC.

figure 2.2: extension map for reference scenario 2030



source ENERGYNAUTICS 2014 - POWE[R]2030.

2.2 inflexible power systems – the reference case

Because of the inflexibility of nuclear, coal and lignite, these power plants can only move within a range of 20% (marked as a pink band in Figure 2.3 on the following page), they cannot reduce when the load sinks further, so instead wind and PV must be curtailed (green area is curtailed energy). In the reference case in 2030, coal and lignite are still providing the majority of the demand in Europe while wind and solar power plants have to reduce output to a large extend as the entire system is inflexible. High shares of inflexible generation capacity have a direct negative impact on renewable energy expansion as this leads to "system conflicts".

2.3 results of the reference scenario

- Very little network expansion (just 23 GVA in total by 2030, at a cost of €8 billion)
- Countries with inflexible coal and nuclear export a lot, with good load factors
- Gas generators have poor load factors (averaging 17% for Europe in 2030) because of prioritisation of nuclear and coal and because of high capacity
- Coverage by renewables is low (37% of load in 2030)
- Curtailment across Europe is high (6.2%) because of inflexibility of coal and nuclear.
- The curtailment in Germany is particularly high (9.8%) as inflexible coal competes with wind and solar generation and causes high economic losses for them

The reference case with its high share of inflexible coal and nuclear power generation forces gas power plants out of the market and keeps flexible renewable power generation on low market penetrations. A dynamic market growth for new flexible and renewable power generation is economically impossible with a base-load driven power plant fleet. The power market is locked in an inflexible system which does not allow any structural changes or forces further network expansion to by-pass system conflicts.

table 2.1: load coverage and load factors by technology/imports in 2030 under the reference scenario

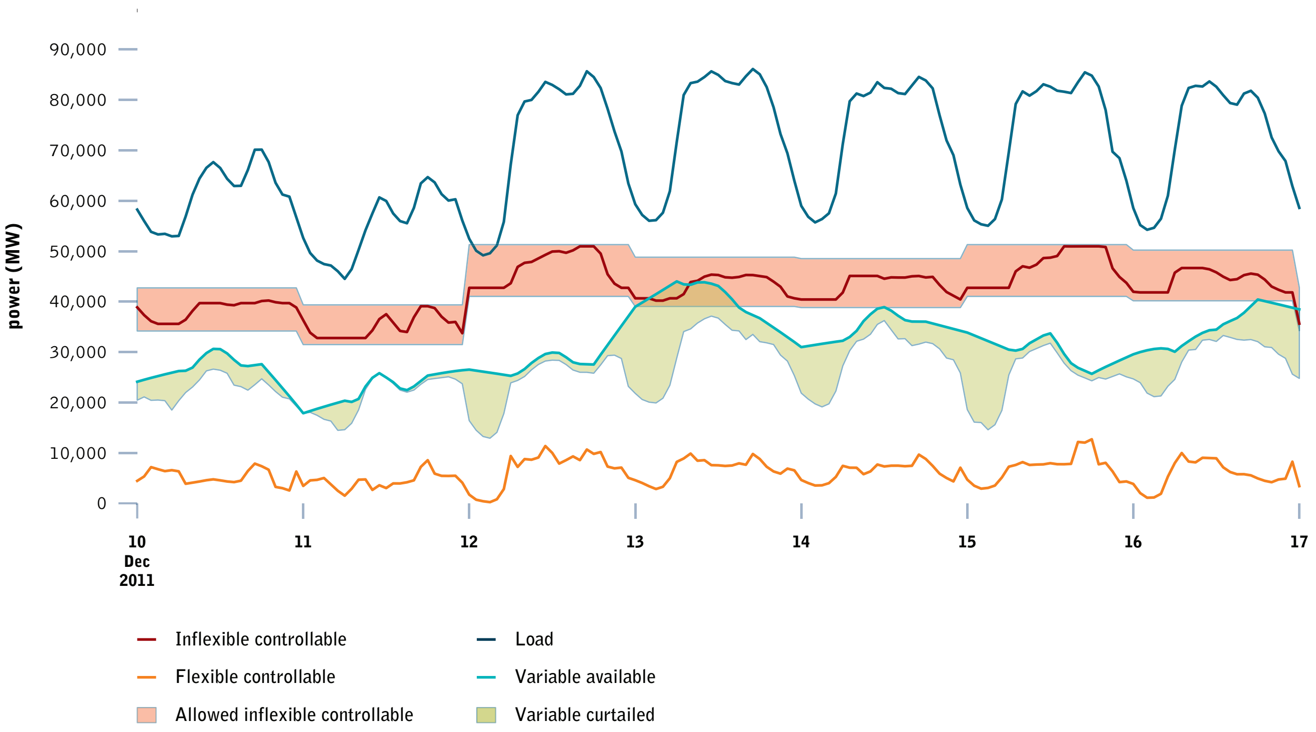
(% COVERAGE OF LOAD)

COUNTRY	IMPORTS	INFLEXIBLE CONTROLLABLE	FLEXIBLE CONTROLLABLE	RENEWABLE	NON-RENEWABLE	GAS LOAD FACTOR	VARIABLE CURTAILMENT
Europe	0.0	51.3	24.8	36.9	63.1	16.6	6.2
France	-15.6	95.5	6.3	18.4	97.2	9.5	0.7
Poland	-14.1	94.9	2.2	18.0	96.1	3.7	4.3
Czech Republic	-9.7	100.1	3.1	9.1	100.5	4.1	0.5
Germany	-6.1	73.1	9.4	26.1	80.0	8.8	9.8
Belgium	38.4	0.0	42.9	27.8	33.8	46.9	0.0
Italy	9.9	22.9	43.9	42.8	47.3	20.5	1.3
Spain	3.3	13.4	41.6	57.9	38.8	24.9	2.2

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

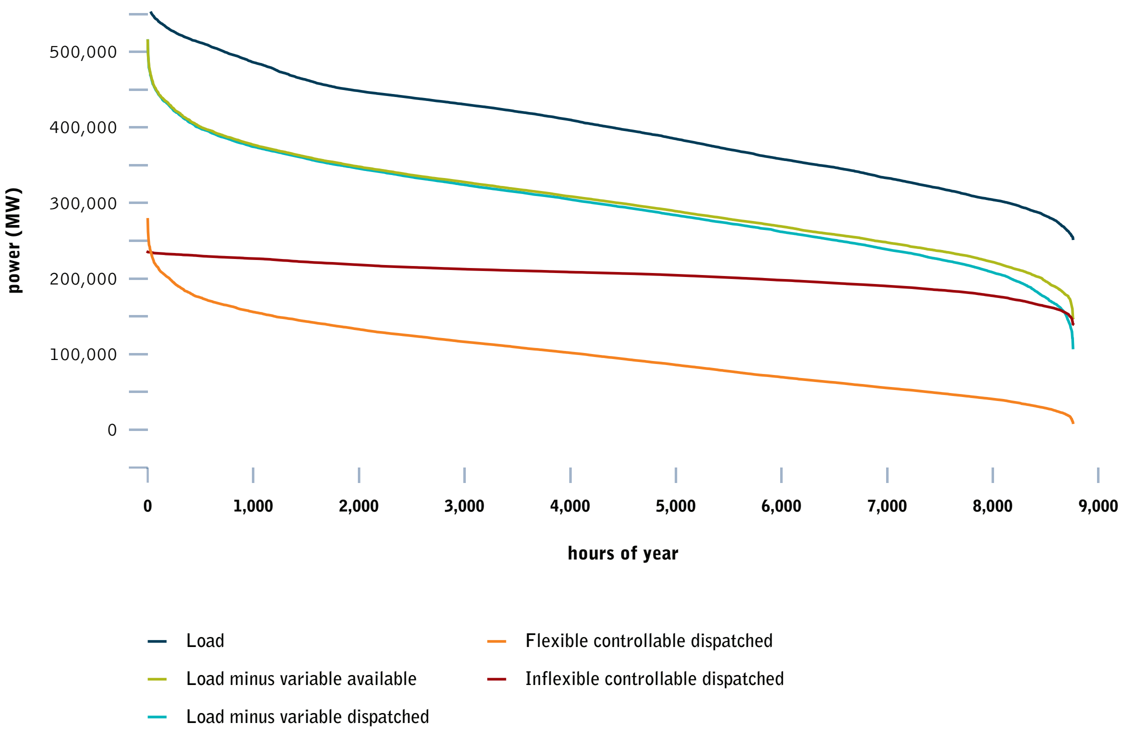
image LA DEHESA, A 50 MW PARABOLIC THROUGH SOLAR THERMAL POWER PLANT WITH MOLTEN SALTS STORAGE. WAS COMPLETED IN FEBRUARY 2011, IT IS LOCATED IN LA GAROVILLA AND IT IS OWNED BY RENOVABLES SAMCA. WITH AN ANNUAL PRODUCTION OF 160 MILLION KWH, LA DEHESA WILL BE ABLE TO COVER THE ELECTRICITY NEEDS OF MORE THAN 45,000 HOMES, PREVENTING THE EMISSION OF 160,000 TONS OF CARBON.

figure 2.3: in germany in windy december you can see the effect of inflexible controllables on renewable curtailment



source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 2.4: (residual) load curves for europe - reference scenario



source ENERGYNAUTICS 2014 - POWE[R]2030.

2.4 conflict scenario

The conflict scenario illustrates what happens if inflexible coal, lignite and nuclear power plants are kept in the system while flexible wind and solar capacities are added across Europe except in France, Poland and Czech Republic which would continue business as usual, by keeping and extending less flexible coal and nuclear power plant fleets. The rest of Europe however would implement high levels of renewables combined with flexible controllable generation.

Coal and nuclear would have priority in merit order, with inflexibly dispatched according to residual load, with a 20% flexibility band. The network expansion would be determined to reduce curtailment of renewables (network expansions are determined with an initial dummy run in which wind and PV may curtail down to 60% of their nominal power if necessary and controllables are fully flexible). PV batteries were assumed to be in 10% of all PV systems by 2030 and no TYNDP projects were assumed; expansion was determined from today's network.

figure 2.5: energy [r]evolution countries versus reference case countries

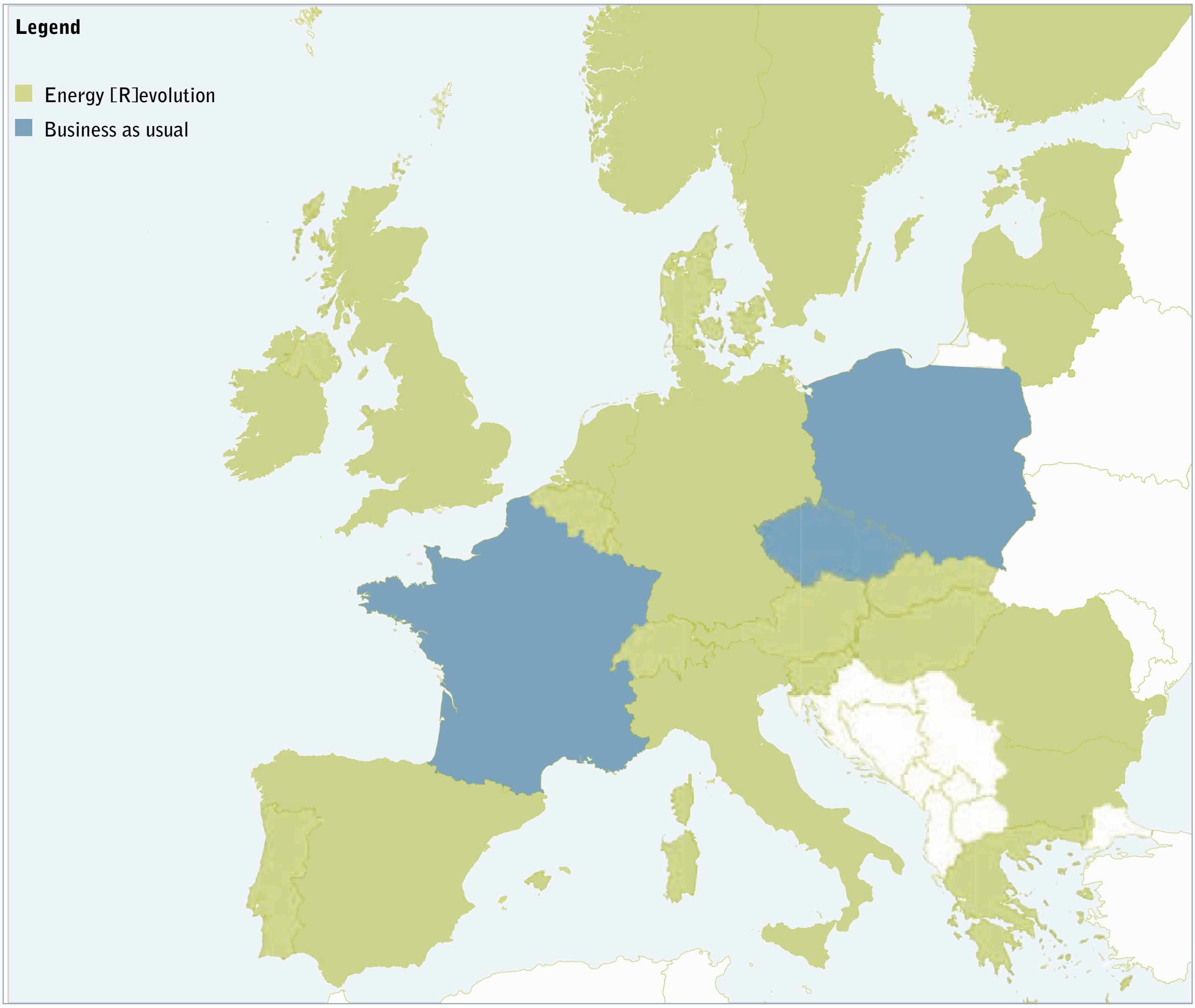


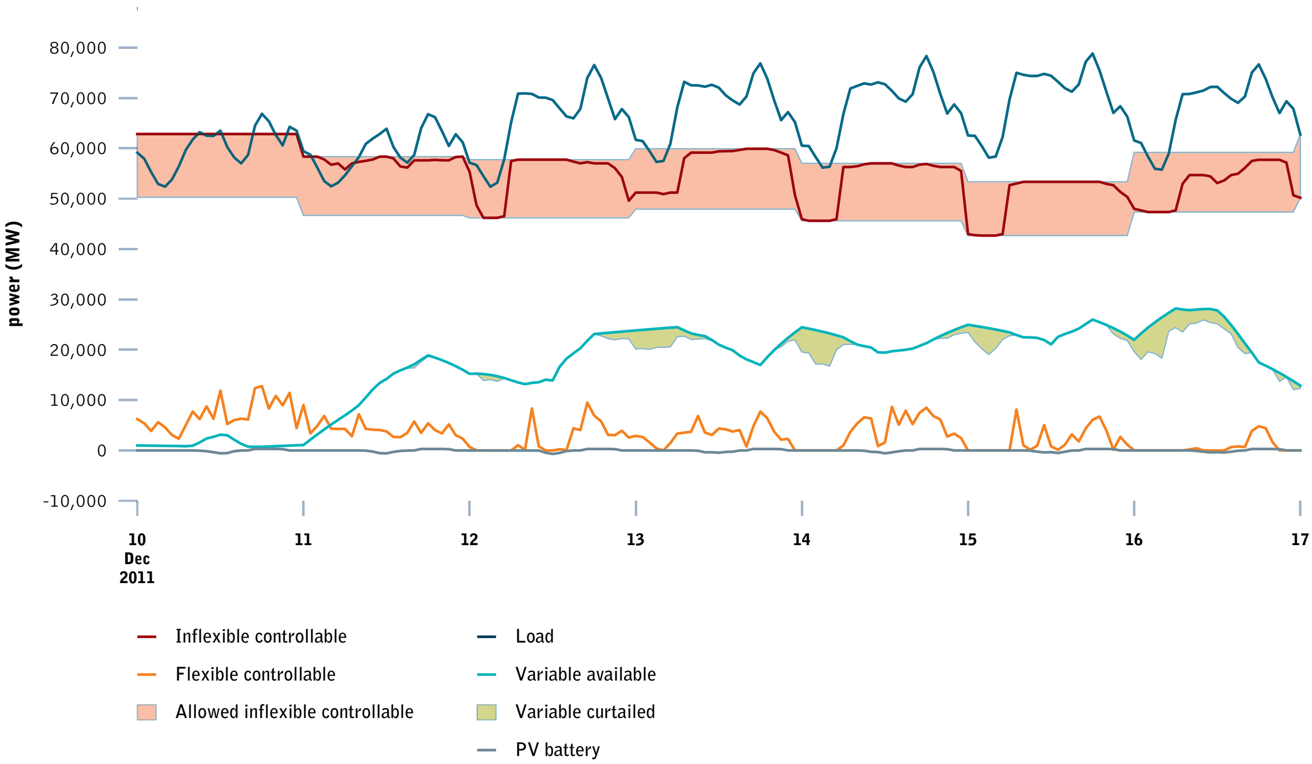
image ELECTRICITY PYLON AT DRAX POWER STATION, A LARGE COAL-FIRED POWER PLANT IN NORTH YORKSHIRE. ITS GENERATING CAPACITY OF 3,960 MEGAWATTS IS THE HIGHEST OF A ANY POWER STATION IN THE UNITED KINGDOM AND EUROPE. BECAUSE OF ITS LARGE SIZE, IT IS ALSO THE UK'S SINGLE LARGEST EMITTER OF CARBON DIOXIDE.

2.5 inflexible power generation and cross border effects

An integrated European power market which develops two very different energy supply concepts – a flexible renewable energy and an inflexible coal and nuclear power based one – in parallel, will have significant problems especially along the borders of high RE and high coal/nuclear penetration. An example of the effects of inflexibility versus flexible renewable curtailment can be seen in the follow figure which shows a situation in France in December.

Because of the inflexibility of coal and nuclear, the "inflexible" controllables dispatch (red) can only dispatch within the allowed flexibility band (pink). The upper bound is set by the daily maximum residual demand; the lower bound is 20% below. As a result, during the night when the load (black) drops, the "inflexible" controllables cannot reduce generation (they hit the bottom of the band) so renewables must curtail instead (green area is curtailment).

figure 2.6: dispatch in france in winter shows conflict between wind and inflexibles in hours of low load



source ENERGYNAUTICS 2014 - POWE[R]2030.

An example of a cross border system conflict is shown in Figure 2.7 by plotting France and Germany together during the summer. There is curtailment of a large PV peak in Germany (yellow area) which would not happen if the inflexible controllables in France (red line) could ramp down further.

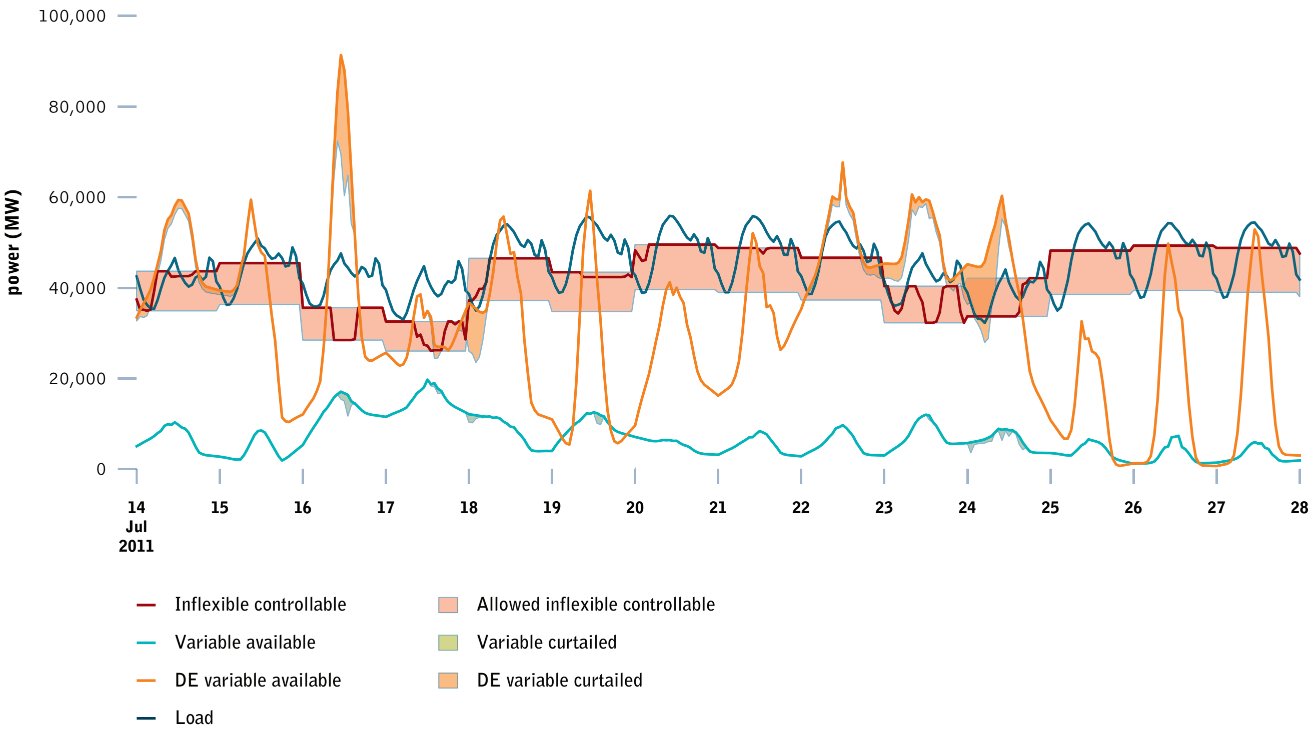
To emphasize the interplay between flexibility and renewable curtailment, several variations were explored in which the range of "inflexible" controllable flexibility was varied:

- Inflexible controllables running flat out at 90% of nominal power the whole year (the 90% reflects downtime for maintenance and refuelling)
- Model simulations with a flexibility band based on the country's daily maximum residual load, but with different band sizes: 0% (dispatch fixed at daily maximum residual demand); 20% (final Conflict Scenario choice); 50% and 100% (corresponding to full flexibility.

2.6 flexible power generation reduces curtailment of renewables

Curtailment can be reduced from 9.5% to 2.9% by increasing flexibility. Comparing the costs of curtailment over 40 years with curtailment costing €50 / MWh it is possible to see that inflexibility is associated with additional costs to RES operators. Even with 20% flexibility it costs €47.5 billion more over 40 years to compensate the curtailment than if the "inflexible" controllables were fully flexible.

figure 2.7: generation in france plotted with variables in Germany shows a system conflict: inflexible generation in france causes curtailment in germany



source ENERGYNAUTICS 2014 - POWE[R]2030.

image GREENPEACE SWITZERLAND'S STAFF PLACES SOLAR CELLS ON THE ROOF OF AN INDUSTRIAL BUILDING IN WOHLEN. ON THE GRID SINCE OCTOBER 2012, THIS IS THE LARGEST PHOTOVOLTAIC PLANT OF GERMAN-SPEAKING SWITZERLAND.

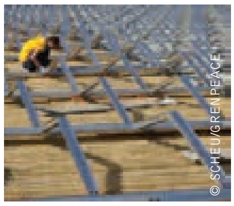
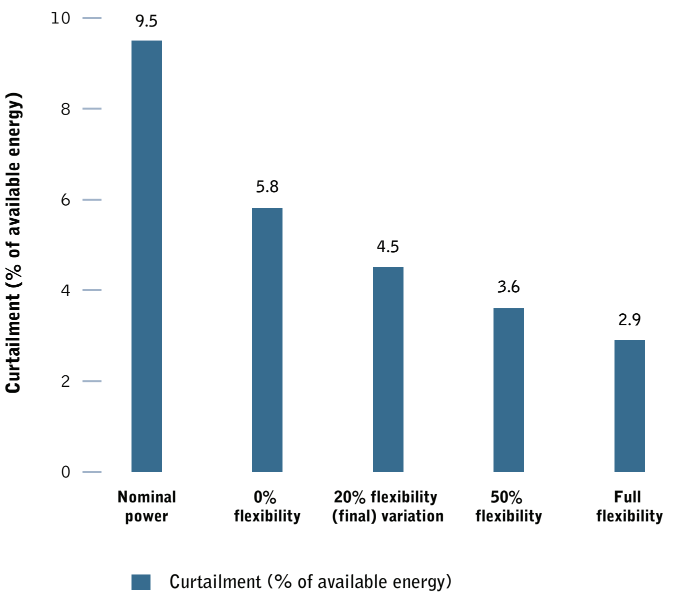
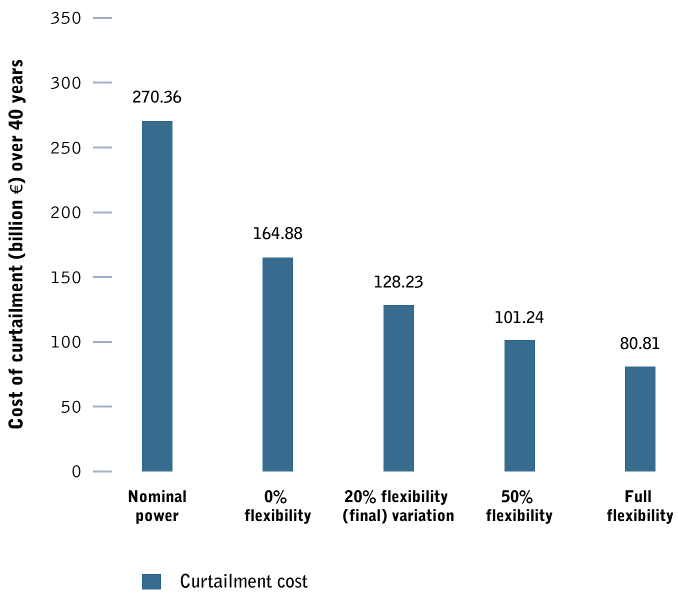


figure 2.8: results of the curtailment as %



source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 2.9: results of the curtailment over 40 years



source ENERGYNAUTICS 2014 - POWE[R]2030.

2.7 results of conflict scenario

- Inflexibility of coal and nuclear in France, Poland and Czech Republic cause additional curtailment of wind and PV and therefore economic damage in Germany
- There is a conflict between inflexible conventional generation and renewables:
  - Either renewables must curtail to accommodate inflexible plant
  - Or nuclear and coal plant must become more flexible, at risk of lower load factors
- The more flexible conventional generation is, the less curtailment there is
- Conflict takes an international dimension if different countries pursue different policies (business as usual versus renewable revolution)
- "Flexible" controllables are squeezed between the "inflexible" controllables and renewables, suffering poor load factors
- Network extension have an important role to play in reducing renewable curtailment; in this conflict scenario, the effect is independent of the inflexibility issue
- Network expansions less than the Energy [R]evolution scenario (54 TVAkm as opposed to 74 TVAkm, mostly in France)

table 2.2: load coverage and load factors by technology/imports in 2030 under the conflict case

(% COVERAGE OF LOAD)

COUNTRY	IMPORTS	VARIABLE DISPATCH	INFLEXIBLE CONTROLLABLE	FLEXIBLE CONTROLLABLE	RENEWABLE	NON-RENEWABLE	GAS LOAD FACTOR	VARIABLE CURTAILMENT
Europe	0.0	42.6	29.3	28.3	59.4	40.6	17.9	4.5
France	-15.2	13.7	94.5	7.1	19.1	96.0	8.8	1.9
Poland	-19.4	17.3	96.7	5.5	19.3	100.1	10.0	3.1
Czech Republic	-20.4	6.3	101.8	12.4	14.5	105.9	32.6	4.8
Germany	10.9	52.0	11.0	26.4	62.0	27.1	24.7	3.8
Belgium	27.7	35.4	0.0	37.0	43.5	28.7	34.8	0.5
Italy	8.8	32.1	23.4	35.9	53.4	37.8	16.1	2.3
Spain	1.3	69.9	0.0	29.1	96.1	2.5	5.4	3.5

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

The conflict scenario shows that inflexible coal and nuclear driven countries cause economic damage due to higher curtailment for neighboring countries which implement high shares of renewables. However Germany can still proceed with future expansion towards a full renewable power supply even if neighboring countries will remain locked-in inflexible nuclear and coal power systems, but it will lead to more investment requirements in grid expansion and storage capacity.

2.8 energy [r]evolution scenario

As opposed to the reference and the conflict case, the Energy [R]evolution scenario has a high level of capacity from renewable energy in all countries. Flexible controllable generation technologies like gas ("flexible") come before inflexible expensive (assuming CO_2 costs) generators like coal and nuclear ("inflexible") in the merit order. All controllable generators are assumed to be retro-fitted for flexibility.

In addition, variable renewables (wind and PV) may be curtailed to 60% of their nominal power in times of high feed-in and network bottle necks, but only when strictly necessary. All controllables are assumed to be available only 90% of the time, due to maintenance; however all load/capacity factors are quoted as percentages of the full nominal power.

Several variations of the "Energy [R]evolution Scenario" for 2030 were tried before the final modeling configuration was chosen as shown in Table 2.3.

The Energy [R]evolution case contains the ideal cost-effective combination of technologies:

- PV batteries are added for 10% of the PV systems in 2030, operating in a "self-consumption-oriented" mode, which reduces sharp in-feed peaks from PV, therefore reducing network expansion
- Simulations are carried out without the TYNDP network extensions already built in, since this was found to significantly reduce the total network expansion and to a lesser extent the costs
- An overlay HVDC super grid was included to facilitate long-distance power transfers. The topology and dimensions of this overlay grid were optimised to reduce the total costs
- In contrast to the scenario "Today + Overlay + PV", the "More HVDC" variation was run with a setting to encourage HVDC over HVAC expansions, since this was found to reduce total network expansions and to reduce total system costs because it resulted in less curtailment of variable renewables
- In the final variation, PV and wind capacities were increased in Belgium and Czech Republic as well as gas in Belgium to increase self-sufficiency in these nations. In addition HVDC connections to Ireland were forced to reduce curtailment there

table 2.3: energy [r]evolution model configuration

(?)

SCENARIO	USE PV BATTERIES	START WITH TYNDP EXTENSIONS	ALLOW HVDC OVERLAY NETWORK	ENCOURAGE HVDC OVER HVAC	MORE RENEWABLES IN BE AND CZ
Energy [R]evolution basic		Yes			
With PV battery	Yes	Yes			
Today + Overlay + PV	Yes		Yes		
More HVDC	Yes		Yes	Yes	
Energy [R]evolution final	Yes		Yes	Yes	Yes

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

image WIND TURBINES IN A WIND PARK NEAR ALTENTREPTOW IN MECKLENBURG-VORPOMMERN, GERMANY.

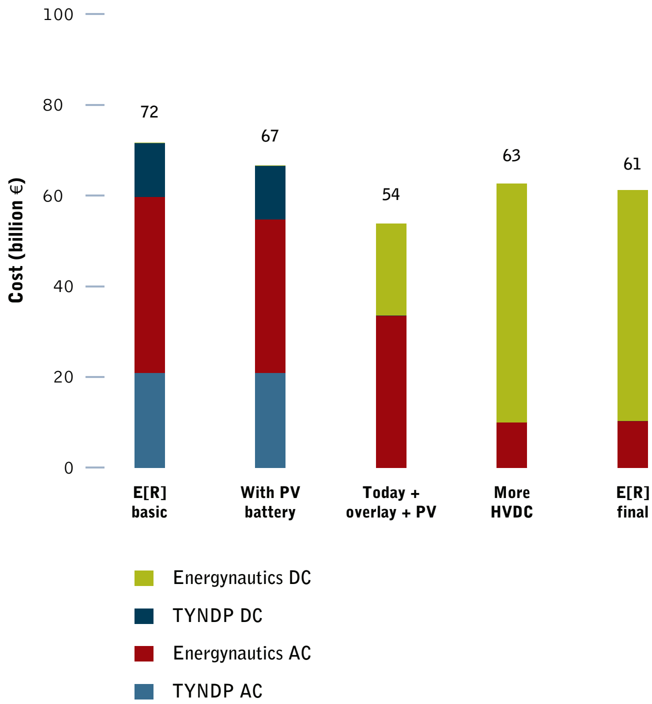
2.9 network expansions and costs for all variations of energy [r]evolution scenario 2030

In Figure 2.9, the extensions are split up into AC and DC and distinguish between extensions outlined in the TYNDP and extensions determined by energynautics during the optimization.

The costs shown in Figure 2.10 do not take into account lower thermal losses in DC compared to AC. There are also lower planning and permission costs for DC because of lower need for transmission line length and cost savings due to reduced curtailment.

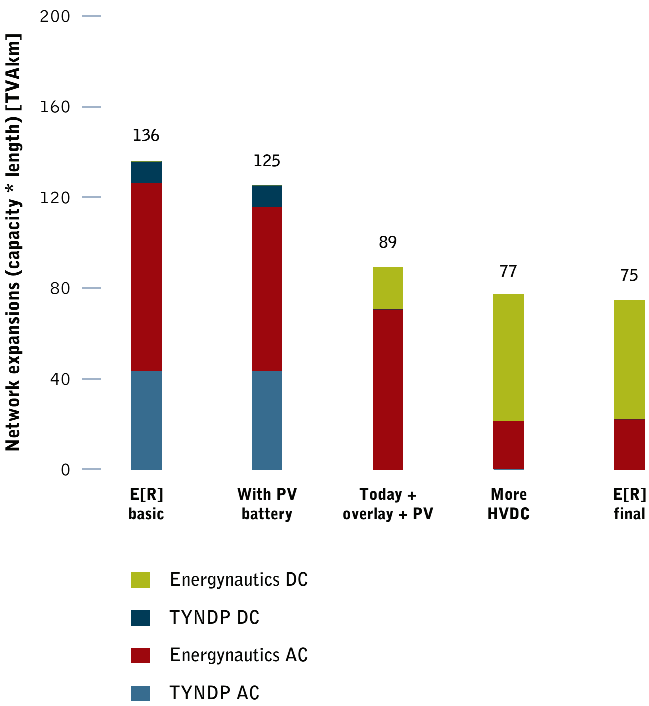
Comparing the length of transmission lines needed for each variation, the Energy [R]evolution final scenario is the most effective. As the HVDC can transport more power for a given transmission line, HVDC has been chosen as the best option.

figure 2.11: costs of network extensions



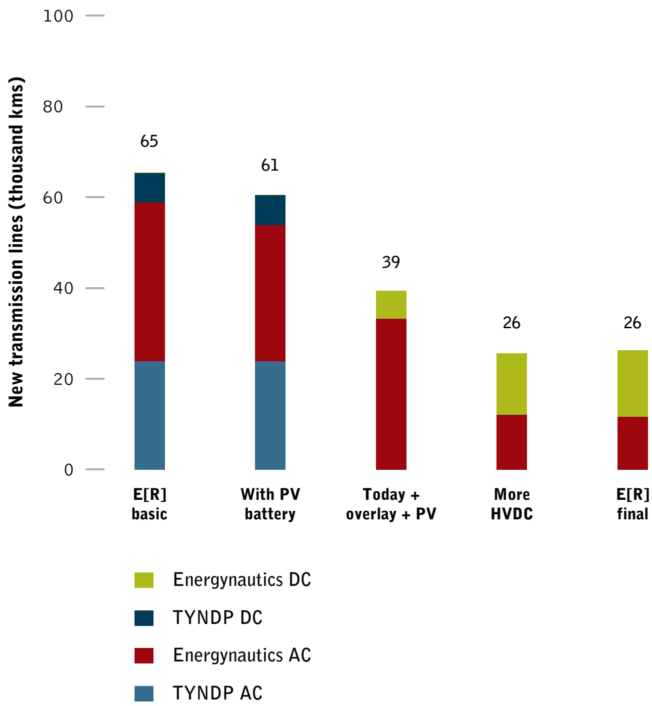
source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 2.10: network expansions and costs for all variations of energy [r]evolution scenario 2030



source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 2.12: split of new transmission lines



source ENERGYNAUTICS 2014 - POWE[R]2030.

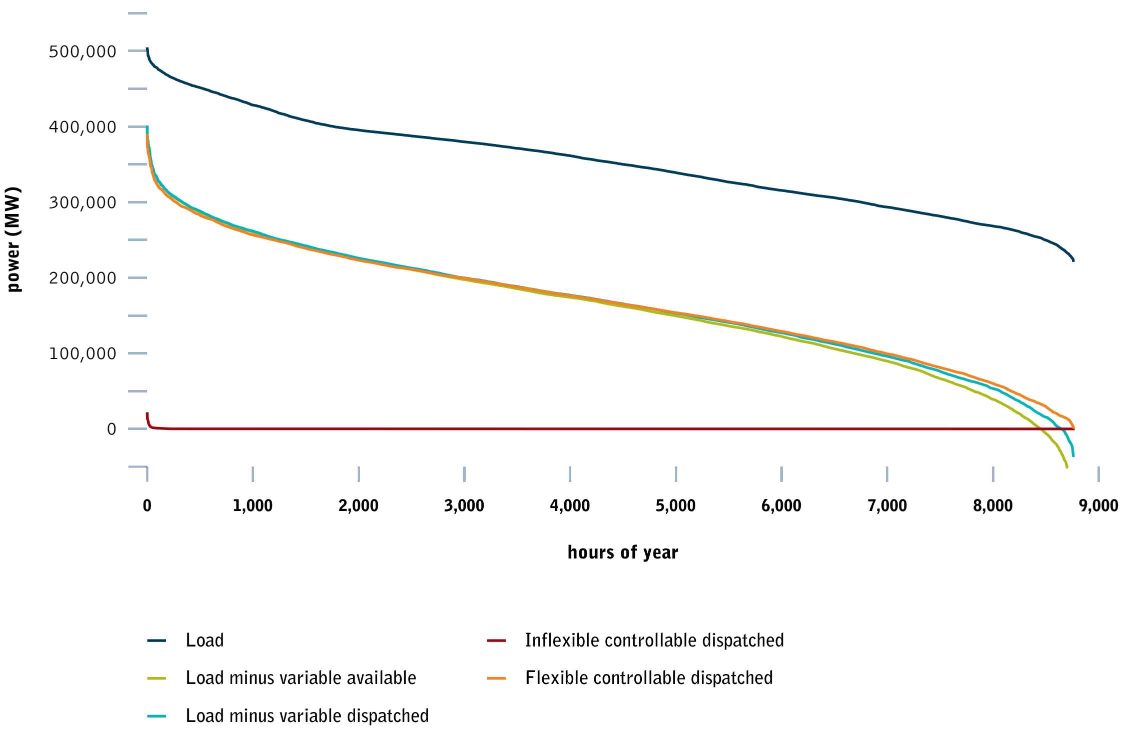
2.10 detailed analysis of the energy [r]evolution scenario 2030

Under the Energy [R]evolution scenario, Europe as a whole covers 53% of its load with wind and PV. Including hydro, biomass, geothermal and CSP – which are "renewable controllables" – the total load coverage by renewables increased to 77% by 2030 across Europe. Compared to the Reference and Conflict cases, France and Poland are covering a lot of their load by variable renewables under this scenario. Overall the import/export balances over the year are more even than in the Reference of Conflict Scenarios, Germany also imports much less than in the Conflict Scenario.

Renewable power supply in all European countries increases with high growth rates and even countries like France and Poland which currently rely on over 70% coal and nuclear power achieve shares of over 50% renewables by 2030. France, Czech Republic, Poland and Spain remain exporters of electricity. Spain will achieve a full renewable electricity supply with a minor need for gas power plant back-up while some gas power plants in France and Czech Republic operate will high capacity factors in 2030. Curtailment of wind and solar power plants are kept to minimum.

The figure below shows the extent to which inflexible controllables are pushed out and flexible controllables are pretty much identical with the residual load. Thus, in the Energy [R]evolution scenario there is no space for any base-load power plants by 2030 anymore.

figure 2.13: (residual) load curves for europe - energy [r]evolution scenario



source ENERGYNAUTICS 2014 - POWE[R]2030.

image WAVE MACHINE PROTOTYPE DEVELOPED BY DONG ENERGY A/S AND WAVE STAR A/S. COMBINING WIND ENERGY AND WAVE POWER.

Results:

- PV batteries (with a nominal power 10% of installed PV capacity) have reduced the network extensions by around 10%, by capping PV peaks
- By starting with today's network instead of the TYNDP and using an optimised overlay HVDC grid, the total network extensions can be reduced by a further 40%
- By encouraging HVDC expansions over HVAC expansions in the Energy [R]evolution scenario the total network extensions have been further reduced by 19%
- The Energy [R]evolution scenario – with its focus on direct current transmission corridors – needs fewer lines because the power is transferred directly from one region to another and stops electricity from spreading out in the neighbouring network ("loop flows") which causes further stress of the AC network and requires more expansion
- As a side effect of the HVAC overlay-network, there is also lower curtailment, which has a big impact on the total system price. HVDC has lower thermal losses and no need for reactive power compensation along the line.

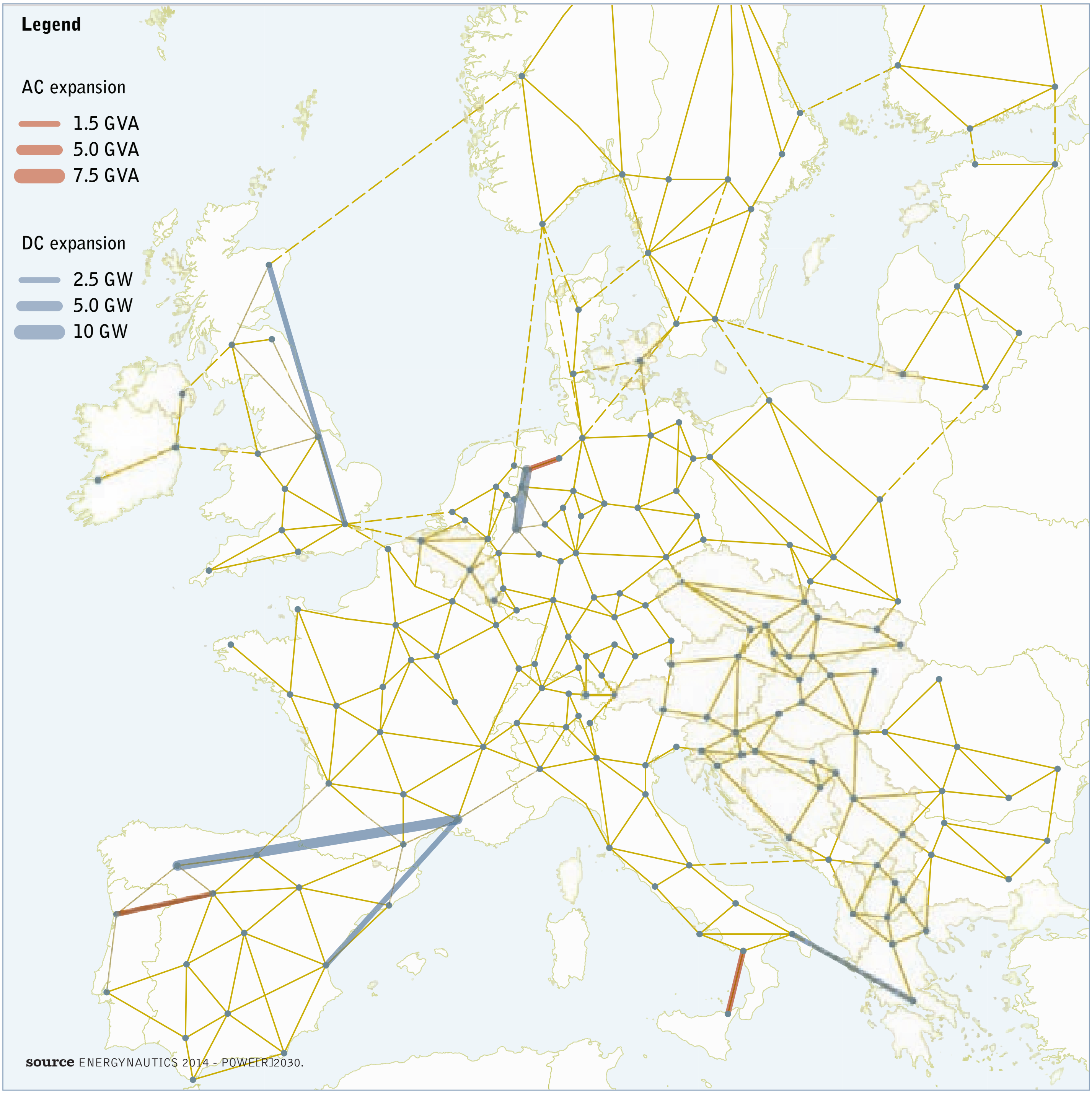
table 2.4: load coverage and load factors by technology/imports in 2030 under the energy [r]evolution scenario

(% COVERAGE OF LOAD)

COUNTRY	IMPORTS	VARIABLE DISPATCH	FLEXIBLE CONTROLLABLE	RENEWABLE	NON-RENEWABLE	GAS LOAD FACTOR	VARIABLE CURTAILMENT
Europe	0.0	52.9	47.3	76.7	23.3	34.1	2.8
France	-3.3	60.6	42.9	84.2	19.2	84.8	1.4
Poland	-14.7	57.4	57.3	75.6	39.1	58.7	3.7
Czech Republic	7.2	30.8	62.2	64.9	27.9	79.4	1.2
Germany	6.2	52.7	41.4	65.5	28.3	43.1	2.4
Belgium	9.0	47.2	44.0	54.4	36.6	35.5	0.9
Italy	12.6	32.6	55.0	57.3	30.1	33.4	0.7
Spain	-9.3	71.0	38.7	106.1	3.2	7.0	2.0

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

figure 2.14: extension map for energy [r]evolution scenario 2020

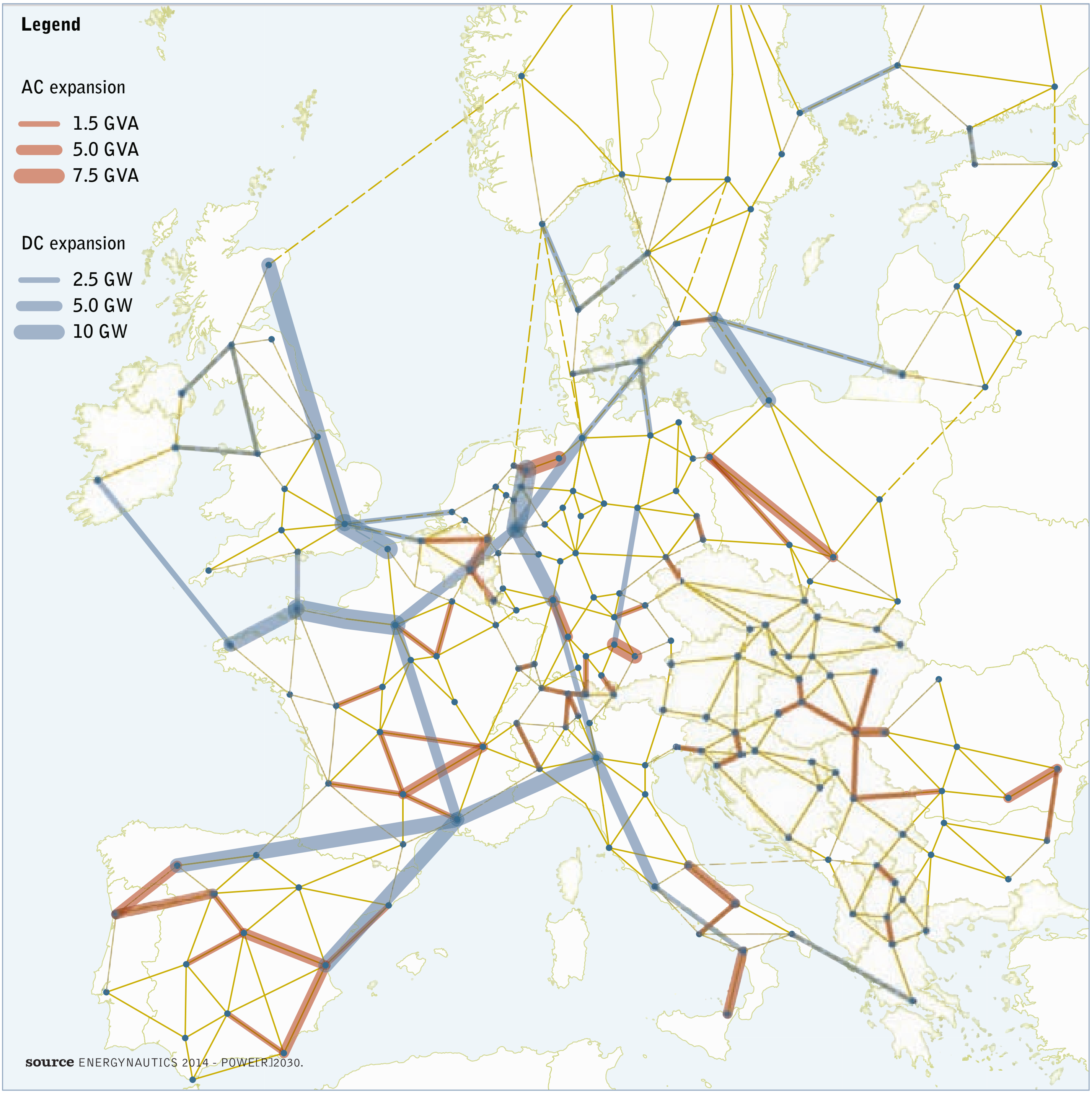


In Figure 2.12 new power corridors includes:

1. Germany's North Sea offshore wind to the Ruhr and then to southern Germany
2. Spain to France to export Spain and Portugal's large wind and PV plants
3. Scotland to Southern England for wind
4. France's Atlantic coast to Paris for wind
5. Through Italy

image CONSTRUCTION OF SIEMENS WIND POWER TURBINE (SWT 6.0 154). WORLD LARGEST ROTOR BLADE (75 METER).

figure 2.15: extension map for energy [r]evolution scenario 2030



source ENERGYNAUTICS 2014 - POWE[R]2030.

2.11 results of the energy [r]evolution scenario by country

There are large regional differences in Europe's power supply and therefore electricity grid systems. Power grids have been expanded according to the countries geographical demand centers and – mostly centralized – power plants. Today Norway covers almost 100% of its electrical load with hydro power plants, France depends to over 75% on nuclear, and Poland's power supply is based to over 90% on coal power plants. Germany's power supply structure is roughly equal to Europe's average technology mix. Thus the regional results of the Energy [R]evolution grid concept vary significantly from country to country. This section provides a summary of the national results and highlights key aspects.

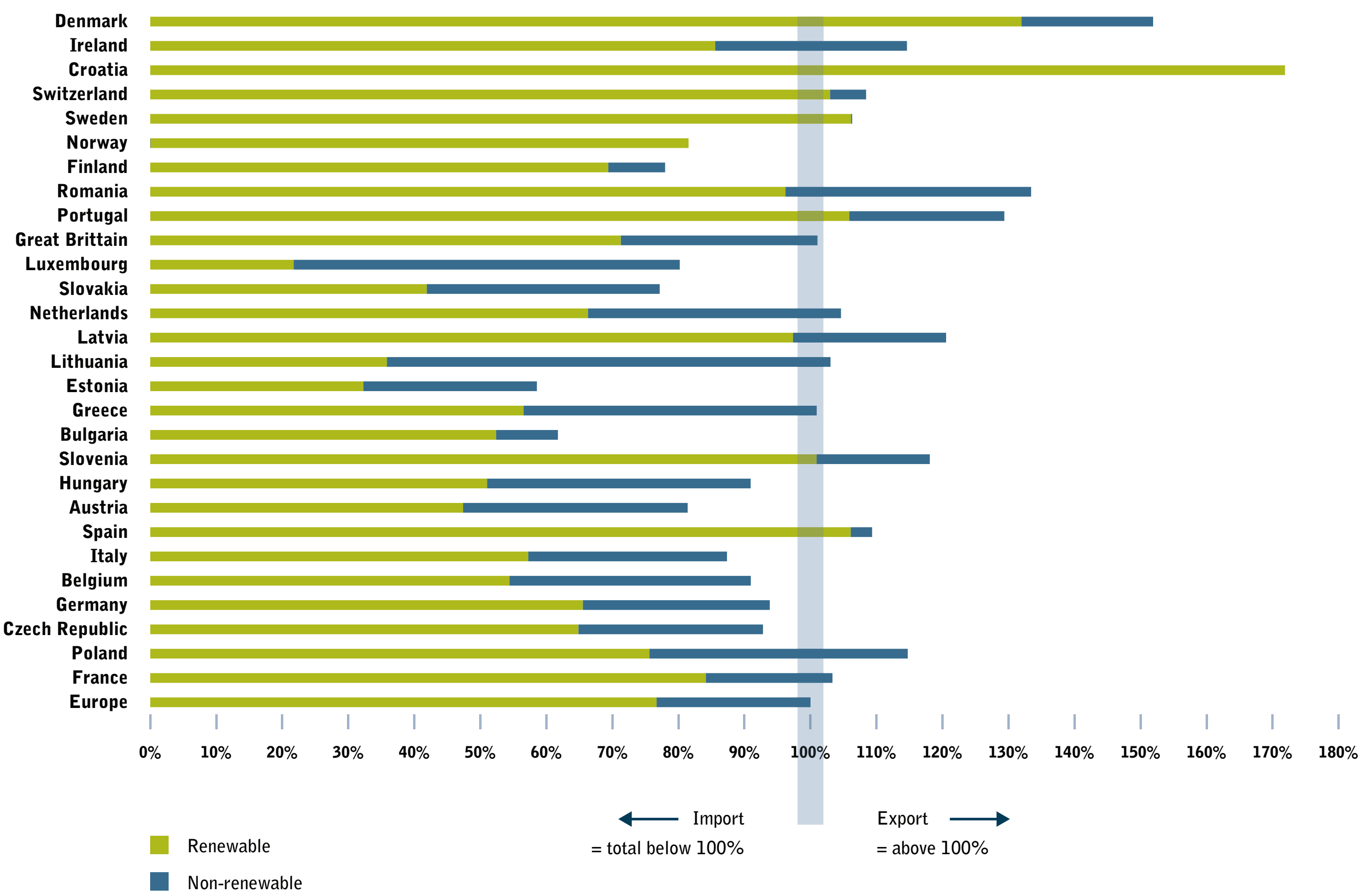
2.11.1 energy [r]evolution load coverage by country for 2030

The load coverage describes the share of renewables and non-renewables which cover the power demand of a country year around. Under the Energy [R]evolution case 77% of the overall European load coverage are coming from renewable energy. Therefore high load coverage from renewables lead to a high security of supply and low fuel costs.

Figure 2.13 shows the overall load coverage and the net imports/exports over the year for each country in 2030 under the Energy [R]evolution scenario.

- On average Europe gets 77% of the total load demand from renewable power plants
- Security of supply increases significantly as RE capacity uses local energy sources
- Only two countries get less than 70% of their load from within the country
- There are 14 countries which have a surplus not only in generated electricity but also in load supply e.g. France, Poland

figure 2.16: load coverage of the energy [r]evolution scenario by country for 2030

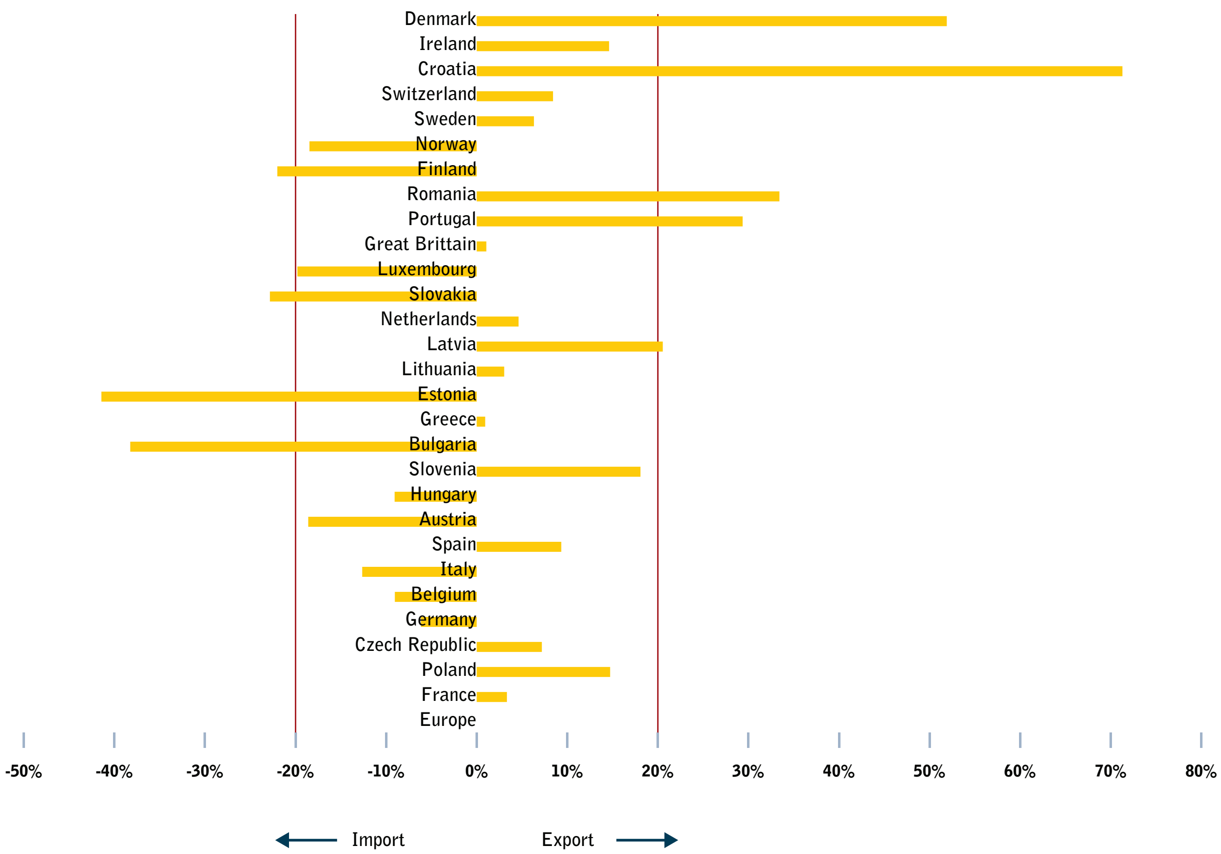


source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

image THE MOCHOVCE NUCLEAR POWER PLANT IN SLOVAKIA.

The import / export balance under the Energy [R]evolution case is shown in figure 2.14. Only two countries – Estonia and Bulgaria have less than 75% local generation, while eight countries – Denmark, Ireland, Croatia, Romania, Portugal, Latvia, Slovenia and Poland - export more than 10% compared to the national demand.

figure 2.17: import and export balance under the energy [r]evolution scenario by country for 2030



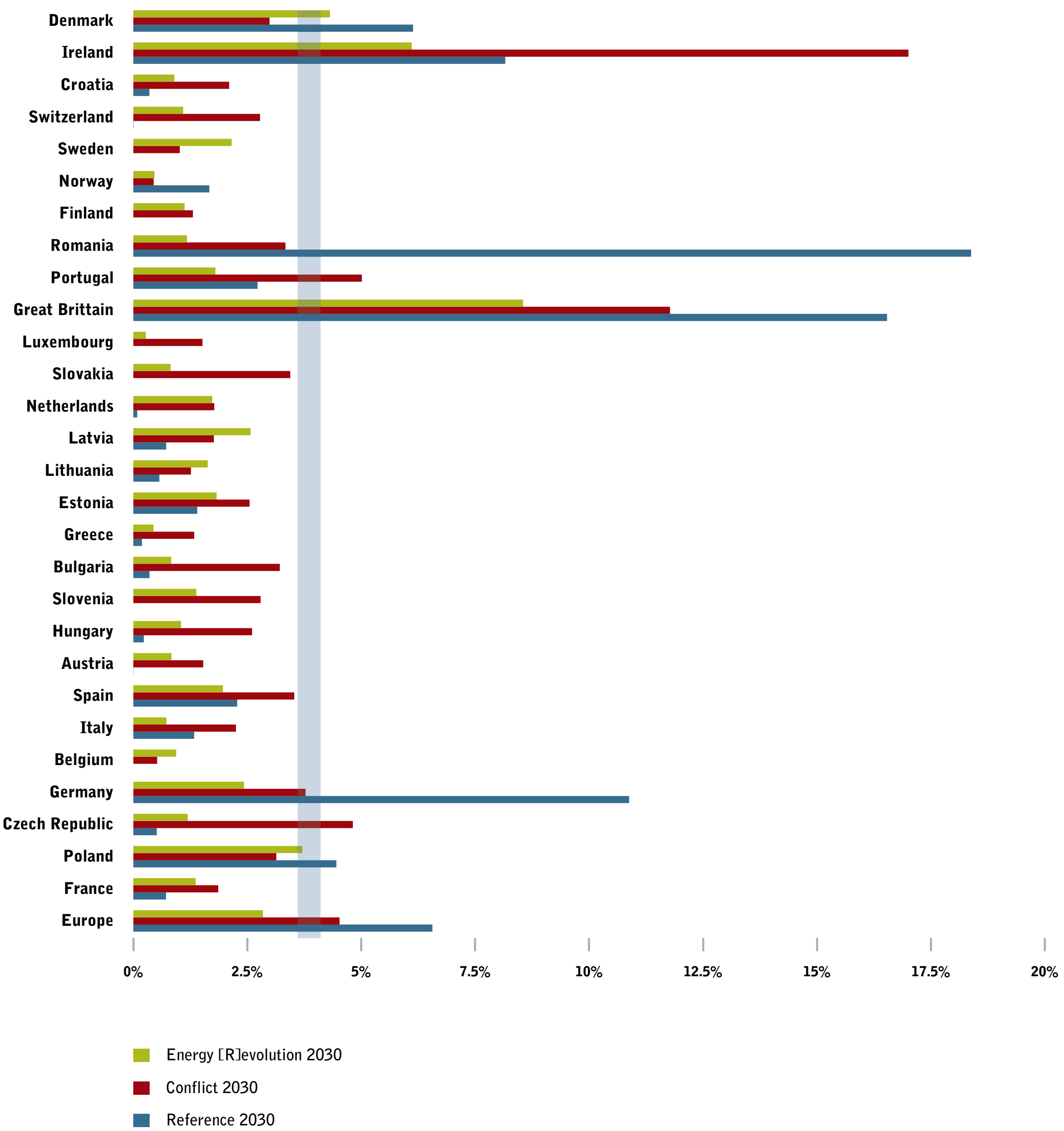
source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

2.11.2 how much solar and wind power will be wasted?

The amount of curtailment of wind and solar electricity is a clear indicator whether or not the power system in a specific region is prepared for an Energy [R]evolution concept. High curtailment in the Reference and Conflict scenarios and high capacity factors of coal and nuclear power plants are directly related. Low curtailment rates for renewables almost certainly linked to low capacity factors for conventional power plants IF the share of renewables is high.

Figure 2.15 shows the percentage of curtailment from all available solar and wind power generation. Across all scenarios, the main bottle necks and therefore the strongest conflict between base load and flexible RE generation appears in Ireland, Romania, the UK and Germany in the reference and /or the conflict case. Relatively high curtailment levels persist in the Energy [R]evolution scenario in Denmark, Ireland and Great Britain due to these countries' high shares of RE and transmission limitations due to their geographical isolation. Curtailment rates above 4.0% are critical for the economic operation of solar and wind projects while rates above 6.5% almost certainly make those projects un-economic.

figure 2.18: curtailment rates of wind and solar power plants by country and scenario for 2030



source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

image HYDROGEN HYBRID POWER STATION IN PRENZLAU IN BRANDENBURG, GERMANY. WIND ENERGY IS TRANSFERED TO HYDROGEN.

Table 2.5 shows, that under the Energy [R]evolution case, coal, lignite and nuclear power plants hardly operate even though there is still an installed capacity available in 2030. The merit order effect in the ER case prefers gas over coal – therefore gas has a higher capacity factor than any other conventional power plant. In the conflict case however, coal power plants still operate under "base-generation" condition, but push out gas.

2.12 comparison to Ten Year National Development Plan (TYNDP)

In the Conflict and Energy [R]evolution scenarios the network expansions in Europe are of the same order of magnitude as those planned in the TYNDP. However in the Reference scenario the question arises as to why the TYNDP see so much more network extension (50,000 km at a cost of €104 billion) compared to our Reference 2030 (3,700 km at a cost of €9 billion), around a factor 10, although they integrate similar amounts of Wind and PV (an extra 220 GW above today's capacities).

The main point and reason is that the network expansions in TYNDP and our network expansions are determined by different methods and with different goals. In this report we want to calculate the minimum network extensions while integrating 220 GW of variables and ensuring security of supply.

For the TYNDP, ENTSO-E has collected the network extension plans of all TSOs in the ENTSO-E area and aggregated them. The TSOs determine their network expansions according to a variety of criteria: long-term analysis of the power system (going out beyond 2022), to integrate renewables (according to individual national targets), to facilitate market integration, to ensure security of supply (n-1 criteria), to connect isolated areas of the grid (Ireland, GB, Spain, Baltics), etc. (i.e. lots of things that have nothing to do with the 220 GW target). The assumptions made on allowable curtailment vary from country to country and are assumed to be very low, which leads to higher network expansion. Then ENTSO-E has tested the network extensions of the individual TSOs in their model of the entire European power system according to different scenarios, one of which (the SOAF 2012 EU 2020 scenario) involves Wind and Solar increasing by 220 GW by 2020. They find (see page 17) that most of the bottlenecks will be solved by planned projects.

So the ENTSO-E extensions were determined by different criteria and then tested against an increase of 220 GW; they were not optimized to integrate 220 GW while minimizing network extensions.In addition a strategic choice has been made in this report to prefer HVDC over HVAC, which results in lower overall network extensions and lower impacts on the landscape.

Results:

- The TYNDP is based on low assumptions for future RES growth (corresponding to our Reference Scenario 2030; the Energy [R]evolution 2030 scenario has more than double the wind and PV capacity)
- More integration is achievable with our network expansions (860 GW of wind and PV integrated with 74 TVAkm of expansion in the Energy [R]evolution 2030, compared to 400 GW in TYNDP with 55 TVAkm of expansion); however TYNDP may use stricter safety criteria
- We take a fully international approach, where TYNDP is still to some extent focused on national projects, although they are also now focusing on international cross-border bottlenecks, particularly with HVDC
- There is a discussion of the costs of TYNDP versus our costs in the Section "TYNDP"

table 2.5: capacity factors of conventional generation in selected countries in the scenarios

COUNTRY	COAL	LIGNITE	GAS	NUCLEAR
France - Conflict 2020	34%	0%	8%	70%
France - Conflict 2030	43%	0%	9%	75%
France - E[R] 2020	0%	0%	90%	18%
France - E[R] 2030	0%	0%	85%	0%
Poland - Conflict 2020	71%	0%	8%	90%
Poland - Conflict 2030	80%	11%	10%	90%
Poland - E[R] 2020	10%	1%	90%	0%
Poland - E[R] 2030	0%	0%	59%	0%
Czech Rep. - Conflict 2020	85%	67%	15%	86%
Czech Rep. - Conflict 2030	81%	68%	33%	82%
Czech Rep. - E[R] 2020	4%	2%	90%	14%
Czech Rep. - E[R] 2030	0%	0%	79%	0%
Germany - Conflict 2020	90%	80%	15%	89%
Germany - Conflict 2030	90%	83%	25%	0%
Germany - E[R] 2020	9%	3%	73%	14%
Germany - E[R] 2030	0%	0%	43%	0%

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

table 2.6: wind and pv capacities for different scenarios

SCENARIO	YEAR	WIND + PV INSTALLED CAP (GW)
TYNDP	2022	400
Reference	2020	292
Reference	2030	400
Energy [R]evolution	2020	480
Energy [R]evolution	2030	860
Today	2013	180

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

2.13 conclusions

A high level of renewables can be integrated into the European power system with only modest changes to the transmission network. With similar investment levels in network infrastructure to those already planned by network operators, Europe can cover up to 77% of its electrical load with RES, including up to 860 GW of wind and PV with low (2.8%) curtailment.

In order to calculate overall power system costs, the network expansion costs, curtailment losses, fuel costs and external costs (with an European Emission Trading price between €5 and €40 per ton of CO_2) are combined. As a result the Energy[R]evolution case, with a share twice as high as in the reference case, turns out to be the most financially sound option. The curtailment costs are lowest and outweigh the additional grid extension costs.

By preferring an Overlay HVDC grid to continued extension of the HVAC transmission network, the total length of new transmission lines can be reduced by a third [from 39,000 km to 26,000 km, see Energy [R]evolution variations and maps thereof]. This minimizes the impact on the landscape and therefore should facilitate public acceptance.

The inflexibility of older nuclear and coal generation plant causes additional curtailment of variable renewables such as wind and PV. In the Conflict Scenario the inflexibility increases curtailment (and its associated costs) by 55% [2.9% curtailment to 4.5%] and could double or even triple curtailment levels if operators of conventional plant seek to improve their load factors [see Variations of the Conflict Scenario].

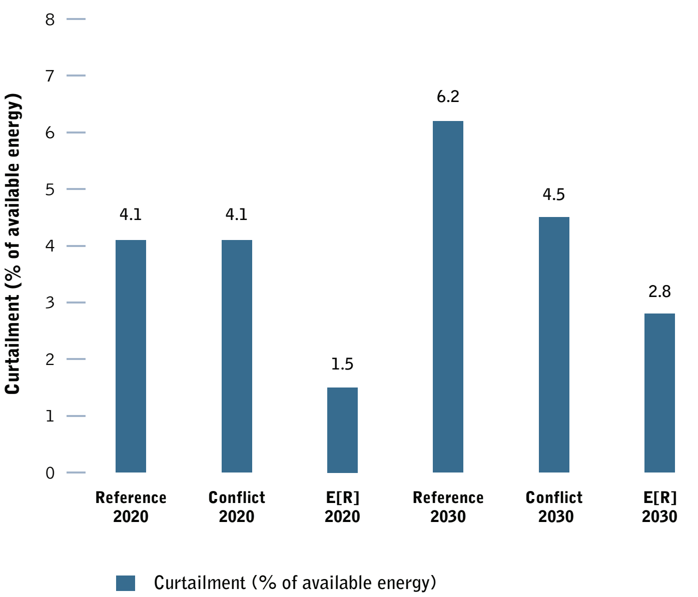
If policy in France, Poland and the Czech Republic continues to favor coal and nuclear, operating them inflexibly and early in the merit order, then it will cost more to integrate lower levels of RES in Europe than if every country follows the Energy [R]evolution scenario. The inflexibility causes additional curtailment, which outweighs the lower network costs. The Reference case showed clearly that a high level of coal and nuclear power capacity operated as the base load mode will lead to very high curtailment rate for wind and solar by up to 9.8%.

However by focusing exclusively on renewable integration and allowing some curtailment, double the wind and PV levels can be integrated into the European power system for similar investment in network infrastructure, when compared with ENTSO-E's Ten Year Network Development Plan 2012.

2.13.1 two times more renewable energy integration with half the transmission line expansion

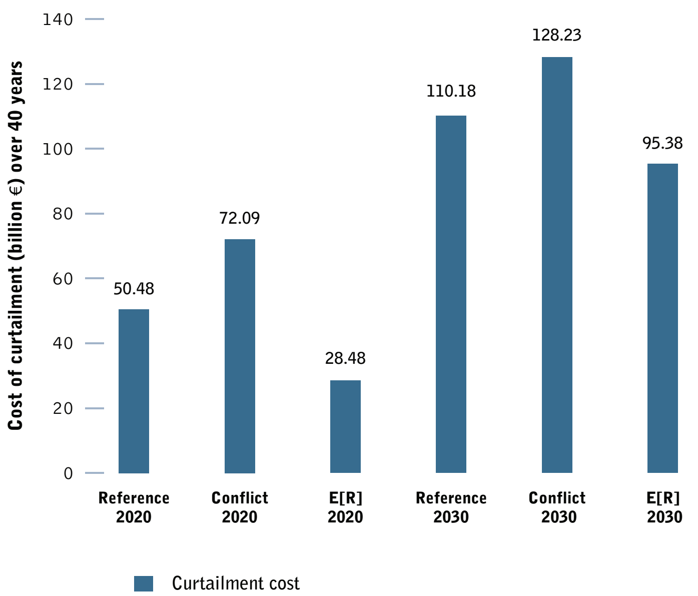
A clear result of this research has been that network expansion must be optimized towards the regional and technical power generation structure, as well as the integration of the latest transmission technologies. The TYNDP is inadequate to integrate high levels of renewables, since it is based on conservative RES targets and the continuance of existing power generation structures. This leads to much higher system costs and potentially to an overcapacity of power generation. The powE[R] 2030 concept outlined in this report is optimized for the highest share of renewables and a phase-out of coal and nuclear across Europe.

figure 2.19: curtailment of variable renewables as % of available energy



source ENERGYNAUTICS 2014 - POWE[R]2030.

figure 2.20: cost of curtailment over 40 years of network asset lifetime (ASSUMING 50 €/MWH TO REPLACE ENERGY)



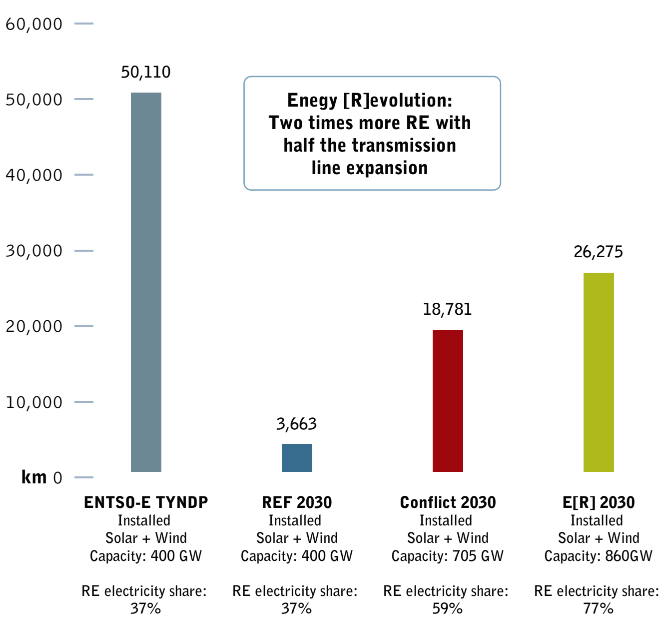
source ENERGYNAUTICS 2014 - POWE[R]2030.

image BROWN COAL POWER PLANT JAENSCHWALDE, GERMANY, OPERATED BY VATTENFALL, NEAR COTTBUS.

Besides the location of the specific network expansion, the chosen technologies for the transmission lines are of great importance. One of the major findings of this research is, that a High Voltage Direct Current (HVDC) "Overlay-Network" avoids a significant amount of conventional transmission line expansion. This is particularly important as new power lines face huge public opposition and therefore many projects have delays of many years if not more than a decade.

An HVDC system transports renewable electricity from generation hubs to load-centers and – combined with smart-grids – can form a secure and economically viable infrastructure for renewable energies. Under the Energy [R]evolution case about 1,500 TWh per year solar and wind electricity will be produced by 2030. If an optimized grid concept reduces the required curtailment by 2% - from e.g. 4.6% down to 2.6% - the saved curtailment costs would add up to €60 billion, which is comparable with the network expansion costs in the Energy [R]evolution 2030 Scenario. Optimizing to a specific energy mix pays off. However if a network operator expands the network simply to minimize conflicts - which is the current approach - this will result in far higher network expansion costs and will also lead to many more overhead power lines which lack public acceptance.

figure 2.21: network expansion in km



source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

table 2.7: key results + comparison with ENTSO-E

CASE	TECHNOLOGY	NETWORK EXTENSION (MVA)[a]	LENGTH (KM)[b]	EXTENSION IN (MVAkm)[c]	TRANSMISSION LINES (KM)[d]	NETWORK EXTENSION COSTS (MILLION €)
Reference 2020	AC	1,500	343	514,500	343	229
	DC	5,000	1,727	1,682,910	1,370	1,968
	AC+DC	6,500	2,070	2,197,410	1,713	2,197
Reference 2030	AC	3,000	562	842,489	562	375
	DC	20,000	2,425	8,145,934	3,101	7,773
	AC+DC	23,000	2,985	8,988,423	3,663	8,148
Conflict 2020	AC	4,500	731	1,095,796	731	530
	DC	16,000	2,895	7,909,550	2,895	6,702
	AC+DC	20,500	3,625	8,005,346	3,626	7,232
Conflict 2030	AC	84,700	8,224	15,188,762	8,779	7,089
	DC	91,000	7,055	39,110,736	10,002	33,563
	AC+DC	175,700	15,279	54,299,498	18,781	40,652
Energy [R]evolution in 2020	AC	4,500	731	1,096,796	731	530
	DC	15,000	2,634	7,648,550	2,634	6,254
	AC+DC	19,500	3,365	8,745,346	3,365	6,784
Energy [R]evolution in 2030	AC	112,200	22,489	22,168,854	11,719	10,314
	DC	148,000	10,738	52,390,238	14,556	50,859
	AC+DC	260,200	22,227	74,559,093	26,275	61,172
ENTSO-E TYNDP	AC		37,520	56,280,000	37,520	25,945
	DC		12,590	25,180,000	12,590	25,205
	AC+DC		50,110	81,460,000	50,110	51,150

notes
a MVA = SUM OF CAPACITY EXTENSION IN MVA FOR EACH LINE.
b MVAkm = CAPACITY EXTENSION IN MVA MULTIPLIED WITH THE LENGTH IN KM OF EACH LINE.
c LENGHT IN KM = LENGTH OF LINE AFFECTED.
d TRANSMISSION LINE LENGTH IN KM = LENGTH OF NEW BUILD TRANSMISSION LINES.

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

image TESTING THE SCOTRENEWABLES TIDAL TURBINE OFF KIRWALL - SCOTRENEWABLES TIDAL POWER LTD IS A RENEWABLE ENERGY RESEARCH AND DEVELOPMENT BUSINESS BASED IN THE ORKNEY ISLANDS.

image AERIALS OF ENERCON WIND TURBINES NEAR STRAUSSBERG (BRANDENBURG), GERMANY, AMONG CLOUDS IN THE MORNING.

© LANGROCK/GREENPEACE

The previous sections have shown what is technically feasible. This section explains in more detail the infrastructural changes and management that would need to take place to make the proposal a reality. The task of integrating renewable energy technologies into existing power systems is similar in all power systems around the world, whether they are large, centralized systems or island systems.

Thorough planning ahead is needed to ensure that the available production can match demand at all times. In addition to balancing supply and demand at all times, the power system must also be able to:

- Fulfil defined power quality standards –voltage/frequency- which may require additional technical equipment in the power system and support from different ancillary services (See Appendix 1 for definitions of terms); and
- Survive extreme situations such as sudden interruptions of supply (e.g. a fault at a generation unit) or interruption of the transmission system.

Typically, power systems use cheap power sources as base-load power plants which operate most of the time at rated capacity. These centralized units are often "inflexible" generation resource, meaning they are quite inefficient and it is expensive to change their output over the day, to match what people actually use (load variation).Generally, coal and nuclear plants run as baseload, meaning they work most of the time at maximum capacity regardless of how much electricity consumers need. Coal and nuclear cannot be turned down which leads to the curtailment of cleaner energy options.

Renewable energy integrated into a smart grid changes the need for baseload power. In countries with good support for renewable energy and natural resources, in Spain for example, the clean, renewable technologies already provide more than 40% of daily demand on certain days. An energy switch based on renewables as demonstrated through the modeling in this report, redefines the need for baseload power. Instead, a mix of flexible energy providers can follow the load during the day and night (e.g. solar plus gas, geothermal, wind and demand management), without black-outs.

3.1 demand side management

In reality, load varies over time which means that additional flexible power generation resources are required to provide the right amount of power. For rural areas, typical technologies are combined-cycle gas turbines (CCGT) or hydro-power stations with a sufficient storage capacity to follow the daily load variations. In conventional island power systems, typically a number of small diesel generators (gensets) are used to provide 24/7 supply. Several gensets have to operate continuously at the point of their highest efficiency, while one is used to follow the load variations.

The impact of adding renewable power generation to a conventionally centralized or island power system will affect the way in which a conventionally-designed electricity system runs. The level of impact depends on the renewable energy technology:

- Biomass/geothermal/solar thermal (CSP)/hydro power with storage: power output can be regulated, i.e. they can supply base load as well as peak load;
- Hydro power without storage (run–of-the-river)/photovoltaic/ wind power: power output these depends on the available natural resources, so the power output is variable.[15]

There are two main types of impact to consider when introducing renewable energy to microgrids, the balancing impact and reliability impact.

Balancing impact relates to the short-term adjustments needed to manage fluctuations over a period ranging from minutes to hours before the time of delivery. In power systems without variable power generation, there can be a mismatch between demand and supply. The reasons could be that the energy load was not forecast correctly, or a conventional power plant is not operating as it is scheduled, for instance a power station has tripped due to a technical problem.

Adding a variable power generation source increases the risk that the forecasted power generation in the power system will not be reached, for instance, due to a weather system moving faster than predicted into the area. The overall impact on the system depends on how large and how widely distributed the variable power sources are. A certain amount of wind power distributed over a larger geographical area will have a lower impact on system balancing than the same amount of wind power concentrated in one single location, as geographical distribution will smoothen out the renewable power generation

System balancing is relevant to:

- Day-ahead planning, which needs to make sure that sufficient generation is available to match expected demand taking into account forecasted generation from variable power generation sources (typically 12 to 36 hours ahead);
- Short-term system balancing, which allocates balancing resources to cover events such as a mismatch between forecasted generation/demand or sudden loss of generation (typically seconds to hours ahead planning).

In island power systems, both aspects must be handled automatically by the system.

Reliability impact is the extent to which sufficient generation will be available to meet peak demands at all times. No electricity system can be 100% reliable, since there will always be a small chance of major failures in power stations or transmission lines when demands are high. As renewable power production is often more distributed than conventional large-scale power plants, it reduces the risk of sudden drop-outs of major individual production units. On the other hand, variable renewable power generation reduces the probability that generation is available at the time of high demand, so adds complexity to system planning.

reference

15 SOMETIMES THESE RENEWABLE ENERGY SOURCES ARE DESCRIBED AS 'INTERMITTENT' POWER SOURCES, HOWEVER, THE TERMINOLOGY IS NOT CORRECT AS INTERMITTENT STANDS FOR UNCONTROLLABLY, I.E. NON-DISPATCHABLE, BUT THE POWER OUTPUT OF THESE GENERATION PLANTS CAN BE FORECASTED, HENCE THEY CAN BE DISPATCHED. FURTHERMORE, THEY CAN ALWAYS BE OPERATED DOWN-REGULATED IF NEEDED, SEE ALSO

Reliability is important for long-term system planning, which assesses the system adequacy typically two to 10 years ahead. Long-term system planning with variable generation sources is a challenge, because of the actual geographical location of the resource. To get a high level of renewable energy into the system, it ideally must be situated at some distance from each other, for example using solar power from Southern Europe when there is no or limited wind power available in Northern Europe.

In island power systems, all power generation is typically close to each other, which means that there must be a mix of different generation technologies in the island system or that they must be partly over-designed to make sure that there is always sufficient generation capacity available. This is typically done by adding some back-up diesel gensets. In addition, island power systems can adjust power demand to meet power supply, rather than the other way round. This approach is called demand-side management. An example of a "flexible" load in island systems for demand-side management is water pumps and irrigation pumps which can be turned on and off depending on how much electricity supply there is.

3.2 base load and system balancing

Energy power balance aims at keeping frequency in the system consistent. The mains frequency describes the frequency at which AC electricity is delivered from the generator to the end user, and it is measured in Hertz (Hz). Frequency varies in a system as the load (demand) changes. In a power grid operating close to its peak capacity, there can be rapid fluctuations in frequency, and dramatic examples can occur just before a major power outage.

The existing power systems around the world have developed certain technologies and generation resources, often influenced by the national energy policy. Typically, power systems were designed around large power stations providing base-load capacity, i.e. base-load power plants of more than 660 MW capacity, operating almost constantly at full output.

These centralized units, typically nuclear or coal power plants, are inflexible generation resources – they can't "follow load", that is to change their supply to match the changing demand through the day. It is inefficient and expensive to change their operating capacity. Furthermore, large, centralised units require significant investment in grid infrastructure.

Load varies over time therefore more flexible power generation resources can "follow the load". Typical technologies which can do this are combined cycle gas turbines (CCGT) or hydro power stations because they have significant storage capacity to match the variations over a day. Power systems with large amounts of inflexible generation resources, such as nuclear power stations, also require a significant amount of flexible generation resources.

3.3 technical or financial barriers?

Now renewable generation takes an increasing market share in the electricity supply, taking it away from conventional fossil power plants. The conventional power plants sell less kWh than originally planned, and they cannot run power plants in base load mode anymore, which increases costs of operation and therefore lowers the profit on each kWh sold.

Hence, the integration of large scale renewable energy is becoming less of a technical issue, but more an economic one. The barriers are from companies reluctant to abandon their economic investment in conventional base-load power plants. Decommissioned power plants, or "stranded assets" for certain companies, are not a sufficiently strong reason for holding up the development of a massive renewable energy infrastructure.

Smart-Grid technology will play a significant role in achieving this, in particular by integrating demand-side management into power system operation.

The future power system will not consist of a few centralized power plants but of tens of thousands generation units such as solar panels, wind turbines and other renewable generation, partly distributed in the distribution network, partly concentrated in large power plants, like offshore wind power plants. Smart-Grid solutions will help to monitor and integrate this diversity into power system operation and at the same time will make interconnection simpler.

The tradeoff is that power system planning will become more complex due to the larger number of generation assets and the significant share of variable power generation causing constantly changing power flows in the power systems. Smart-Grid technology will be needed to support power system planning, i.e. actively support day-ahead planning and power system balancing by providing real-time information about the status of the network and the generation units in combination with weather forecasts. Smart-Grid technology will also play a significant role in making sure systems can meet the peak demand at all times. Smart-Grid technology will make better use of distribution and transmission assets thereby limiting the need for transmission network extension to the absolute minimum.

Smart Grids use information and communication technology (ICT) to enable a power system based on renewable energy sources.

ICT in smart grids is used to:

- easily interconnect a large number of renewable generation assets into the power system (plug and play)
- create a more flexible power system through large-scale demand-side management and integrating storage to balance the impact of variable renewable generation resources
- provide the system operator with a better information about the state of the system, which so they can operate the system more efficiently
- minimize network upgrades using of network assets efficiently and supporting an efficient coordination of power generation over very large geographic areas needed for renewable energy generation

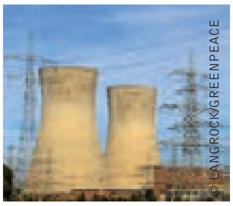
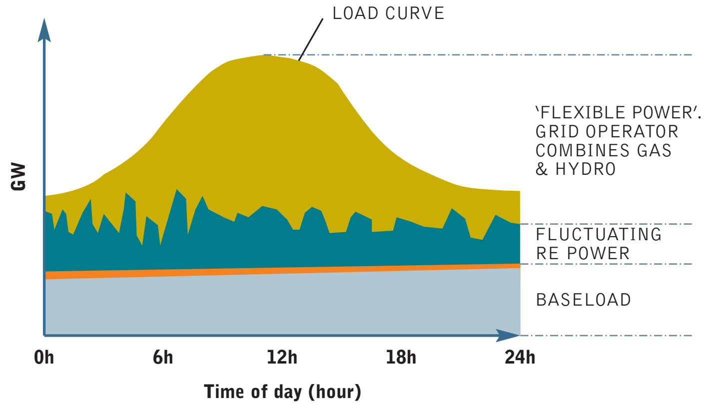


figure 3.1: the evolving approach to grids

Current supply system

- Low shares of fluctuating renewable energy
- The 'base load' power is a solid bar at the bottom of the graph.
- Renewable energy forms a 'variable' layer because sun and wind levels changes throughout the day.
- Gas and hydro power which can be switched on and off in response to demand. This is sustainable using weather forecasting and clever grid management.
- With this arrangement there is room for about 25 percent variable renewable energy.

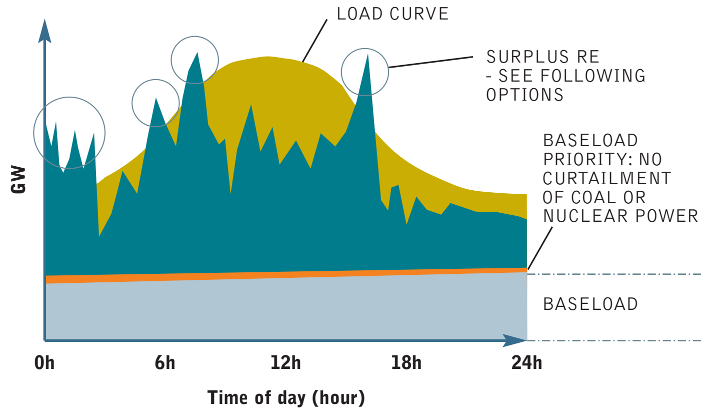
To combat climate change much more than 25 percent renewable electricity is needed.



Supply system with more than 25 percent fluctuating renewable energy > base load priority

- This approach adds renewable energy but gives priority to base load.
- As renewable energy supplies grow they will exceed the demand at some times of the day, creating surplus power.
- To a point, this can be overcome by storing power, moving power between areas, shifting demand during the day or shutting down the renewable generators at peak times.

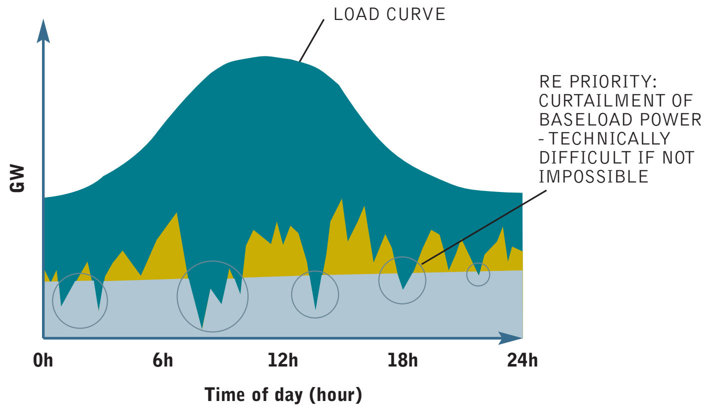
Does not work when renewables exceed 50 percent of the mix, and can not provide renewable energy as 90- 100% of the mix.



Supply system with more than 25 percent fluctuating renewable energy – renewable energy priority

- This approach adds renewables but gives priority to clean energy.
- If renewable energy is given priority to the grid, it "cuts into" the base load power.
- Theoretically, nuclear and coal need to run at reduced capacity or be entirely turned off in peak supply times (very sunny or windy).
- There are technical and safety limitations to the speed, scale and frequency of changes in power output for nuclear and coal-CCS plants.

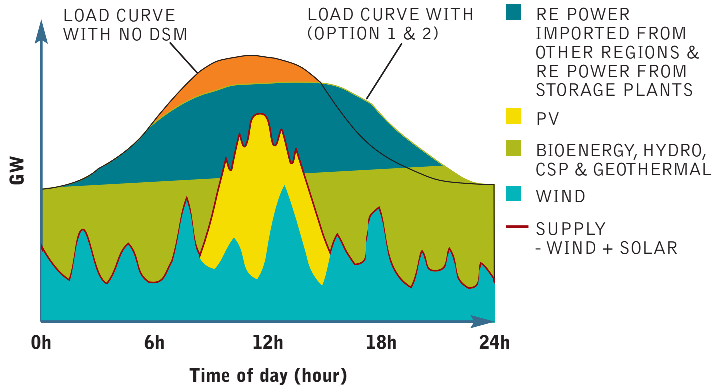
Technically difficult, not a solution.



The solution: an optimised system with over 90% renewable energy supply

- A fully optimised grid, where 100 percent renewables operate with storage, transmission of electricity to other regions, demand management and curtailment only when required.
- Demand-side management (DSM) effectively moves the highest peak and 'flattens out' the curve of electricity use over a day.

Works!

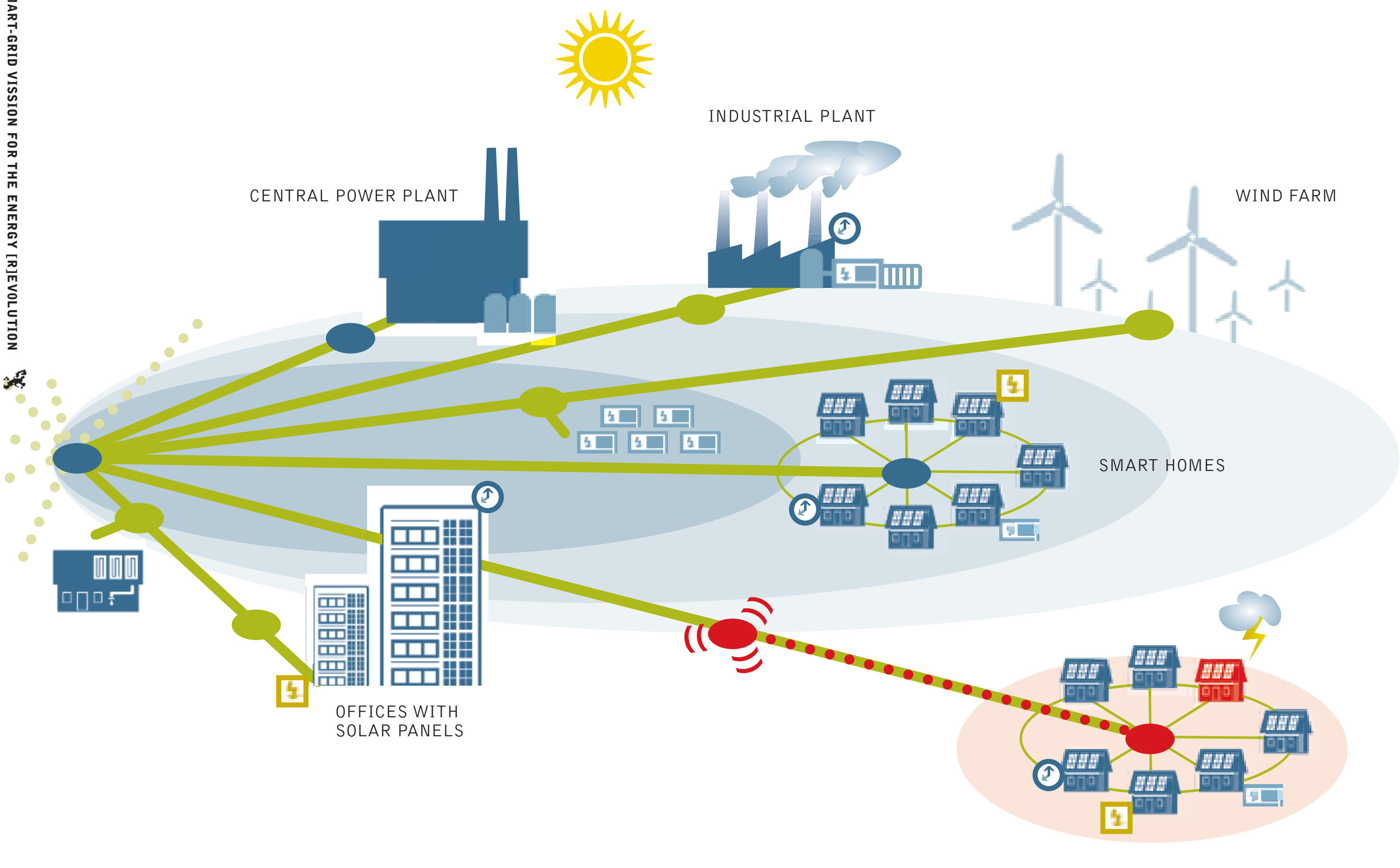


3.4 the smart-grid vision for the energy [r]evolution

To develop a power system based almost entirely on renewable energy sources will require a new overall power system architecture –including Smart-Grid Technology, which will need substantial amounts of work to emerge.[16] Figure 3.2 shows a very basic graphic representation of the key elements of future, renewable-based power systems using Smart Grid technology.

figure 3.2: the smart-grid vision for the energy [r]evolution

A VISION FOR THE FUTURE – A NETWORK OF INTEGRATED MICROGRIDS THAT CAN MONITOR AND HEAL ITSELF.



PROCESSORS
EXECUTE SPECIAL PROTECTION SCHEMES IN MICROSECONDS

SENSORS ('ACTIVATED')
– DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED

GENERATORS
ENERGY FROM SMALL GENERATORS AND SOLAR PANELS CAN REDUCE OVERALL DEMAND ON THE GRID

DISTURBANCE IN THE GRID

SENSORS (ON 'STANDBY')
– DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED

DEMAND MANAGEMENT
USE CAN BE SHIFTED TO OFF-PEAK TIMES TO SAVE MONEY

STORAGE ENERGY GENERATED AT OFF-PEAK TIMES COULD BE STORED IN BATTERIES FOR LATER USE

SMART APPLIANCES
CAN SHUT OFF IN RESPONSE TO FREQUENCY FLUCTUATIONS

reference
16 SEE ALSO ECOGRID PHASE 1 SUMMARY REPORT, AVAILABLE AT: http://www.energinet.dk/NR/rdonlyres/8B1A4A06-CBA3-41DA-9402-B56C2C288FB0/0/EcoGriddk_phase1_summaryreport.pdf

image OFFSHORE CONSTRUCTION OF WIND TURBINES IN BREMERHAVEN AT OFFSHORE CONSTRUCTION COMPANY WESERWIND GMBH. THE FOUNDATIONS WILL BE USED AT OFFSHORE WIND PARK GLOBAL TECH ONE IN THE GERMAN NORTH SEA.

3.5 "overlay" or "super grid" – the interconnection of smart grids

Based on the current technology development of energy storage technologies, it is difficult to envision that energy storage could provide a comprehensive solution to this challenge. While different storage technologies such as electrochemical batteries are already available today, but it is not clear whether large-scale electricity storage, other than hydro power described in the previous section, will become technically and economically viable.

Feasible storage systems would have to cover most of the European electricity supply during up to two successive weeks of low solar radiation and little wind – this is difficult to envision based on current technology development. To design a power system that can adequately react to such extreme situations a substantial amount of planning ahead is needed in order to ensure available generation capacity together with sufficient network capacity can match demand. In order to do so, different timescales must be considered:

- Long-term system plans to assess the system adequacy over the coming years (typically a time horizon of 2 to 10 years ahead is considered)
- Day-ahead planning, making sure that sufficient generation is available to match expected demand (typically 12 to 36 hours ahead)
- Short-term balancing, covering events such as a mismatch between forecasted generation/demand or sudden loss of generation (typically seconds to hours ahead planning)

3.6 benefits of a super grid

From around 1920 each load centre in Europe had its own isolated power system. With the development of transmission lines using higher voltages, the transport of power over larger distances became feasible, and soon the different power systems were interconnected. In the beginning, only stations in the same region were interconnected. Over the years, technology developed further and maximum possible transmission line voltage increased step by step.

The main driver of extending network structure had two main reasons:

- Larger transmission networks and high voltage lines meant suppliers could follow the aggregated demand of a large number of customers, instead of the demand variation of one customer -which can change significantly over time- with one generation resource. The demand of those aggregated customers became easier to predict and generation scheduling therefore significantly easier.
- The larger transmission networks created economies of scale by installing larger generation units. In the 1930s, the most cost-effective size of thermal power stations was about 60 MW. In the 1950s, it was 180 MW, and by the 1980s about 1,000 MW. This approach made only economic sense because extending the power system was cheaper than adding local generation capacity.

The approach includes some major risks, like the break-down of a large power station or the interruption of a major transmission line, which can interrupt of the power system over a large area.

To be better prepared for such situations national transmission systems in Europe and elsewhere were interconnected across borders. Countries can help each other in case of emergency situations by cooperating in the organization of spinning reserve, reserve capacity and frequency control.

Shifting to an energy mix with over 90% of the electricity supply coming from renewable energy sources will also require a significant redesign of the transmission network to adapt to the needs of the new generation structure. The right kind of grid provides an economic, reliable and sustainable energy supply.

In principal, over-sizing local generation locally would reduce the need for large-scale renewable generation elsewhere as well as upgrading the transmission network.[17] However, making local plants bigger (over-sized) is less economic compared to installing large-scale renewable energy plants at a regional scale integrating them into the power system via extending the transmission system. The allocation of 70% distributed renewable generation and 30% large-scale renewable generation is not based on a detailed technical or economic optimization – in each location the optimum mix is specific to local conditions. Further detailed studies on regional levels will be needed to better quantify the split between distributed and large-scale renewable generation better.

An appropriately designed transmission system is the solution in both cases as it can be used to transmit the required electricity from areas with surplus of generation to areas that have an electricity deficit.

In general, the transmission system must be designed to cope with:

- Long-term issues: Extreme variations in the availability of natural resources from one year to another, e.g. the output of wind turbines in any given area can vary by up to 30% from one year to the next, for hydro power the variations can be even larger
- Medium-term issues: extreme combinations in the availability of natural resources, e.g. no wind over main parts of Europe during the winter, when solar radiation is low
- Short-term issues: Significant mismatch between forecasted wind or solar production and actual production with significant impact on power system operation in the range of 15 minutes to 3 hours
- Loss of a significant amount of generation due to unscheduled break-down or network interruption, impact within milliseconds. The mainland European power system is currently designed to cope with a maximum sudden loss of generation of 3,000 MW. If this is sufficient for the future depends, for example, on the maximum transmission capacity of a single transmission line. Most likely the maximum transmission capacity of a single transmission in the future HVDC Super Grid will exceed a capacity of 3,000 MW, hence sufficient spare generation and/or network capacity must be considered when redesigning the power system (considered in the simulation report by loading the Super Grid to maximal 70%)

reference
17 IN THIS CASE THE LOCAL POWER SYSTEM WILL EVOLVE INTO A HYBRID SYSTEM THAT CAN OPERATE WITHOUT ANY OUTSIDE SUPPORT.

3.7 super grid transmission options

In principal different technical options exists for the redesign of the onshore transmission network. In the following, the following technical options are briefly presented, followed by a general comparison.

- HVAC (High Voltage Alternating Current)
- HVDC LCC (High voltage direct current system using line commutated converter)
- HVDC VSC (High voltage direct current system using voltage source converter)
- Other technical solutions

3.7.1 HVAC

A high voltage AC transmission (HVAC) using overhead line has become a leading technology in electrical networks.[18] Its advantage is in using transformers to increase the typical, rather low voltage at the generators to higher voltage levels, which is a significantly cheaper approach than the AC/DC converter stations for the HVDC technologies. Transmission over long distances with low or medium voltage will result in high and prohibitively expensive losses, so high voltage AC (400 kV or more) over medium distance (a few hundred kilometres) is typically the most cost effective solution. As AC systems develop, there are increases in transmission voltage. Typically, doubling the voltage quadruples the power transfer capability. Consequently, the evolution of grids in most countries is characterised by the addition of network layers of higher and higher voltages.

Today the highest HVAC voltage used is around 800 kV for overhead lines. The Canadian company Hydro Quebec, for instance, operates a massive 735 kV transmission system using overhead lines, the first line was in operation 1965. 1,000 kV and 1,200 kV AC has been tested in several test-installations and even short-term commercial applications but is not currently used in any commercial application.[19] There are several challenges involved in building such lines and new equipment needing to be developed includes transformers, breakers, transformers, and switches.

The major advantage of an AC-based system is the flexibility with which loads and generation along the route can be connected. This is especially important if the transmission route passes through a highly populated area and if many local generation facilities are located at many places along the route. The disadvantage of HVAC systems are the comparatively high costs for transmission of large capacity (> 1,000 MW) over very long distances (> 1,000 km) due to the additional equipment required for keeping the voltage level on the overhead lines, for instance.

3.7.2 HVDC LCC

The advantage of line commutated converter (LCC) based high voltage DC (HVDC) connections is certainly its proven track record. The first commercial LCC HVDC link was installed in 1954 between the island of Gotland and the Swedish mainland. The link was 96 km long, 20 MW rated and used a 100 kV submarine cable. Since then, LCC based HVDC technology has been installed in many locations in the world, primarily for bulk power transmission over long geographical distances and for interconnecting power systems, e.g. the different island systems in Japan or New Zealand. Other well-known examples for conventional HVDC technology are:

- The 1,354 km Pacific Interie DC link with a rating of 3,100 MW at a DC voltage of ± 500 kV
- The Itaipu link between Brazil and Paraguay, rated at 6,300 MW at a DC voltage of ± 600 kV (2 bipoles x 3,150 MW)

The total conversion efficiency from AC to DC and back to AC using the two converters lies in the range of 97 to 98 % and depends on design details of the converter stations. A system design with a 98 % efficiency will have higher investment costs compared to a design with lower efficiency. The advantage of an LCC HVDC solution are comparatively low losses – in the order of 2-3 % for a 500 MW transmission over 100 km, including losses in converters and transmission. In addition, the higher transmission capacity of a single cable compared to the HVAC transmission or the voltage source converter based transmission can be an advantage when transmitting large capacities. The disadvantage of the HVDC LCC design is lack of power system support capability. Typically, a strong HVAC network is required on both sites of the HVDC LCC connection. Hence, to build up an entire HVDC back-bone network using HVDC LCC technology that has to support the underlaying HVAC network is technically challenging and only possible with the installation of additional equipment such as Statcoms.[20]

3.7.3 HVDC VSC

The voltage source converter (VSC)[21] based HVDC technology is capturing more and more attention. This comparatively new technology has only become possible due to advances in high power electronics, namely Insulated Gate Bipolar Transistors (IGBTs). This way Pulse Width Modulation (PWM) can be used for the VSC converter, as opposed to thyristor based line-commutated converters used in the conventional HVDC technology.

The first commercial VSC-based HVDC link was installed by ABB on the Swedish island of Gotland in 1999. It is 70 km long, with 60 MVA at ± 80 kV. The link was mainly built in order to provide voltage support for the large amount of wind power installed in the South of Gotland.

Today about 10 VSC-based HVDC links are in operation world-wide. Key projects are:

- In 2000, the Murraylink was built in Australia with a length of almost 180 km. This connection was the longest VSC-based HVDC link in the world until 2009. It has a capacity of 220 MVA at a DC voltage of ±150 kV

references

18 HVAC CABLE SYSTEMS ARE CURRENTLY LESS ATTRACTIVE AS CABLE LOSSES ARE HIGHER AND TRANSMISSION CAPACITY IS LESS THAN WITH HVAC OVERHEAD LINES.
19 IN 1986 A 1200 KV AC TRANSMISSION LINE, CONNECTING RUSSIA AND KAZAKHSTAN, WAS PUT INTO OPERATION. THE LINE, HOWEVER, WAS TAKEN OUT OF OPERATION IN 1996
20 STATCOM = STATIC SYNCHRONOUS COMPENSATOR.
21 ALSO KNOWN AS FORCED COMMUTATED CONVERTER.

image SOLNOVA 1,3,4, PS10 AND PS20 SOLAR TOWER PLANTS SIT AT SANLUCAR LA MAYOR OUTSIDE SEVILLE. THE SOLAR TOWER PLANT, THE FIRST COMMERCIAL SOLAR TOWER IN THE WORLD, BUILT BY THE SPANISH COMPANY SOLUCAR (ABENGOA), CAN PROVIDE ELECTRICITY FOR UP TO 6,000 HOMES. SOLUCAR (ABENGOA) PLANS TO BUILD A TOTAL OF 9 SOLAR TOWERS OVER THE NEXT 7 YEARS TO PROVIDE ELECTRICITY FOR AN ESTIMATED 180,000 HOMES.

- The Bard Offshore 1 Project BorWind in Germany connects a 400 MW offshore wind farm to the onshore grid using a 203 km long cable, operating at a DC voltage of ±150 kV
- The longest HVDC VSC project is the Caprivi link in Namibia. It is 970 km long and operates at ±350 kV, which is the highest voltage level used so far for HVDC VSC projects, to transmit a capacity of 300 MW

The total efficiency of a VSC-based HVDC system is slightly less than that of a LCC HVDC system, but it is expected that the efficiency will improve in the future due to future technical development. Also, rating per converter is presently limited to approximately 400-500 MW, while the cable rating at +/-150 kV is 600 MW. More cable and converter stations are required for a VSC based HVDC solution compared to a LCC based HVDC solution, however, manufacturer already working on converter stations with higher ratings and increased cable ratings. The significant advantages of VSC-based HVDC solutions are its power system support capabilities such as independent control of active and reactive power. In addition, a VSC-based HVDC link does not require a strong AC network, it can even start up against a non-load network. Building up a VSC based HVDC back-bone network will be technically easier than using LCC based HVDC technology. However, Multi-terminal VSC HVDC systems are also new for the power system industry, so there will some learning curve to achieve it.

3.8 comparison of transmission solutions

Table 3.1 compares the three standard transmission solutions. The technical capabilities of each system can probably be improved by adding additional equipment to the overall system solution.

The cost of transmitting electricity is dominated by the investment cost of the transmission lines and by the electricity losses during transmission. At present, overhead lines are predominant since costs of overhead lines are about 20 % of that for ground cables. The transmission losses of HVAC overhead lines are roughly twice as high as those of HVDC. On the one hand, the cost of overhead lines is similar for the lower voltage level, but at 800 kV HVDC lines are much less expensive than comparable AC lines. On the other hand, AC/DC converter stations for HVDC technology are considerably more expensive than the transformer stations of AC systems. Therefore, for shorter distances and lower voltages AC is typically the most economical solution, while HVDC lines are applied at distances well over 500 km (see Figure 3.3).

table 3.1: overview of the three main transmission solutions

	HVAC	LCC HVDC	VSC HVDC
Maximum available capacity per system	Cable system: • 200 MW at 150 KV; • 350 MW at 245 KV; Overhead lines: • 2,000 MW at 800 KV • 4,000 MW at 1000 kV (under development)	Cable system: • ~ 1200 MW Overhead lines: • 3,150 MW at ± 600 kV • 6,400 MW at ± 800 kV (under development)	Cable/Overhead: • 400 MW • 500 - 800 MW announced
Voltage level	Cable system: • Up to 245 kV realistic, short cables up to 400 kV possible Overhead lines: • Up to 800 kV • 1,000 kV under development	Cable system: • Up to ± 500 kV Overhead lines: • Up to ± 600 kV • ± 800 kV under development	Cable: • Up to ± 150 kV, higher voltages announced Overhead lines: • Up to ± 350 kV
Transmission capacity distance depending?	Yes	No	No
Total system losses	Distance depending	2 - 3 % (plus requirements for ancillary services offshore)	5 – 10 %
Black start capability	(Yes)	No	Yes
Technical capability for network support	Limited	Limited	Large range of possibilities.
Space requirements for substation.	Small	Depending on capacity. Converter larger than VSC.	Depending on capacity. Converter smaller than LCC but larger than HVAC substation.

source ENERGYNAUTICS/GREENPEACE/TESKE 2014 - POWE[R]2030.

The most economical system design is typically a combination of HVAC and HVDC technology. HVAC is a cost-effective and flexible solution over medium distances (up to 1,000 km), for instance to distribute power along the route to different load centres or to collect locally distributed generation and transmit the surplus electricity to other regions. HVDC technology can be used as an overlaying network structure to transmit bulk power, i.e. large capacity, over long distances to the areas where the energy is needed. An HVDC Super Grid will have only a very limited number of connection points, because the substation (converter station) costs are significant.

In addition, an HVAC solution will require significantly more lines than HVDC solutions. The transmission of 10,000 MW or 10 GW, for instance, can be achieved with two lines using 800 kV and applying LCC HVDC technology, while transmitting the same power with 800 kV AC would require five lines. For a given transmission capacity of 10 GW, the space requirement of HVDC overhead lines can be four times lower than that of HVAC lines (Figure 3.4). While an 800 kV HVAC line would require a width of 425 meters over the total length of a power link of 10 GW, a HVDC line of the same capacity would only require a band of a width of 100 meters. This leads to considerable differences in the environmental impact of both technologies.

A final advantage of using HVDC technology is that it is easier to move the entire HVDC Super grid underground by using HVDC cables. This approach will be more costly, but following existing transporting routes, e.g. laying the cables along motorways, railway tracks or even in rivers will allow a fast roll-out of the HVDC Supergrid infrastructure and reduce the visual impact of the installation.

figure 3.3: comparison of AC and DC investment costs using overhead lines. BREAK EVEN POINT IS TYPICALLY BETWEEN 500 TO 1,000 KM.

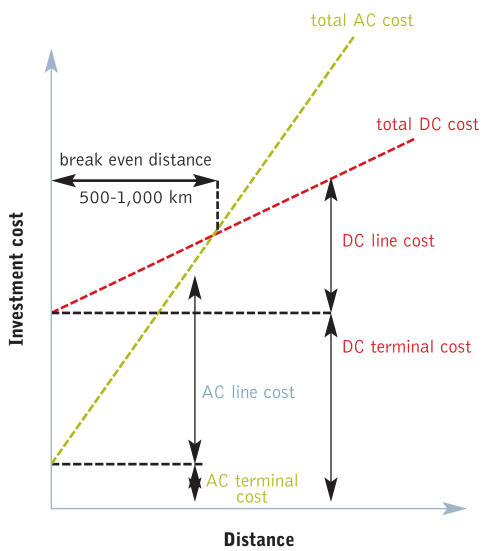


figure 3.4: comparison of the required number of parallel pylons and space to transfer 10 GW of electric capacity

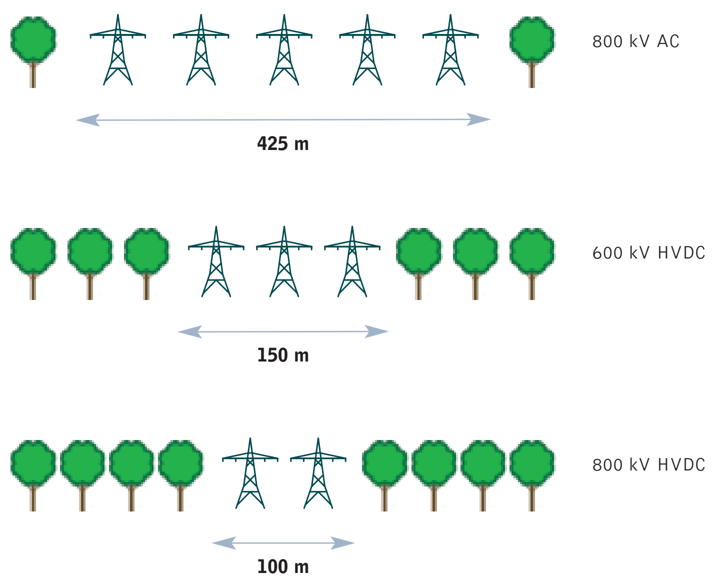


image BORKUM RIFFGAT, ALSO KNOWN AS OWP RIFFGAT IS AN OFFSHORE WIND FARM UNDER CONSTRUCTION 15 KILOMETRES TO THE NORTH-WEST OF THE GERMAN ISLAND OF BORKUM. THE WIND TURBINES ARE BUILT ACROSS AN AREA OF 6 SQUARE KILOMETRES. IT WILL CONSIST OF 30 TURBINES WITH A TOTAL CAPACITY OF 108 MEGAWATT (MW), AND IS EXPECTED TO GENERATE ENOUGH ELECTRICITY FOR 112,000 HOUSEHOLDS.

GREENPEACE

Greenpeace is a global organisation that uses non-violent direct action to tackle the most crucial threats to our planet's biodiversity and environment. Greenpeace is a non-profit organisation, present in 40 countries across Europe, the Americas, Africa, Asia and the Pacific. It speaks for 2.8 million supporters worldwide, and inspires many millions more to take action every day. To maintain its independence, Greenpeace does not accept donations from governments or corporations but relies on contributions from individual supporters and foundation grants. Greenpeace has been campaigning against environmental degradation since 1971 when a small boat of volunteers and journalists sailed into Amchitka, an area west of Alaska, where the US Government was conducting underground nuclear tests. This tradition of 'bearing witness' in a non-violent manner continues today, and ships are an important part of all its campaign work.

Greenpeace Germany
Hongkongstraße 10,
20457 Hamburg, Germany
t +49 40 306 180
www.greenpeace.de

image EARTH'S CITY LIGHTS. EVEN MORE THAN 100 YEARS AFTER THE INVENTION OF THE ELECTRIC LIGHT, SOME REGIONS REMAIN THINLY POPULATED AND UNLIT. ANTARCTICA IS ENTIRELY DARK. **front cover images** ANDASOL 1 SOLAR POWER STATION IS EUROPE'S FIRST COMMERCIAL PARABOLIC TROUGH SOLAR POWER PLANT. © GREENPEACE / REDONDO. HIGH VOLTAGE POWER LINES IN GERMANY. © GREENPEACE / LANGROCK. FULLY DARK (CITY LIGHTS) IMAGE OF EUROPE. © AVHRR, NDVI, SEAWIFS, MODIS, NCEP, DMSP AND SKY2000 STAR CATALOG.