

## Impact of Variable Renewable Energy on European Cross-Border Electricity Transmission

Carlo Brancucci Martínez-Anido<sup>1,2</sup>, Laurens de Vries<sup>2</sup>, Gianluca Fulli<sup>1</sup>

<sup>1</sup>European Commission, Joint Research Centre, Institute for Energy and Transport,  
Westerduinweg 3, Petten, 1755LE, The Netherlands.

<sup>2</sup>TU Delft, Infrastructure Systems and Services Department, Energy and Industry,  
Jaffalaan 5, 2628BX, Delft, The Netherlands.

[carlo.brancucci@ec.europa.eu](mailto:carlo.brancucci@ec.europa.eu), [L.J.deVries@tudelft.nl](mailto:L.J.deVries@tudelft.nl), [gianluca.fulli@ec.europa.eu](mailto:gianluca.fulli@ec.europa.eu)

**Abstract.** *The estimated growth of Europe's electricity demand and the policy goals of mitigating climate change result in an expected increase in variable renewable energy. A high penetration of wind and solar energy will bring several new challenges to the European electricity transmission network. The objective of this paper is to understand the effects of a high penetration of variable renewable energy sources (RES) on the demand for cross-border electricity transmission in Europe. EUPowerDispatch, a minimum cost dispatch model is used to compare the impacts of different electricity generation and transmission portfolios on cross-border electricity transmission in 2025. The analysis makes use of the best-estimate scenario developed by the European Network of Transmission System Operators for Electricity (ENTSO-E). Wind and solar energy curtailment needs and variations in load duration curves are analyzed for different scenarios. In addition, the role of hydro energy storage and pumping is analyzed as a complementary technology to transmission in the context of a high penetration of variable RES. The study shows that the planned expansion of the European transmission network is adequate for meeting the expected RES increase and it is needed to maintain the current level of security of supply in the face of the expected demand growth. If RES growth is faster than expected, cross-border transmission capacity will have to increase accordingly if significant RES curtailment is to be avoided.*

**Keywords.** *Renewable Energy, Electricity Transmission, Hydro Storage.*

### 1 Introduction

The European Commission (EC) recently called for a European power sector which “can almost totally eliminate CO<sub>2</sub> emissions by 2050” (EC, 2011). Such an ambitious target is needed to reduce greenhouse gas (GHG) emissions by about 80% by that time across the economy. The full decarbonization of the power sector is technically feasible but requires substantial investment. The most critical ones for managing the transition from today's reality are grid extension, renewable energy sources (RES) and carbon capture and storage (CCS) deployment and increased energy efficiency (Roadmap2050, 2011).

In order to reach a fully decarbonized European power sector by 2050, the electricity network must undergo several challenges in the nearer future. First of all, in 2009 the EU adopted the Renewable Energy Directive (EC, 2009), which endorsed a mandatory target of 20% share of energy from RES. Such a target implies that 34% of EU's electricity consumption will come from RES. This target must be met with an estimated growth of electricity consumption in Europe of 30% in 2025 compared to 2010 levels (ENTSO-E, 2011). RES deployment expectations represented in several scenarios, designed by different European organizations, converge around the previously mentioned target (EWEA, 2011).

ENTSO-E's 2025 best-estimate scenario (ENTSO-E, 2011) is used as reference for the net generation capacity of each energy source in every European country in the analysis. Power generation is modeled within EUPowerDispatch, a minimum cost dispatch model developed by the EC's Joint Research Centre (JRC) Smart Electricity Systems research group (SES, 2012).

The objective of this paper is to model the European cross-border electricity network flows in 2025 in order to study the impacts of variable RES on the demand for cross-border transmission capacity. Interconnection capacity is considered a key element in the integration of RES around Europe. A lack of coordination between all actors in the European power system, including generation and transmission players, may lead to underinvestment (Ifri, 2012). In this paper, we ask the question whether the planned cross-border transmission capacity investments for 2025 are adequate, considering the assumed generation scenarios, which include a high RES penetration? We evaluate the impact of transmission capacity on the curtailment of wind and solar energy.

Variable RES penetration is not only constrained by cross-border transmission. Internal transmission and distribution congestion, as well as network stability concerns, can also hinder RES generation. In order to evaluate these potential issues, load duration curves (LDCs) are considered for the overall European power network as well as for single countries. The impacts of wind and solar variable electricity production on national LDCs are studied.

Finally, the role of hydro energy storage and pumping in a power grid with a high RES penetration is studied. In addition, optimized annual hydro reservoir management is analyzed for different scenarios.

The paper is structured as follows. Section 2 describes the methodology and the scenarios. Section 3 provides the results and section 4 analyses them. Finally, section 5 summarizes the main outcomes of the study and proposes future work.

## 2 Methodology & Scenarios

The model EUPowerDispatch is used in order to study the impacts of variable RES on the European cross-border transmission capacity needs in 2025. EUPowerDispatch models 32 interconnected European countries, each represented as a single node, meaning that internal network constraints are not considered. Cross-border network capacities are considered and cross-border electricity exchanges are modeled.

Installed net generation capacities per energy source for each node and maximum cross-border interconnection capacities are the major inputs to the model. The main model outputs which are analyzed within the scope of this paper are RES curtailment needs and load not served.

### 2.1 Model Definition

EUPowerDispatch is a minimum cost dispatch model, the optimization of which is coded in the General Algebraic Modeling System (GAMS, 2012). CPLEX, a high-performance mathematical programming solver (IBM, 2012) is used to solve the model coded in the form of a mixed-integer linear problem. The objective function is the minimization of annual electricity variable production costs in the interconnected European power network.

The model covers a time-frame of one year with a time-step of one hour. A preliminary run covering a whole year and with weekly time-steps sets the hydro seasonal reservoir levels at the start and end of each week at each node. The reservoir levels are inputs for 52 runs, each covering a week, with one hour time-step. All the variables are modeled within the weekly run apart from the hydro seasonal reservoir levels which have an annual management.

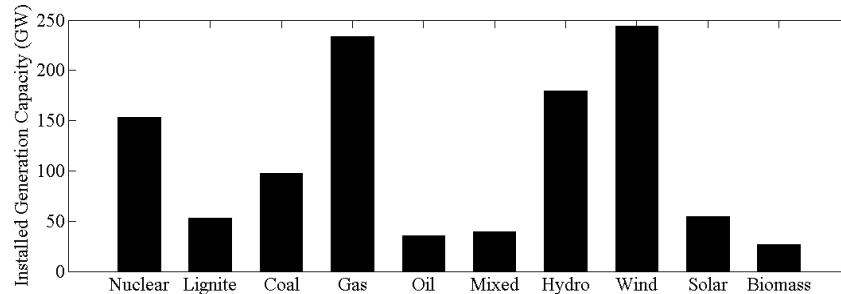
### 2.2 Electricity Consumption

In order to model electricity demand in 2025 for each European country included in the model, one hour national time-series (ENTSO-E 2012) for year 2010 are considered. Individual national demand growths up to 2025 are calculated (ENTSO-E, 2011), (EC, 2010). Overall electricity consumption in the European countries considered will increase by 30% in 2025 compared to 2010.

### 2.3 Generation

Power generation is modeled at each node for different energy sources: nuclear, fossil fuels, hydro and renewable energies. A virtual power plant for each energy source represents the total net installed generation capacity at each node based on the 2025 best-estimate scenario (ENTSO-E, 2011). Generation availability factors are considered for each energy source (e.g. 84.5% for nuclear and 90% for fossil fuels) and take into account power plant's planned and unplanned unavailability.

Fig. 1 shows the total installed generation capacities in Europe in 2025 for each energy source.



**Fig. 1.** Total installed generation capacities in Europe in 2025.

Different operational constraints are considered for each energy source. Nuclear virtual power plant output is constrained between 70 and 100% of the available power. Fossil-fired power plants are divided in the following categories: lignite, hard coal, gas, oil and mixed fuels (oil and gas).

Lignite and hard coal virtual power plants are modeled differently from the other ones. They are considered base load generation plants and their slower and costly turn-on, ramp-up and shut-down times must be taken into account. The model divides the total installed capacity of either lignite or hard coal power plants in a country in single units of around 750 MW. Each unit is represented by a binary variable allowing switching the power plant on or off and keeping the time between shut-down and start-up and vice versa to a minimum of 4 hours. The present available computational capabilities do not allow stricter constraints and therefore it is assumed that lignite and hard coal power plants always have a hot start-up. Their unit power output is limited between 70 and 100% of the rated available capacity.

Gas, oil and mixed fuels power plants are considered fast-reacting and therefore the corresponding virtual power plant output is not constrained taking into account the one-hour time-step.

Renewable energy sources including wind (both onshore and offshore), solar photovoltaic (PV) and biomass are separately modeled as a virtual power plant at each node. 2010 6-hour wind speed time series (Kalnay et al., 1996) with a 2.5° latitude – longitude spatial resolution and linearly interpolated in time, are used together with regional wind farm installed capacity data (Toorn, 2007) in order to obtain average onshore and offshore wind power outputs for each hour of the year for each country. For solar energy, 1-hour solar radiation data time-series (Suri et al., 2007), with a 1.51° latitude – longitude spatial resolution, represent the energy output delivered to the grid (kW hour/MW installed). Due to data unavailability, PV installed capacity is assumed to be equally distributed across a single country. The biomass virtual power plant at each node is only constrained by the installed generation capacity. Its weekly availability is constrained to 50% in order to take into account the fuel's accessibility.

In order to simplify the modeling effort and to have a common approach throughout Europe, hydro power plants are classified in three categories: run of river plants with

an uncontrollable generation which depends on natural inflows, seasonal storage plants with an upper reservoir which is fed by a natural inflow and which is managed with seasonal and daily strategies, and finally pure pumping plants which have a daily dispatch strategy and where water is pumped from a lower reservoir into an upper one with no natural inflow. In mountainous countries (e.g. Austria, Norway, Switzerland or Sweden) water can be pumped in seasonal storage reservoirs which are also fed by natural inflows. An ideal flexibility is assumed with negligible start-up, shut-down, ramp-up or ramp-down costs. Reservoir levels are optimized for overall variable electricity production costs only and the lower limits are set to 30% on seasonal reservoir levels in order to partially consider environmental and landscape constraints. Round trip pumping efficiency is assumed to be 75%.

## 2.4 Variable Electricity Production Costs

EUPowerDispatch's objective function is the minimization of the annual European electricity variable production costs. Each energy source has a different variable electricity production cost. It comprises variable maintenance and operational costs, fuel costs and CO<sub>2</sub> taxes. The values, shown in Table 1, result from own calculations and (Korpas et al., 2007). CO<sub>2</sub> price is assumed to be equal to 22.5 Euro/tonne.

**Table 1.** Variable Electricity Production Costs in 2025.

Energy Source	Var. El. Prod. Cost (Euro/MWh)	Energy Source	Var. El. Prod. Cost (Euro/MWh)
Nuclear	11.00	Mixed Fuels	103.59
Lignite	47.61	Wind	0.00
Hard Coal	43.18	Solar (PV)	2.00
Gas	55.88	Biomass	53.09
Oil	98.40	Hydro	3.00

## 2.5 Transmission

EUPowerDispatch models the cross-border electricity flows between the 32 countries considered. Each interconnection is defined by its maximum transfer capacity following an approach developed by RSE (L'Abbate, 2012), which is based on the ENTSO-E's Ten-Year Network Development Plan (TYNDP) 2010-2020 (ENTSO-E, 2010). Fig. 2 shows the assumed maximum cross-border transmission capacities, for both directions, in 2025 for the European countries considered in the model.

Cross-border transmission losses are included in a simple way in order to avoid electricity being transferred across borders at zero cost. Cross-border electricity flows are subject to transmission losses which are proportional to the square root of their geographical areas. In other words, power flows between two geographically large countries are subject to higher losses than between two smaller ones.

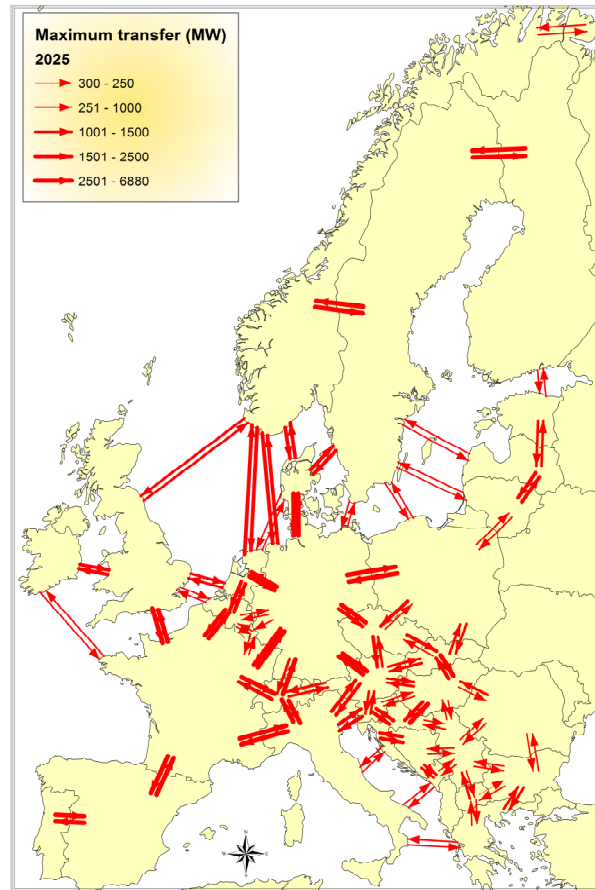


Fig. 2. Maximum cross-border transfer capacities (MW) in 2025.

## 2.6 Scenarios

In order to study the impacts of variable RES on the European cross-border transmission capacity needs in 2025, the base case scenario is compared to three different ones:

- **Scenario A:** RES generation capacity is double compared to the base case scenario.
- **Scenario B:** No cross-border transmission capacity investment is considered after 2010. In other words, 2010 cross-border transmission network is taken.
- **Scenario C:** Both assumptions above are considered.

### 3 Results

Table 2 provides the main results from the EUPowerDispatch simulations for the four scenarios in 2025. Solar and wind curtailment needs are measured as volume of curtailed energy divided by the total potential energy production by that source. Unserved load is calculated in an analogous manner. The last line of the table indicates the volume of energy that is stored in pumped hydro.

**Table 2.** Main Results.

<b>Scenario</b>	<b>Base Case</b>	<b>A</b>	<b>B</b>	<b>C</b>
<b>Solar Curtailment (%)</b>	0.000	0.000	0.000	0.000
<b>Wind Curtailment (%)</b>	0.000	1.276	0.033	2.610
<b>Load Not Served (%)</b>	0.000	0.000	0.498	0.377
<b>Hydro Pumping (TWh)</b>	8.978	9.329	24.580	22.950

Table 3 shows the European countries with higher variable RES share (wind and solar energy) in the energy mix for the base case scenario. The RES share is calculated as the volume of energy that is produced as a percentage of the total volume of electricity generation in the country. In addition, the net generation capacities of wind and solar plants as well as peak load are given.

**Table 3.** Countries with higher RES (wind& solar) share in energy mix (base case scenario).

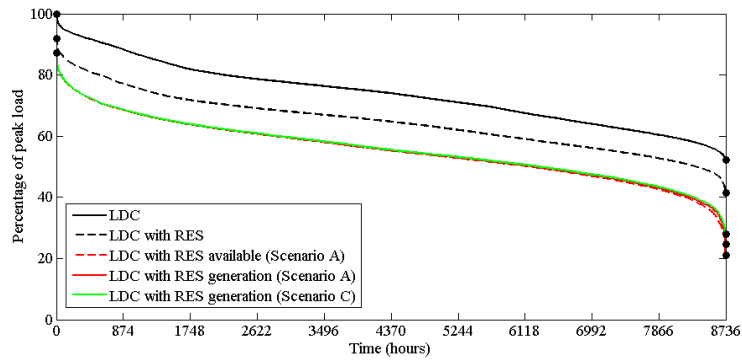
<b>Country</b>	<b>RES (wind &amp; solar) in energy mix (%)</b>	<b>Installed Wind (GW)</b>	<b>Installed Solar (GW)</b>	<b>Peak Load (MW)</b>
<b>Denmark</b>	39.1	6.97	0.00	7214
<b>Portugal</b>	35.1	7.95	0.54	1153
<b>Ireland</b>	33.6	4.89	0.00	6401
<b>Greece</b>	26.7	9.10	2.45	1232
<b>Spain</b>	21.6	40.20	11.20	5774
<b>Latvia</b>	21.0	0.75	0.00	1671
<b>Italy</b>	20.2	21.20	1.50	6932
<b>United Kingdom</b>	19.2	31.12	0	6672
<b>Germany</b>	16.7	52.50	20.00	9993
<b>Belgium</b>	10.8	4.82	2.00	1711

Table 4 shows the European countries with higher wind curtailment needs in scenarios A and C.

**Table 4.** Countries with higher wind curtailment needs (%) for scenarios A and C.

Country	Scenario A	Scenario C
<b>Portugal</b>	8.32	9.12
<b>Ireland</b>	6.59	21.45
<b>Greece</b>	2.84	5.11
<b>Spain</b>	2.84	4.43
<b>United Kingdom</b>	1.71	3.27
<b>Denmark</b>	0.69	5.11
<b>Germany</b>	0.0105	0.3624
<b>Latvia</b>	0.00	8.91
<b>Lithuania</b>	0.00	4.15

Fig. 3 shows the LDC for overall Europe. The solid black line is the load; the dotted is the residual load (load minus variable RES generation) in the base case scenario. The red lines represent scenario A. The dotted red line shows the potential residual load curve if all RES are utilized; the solid red line represents the same scenario, but with curtailment of RES due to cross-border transmission constraints. The green line represents scenario C, in which there is no increase in cross-border transmission after 2010.



**Fig. 3.** LDC for Europe.



Fig. 4 shows the LDC for Portugal, Ireland and Denmark. The lines in the graphs below represent the same scenarios as in Fig. 3.

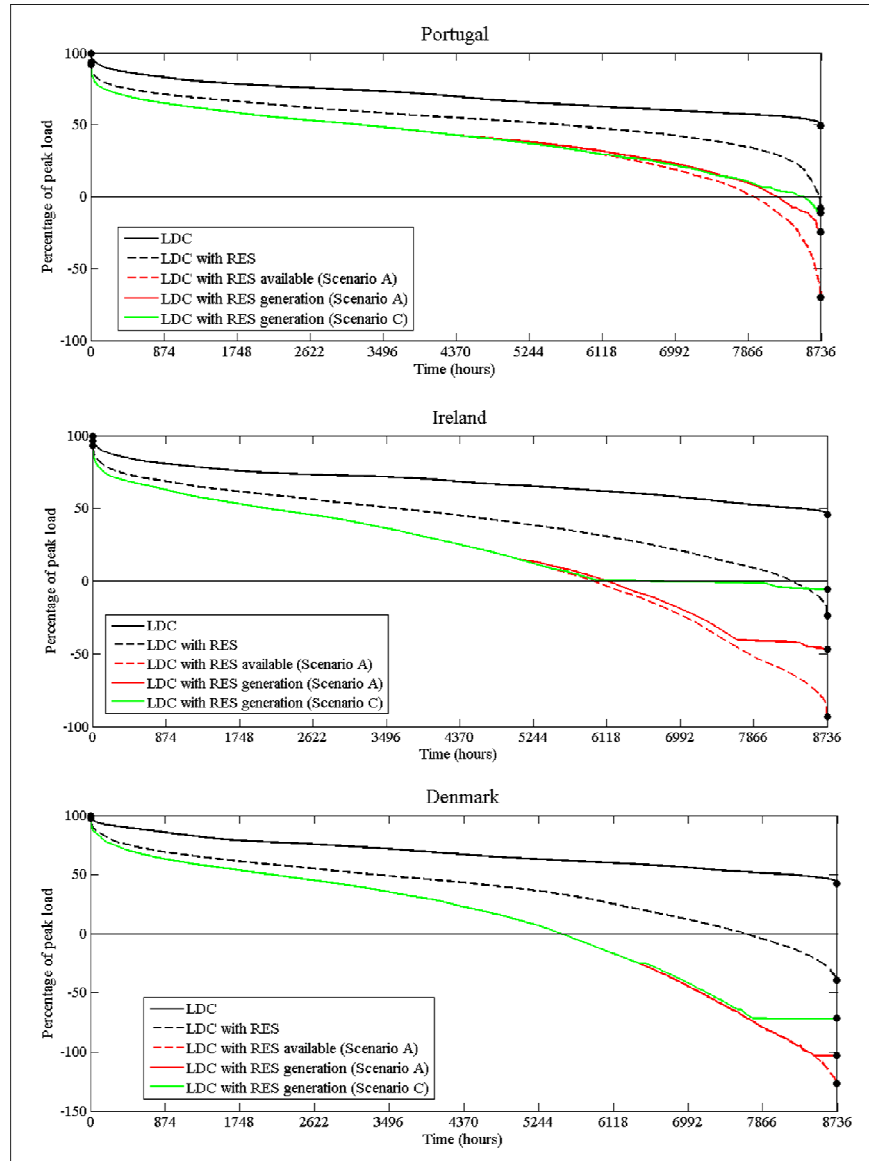
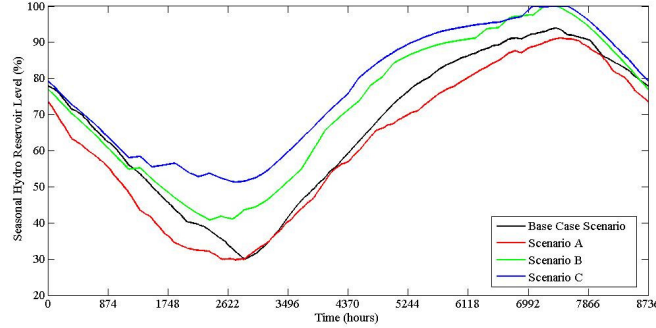


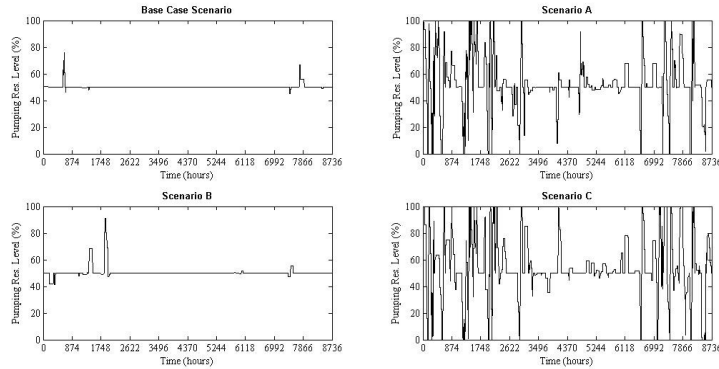
Fig. 4. LDC for Portugal, Ireland and Denmark.

Fig. 5 shows the seasonal hydro reservoir level for Norway (the country with largest total seasonal hydro reservoir) for the four scenarios.



**Fig. 5.** Seasonal Hydro Reservoir Level for Norway for the four scenarios.

Fig. 6 shows the small pumping hydro reservoir level for Spain for the four scenarios.



**Fig. 6.** Small Pumping hydro reservoir level for Spain for the four scenarios.

#### 4 Analysis

The objective of this paper is to understand the impact of variable RES on the European cross-border electricity transmission network in 2025. First of all, the need to curtail solar and wind energy was analyzed. As shown in Table 2, solar curtailment is never needed in any of the four scenarios under analysis. Solar energy is assumed to have zero variable electricity production cost and it is always dispatched fully. Wind is also not curtailed in the base case scenario. These two results indicate that the planned cross-border transmission investments by 2025 are adequate in order to avoid

variable RES curtailment. (Note that we only analyzed the impact of cross-border transmission capacity on curtailment; we cannot exclude the possibility that curtailment may be necessary due to constraints within the national networks.)

In scenario B, in which cross-border transmission capacities are kept the same as in 2010, solar curtailment still is zero and wind curtailment is insignificant, below 0.1% of the available wind power. This result would suggest that no cross-border transmission capacity investments are needed by 2025. However, in this case there would be an equivalent of about two days of unserved load for the whole European region, so the transmission capacity is needed for security of supply. In addition, several model assumptions must be taken into account. For instance, internal transmission and distribution congestion and a more realistic representation of start-up costs and time of base load power plants are not considered due to data and computational capacity constraints. Curtailment needs for variable RES would be larger if the latter two features would be considered.

In scenarios with high volumes of variable RES generation, scenarios A and C, the need to curtail wind increases. Curtailment is highest in scenario C in which the cross-border transmission capacities are smaller. Table 3 and Table 4 show how countries with higher variable RES shares in their energy mix have higher wind curtailment needs. The two countries with the highest wind curtailment needs in scenarios A and C are Portugal and Ireland, which are only interconnected with one and two other countries respectively. This result illustrates the importance of cross-border transmission in a power network with a high share of RES. We may conclude that if the variable RES penetration in Europe turns out to be higher than in ENTSO-E's best-estimate scenario, the importance of investment in cross-border transmission capacity becomes even more important for the energy transition. At this point, for instance, Italy already has more installed photovoltaic capacity than is expected in 2025 in the ENTSO-E best-estimate scenario (GSE, 2012).

The model shows that cross-border electricity exchanges do not substitute the need for backup generation capacity. When looking at Portugal, Ireland and Denmark (Fig. 4), it can be observed how the need to curtail wind increases as the RES generation capacity increases as a result of cross-border transmission constraints. This effect becomes larger, of course, when cross-border transmission capacity is lower.

Another interesting and challenging issue when increasing the variable RES penetration is the possible negative effects that it can cause on the power network stability. Fig. 4 shows how in Denmark there are several hours in the year in which available RES generation is higher than peak demand. There are many more hours in the year in which RES generation is larger than the electricity load at that moment, mainly in low demand periods. During these hours, the excess RES generation needs to be exported or curtailed. This effect increases with more RES generation capacity and is visible for Portugal and Ireland as well. Can a power network manage a variable RES generation which is higher than the load in a secure and reliable way?

Cross-border electricity transmission is not the only helpful and necessary feature of a power system for managing a high penetration of RES. Hydro reservoirs are a crucial element for managing more efficiently the variability of RES. As shown in Fig. 5, hydro generation is managed and controlled differently depending on the installed

RES and on the available transmission capacities. Hydro pumping is also very important for managing RES. Spain is one of the countries with higher RES penetration and hydro pumping capacity. As shown in Fig. 6, hydro pumping in pure pumping stations increases exceptionally as RES capacity is doubled. This increase is also noticed if cross-border transmission capacity is decreased. Table 2 shows how in Europe hydro pumping triplicates in 2025 if cross-border transmission investments are not considered since 2010. These results show how energy storage, in this case hydro storage and pumping, is a complementary technology to electricity transmission in the context of a large RES penetration.

#### 4 Conclusions & Future Work

The planned expansion of the European transmission network is adequate for meeting the expected increase in variable renewable energy generation, as described in the ENTSO-E's TYNDP and best-estimate scenario (2011-2025). The planned expansion of cross-border transmission capacity is also needed to maintain the current level of security of supply in the face of the expected demand growth. If the growth in renewable energy is faster than expected, cross-border transmission capacity will have to increase accordingly if significant curtailment of renewable energy sources is to be avoided. Cross-border transmission capacity reduces the need for back-up generation capacity to some degree, but it is not a substitute in scenarios with high volumes of renewable energy.

Hydro energy storage and pumping are complementary technologies for managing a European power network with a very large share of variable generation. If in the future other forms of efficient and affordable energy storage would be available, they would definitely contribute to a smoother energy transition.

The needs for cross-border transmission capacity investments will be further analyzed in the future by taking into account the effects on CO<sub>2</sub> emissions and social welfare benefits. In addition, EUPowerDispatch will be used to study the future impacts of electric vehicles and the effects of climate change on the European power network.

**Acknowledgments.** The authors would like to thank Angelo L'Abbate (RSE) for his contribution providing the 2025 expected maximum cross-border transmission capacities and Corina Alecu (EC JRC Smart Electricity Systems research group) for her contribution drawing the European map.

## References

- EC (2009), Directive 2009/28/EC of the European parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable energy sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
- EC (2010), EU Energy Trends to 2030 – update 2009. A report from European Commission DG-Energy.
- EC (2011), A roadmap for moving to a competitive low carbon economy in 2050. European Commission Communication SEC 2011 (211).
- ENTSO-E (2010), Ten-Year Network Development Plan (TYNDP) 2010-2020. <https://www.entsoe.eu/index.php?id=232>
- ENTSO-E (2011), Scenario Outlook & Adequacy Forecasts, 2011 – 2025. <https://www.entsoe.eu/system-development/system-adequacy-and-market-modeling/soaf-2011-2025/>
- ENTSO-E's consumption data. <https://www.entsoe.eu/resources/data-portal/consumption/>. (last accessed on 15 January 2012)
- EWEA, European Wind Energy Association (2011), EU Energy Policy to 2050, achieving 80-95% emissions reductions.
- GAMS, <http://www.gams.com/>. (last accessed on 27 February 2012).
- GSE, Gestore Servizi Energetici, <http://www.gse.it/>. (last accessed on 27 February 2012).
- IBM, <http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/>. (last accessed on 27 February 2012).
- Ifri, Institut français des relations internationales (2012), The European Power System, Decarbonization and Cost Reduction: Lost in Transmission?
- Kalnay et al. (1996), The NCEP/NCAR 40-year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437-470.
- Korpas, M., Warland, L., Tande, J.O.G., Uhlen, K., Purchala, K., Wagemans, S. (2007), TradeWind Deliverable D 3.2 Grid modelling and power system data.
- L'Abbate, A. (2012), Transmission interconnections database, RSE, 2009-2011.
- Roadmap2050 (2011), Power Perspectives 2030, on the road to a decarbonised power sector. A contributing study to roadmap 2050: a practical guide to a prosperous, low-carbon Europe.
- SES, Smart Electricity Systems, <http://ses.jrc.ec.europa.eu/>. (last accessed on 27 February 2012).
- Suri, M., Huld, T., Dunlop, E., Ossenbrink, H. (2007), Potential of Solar Electricity Generation in the European Union Member States and Candidate Countries, SOLAR ENERGY vol. 81 no. 10 p. 1295-1305.
- Toorn G. (2007), EU Tradewind, WP2.1: Wind Power Capacity Data Collection. [http://www.trade-wind.eu/fileadmin/documents/publications/D2.1\\_Scenarios\\_of\\_installed\\_wind\\_capacity\\_WIT\\_H\\_ANNEXES.pdf](http://www.trade-wind.eu/fileadmin/documents/publications/D2.1_Scenarios_of_installed_wind_capacity_WIT_H_ANNEXES.pdf)