Technical University of Denmark

TradeWind Deliverable 5.1: Effects of increasing wind power penetration on the power flows in European grids

Lemström, Bettina; Uski-Joutsenvuo, Sanna; Holttinen, Hannele; Cutululis, Nicolaos Antonio; Sørensen, Poul Ejnar; Warland, Leif; Korpås, Magnus; Kreutzkamp, Paul

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

Further Developing Europe's Power Market
for Large Scale Integration of Wind Power

Effects of increasing wind power penetration on the power flows in European grids

Bettina Lemström, Sanna Uski-Joutsenvuo, Hannele Holttinen
VTT

Nicolaos A Cutululis, Poul Sørensen
Risø DTU

Leif Warland, Magnus Korpås
SINTEF Energy Research

Paul Kreutzkamp
dena

October 2008

Agreement n.:	EIE/06/022/SI2.442659
Duration	November 2006 – October 2008
Co-ordinator:	European Wind Energy Association
Supported by:	Intelligent Energy Europe

Document information

Document Name:	Effects of increasing wind power penetration on the power flows in European grids
Document Number:	D5.1
Authors:	B. Lemström, S. Uski-Joutsenvuo, H. Holttinen, N. Cutululis, P. Sørensen, L. Warland, M. Korpås, P. Kreutzkamp
Date:	04.02.2008
WP:	WP5
Task:	Task 5.1, 5.2 and 5.3
Revision:	
Approved:	

Diffusion list

All TradeWind Consortium Partners

Documents history

Revision	Date	Summary	Author
01			
02			
03			

CONTENTS

APPENDIXES

1. Installed wind power per country (MW) and its geographical distribution in the scenarios

2. Simulation results; power line congestion sensitivities between countries

3. Simulation results; interconnection congestion sensitivities between countries due to NTC

4. Simulation results; power exchange congestion (due to NTC) hours and power flow duration hours between countries

5. Simulation results; power exchange congestion (due to line ratings) hours

6. Capacity factors during peak load situations

7. Detailed description of the capacity credit calculations using the probabilistic approach

1 INTRODUCTION

This report presents the main activities and results of *Work Package 5 – Effects of increasing wind power penetration on the power flows in European grids* in the TradeWind project.

VTT is the leader of Work Package 5 and carries the overall responsibility of this report. The work is based on power flow simulations with a grid and market model developed in TradeWind Work Package 3, led by Sintef Energy Research.

VTT, Sintef Energy Research and Risø have carried out the simulations of the different scenarios, analysed the results and written Chapter 4 about the *impact of wind power on cross-border transmission*. Risø has written section 4.2 about the *impact of prediction errors of wind power production.*

VTT has carried out the *model evaluation* described in Chapter 3. Furthermore VTT has analysed the *wind speed data*, studied the *moving weather effects* and the *capacity factor method* presented in section 2.1, Chapter 5 and section 6.1, respectively.

dena has made the calculations with the *probabilistic method* and written section 6.2.

2 METHOD AND INPUT DATA

2.1 Wind speed data

The wind speed data used in the TradeWind project are obtained from Reanalysis data for the whole of Europe, see Tradewind deliverables D2.3 [1] and D2.4 [2]. The RDP data are determined and given for every 6^{th} hour for data point squares of about 140…230 x 280 km each, depending on the latitude. This approach ensured consistency of simultaneous weather data for all of Europe – for some countries hourly wind power production data would be available, but for most countries not. Also the future offshore site data would have to be generated and simulated in some way if using measured wind power production data as the starting point. The Reanalysis data are not as accurate as measured wind power production data (see D2.3 [1]) but are considered to capture the broad overall production over Europe.

The wind data was scaled up to represent wind speeds at hub height of a wind turbine. The upscaling factors were terrain specific (lowland 1.0, highland 1.2, offshore 1.3). In addition to this an upscaling factor was used for Spain, Poland, Greece and Austria and downscaling for Great Britain, Ireland and Germany, Belgium, Netherlands and Italy to correct for the general wind speed over or underestimation perceived in the data in the validation process of WP2 (deliverable D2.3 Characteristic Wind speeds [1]).

The wind data was converted to wind power production data using power curves. These are regional power curves – not single turbine power curves – to account for large scale regional power production. The procedure linking the Reanalysis grid points to the simulations nodes /country-wise wind power production is described in TradeWind deliverable D2.4 [2].

The RDP data were 6 hourly and were interpolated to make hourly data for the simulations. This has the effect of reducing the variability in the data. This was checked for Denmark: The standard deviation value from the time series of hourly variations for large scale wind power production data available at www.energinet.dk are 3.4 % for Denmark East and 3.2 % for Denmark West. From the RDP hourly variability time series the corresponding values were 2.5 % for Denmark East and 2.2 % for Denmark West. This shows that the RDP data underestimates the variability for power production time series. However, this difference was considered to be small enough to produce a reasonably small error in the results presented in this report.

Wind data are for 7 years; 2000-2006. The simulations have been made for one year. For the simulations a year with high winds is sought for, as that will represent the more challenging cases for wind integration. According to an analysis of the yearly capacity factors from the wind data for each country, year 2004 was selected as the simulation year. Year 2004 was among the best three in all investigated areas and the best for Germany that is dominating the actual wind power production in installed capacity.

The best years according to average power production are:

- For GB/Ireland 2004, 2003, 2005
- For Germany 2002, 2004, 2005
- For Spain 2001, 2002, 2004
- For Nordic countries 2005, 2000, 2004

The best years according to the amount of time of high power production (>80 of % capacity) are:

- For GB/Ireland 2004, 2005, 2003 (same years, different order)
- For Germany 2004, 2005, 2002 (same years, different order)
- For Spain 2001, 2002, 2004 (same)
- For Nordic countries 2005, 2000, 2004 (same)

Wind production index data would suggest choosing year 2000: highest wind years for Germany (2000, 2002, 2004), Denmark (2004, 2002, 2000), Netherlands (year 2000 or 2002) and Sweden (2000, 2004, 2002).

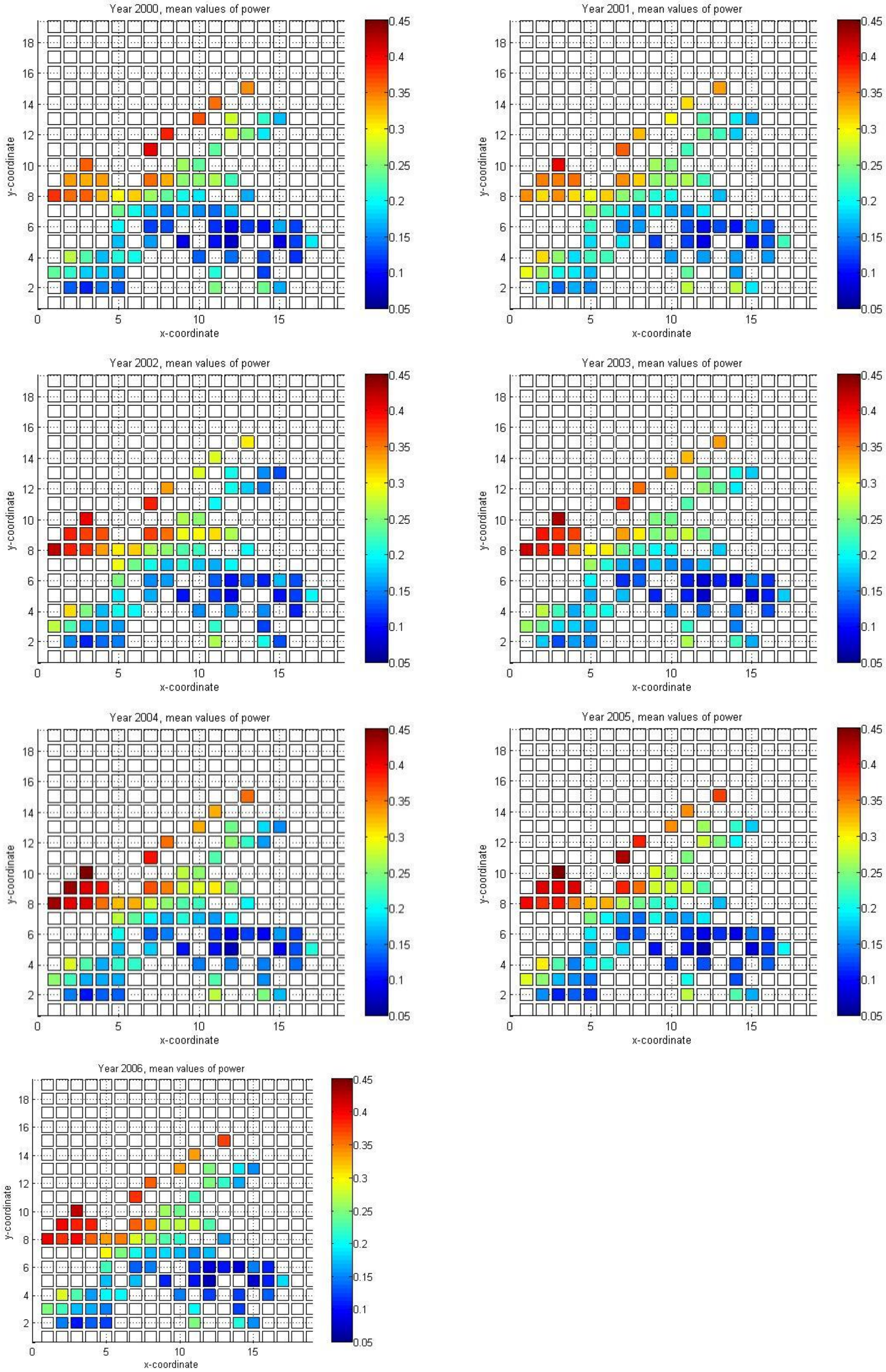


Figure 1. Average power in the reanalysis data points for different years (before the country-correction factors, for comparison between the years only).

Statistics and graphs of wind/power data are presented in Figure 1 and Table 1.

Table 1. Average power in 28 model simulation points that have most of the installed power (before the country-wise correction factors, so for comparison between the years only): Year 2004 is among the highest average power years for most points.

RDP	Reanalysis points/zones	Capacity 2008 mid	Average power	Max year	2000	2001	2002	2003	2004	2005	2006
143	GER1	8932	21 %	22 %	19 %	20 %	**22 %**	19 %	**22 %**	**21 %**	**21 %**
161	DEN2-2, GER2	8592	27 %	29 %	25 %	25 %	**29 %**	25 %	**28 %**	**28 %**	26 %
59	PRT1, ESP3, 11	4042	29 %	31 %	27 %	**31 %**	**31 %**	27 %	28 %	**30 %**	28 %
61	ESP2-2,7-2,12,15,216	3280	17 %	18 %	**17 %**	**18 %**	**17 %**	**17 %**	**17 %**	15 %	16 %
142	GER3	2851	22 %	23 %	20 %	21 %	**23 %**	20 %	**23 %**	**22 %**	**23 %**
42	ESP6, ESP13	2480	17 %	19 %	18 %	**19 %**	17 %	**18 %**	17 %	15 %	16 %
140	NED1, NED2	2228	26 %	29 %	26 %	25 %	27 %	24 %	**28 %**	27 %	**29 %**
49	ITA4	2142	22 %	24 %	21 %	**24 %**	22 %	22 %	**23 %**	20 %	20 %
141	GER5-1	1462	24 %	26 %	23 %	23 %	25 %	22 %	**25 %**	24 %	**26 %**
122	GER5-2	1462	16 %	17 %	14 %	**16 %**	**17 %**	14 %	**16 %**	14 %	**17 %**
43	ESP2-3, 8-2,9-1	1439	16 %	17 %	**16 %**	**17 %**	**16 %**	**17 %**	**16 %**	14 %	15 %
139	BEL2, GBR4-1	1383	32 %	35 %	32 %	32 %	32 %	30 %	**33 %**	**33 %**	**35 %**
30	ITA5	1377	26 %	27 %	24 %	**27 %**	**27 %**	**27 %**	**27 %**	**27 %**	24 %
40	PRT2	1349	23 %	26 %	22 %	**26 %**	23 %	24 %	22 %	**25 %**	22 %
106	AUT	1015	12 %	14 %	11 %	**13 %**	**14 %**	11 %	12 %	12 %	12 %
180	DEN2-1	1013	26 %	28 %	26 %	26 %	**27 %**	25 %	**27 %**	**28 %**	26 %
174	GBR3-1	1012	42 %	46 %	36 %	41 %	41 %	43 %	**45 %**	**46 %**	42 %
60	ESP5, ESP7-1	953	23 %	25 %	**23 %**	**25 %**	**25 %**	22 %	**23 %**	**23 %**	**23 %**
41	ESP7-3, ESP10	916	18 %	20 %	18 %	**20 %**	17 %	**19 %**	17 %	17 %	17 %
162	DEN1, DEN3-2, GER7, SWE4-1	871	27 %	30 %	26 %	26 %	**30 %**	26 %	**29 %**	28 %	27 %
39	PRT3	746	26 %	29 %	23 %	**29 %**	**27 %**	26 %	25 %	**29 %**	25 %
23	ESP1-3, ESP14	702	14 %	17 %	15 %	**17 %**	14 %	**16 %**	13 %	13 %	13 %
155	GBR3-2	675	37 %	41 %	33 %	34 %	37 %	38 %	**41 %**	**41 %**	**39 %**
62	ESP2-1	658	21 %	22 %	**21 %**	**22 %**	**21 %**	**21 %**	**22 %**	19 %	20 %
154	IRL1,IRL2	650	39 %	43 %	33 %	35 %	39 %	39 %	**43 %**	**41 %**	40 %
63	FRA3-1,ESP8-1	587	21 %	22 %	20 %	**22 %**	20 %	**21 %**	**22 %**	**21 %**	20 %
67	ITA2, ITA3	561	15 %	16 %	13 %	**16 %**	**15 %**	**16 %**	**15 %**	13 %	**15 %**
102	FRA2	560	13 %	15 %	12 %	**15 %**	**15 %**	12 %	**13 %**	12 %	**13 %**

2.2 Installed wind power capacity

Wind power capacities used in this study are described and published in detail in TradeWind deliverable D2.1 [3].

For each scenario year there are three wind power scenarios: Low, Medium and High. The Medium scenario is the outcome the TradeWind consortium sees most likely; the High and Low are the highest and lowest credible outcomes. The total installed wind power capacity of the countries included in the grid model is shown in Figure 2. The wind power capacity increases more than six folded from the actual amount of 42 GW in the year 2005 to 268 GW in the medium scenario of 2030. An overview of country specific wind power capacity scenarios and total capacities at European level are shown in Appendix 1.

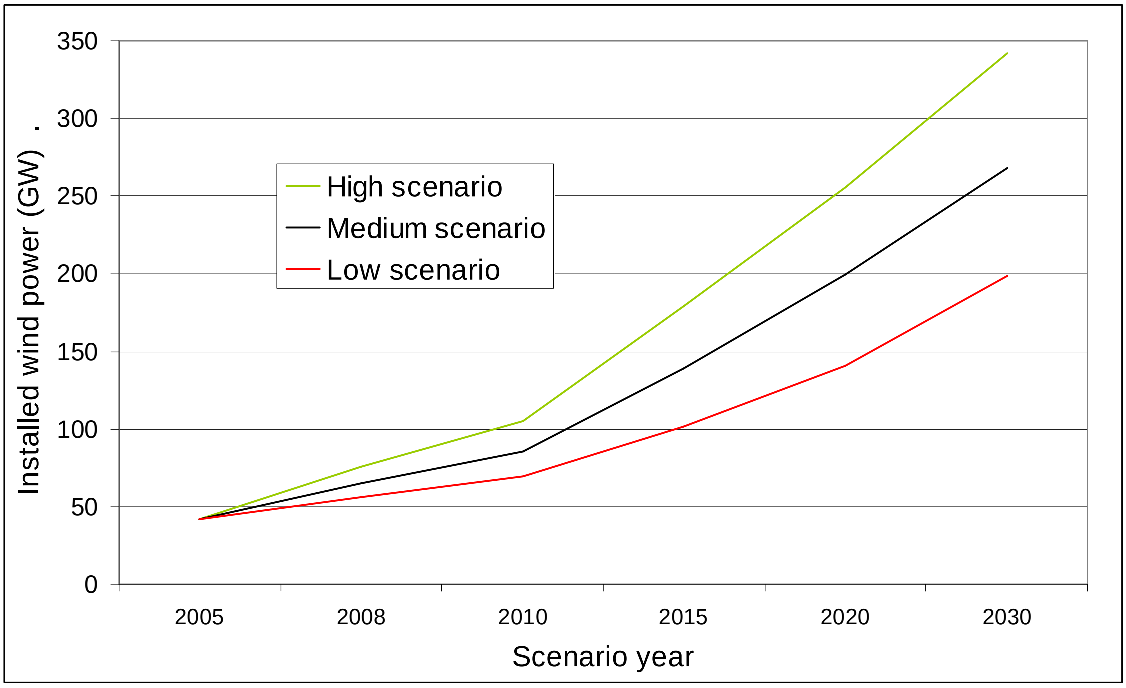


Figure 2. Installed wind power capacity in different scenarios and years.

The wind power capacity of each country is regionally allocated to one or more geographical zones within that country. The zones are in turn connected to nodes of the grid model. Each zone is facing the wind from one or several Reanalysis points. The wind power capacities are split between offshore and two types of onshore wind power (lowland, upland), each of these having their own aggregated power curve [4]. The wind power capacity at each Reanalysis point is visualised and presented in Appendix 1.

In order to assess the impact of wind power on power flow and the congestion of cross-border connections, a case with no additional wind power is used as basic reference case. The wind power capacities in this case are the actual wind power capacities of the countries concerned in the year 2005.

2.3 Other generation

In the simulation model two other-than-wind generation scenarios, named Generation A and Generation B, are applied. The scenarios are described in more detail in TradeWind deliverable D3.2 [5] and in [6].

The generation scenarios A and B differ from each other only on UCTE, while values of Nordel, UK and Ireland are the same in both scenarios. Other-than-wind generation scenario for other countries than those in UCTE, were obtained from EURPROG Statistics [7]. The year 2030 is only specified for scenario B, and those values are obtained for all countries from EURPROG Statistics.

The scenario Generation B was chosen to be used for these WP5 simulations as it includes future power plants whose commissioning is considered probable, whereas scenario Generation A only considered those future power plant projects that are firm in the UCTE. Total capacities in both scenarios are shown in Figure 3 together with the Medium wind power scenario.

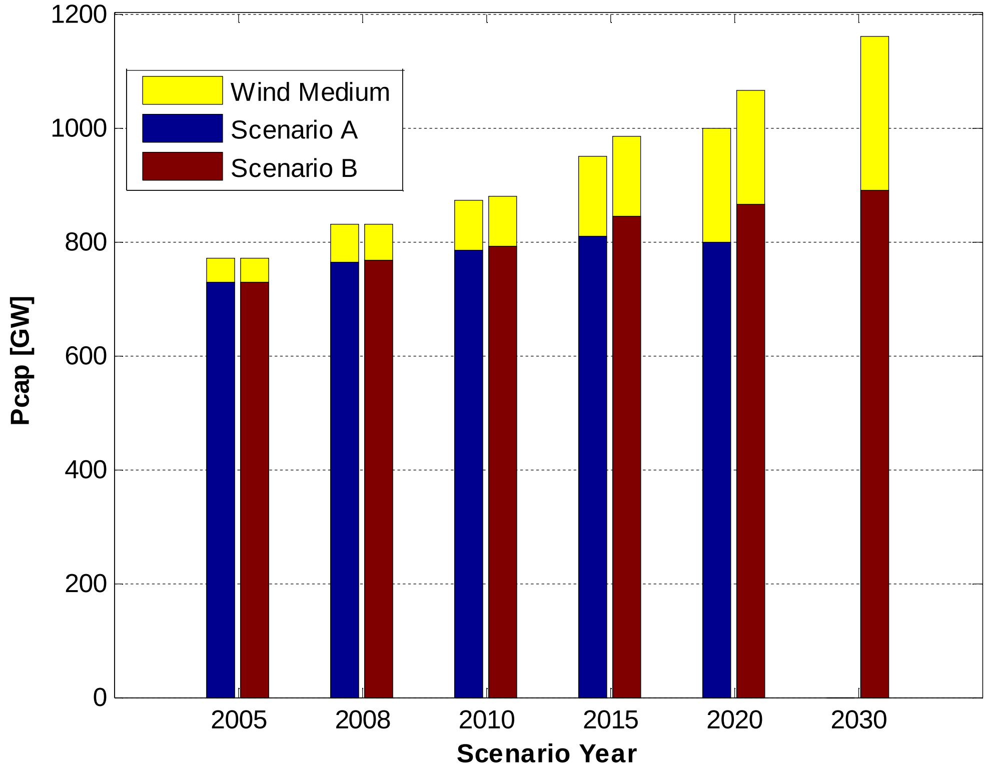


Figure 3. Medium wind power scenario and other-than-wind power production capacity scenarios A and B.

2.4 Load data

The load data used in the simulations are from TradeWind deliverable D3.1 [8] and the data application in the simulation model is described in more detail in deliverable D3.2 [5]. The load data consist of country-wise load profiles of year 2006, and relative load value coefficient of the year to be simulated to year 2006 load. Thus the load for year to be simulated is determined by the load profile and load value coefficient for each load component in the model.

2.5 Grid model

The grid model used for the simulations is a combination of separate equivalent power system models of UCTE, Nordel and the Great Britain and the island of Ireland. The European grid model is composed by combining these three models together. The created 2005 base model consists of 1380 nodes, 2220 branches, 9 HVDC connections and 560 generators of other type than wind. Wind power production is aggregated in total 129 buses. A description of the grid model can be found in deliverable D3.2 [5] and its appendix [9].

Also future HVDC and HVAC lines are included in the model, see Table 2. New lines are used in the simulation in case they are scheduled to be in operation that particular simulation year.

Table 2. New lines and their thermal capacity.

Year	Connection	Capacity [MW]	Type	Info
2008	B - FR	400*	AC	Chooz - Jamiolle - Monceau
	GR - MK	1420	AC	Bitola - Florina
	AT - CZ	1386	AC	2d line Slavetice - Durnrhor
2010	ES - FR	3100	AC	France – Spain: eastern
	DE - DKW	1660	AC	Upgrading of Jutland - Germany
	N - NO	700	HVDC	NORNED
	DKW - DKE	600	HVDC	Great Belt
	IR - GB	500	HVDC	East-West interconn.
2015	IT- SV	3100	AC	Udine - Okroglo
	NO - SE	800*	AC	Nea - Jarpsstrommen
	P - ES	1500	AC	Valdigem – Douro Int. – Aldeadavilla
	P - ES	3100	AC	Algarve - Andaluzia
	P - ES	3100	AC	Galiza - Minho
	RO - SC	1420	AC	Timisoara - Varsac
	NL - GB	1000	HVDC	BritNed
	SE - SF	800	HVDC	Fenno Scan2
2020	AT - IT	3100	AC	Thaur – Bressanone
	AT - HU	1514	AC	Wien/Südost - Gÿor
	AT - IT	530	AC	Nauders - Curon / Glorenza
	AT - IT	3100	AC	Lienz - Cordignano
	NO - DKW	600	HVDC	Skagerrak 4
	NO - DE	1400	HVDC	NorGer

2.6 Transmission restrictions

In the grid model, restrictions on individual connections are included, as well as restrictions in total cross-border transfer. The individual connection restrictions are usually the thermal line limit or summed limits of equivalent of connections. The cross-border limits are defined for transfer between interconnected systems and are usually weaker than connections within the countries.

For cross-border transfer limits the transmission system operators (TSOs) define Net Transfer Capacities (NTCs). NTCs are specified and publicly available for a couple of load/transmission occasions for the present or next year. The usual occasions assessed most critical, and for which the NTCs are published, are winter and summer working day peak hours. Thus these NTC values apply only for few hours of the year, and at other times power transfer limits between countries may have different values. Due to the lack of further knowledge, it was chosen to utilise the Winter 2007-2008 working day peak hour NTCs [10] throughout the whole year and for all years in WP5 simulations, thus taking possibly a rather conservative approach. The NTCs can only be defined by the TSOs as their values depend on e.g. stability issues etc. and their definition procedure is impossible without detailed knowledge of the system and its operation.

HVDCs are not included in the NTC restriction values used in the model, i.e. the total transfer capacity between two countries is the NTC value + the HVDC capacities.

For simplicity, in the future years the grid model assumes that NTC increases in same proportion as the increase of individual interconnection transmission capacity is to the original sum of interconnection capacity between two countries:

$$NTC_{new} = NTC_{old} \frac{ATC_{new}}{ATC_{old}}$$

where:

- ATC – Available Transfer Capacity (sum of line capacities)
- NTC – Net Transfer Capacity.

3 MODEL EVALUATION

Comparisons of simulation results to actual data were made in order to assess the accuracy and quality of the model performance. The assessment of the model in terms of moving weather fronts is discussed first, to see and assess the accuracy of short term issues, and then the assessment is expanded to the results given by the model in a yearly time scale.

Simulations were run to compare the sensitivity of input data on results, mainly the transmission bottlenecks in the system and their criticality and ranking.

3.1 Validation

3.1.1 Wind power production and moving weather fronts

The study periods of the moving low pressures are rather short, i.e. a few days. These phenomena are also somewhat extreme cases where the wind speeds may locally increase to rather high values at times, and the wind speed change rates can be high. Due to the nature of the original Reanalysis wind speed data, i.e. rather long time average on fairly large area (see 2.1), the highest local wind speed peaks, and even lowest drops, are smoothed in the data. Also the fast large changes in wind speed over just a couple of hours are smoothed and can not be seen. The wind speeds are scaled with suitable factors to be reasonable in different locations. In the model the individual wind turbine and farm shut-downs are implemented in such a way that after a certain wind speed value at wind power production node, the more wind speed increases above the limit wind speed, the less wind power is produced. Power curves used for the wind power generation are explained in more detail and shown in TradeWind deliverable D2.4 [2].

Gudrun/Erwin (see more in chapter 5) in January 2005 is known as the storm causing rather fast disconnection of huge part of wind power production in Denmark. Year 2005 there was already significant amount of wind power in the two Danish power systems. The Danish peak demands year 2005 were 3698 MW for West-Denmark and 2619 MW for East-Denmark (taking place at different dates and times of the year, and announced separately for East and West side because they belong to two separate interconnected systems, UCTE and Nordel respectively) and combined wind power capacity of 3130 MW. The Danish power systems faced disconnection of wind power from about 2660 MW total production to 420 MW over about six hours (see Figure 5).

Simulation run for the storm period was run with 2005 data, and the results were compared to the actual data provided by Energinet.dk [11]. The comparison is shown in Figure 5, and the wind speeds at three model nodes in Denmark are shown in Figure 4. In Figure 4 it is clearly seen that the wind speeds increase in all of the nodes quite high, and wind turbine shut-down must occur. In Figure 5, the moving weather phenomenon is seen in both simulation and actual data. The curves, however, do differ from each other in certain respects. First, the decrease rate of wind power production in reality is higher than in the simulation. This weakness of the model, or more specifically of the input wind speed data, has been noted as discussed earlier. The power production levels, i.e. the before shut-down starting level and the lowest production level during the storm, seem to correspond to each other quite well. There are also differences in the pre- and post-shut-down period productions.

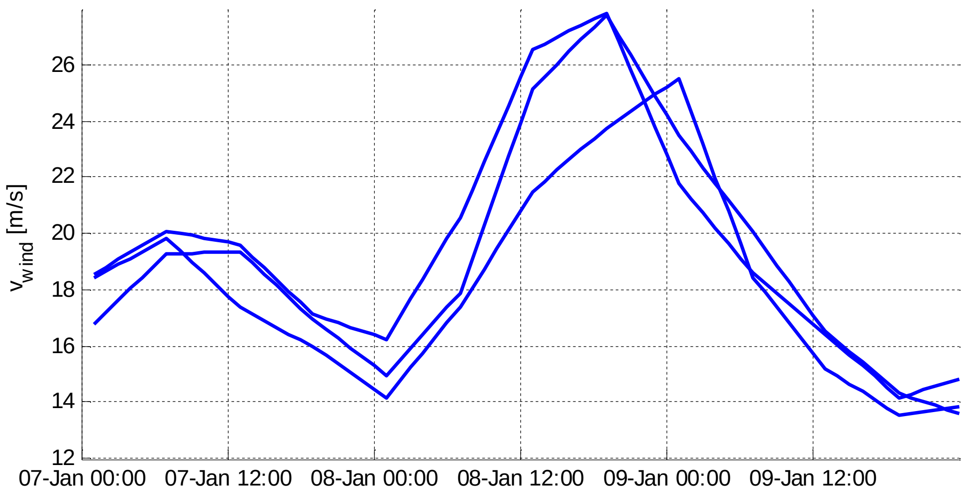


Figure 4. Wind speeds in the three Reanalysis data points in Denmark during Gudrun/Erwin passing in the afternoon of January 8th 2005.

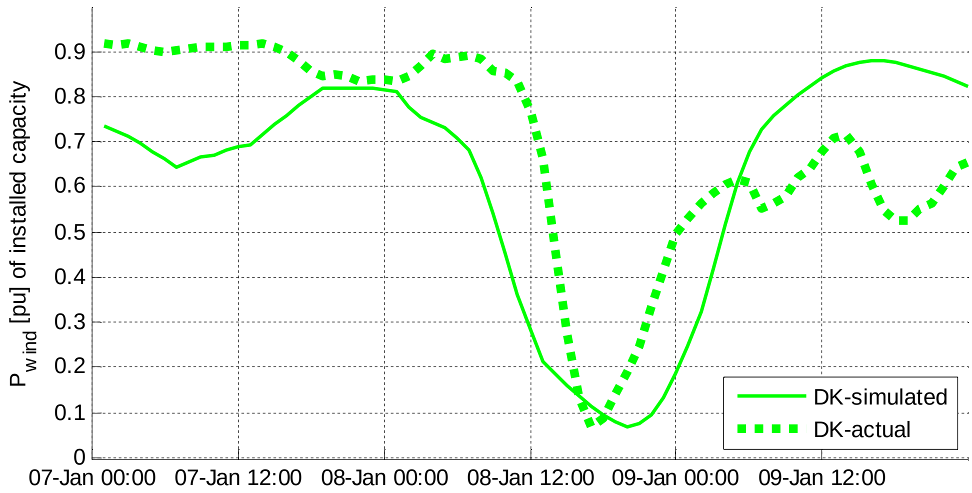


Figure 5. Wind power production in Denmark during Gudrun/Erwin passing in the afternoon of January 8th 2005. Simulation vs. actual.

In Figure 6 the whole Danish January 2005 wind power production is shown and compared to the actual data of that period. The period is chosen to be shown to illustrate how well the wind power production in simulation corresponds to the actual data in normal situations at other times than during storms. It can be noted that the wind power variations in simulation results correspond to the actual data, but there still are some, even large, differences if the data are compared in the short-time scale. Short-time scale differences should not be an issue, or under too strict consideration, due to the facts discussed earlier about the accuracy of input wind speed data. On the other hand in the whole year analysis, it should not be an issue if wind power production is not “correct” at individual hours, as the wind speed is anyhow somewhat random variable. What is important instead, is the wind speed data to be feasible, e.g. to have possible increase/decrease rates, plausible wind speed variation range, and to enable correct yearly wind power production etc.

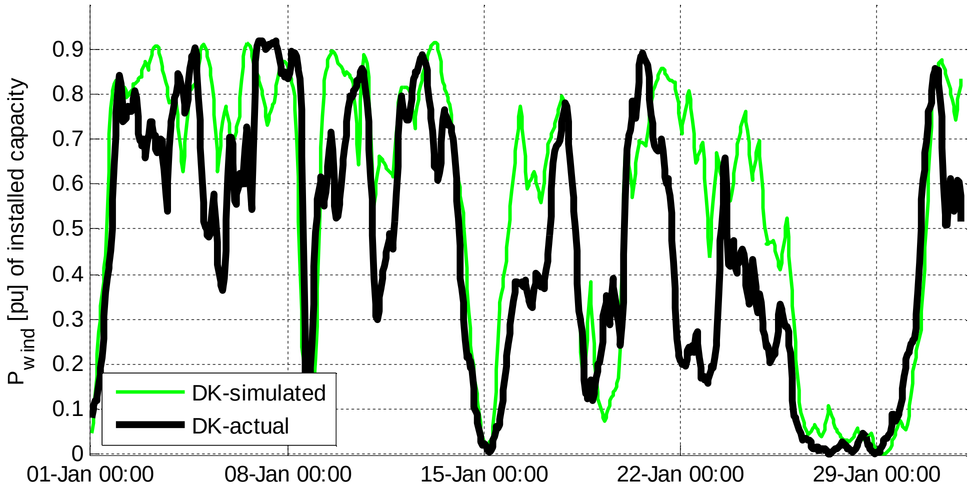
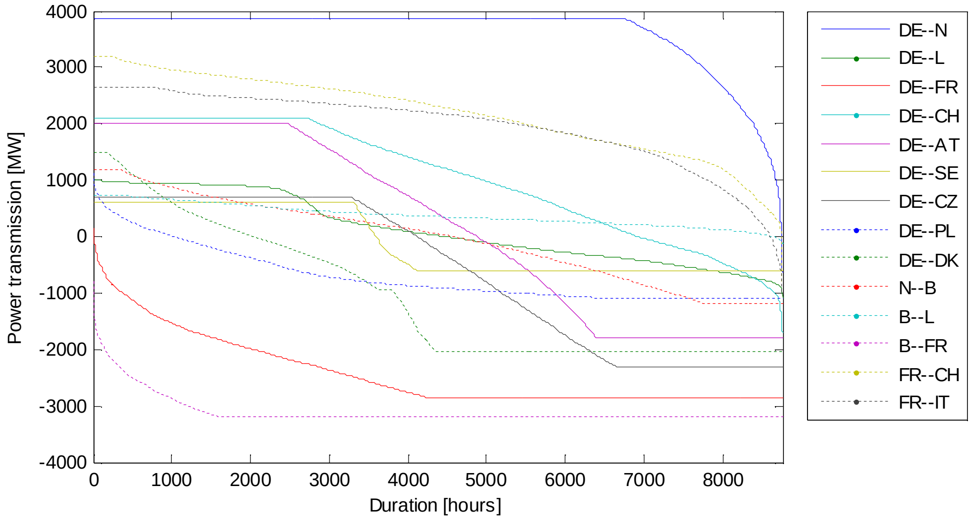
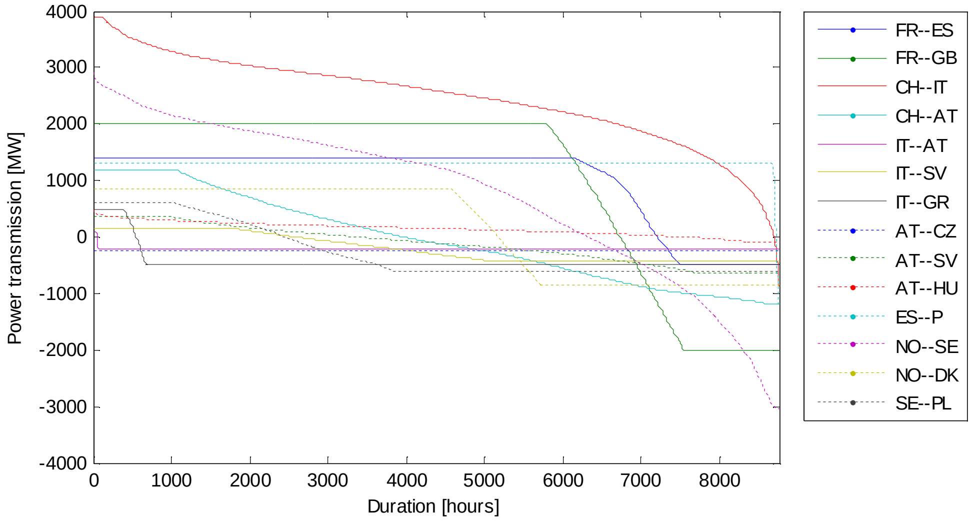


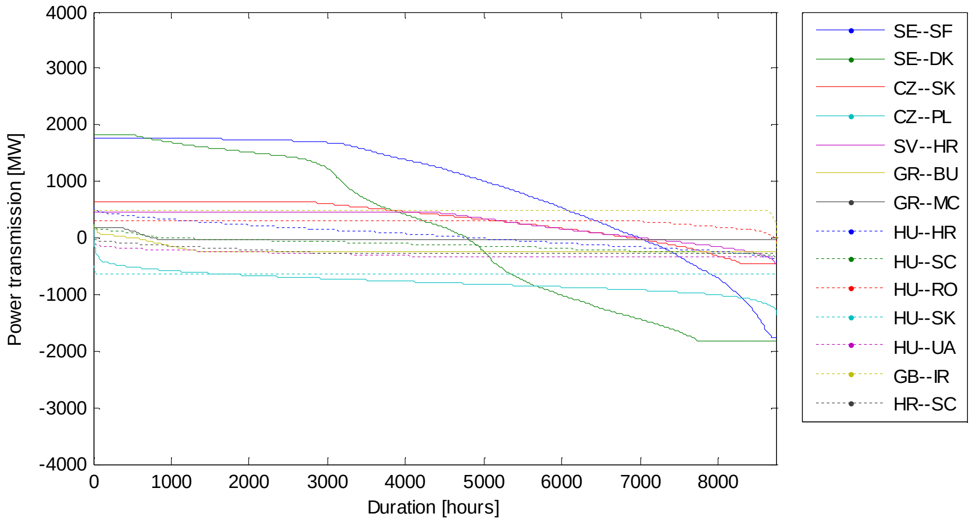
Figure 6. Wind power production in Denmark January 2005. Simulation result compared to the actual data.

3.1.2 Year 2005 validation

The year 2005 was used to assess the model performance. A simulation was run with 2005 wind power capacity, wind speed data and load and other-than-wind power production capacity. For modelling simplicity, the used NTC values are those used throughout the study for winter 2007-2008 working day peak hours. In the graphs in Figure 7 power transfer duration curves between countries of 2005 simulation are shown.


Power transmission [MW]
Duration [hours]
DE--N
DE--L
DE--FR
DE--CH
DE--AT
DE--SE
DE--CZ
DE--PL
DE--DK
N--B
B--L
B--FR
FR--CH
FR--IT


Power transmission [MW]
Duration [hours]
FR--ES
FR--GB
CH--IT
CH--AT
IT--AT
IT--SV
IT--GR
AT--CZ
AT--SV
AT--HU
ES--P
NO--SE
NO--DK
SE--PL


Power transmission [MW]
Duration [hours]
SE--SF
SE--DK
CZ--SK
CZ--PL
SV--HR
GR--BU
GR--MC
HU--HR
HU--SC
HU--RO
HU--SK
HU--UA
GB--IR
HR--SC

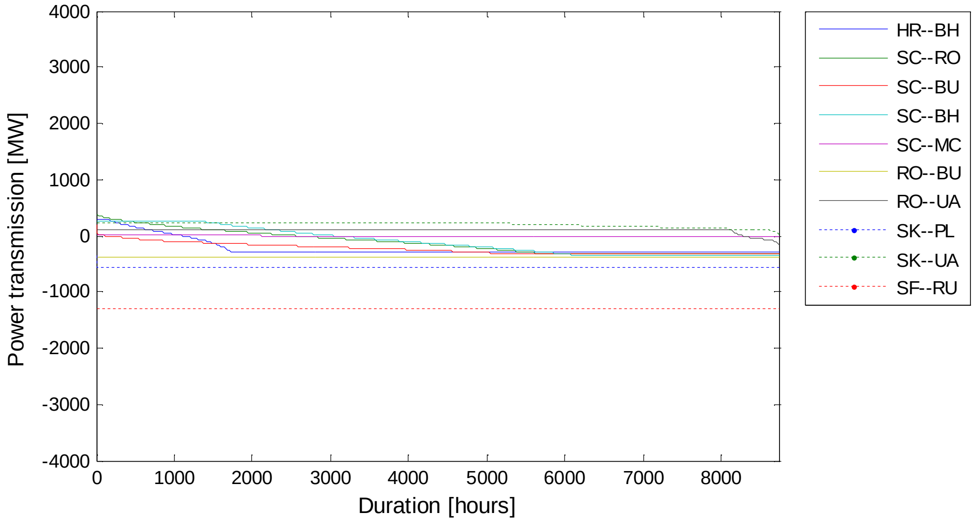


Figure 7. Duration curves of power transfer between European countries in 2005 simulation.

The power transfer duration curves are shown to give some reference when studying the actual study cases of future years, and also for assessing how the model functions compared to real life today. The simulated duration curves for year 2005 are not exactly like they were in reality. One reason is that the model assumes one single European-wide and ideal market, and thus the simulation results cannot even be expected to correspond accurately to actual data.

The induced bottlenecks can be given a monetary value. It is given as sensitivity of transmission, which expresses the total money saved in the market in case a specific interconnection transmission capacity was 1 MW larger. The sensitivity value unit is Euros/MW. There are two sensitivity values calculated in the simulations; “sensitivity of power line capacity” and “sensitivity of NTC”, the first being calculated by assessing single interconnection line 1 MW capacity increase, and the latter by assessing NTC value 1 MW increase. At the times the lines are not operating at their limits, or cross-border transmission being below NTC, the respective sensitivity value is zero. Thus the sensitivity value tells how significant the congestion on the interconnection or cross-border concerned is. Sensitivity of power line capacity is defined and described in more detail in TradeWind deliverable D3.2 [5].

As the transmission restrictions, on the one hand are due to individual line transmission capacities, and on the other hand due to TSO defined NTC values, the sensitivities of these characters give indication of the reason of congestion. Large and significant power line sensitivity value implicates that there is possibly not enough transmission (line) capacity on the cross-border, where as large and significant NTC sensitivity value implies that there might be a need for system reinforcements (not necessarily only on internal transmission bottlenecks, but also due to stability issues etc.) in at least one of the countries interconnected in order to be able to withstand more cross-border transmission, and thus larger NTC values.

The power line capacity sensitivity values for 2005 case for cross-border transmission are shown in Figure 8, where the most significant ones are highlighted and named. In Figure 9 the highest 13 sensitivity value sums over the year 2005 are shown. The corresponding most significant sensitivity duration curves and sensitivity sums for NTC sensitivities are shown in Figure 10 and Figure 11 respectively.

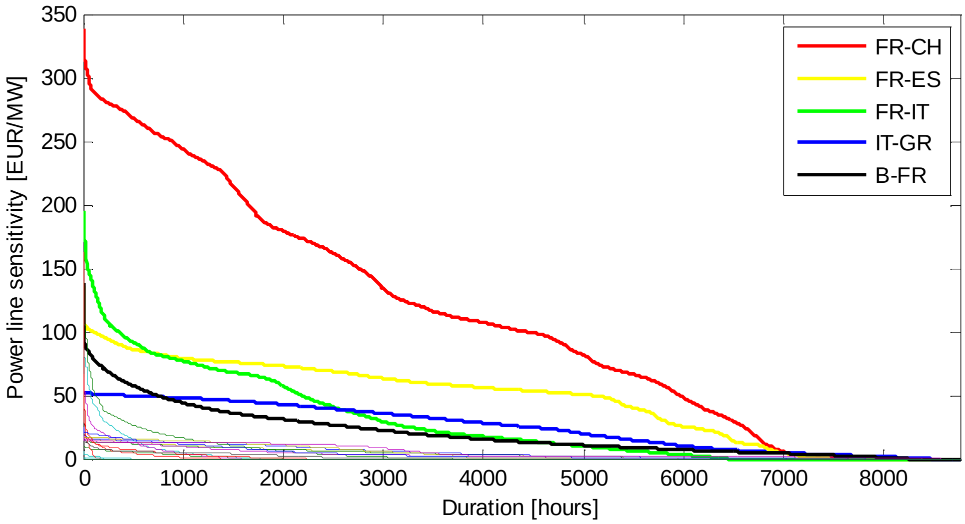


Figure 8. Duration curves of power line sensitivity values on cross-borders in 2005 simulation. The most significant sensitivity value duration curves highlighted and named.

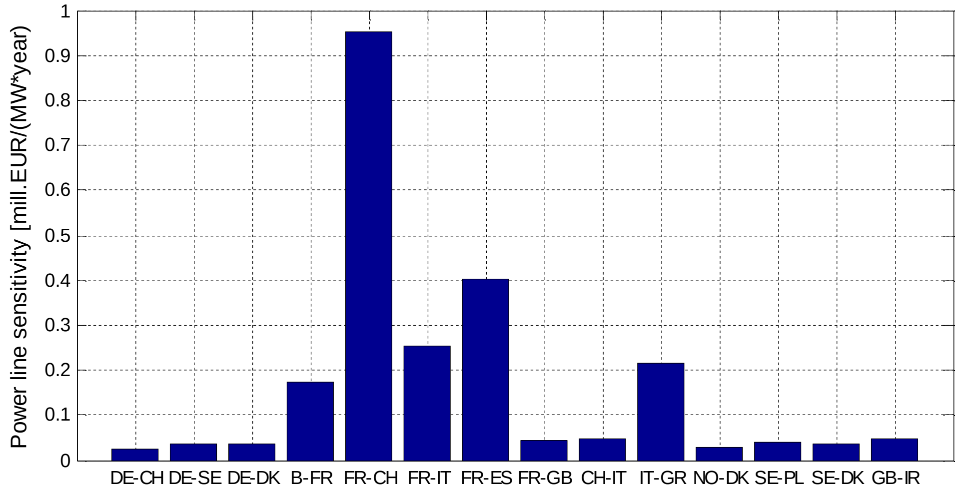


Figure 9. Power line sensitivity value sums for the whole year 2005 of the most congested cross-borders.

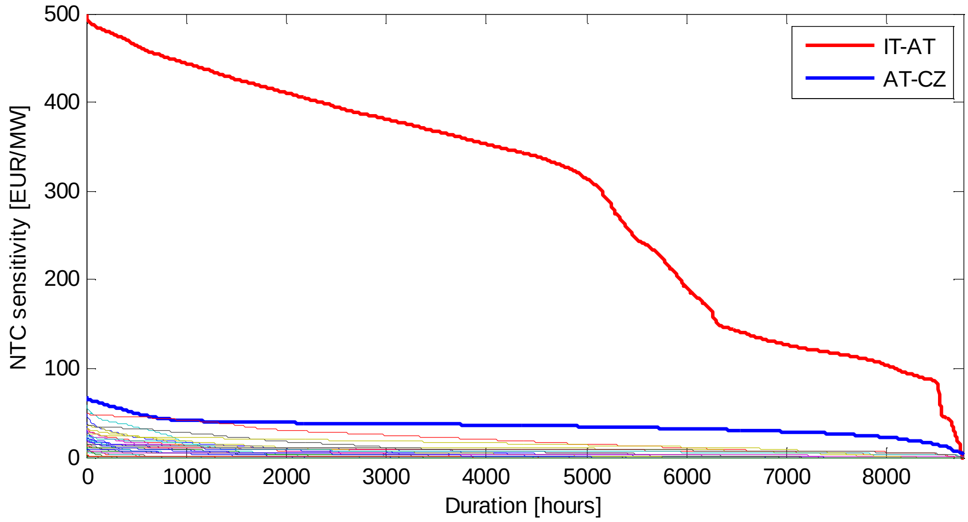


Figure 10. Duration curves of NTC sensitivity values on cross-borders in 2005 simulation. The most significant sensitivity value duration curves highlighted and named.

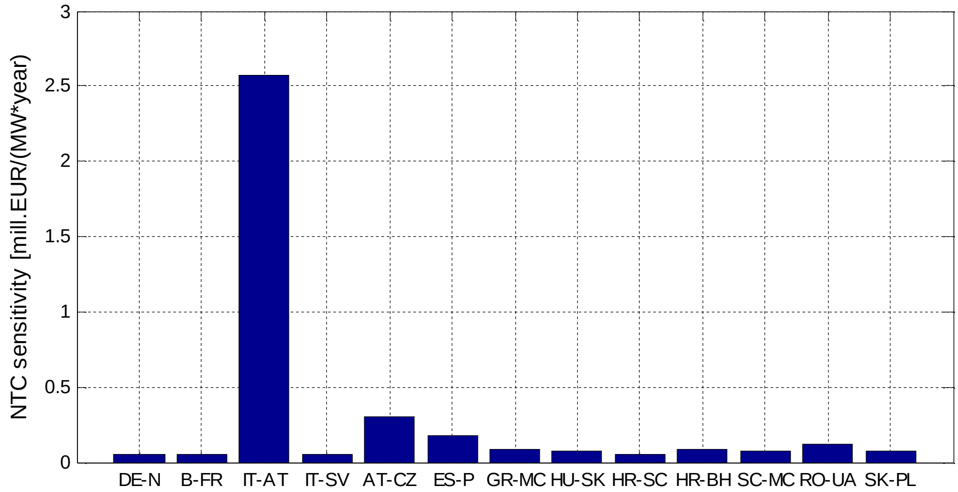


Figure 11. NTC sensitivity value sums for the whole year 2005 of the most congested cross-borders.

Both Figure 8 and Figure 9 tell that the most constrained connection considering the power line transmission capacity is between France and Switzerland. After that most critical cross-borders are France-Spain, France-Italy, Italy-Greece and Belgium-France. There occurs congestion on France-Great Britain cross-border as well, so it seems like France's interconnections to all the neighbouring countries (in the model, there is no connection between France and Luxemburg) are at least a bit weak and among the most critical in Europe. Many of the cross-borders with smaller power line sensitivity values are between countries with sea cable connections (i.e. DE-SE, DE-DK, FR-GB, IT-GR, NO-DK, SE-PL, SE-DK, GB-IR). The reason for sensitivity values on these HVDC connections is due to the fact that at many times the HVDCs are operated at full power, and thus the model assumes congestion on these connections and defines sensitivity for these connections.

FR-CH, FR-IT

On France-Switzerland connection there is largest congestion due to power line capacity of the simulation. UCTE states that power flows on this Central South area connection depend e.g. on France-Italy exchange, but that there occurs some congestion between FR-CH [12]. In TradeWind deliverable D7.1 [13] the France-Italy connection is marked as significant, and according to UCTE there occurs some congestion on this connection. In Figure 9 above, the France-Italy connection is the third critical in the simulation regarding power line capacity. A HVDC project is being studied to use the Fréjus tunnel as a 1000 MW interconnection between France and Italy, and several smaller grid upgrading projects are also planned [12]. Furthermore, there are different projects currently under study for strengthening the France-Switzerland interconnection. Reinforcements of the FR-IT and FR-CH interconnections are included as part of TradeWind Task 6.3 Grid Upgrade Options [14].

FR-ES

In South West region Spain-France connections are marked as significant ones in D7.1, there are development plans according to UCTE [12], and in the simulation results this cross-border is seen the most critical after FR-CH.

B-FR

In TradeWind deliverable D7.1 it is mentioned that the Belgian-French border is frequently congested. UCTE recognizes in [12] also one connection between Belgium and France being the most limiting element in the Central West (B, N, L, DE and FR) UCTE system, where there is an update scheduled to be completed between 2010 and 2015. Figure 8 shows that there occurs congestion on B-FR cross-border due to transmission line capacity most of the time of the year, and Figure 9 shows this cross-border to be 5th important congested cross-border in the model quantified by transmission sensitivity value. In addition there occurs some congestion due to NTC in the simulation (Figure 11).

IT-SV, GR-IT, GR-BU

Deliverable D7.1 points out that in the Central South area (AT, FR, DE, GR, IT, SV, CH) connections Italy-Slovenia – on which connection UCTE also admits having congestion currently and is upgrading [12] – and the Greek connections are poor. Italy-Slovenia cross-border is congested only lightly due to NTC in the simulation. The Greece-Italy cross-border is among the most constrained ones also in the simulation due to power line capacity (the HVDC-link). There are development plans defined for Greek connections to Bulgaria and increase the capacity on the GR-IT HVDC-link [12].

IT-AT, IT-CH

For other Italian connections, to Austria and Switzerland, there are development plans according to [12], and the Austria-Italy connection is identified as significant connection in deliverable D7.1. In simulation IT-AT has no sensitivity value of power line capacity, but on this cross-border there occurs the largest sensitivity value of NTC (Figure 11), which is over double the largest sensitivity of power line capacity value. Thus the simulations identify this cross-border as the most critical one. The reason for the high sensitivity of the AT-IT connection is that the NTC are very low (220 MW in the direction of

IT and 80 MW in the opposite direction). Figure 12 shows that the simulated annual electricity exchange between AT and IT corresponds well with the actual exchange, and that the flow is merely in the AT → IT direction. As mentioned before, the simulation was run with winter 2007-2008 working day peak hours NTC values, instead of those for year 2005. Using the 2005 NTC values would not be any better, as the value in direction AT → IT is the same, and for 2005 IT → AT value was not given, but instead mentioned "not realistic limit" in [15] and [16]. In the simulation there occurs some congestion also on Italy-Switzerland connection, but due to power line capacity (Figure 9).

<u>DE-DK, DK-NO, DK internal, SE-SF, PL-DE</u>

In deliverable D7.1 significant cross-borders in the Northern area (Nordel countries with Germany and Poland) in terms of wind power market were listed to be Germany-Denmark West, Denmark West-Norway, Denmark West-Denmark East, Finland-Sweden and Poland-Germany. To all of these connections there are also planned developments in the early 2010's. Of these Sweden-Finland and Poland-Germany cross-borders are not among those shown in Figure 9 and Figure 11. On both of these cross-borders there occurs little congestion, on SE-SF due to power line capacity and on DE-PL due to NTC. According to Figure 9 the cross-borders DE-DK and DK-NO are congested in some degree, but are not among the most critical ones in year 2005 in Europe.

<u>GB-IR, GB-FR</u>

Ireland-Great Britain connection is mentioned in deliverable D7.1 to be rather weak – for which there are also development plans – but the connection from Great Britain to France to be rather good (2000 MW NTC value at winter). Both of these connections are shown in Figure 9 to have sensitivity value different from zero, i.e. congestion occur. It might well be that in the ideal liberalized market, which the model assumes, 2000 MW transmission capacity is still rather small when connecting (isolated) GB system of about 59 GW peak load to UCTE. For this there is e.g. coming a 1000 MW improvement when the GB-N cable BritNed comes in operation in 2010.

<u>Central East and South-East area</u>

Central East / South East region interconnection between countries are not very strong, but there are many upgrade plans in the area. In the simulation the interconnections in this area are congested in some degree due to NTC, as seen in Figure 11. Austria-Czech Republic is the second critical congested cross-border due to NTC, and is among the top five overall critically congested cross-borders (see Figure 9 and Figure 11). According to [12] (n-1) security is partly a limiting factor on this particular cross-border and there are reinforcement plans to increase the security level along with transmission capacity. In simulation there occurs some congestion due to NTC on Slovakia-Poland cross-border. UCTE has acknowledged there is a need for additional transmission capacity between SK-PL, but in order to able to build more cross-border capacity, internal reinforcements needs to be done in Poland first [12].

ES-P

There occurs some congestion due to NTC in the simulation on ES-P cross-border. In [12] UCTE states that in long term two interconnections between Spain and Portugal will be planned particularly in order to reach a higher NTC value in both directions.

Table 3. Overview of 2005 simulations correspondence with actual congested cross-borders.

Cross-border	Correspondence between simulation and reality	Comments
B-FR	ok - congested	
FR-CH	ok - congested	
FR-IT	ok - congested	
FR-ES	ok - congested	
FR-GB	ok - congested	
IT-AT	so-so - congested	very significant congestion due to NTC in simulations and low transmission capacity, but although there are many interconnection plans, UCTE does not point this THAT significant/critical
IT-SV	so-so - congested	
IT-GR	ok - congested	
AT-CZ	ok - congested	congestion due to NTC in simulations, UCTE states that reinforcements needed to increase (n-1) security which is a limiting factor (NTC)
ES-P	ok- congested	congestion due to NTC in simulations, UCTE plans to make reinforcement plans in order to increase NTC
GR-BU	? – congestion not seen	
SK-PL	ok - congested	congestion due to NTC in simulations, UCTE states that internal reinforcements needed before building new interconnections (thus NTC possibly limiting factor)

The TSOs have published the yearly electricity net transfers between countries for past years. The simulated year 2005 electricity transfers between countries are compared to these actual transfer values given by TSOs in [17, 18, 19]. The comparison is shown in Figure 12.

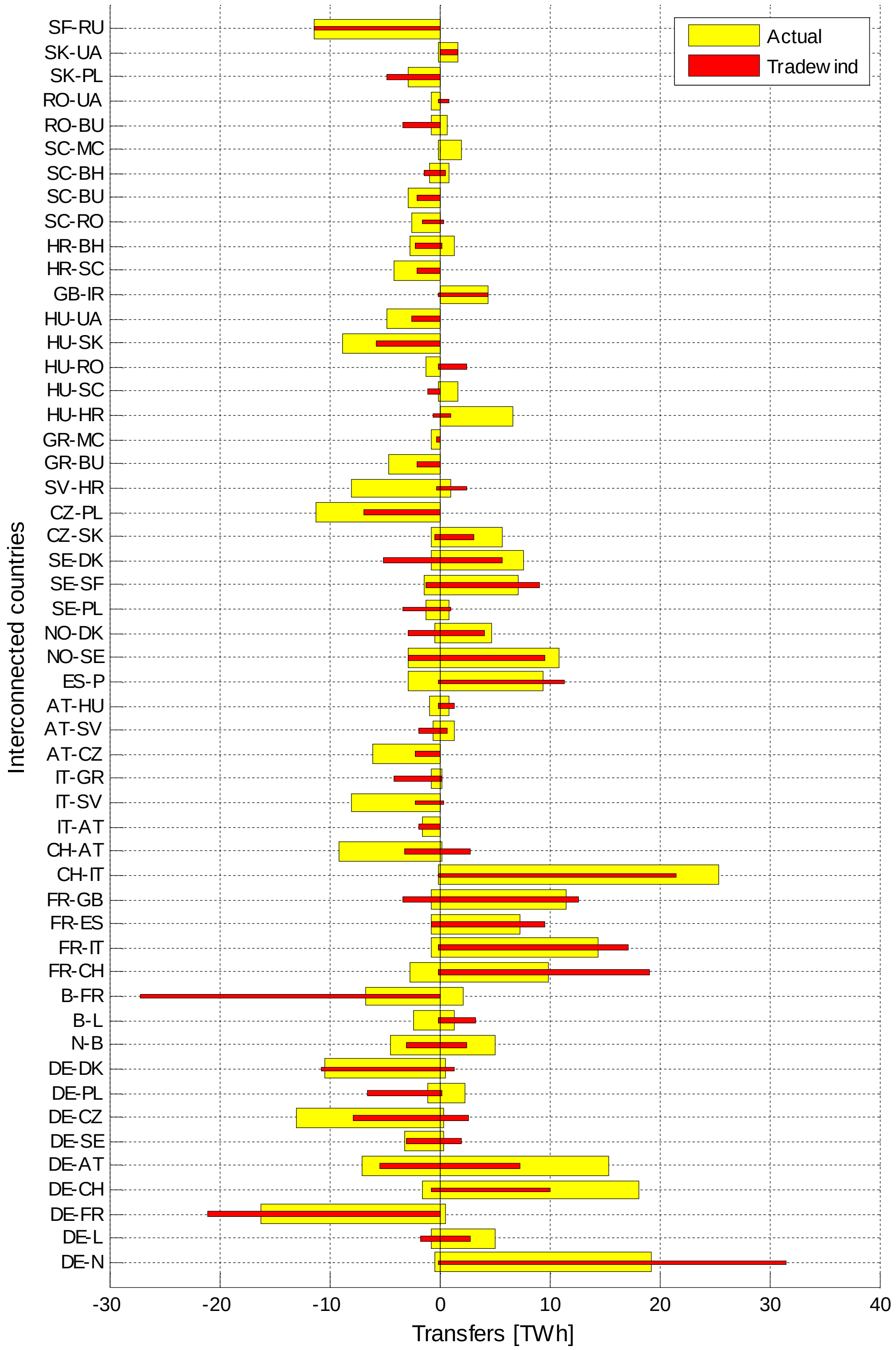


Figure 12. Electricity transfers between countries year 2005, simulation results vs. actual transfers [17, 18, 19].

The simulated net transfer corresponds reasonably well to actual values for most of the cross-borders. There are several possible explanations for the differing values. The first, and probably the most significant one is the fact that the model assumes one single and ideal electricity market, whereas the actual market in 2005 was rather regional and a bit far from ideal. The second explanation can be the usage of a single NTC-value set[1] throughout the year, although it really applies only for a specific system state. At other times there might be possibilities to transfer more power – or even less. Also the imperfections in the modelling due to unavailability of more precise information of the system is a probable cause of differing simulation outcome. This refers especially to:

- Lack of knowledge on locations and actual marginal costs of different types of thermal generators
- Internal line constraints were not available, except for Nordel, parts of Northern Germany and a few lines in Belgium and France (list of internal line constraints is given in D6.1 report)
- Lack of network detail on the GB and Ireland systems in the model
- Strategy for use of reservoir water to hydro power plants is based on external input to the model (water values)

3.2 Sensitivity analysis

3.2.1 Wind year sensitivity

Year 2010 Medium wind power scenario is used as the comparison case in all sensitivity analysis simulations. At later years the system model may be insufficient due to reinforcements done that are not included in the model, and for this reason year 2010 was chosen as the base year. The wind power amount, however, is not that large this year yet, but the sensitivity analysis results can be observed keeping in mind that on later years' simulations the wind power share of total production is larger and thus may affect the results accordingly.

There are wind speed data available of years 2000-2006 to be used in the simulations. As stated in section 2.1, year 2004 was chosen to be used in the simulations. The influence of the wind year was studied by comparing the sensitivities of power line capacity and NTC, as well

[1] ETSO "Winter 2007-2008, working day, peak hours"-values are used for all years in WP5, due to the lack of further knowledge.

as the energy produced by wind power in each country the simulated year.

The wind power production in different countries simulated with different wind year data are shown in Figure 13. There occurred no wind power reduction due to power transmission constraints.

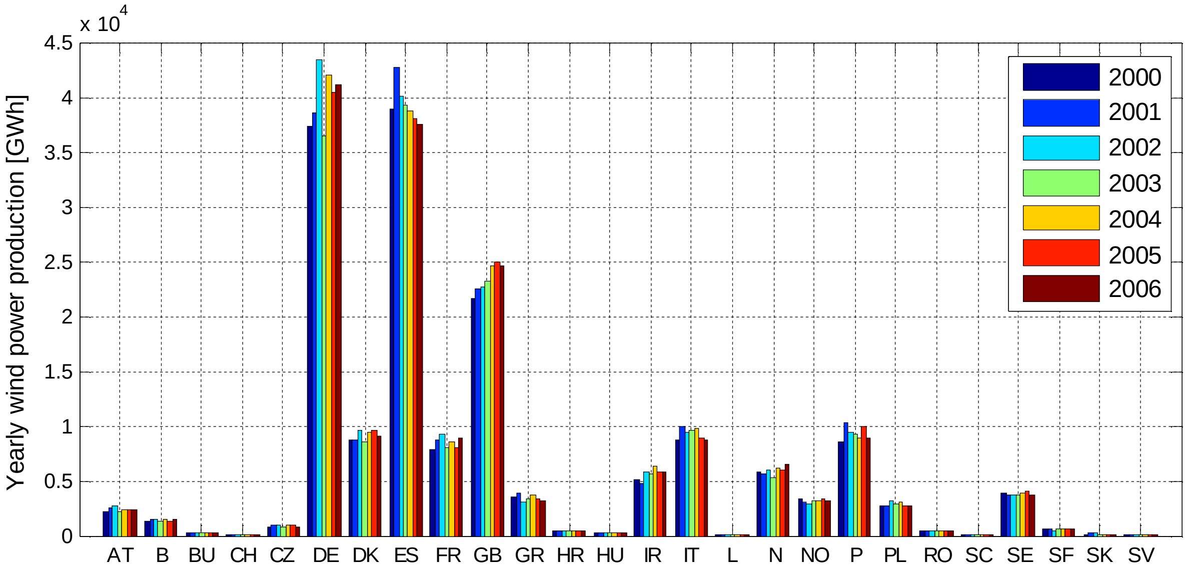


Figure 13. Wind power production with year 2010 medium scenario in European countries when simulated with different wind speed data (2000-2006).

The most significant connection sensitivities of power line capacities and NTC simulated on different wind years are shown in Figure 14 and Figure 15. The differences on wind speed data years do not seem to have much influence on final results over the whole years.

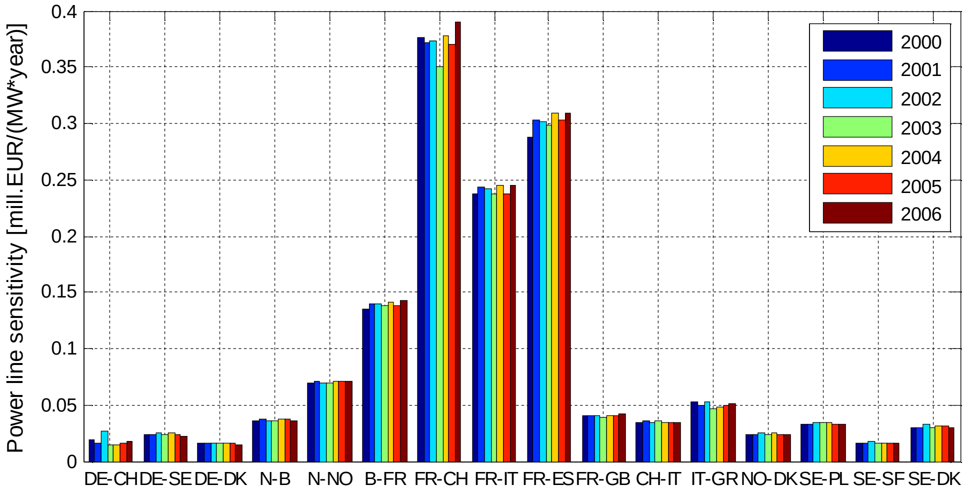


Figure 14. Comparison of influence of the choice of wind data year on power line capacity sensitivities on the most critical cross-borders in year 2010 medium scenario.

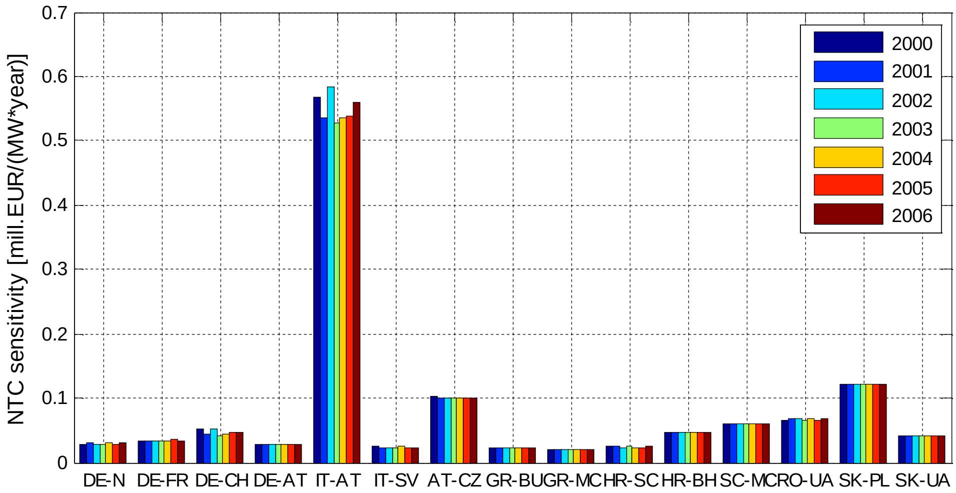


Figure 15. Comparison of influence of the choice of wind data year on NTC sensitivities on the most critical cross-borders in year 2010 medium scenario.

3.2.2 Other-than-wind power production capacity sensitivity and load forecast scenario sensitivity

Comparison between the other-than-wind power production scenarios (Generation A and Generation B, see Figure 3) and wind power production scenarios (medium, low and high, see Appendix 1) was done. Year 2010 Medium wind power scenario (85 GW wind) combined with Generation B scenario was used as the base case. The same medium wind power scenario was simulated with Generation A scenario, and also high (105 GW) and low (69 GW) wind power scenarios were simulated with Generation B scenario. The comparison of the influence of these different scenarios is done by comparing the sensitivities of power line capacity on cross-border connections. The connections with most significant sensitivity values of power line capacity and NTC are shown in Figure 16 and Figure 17 respectively.

The demand forecast scenario chosen to be used in the simulations is EurProgForecast (see TradeWind deliverable D3.2, appendix: Model Updates). Also the results simulated with the alternative load forecast (see for more information D3.2) available to be used in the model are shown in Figure 16 and Figure 17.

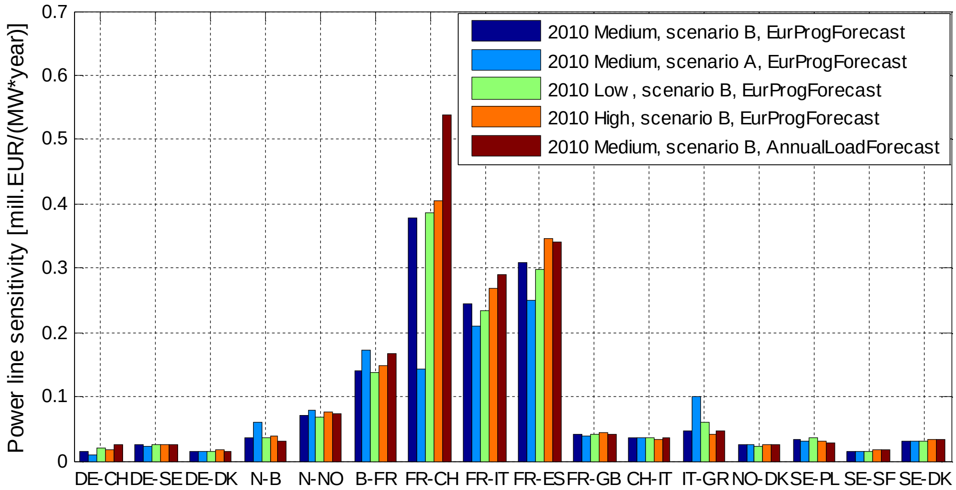


Figure 16. Comparison of the influence of 1) other-than-wind power production scenario selection, 2) different wind power scenarios year 2010, and 3) load forecast scenario selection. The sensitivity values of power line capacity.

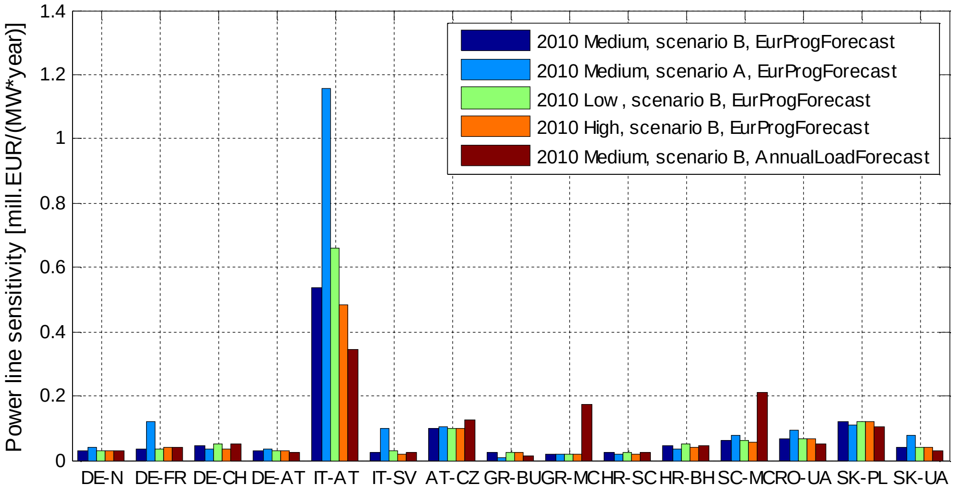


Figure 17. Comparison of the influence of 1) other-than-wind power production scenario selection, 2) different wind power scenarios year 2010, and 3) load forecast scenario selection. The sensitivity values of NTC.

Based on results shown in Figure 16 and Figure 17, a conclusion can be drawn that in most cases the selection of wind power scenario, different other-than-wind power production capacity scenarios, or load forecast scenario does not make too much difference on power transmission congestion between countries. Of course it should be kept in mind that the difference between the Generation scenarios A and B is rather small, as well the differences and the total amounts of wind power in different wind power scenarios for year 2010. Later years there is a lot more uncertainty in the other-than-wind power capacity, as well as the wind power amounts, and the differences between the scenarios will be larger.

Above all, according to Figure 16 and Figure 17, selection of wind power production (i.e. Low, Medium, High) scenario seems to have the least influence on power transmission sensitivity compared to selection of other than-wind-power production capacity (A or B) or load forecast method selection (EurProgForecast or AnnualLoadForecast). The influence can be positive or negative depending on location of the connection. The total capacity difference of other-than-wind power scenarios is smaller (10 GW) than the differences between the wind power scenarios (low-medium 16 GW, medium-high 20 GW and low-high 36 GW). In the wind power scenarios, the added wind power is distributed of course more evenly throughout the system. Simulations, where on some locations there might be capacity according to low wind power scenario, and at some other locations according to the high wind power scenario, have not been run.

It ought to be noted that the other-than-wind power production may have an equal or even bigger, influence than wind power on cross-border transmission. The simulations in this study are run based on best knowledge and assumptions made, and the results should be considered in this respect.

4 IMPACT OF WIND POWER ON CROSS-BORDER TRANSMISSION

Based on simulations this chapter tries to identify wind power induced bottlenecks upcoming years for different generation, load and wind power penetration cases. The uncertainty induced by wind power forecast errors on the predicted cross border power flows is also discussed.

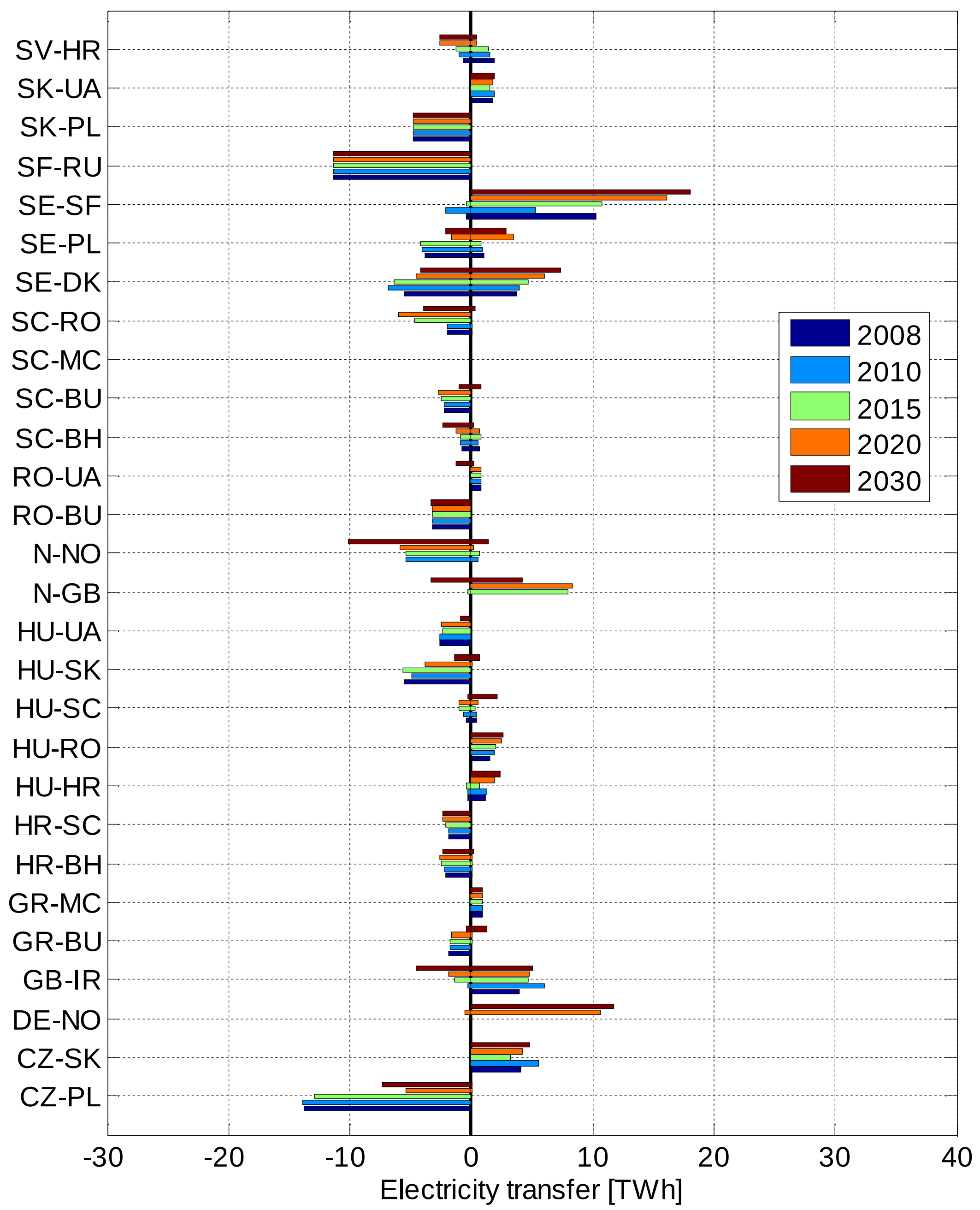
The work is based on power flow simulations with the simulation model described in the previous chapter. The model covers continental UCTE, Nordel, Ireland and Great Britain. TradeWind countries not included here are Estonia, Latvia, Lithuania, Malta and Cyprus.

4.1 Wind power induced bottlenecks

The bottlenecks and congestion due to wind power – or congestion relieved by wind power – in the future years were studied. Simulations were run for years 2008, 2010, 2015, 2020 and 2030 on three wind power scenarios, Low, Medium and High. The exact wind power capacity amounts each year in all of the countries are shown in Appendix 1 both in numbers and graphically. In order to show the influence of wind power, the years were simulated also with 2005 wind power capacity. To evaluate significance of different bottlenecks, i.e. to see how significant they are and how they can be ranked by their criticality, the power line and NTC sensitivity values were studied.

The simulation results in full are shown in Appendixes 2, 3, 4 and 5 in graphical form, and the results from these graphs by cross-borders are gathered in verbal form in

Table 4. Figure 18 shows the annual exchange for years 2008, 2010, 2015, 2020 and 2030 using the Medium wind power scenario.



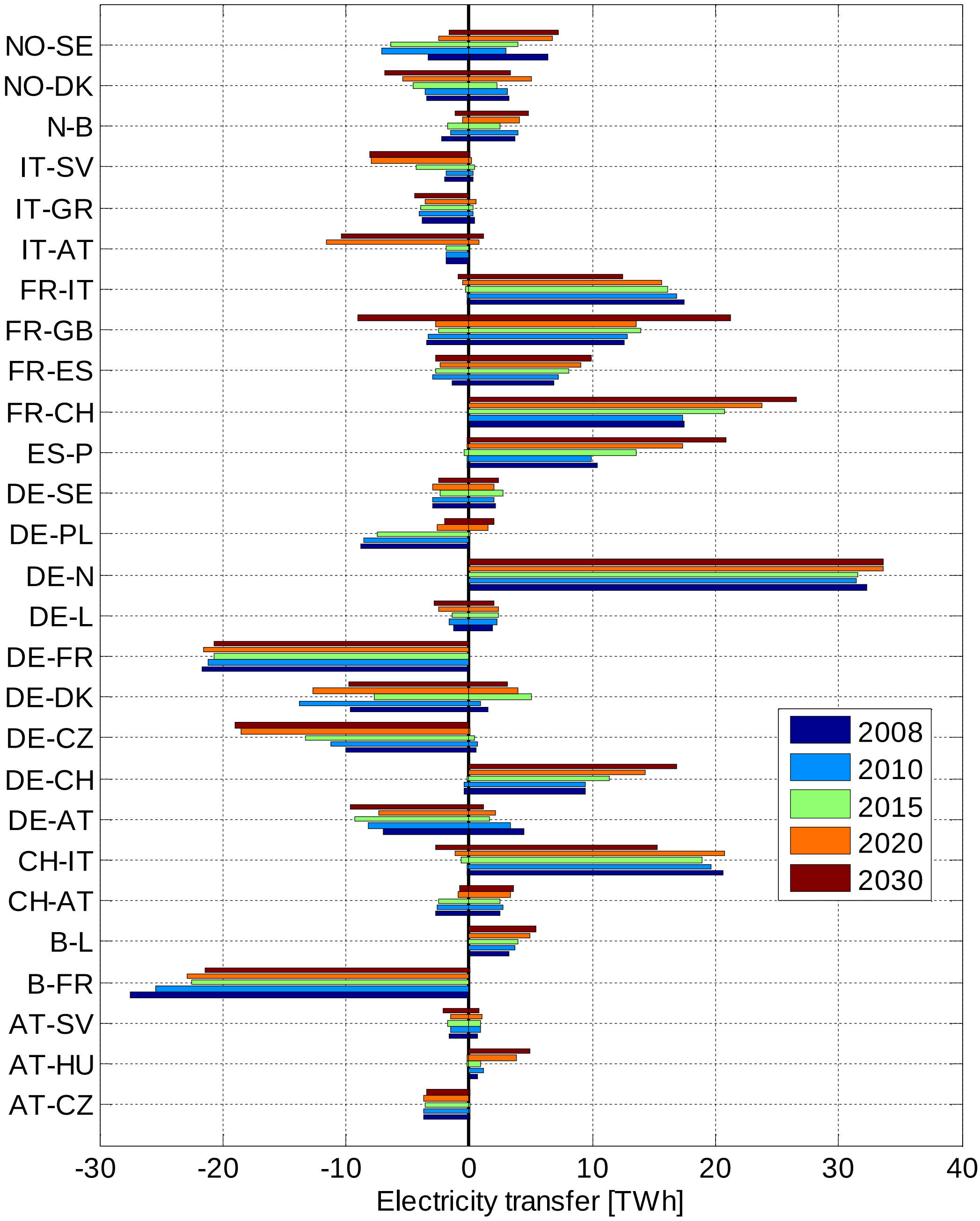


Figure 18. Electricity transfers between countries for the years 2008, 2010, 2015, 2020 and 2030, Medium wind scenario.

The most noticeable developments based on observations from Figure 18 are:

- The 2008 and 2010 simulations show a significant export from Denmark to Germany. With the increased wind power capacity in Northern Germany in years 2020 and 2030, the situation changes to a more balanced exchange between Denmark and Germany. This again leads to more export from Denmark to Norway. The NorGer cable which is introduced in 2020 and 2030 simulations is almost entirely used for transporting wind power from North Germany to South Norway. At the same time, South Norway exports power to Netherlands via the NorNed cable. This leads to the observation that Norway is used as a transit point for export of excess power from Germany to Netherlands which has significantly higher marginal costs. This is as expected from the model, since HVDC links are modelled as fully controllable and HVDC losses are not included.
- The increase in export from Austria to Southern Germany can be explained by investigating the wind power capacity scenarios (see e.g. D2.1 [20]), which show that the 2030 Medium scenario for Austria is as high as 4300 MW, while the neighbouring South East of Germany only have 368 MW.
- The 2030 simulations use updated values for offshore wind power capacity in Great Britain. In the original Tradewind scenarios (D2.1 Wind Power Capacity Data Collection [20]), the scenario for offshore wind power capacity in Great Britain was set to 7.8 GW for 2030 Medium. For the 2030 grid simulations, it was decided to increase the offshore wind capacity in Great Britain to 33 MW (See D6.1 report [14]). The high amounts of offshore wind power in Great Britain in the 2030 scenario gives a significant increase in export to France, and also to Nertherlands via the BritNed cable that is included for year 2015 and onwards.

Table 4. Yearly power flows and their congestions in simulations. See for more information the figures in Appendixes 2 - 5.

Connection	Dominant power transmission direction and duration	Congestion cause(s), duration(s) and its significance
DE-N	Always DE → N.	NTC, most of the time in all cases, later years even more. Moderate sensitivity values of NTC.
DE-L	Both directions quite evenly, DE → L transmission hours slightly grow by the years. Wind power resists this growth year 2030.	Line ratings in direction DE → L, 1000...1800 hours, highest numbers of hours years 2015 and 2020. Insignificant sensitivity values of power line capacity.
DE-FR	Always FR → DE.	NTC, about half of the time. Year 2030 wind power reduces congestion hours. Moderate sensitivity values of NTC.
DE-CH	DE → CH from ~7500 h in 2008 to all the time in 2030.	NTC and line ratings. Congestion hours due to line ratings increase by the years from ~1500 to ~5000, and the congestion hours due to NTC are about the double all the years. 2015-2030 wind power increases congestion hours due to line ratings, and decreases them due to NTC. Moderate sensitivity values of power line capacity, as well as those of NTC in the early years. 2030 sensitivity values of NTC are ones of the highest, and wind power decreases the value slightly.
DE-AT	About 2/3 of the time AT → DE, and the hours slightly grow – early years independent of wind, later growth slightly supported by wind - by the years, except 2020 when they go back to 2010 level.	NTC and line ratings. Congestion (~4000h) due to NTC proportional to directional transmission hours, except 2020 less congestion hours due to NTC and 2030 having less wind power decreases hours of congestion due to NTC. Earlier years low number of congestion hours (~500) due to line ratings and year 2030 from ~4000 up to ~7000 h increased by wind power. Sensitivity value of NTC moderate in all cases, insignificant value of line capacity earlier years, and value varies by wind power scenario in 2030, being moderate with low wind power capacity and one of the most significant values with high capacity.
DE-NO HVDC	Almost all the time DE → NO, 2030 even more than 2020.	Line ratings, almost all hours. Sensitivity values of line capacity with some significance with larger wind power capacity.
DE-SE HVDC	Both directions. Later years transmission emphasizes towards DE → SE, but wind power diverts the transmission direction strongly back towards SE → DE.	Line ratings, almost all hours. Moderate sensitivity values of line capacity, and either year or wind power scenario has hardly influence on them.

DE-CZ	CZ → DE most of the time, and later years almost all the time.	NTC, a quarter of the time in 2008, and increasing to almost full time in 2030 (with 2005 wind power capacity). Wind power reduces the number of hours of congestion significantly. Moderate sensitivity values of NTC.
DE-PL	2008-2015 almost always PL → DE, later years both directions, hours depending on wind power. Wind power adds strongly DE → PL transmission hours.	NTC, over half of the time in 2008, decreasing by the years to few hundreds of hours in 2030. Wind power has no significant influence. Insignificant sensitivity values of NTC.
DE-DK (incl. HVDC)	Both directions, about 2/3 DK → DE. Wind power adds slightly DE → DK transmission hours, except 2030 high wind power scenario does the other way round.	Line ratings, most of the time in all cases, later years a bit less than earlier years. Moderate sensitivity values of line capacity, and either year or wind power scenario has hardly influence on them.
N-B	Both directions, about 2/3 of time N → B and exact hours vary by years. Wind power tends to increase transmission hours slightly to B → N.	NTC and line ratings, mostly on direction N->B. Congestion due to line ratings more dominant, ~4000…8000 h, while congestion due to NTC occurs ~1000…2000 h. Both type congestion hours increase by the years. Insignificant sensitivity values of NTC, and moderate values of line capacity early years, but later years wind power brings some significance to them.
N-NO HVDC	Most of the time NO → N, which wind power slightly tends to add.	Line ratings, almost all hours in all cases. Moderate sensitivity values of line capacity, and wind power increases them but they still are on the same level 2030 with high wind power capacity as the early years.
N-GB HVDC	First years of operation almost all the time N → GB, 2030 only roughly over half of the time. Wind power adds slightly the GB → N transmission hours.	Line ratings, almost all hours, 2030 a bit less. Small sensitivity values of line capacity.
B-L	Always B → L.	Line ratings, from only hundreds of hours in 2008 to ~1500 hours in 2005 wind power capacity scenarios later years or any scenario early years. Wind power increases the number of congestion hours later years up to 6000 hours. Insignificant sensitivity values of line capacity, except wind power brings some significance to them in 2030 higher wind power scenarios.
B-FR	Always FR → B.	NTC and line ratings. Congestion due to line ratings more dominant, 4000…8000 h, decreasing by the years. Congestion due to NTC less than 4000 h, later years smaller but increased by wind power.

		Moderate sensitivity values of NTC and line capacity.
FR-CH	Always FR → CH.	NTC and line ratings. Congestion due to NTC increases over the years (and wind power capacity) from almost none to over 7000 h. Congestion due to line ratings (independent of wind power) is over 6000 h in 2008 and increases over the years up to over 8000 h by 2020, and year 2030 halves down to ~3000 h. Sensitivity values ones of the highest due to NTC with wind power in 2030. Also ones of the highest sensitivity values of line capacity in all cases, except 2030 wind power drops value in moderate level.
FR-IT	Almost all the time FR → IT. Transmission hours to IT → FR increases a bit by the years.	NTC and line ratings. Congestion due to NTC less than 1000 h in all cases, and due to line ratings over 6000 h in all cases. Small sensitivity values of NTC and sensitivity of line capacity values with some significance.
FR-ES	Both directions, more FR → ES. Varies by the years, and tends to divert transmission direction hours in direction ES → FR. But wind power diverts the power transmission hours back to FR → ES direction the later years.	NTC and line ratings in both directions. Congestion due to NTC ~4000...7000 h depending on the case, and due to line rating ~7000 h most cases. Small sensitivity values of NTC and sensitivity values of line capacity have some significance all other years, but 2030 they drop in moderate level in all wind power scenarios.
FR-GB HVDC	Most of the time FR → GB. Wind power keeps this direction, with 2005 wind power capacity the transmission direction hours diverts to GB → FR direction.	Line ratings, most of the time in all cases. Moderate sensitivity values of line capacity.
CH-IT	Most of the time CH → IT, but decreases a bit by the years.	NTC and line ratings. Congestion hardly affected by wind power. Congestion due to NTC increases over the years from almost none to less than 2000 h, and being only in direction IT → CH year 2030. Congestion due to line ratings – mainly in direction CH → IT – ranges from ~3000 h to ~6000 h, with 2020 the highest values. Insignificant sensitivity values of NTC increase a bit to 2030, and moderate sensitivity values of line capacity increase to have some significance the later years.
CH-AT	Both directions quite evenly, later years emphasises more to CH → AT.	NTC and line ratings, both limited to less than 1000 h in all cases. Congestion due to line ratings only in direction AT → CH, and decreases over the years. Insignificant sensitivity values in all cases.
IT-AT	Early years all the time AT → IT,	2008-2015 NTC and 2020 and 2030 line

	later years only most of time, i.e. some transmission hours also to opposite direction. Later years wind power slightly adds AT → IT transmission hours.	ratings. Congestion due to NTC most of the time 2008-2015, and only few hundreds of hours congestion years 2020 and 2030. Congestion due to line ratings in 2020 and 2030 ~1000...3000 h. Very small sensitivity values of power line capacity and ones of the largest sensitivity values of NTC (the earlier years), which wind power reduces.
IT-SV	Most of the time SV → IT, earlier years a bit less, later years more.	NTC. About half of the time all cases, but 2015 less than 1000 h. Moderate sensitivity values.
IT-GR HVDC	Most of the time GR → IT, 2030 all the time.	Line ratings, almost all the hours in all cases. Moderate sensitivity values of line capacity, and later years with some significance.
AT-CZ	Almost always CZ → AT.	NTC, almost all the time in most of the cases. Very small number of hours also congestion due to line ratings. Moderate sensitivity values of NTC, and insignificant values of line capacity.
AT-SV	Both directions quite evenly. Transmission direction hours depend on the year, and wind power adding slightly AT → SV transmission hours.	NTC, both directions, altogether ~1500...4000 h. Moderate sensitivity values.
AT-HU	Most of the time AT → HU, later years even more, except 2015 when about 2/3 this direction.	NTC, increasing by the years from few hundreds of hours to ~1500 h. Wind power increases the number of congestion hours year 2030 up to almost 4000 h. Small sensitivity values.
ES-P	Almost always ES → P.	NTC and line ratings. 2008 and 2010 over 7000 h, 2015 almost none, and 2020 and 2030 less than 3000 h congested due to NTC. Congestion due to line capacity hours increase by the years from ~1000 to almost 6000. Moderate sensitivity values in all cases.
NO-SE	Both directions, transmission direction hours vary strongly by the years and wind power scenarios especially the later years. With 2005 wind power capacity transmission direction hours tends towards SE → NO, but wind power adds strongly NO → SE transmission.	A small number of hours due to line ratings in some cases. Insignificant sensitivity values.
NO-DK HVDC	Both directions quite evenly. Later years wind power adds DK → NO transmission.	Line ratings, most of the time in all cases. Moderate sensitivity values of line capacity.
SE-PL HVDC	Both directions, transmission direction hours vary by the years and wind power scenarios. Early	Line ratings, almost all hours in all cases. Moderate sensitivity values of line capacity.

	years most of the time PL → SE. Especially later years wind power adds strongly SE → PL transmission hours.	
SE-SF (incl. HVDC)	Most of the time SE → SF, the transmission direction hours vary by the years. Later years wind power adds strongly SE → SF transmission hours.	Line ratings, almost all hours in all cases.[2] Moderate sensitivity values of line capacity.
SE-DK HVDC	Both directions quite evenly. Transmission duration hours vary by years, and later years wind power adds SE → DK transmission hours.	Line ratings, almost all hours in all cases. Moderate sensitivity values of line capacity.
CZ-SK	Almost always CZ → SK.	NTC. Ranges from ~1500 h to almost 8000 h from year to year. Moderate sensitivity values.
CZ-PL	Almost always PL → CZ.	NTC, about half of the time early years, and decreasing by the years being hardly any 2020 and increasing to less than 1000 h year 2030. A small number of congestion hours occur also due to line ratings in some cases. Insignificant sensitivity values.
SV-HR	Both directions. Diverts from SV → HR majority transmission hours to HR → SV majority transmission hours by the years.	NTC, ranges from ~3000 h to ~5000 h from year to year. Small sensitivity values.
GR-BU	Most of the time BU → GR, but 2030 most of time GR → BU, and wind power adds it.	NTC, over 6000 h almost all cases. Moderate sensitivity values.
GR-MC	Both directions quite evenly.	NTC, ~4000...5000 h, more to MC → GR direction. Moderate sensitivity values.
HU-HR	Most of the time HU → HR, later years even more.	No congestion.
HU-SC	Most of the time SC → HU, and increasing by the years, but year 2030 mainly HU → SC.	NTC later years, 2030 over 3000 h. Wind power slightly decreases congestion hours. Small or moderate sensitivity values, which wind power decreases.
HU-RO	Almost all the time HU → RO.	NTC. Congestion hours increase by the years from ~3000 h to almost all the time. Sensitivity values are moderate until in 2030 become significant. Wind power reduces the sensitivity value significantly.
HU-SK	Almost always SK->HU, except year 2030 when about 1/3 HU → SK.	NTC. Congestion duration hours range from a few hundreds to over 8000 h by the years, the fewer hours being in 2030 and most 2015. Moderate sensitivity values.
HU-UA	Almost always UA → HU, 2030 only about 2/3 and up to 1000 h	NTC, ~2000 h year 2030, other cases from none to few hundreds. Moderate

[2] This may be because there is an HVDC connection along with an AC connection.

	to HU → UA, thus signifying there is no transmission on either directions for some time.	sensitivity values.
GB-IR HVDC	Most of the time GB → IR. Wind power adds strongly IR → GB transmission hours.	Line ratings, duration hours ranging from 2008 almost all hours to few hundreds of hours in 2030. Small sensitivity values.
HR-SC	Always SC → HR.	NTC, increasing by the years from over 3000 h to all the time. Wind power hardly makes significance. Sensitivity values are moderate until in 2030 become significant independent of wind power.
HR-BH	Most of the time BH → HR. Year 2030 wind power adds HR → BH transmission duration hours.	NTC, from over 6000 h to almost all the time. A small number of congestion hours occur also due to line ratings in some cases. Sensitivity values are small, but values due to NTC become significant in 2030 without wind power.
SC-RO	Most of the time RO → SC. Transmission duration hours vary by the years.	NTC, about half of the time, and varies by the years. Moderate sensitivity values.
SC-BU	Always BU → SC, except year 2030 when about 1/3 SC → BU, and wind power adds it.	NTC, from almost 4000 h to 8000 h increasing by the years 2008-2020. 2030 ~3000 h. Later years with more wind power, the congestion hours are less. Moderate sensitivity values.
SC-BH	Both directions, wind power diverts transmission direction hours towards BH → SC in 2030.	NTC, congestion occurring to both directions, and increasing by the years from less than 2000 h to almost 7000 h. Moderate sensitivity values.
SC-MC	About 2/3 of the time MC → SC, later years more. Some hours with no transmission in either direction.	NTC, all the tome of transmission. Moderate sensitivity values.
RO-BU	Always BU → RO.	NTC, most of the hours in all cases. Sensitivity values are moderate, and become to have some significance in 2030, and increasing by wind power.
RO-UA	Most of the time RO → UA, except most of the time UA → RO in 2030. Wind power tends to add RO → UA transmission hours.	NTC, congestion only, and almost always in all cases, in RO → UA direction. Moderate sensitivity values.
SK-PL	Always PL → SK.	NTC, always, and later years almost all hours. Moderate sensitivity values.
SK-UA	Always SK → UA.	NTC, most of the time, exact magnitude depending on the year. Moderate sensitivity values.
SF-RU HVDC	Always RU → SF. (one directional DC)	Line ratings, less than 1000 h in 2030 high wind power scenario. Moderate sensitivity value.

Some important observations from the congestion plots in Appendixes 2 - 5 are:

- Since the HVDC connections are modelled as controllable, they are fully utilized most of the time in one of the directions, independent of the wind power capacity scenario. Therefore, many of the interconnections containing HVDC connections are shown in Appendix 4 as highly “congested”, since “congestion” is related to maximum power flow on the connections in this study.
- In the 2015 and 2020 scenarios, the cable between France and Great Britain and the planned cable between Netherlands and Great Britain is most of the time fully utilized in the direction towards Great Britain. However, in 2030 the number of congestion hours increased in the opposite direction, as more wind power is exported from Great Britain.
- Russia is only modelled by a single generator and a HVDC link to Finland, which makes it possible to include export of power from Russia. The HVDC cable capacity was set equal to 1300 MW, in order to simulate the exact 2005 export to Finland (11.4 TWh) without needing to include a detailed description of the Russian power system in the model. Therefore, the sensitivity of the SF-RU is zero, although the cable is used at full capacity the whole year.
- The connection between Austria and Germany is initially not much congested (year 2015) due to line ratings, but there are significant numbers of hours of congestion due to NTC. As the export hours from Austria increase in 2030, there is a significant increase in number of power line congested hours in the direction of Austria, which wind power even adds.
- As seen from the 2030 results, the number of congestion hours in the direction France -> Spain is much lower when simulating with 2005 wind power capacity than using 2030 Low, Medium and High capacities. The significant increase of wind power in France between 2008 and 2030, and due to low marginal cost of French conventional generation, France becomes a surplus country. From 2005 to 2030 (Medium), the wind power capacity in France increases from 0.7 GW to 45 GW, while the increase in Spain is from 11 GW to 48 GW.
- It is evident that the NorGer cable is mostly used for exporting German wind power (wind power amounts in Germany in any scenario are very large compared to any other country), since the sensitivity for the 2020 and 2030 simulations with 2005 wind power capacity is quite much lower, and the number of congestion hour some what smaller than for the other scenarios.

- As more wind power is installed in North East Germany, the exchange between Germany and Poland changes from the direction of Poland -> Germany (2008, 2010) to a more balanced situation (2020 and 2030). The NTC congestions are almost eliminated in the 2030 scenarios. Wind power does cause this change alone; the thermal generation scenarios for Poland show that cheap coal is gradually replaced by more expensive gas. At the same time the consumption increases significantly. The Czech Republic experiences less consumption increase, and also an increase in nuclear power capacity. These developments seem to cause the main German import and congestions in the Eastern part to gradually switch from Poland to the Czech Republic. The congestion plots also show that the PL-> CZ export and congestions are mainly reduced along the simulation years.
- In the Nordic area, increased wind power generally gives higher transfers in the following directions
  - NO -> SE
  - SE ->SF
  - SE -> PL
  - SE -> DE
  - SE -> DK (Southern Sweden is partly used as transit point for export of wind power from DK West to DK East)
- The use of the DE-NO, N-NO, DK-NO and DK-DE connections does not change much for the different wind power scenarios.
- Italy is an energy deficit area in 2005, and this situation is gradually worsening in the following years, causing e.g. power flow on the IT-GR link to be mostly in the direction of Italy regardless of the wind power scenario.

4.2 Impact of prediction errors of wind power production

In power systems, large amounts of wind power have an impact on the technical operation as well as the market behaviour in the system. Thus, the prediction error due to the stochastic nature of the wind must be taken into account in the planning and operation of power systems with large-scale wind power.

Short-term forecasting of wind power has evolved to become an indispensable tool in systems where wind energy penetration surpasses 5 to 10 % of the total demand. It is used by both systems operators and market actors. Therefore, already in 1990 the first tool was developed in Denmark. A thorough overview of the state-of-the-art in short term prediction can be found in [21].

The scope here is to investigate the uncertainty induced by the day-ahead wind power forecast errors on the predicted cross border power flows. In order to be able to do that, simulation of wind power forecast errors for the whole Europe had to be implemented. A simplified approach was chosen. Few data concerning wind power forecast errors over large regions are available in the literature. Furthermore, since the simulations are done for 2015, an estimation of the evolution of the short-term forecasting accuracy was necessary.

Forecast errors are defined in two steps. First, the standard deviation of the forecast error is considered to be the same for whole Europe, and it is considered to be 1.5 m/s. This simplified approach considers that the root mean square error (RMSE) of the wind speed, which for a Gaussian distribution is equivalent to the standard deviation, is similar for all Europe. The value was extrapolated from [22]. The wind speed forecast error is then generated as one-dimension independent random numbers vector with Gaussian distribution. The resulted forecast error time series, with 1-hour resolution, considers that the forecast error at time *t* is independent from the forecast error at *t*-1, i.e. forecast errors are not auto correlated. This is considered acceptable, as a first approach, since PSST runs an optimal power flow for each hour independently. Furthermore, forecast error for the wind speed in different geographical points, e.g. North Germany and West Denmark, are not correlated. The Reanalysis data points, used to obtain the wind speeds, are given for data points covering squares of about 140...230 X 280 km each. According to TradeWind deliverable D2.2 [23], the spatial cross-correlation of predictions deviations is steeply decreasing with the distance, being almost zero at the values of the data squares covered by the Reanalysis data. Thus, the spatial cross-correlation was not included in the forecast error modelling.

The duration curve of the wind speed in one of the reanalysis point in Northern Germany is presented in Figure 19. The “actual” (Reanalysis) wind speed distribution is shown together with the simulated (Reanalysis + simulated Gaussian forecast error) “predicted” wind speed distribution

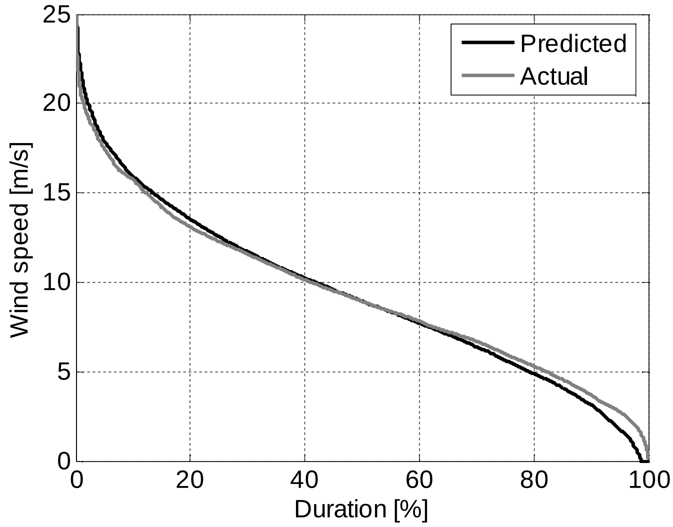


Figure 19. Actual and predicted wind speed for one reanalysis point (RDP 161) in Northern Germany

It is desired to generate a distribution of the predicted wind speed which is similar to the distribution of the actual wind speed. As it can be observed from Figure 19, the statistical distributions of actual and predicted are quite close, although it is visible that the predicted wind speed has a little wider distribution than the actual. Also the differences between the distributions are the most significant for low wind speeds where the wind power is close to zero and for high wind speeds where power is close to rated.

This means that the forecast error induces differences in the wind speed value, but it does not alter the statistical distribution of the wind speed, being almost symmetrical, as shown by the distribution (Figure 20) of the hourly difference between the actual and predicted wind speed time series (i.e. the forecast error).

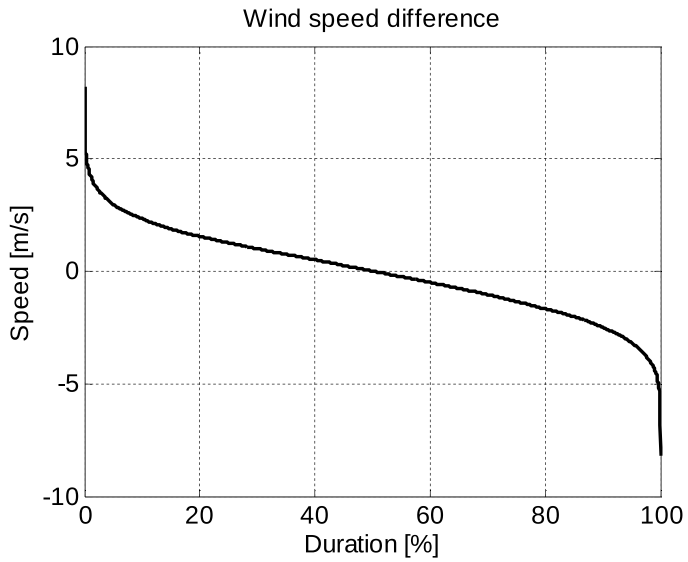


Figure 20. Difference between actual and predicted wind speed

Similarly to the way the synthetic wind speed time series are constructed, terrain adjustment factors are used to scale the forecast error for different areas in the European grid model. The calibration aims at obtaining wind power forecast errors for large areas, i.e. whole countries, similar to the rather few data available in the literature. In [24], the day-ahead deviation (Root Mean Square Error, RMSE, expressed in percent of the installed capacity) is given to be 5-6 % for the whole German grid in 2006, while for the whole Spain grid in 2006 it is about 4.5-5 % [25]. Starting from these values, the calibration of the terrain adjustment factors used in the simulations are 1.2, 2.2 and 1.8 for lowland, upland (>400m) and offshore, respectively. With those values, the simulated forecast errors for 2015 medium wind scenario, for all countries, are presented in Figure 21. Compared to the available literature data, the forecast errors are smaller, i.e. for Germany has MAE app. 2.8 % and RMSE app. 3.7 %, while for Spain the values are app. 3 and app. 3.9 %, respectively. Thus, the country wise forecast errors, for 2015, are generally smaller than those in 2006. A reason for this is that according to the estimated wind power development scenario, the wind power installed, for example, in Spain in 2015 will be more spatially distributed than today (see Figure 22) and thus the country-wise error smoothing will be bigger.

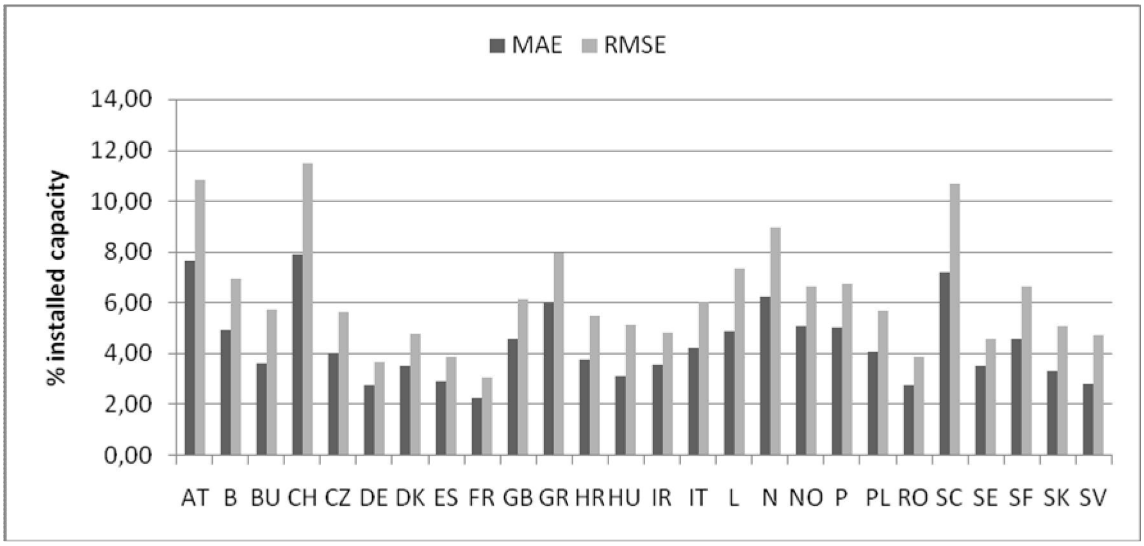


Figure 21. Simulated forecast errors, day-ahead forecast horizon

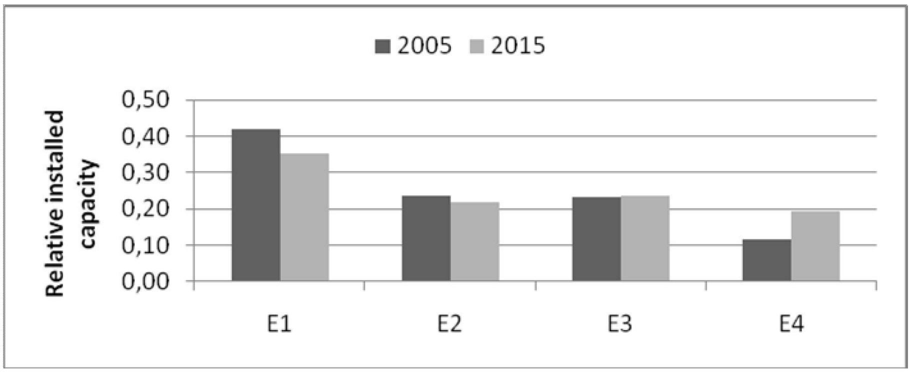


Figure 22. Wind capacity distribution in Spain

The actual and predicted wind power for Germany is presented in Figure 23.

Similarly to the wind speed, the actual and predicted wind power have similar statistics. Hence, the wind power forecast error influence the hour-by-hour wind power production without altering the overall production.

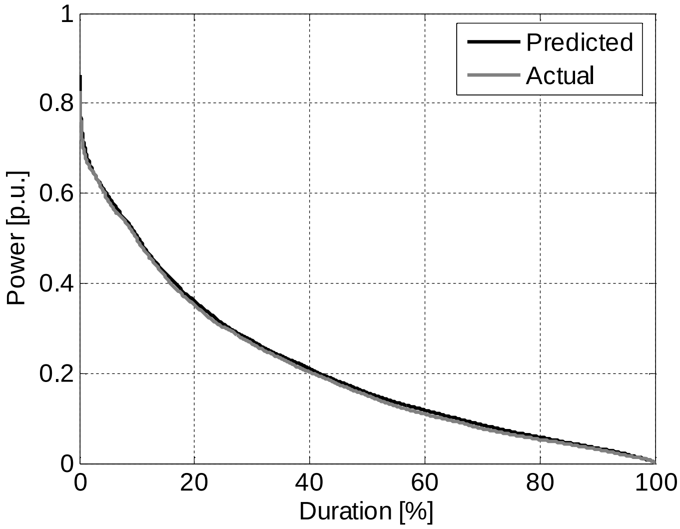


Figure 23. Actual and predicted wind power production in Germany

The uncertainty induced by wind power forecast errors was assessed for 2015. In the following, the results of the actual and predicted cross border power flow for 2015, using the medium wind power development scenario, are presented.

The hour-by hour difference between the predicted and actual power flow for the cross border interconnections of Denmark are presented in Figure 24.

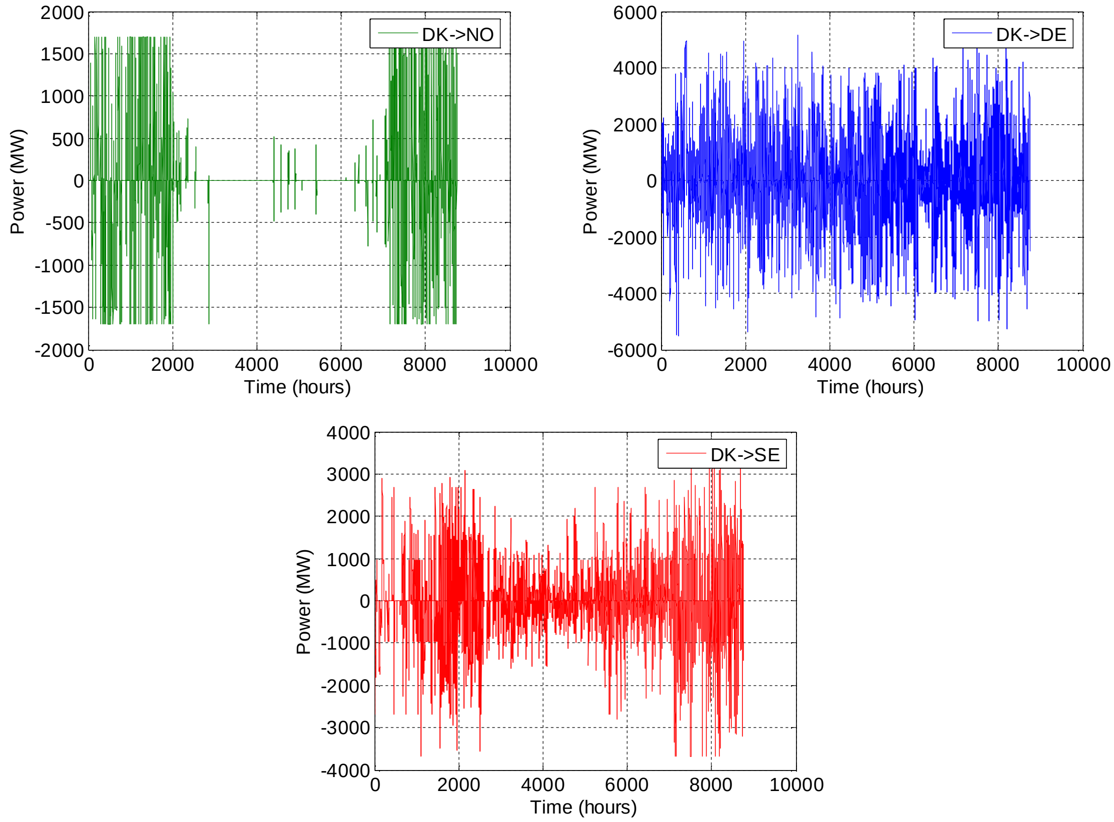


Figure 24. Hourly difference between actual and predicted power flow

As it can be observed, the wind power forecast error can lead to significant differences between the predicted and actual cross border power flow, except for the DK-NO connection. This is because this is an HVDC connection and is used at full power for most of the time. The duration curves of the flow difference between predicted and actual power flow are presented in Figure 25. The wind power forecast error induces significant uncertainty in the cross border power flow, with the actual power flow being different from the predicted one, i.e. values different from zero on the graph, for periods of time up to over 7000 hours for the connection to Germany. The results are similar for other cross border connections across Europe.

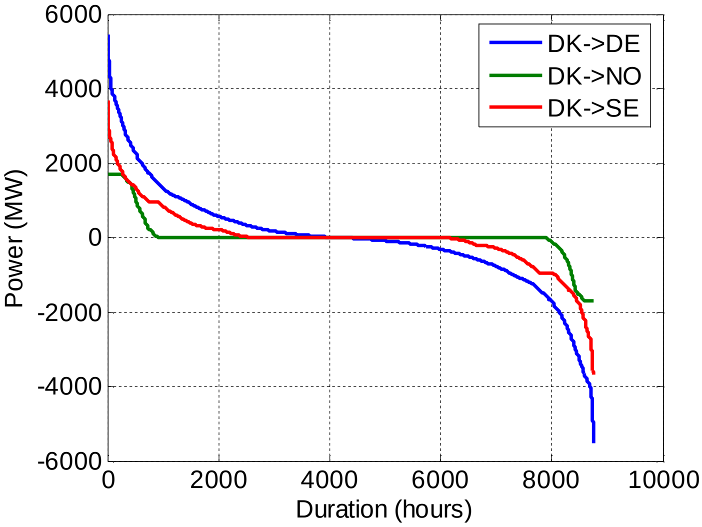


Figure 25. Distribution of the power flow difference

The difference between actual and predicted power flow, for all cross border connections in Europe, are presented in Figure 26. The graph shows, for all cross border connections, the number of hours that there is a flow difference. The cross border connections are the total connections between two countries, i.e. DE → DK is the total power flow, including both AC and HVDC connections between Germany and Denmark. For the flow difference, several thresholds were used. First, the hours for which the difference, i.e. actual minus predicted flow, is bigger than 1 % of line ratings were plotted. With this threshold, the power flow is different than the predicted for a significant period of time. When the threshold is put to 10 and 20 %, the period of time decreases significantly, less than half for several connections or even done to zero for a few. Thus, the wind power forecast error does affect the hourly cross-border power flow, but most of the time the difference is in the range 0-20 % of the line power.

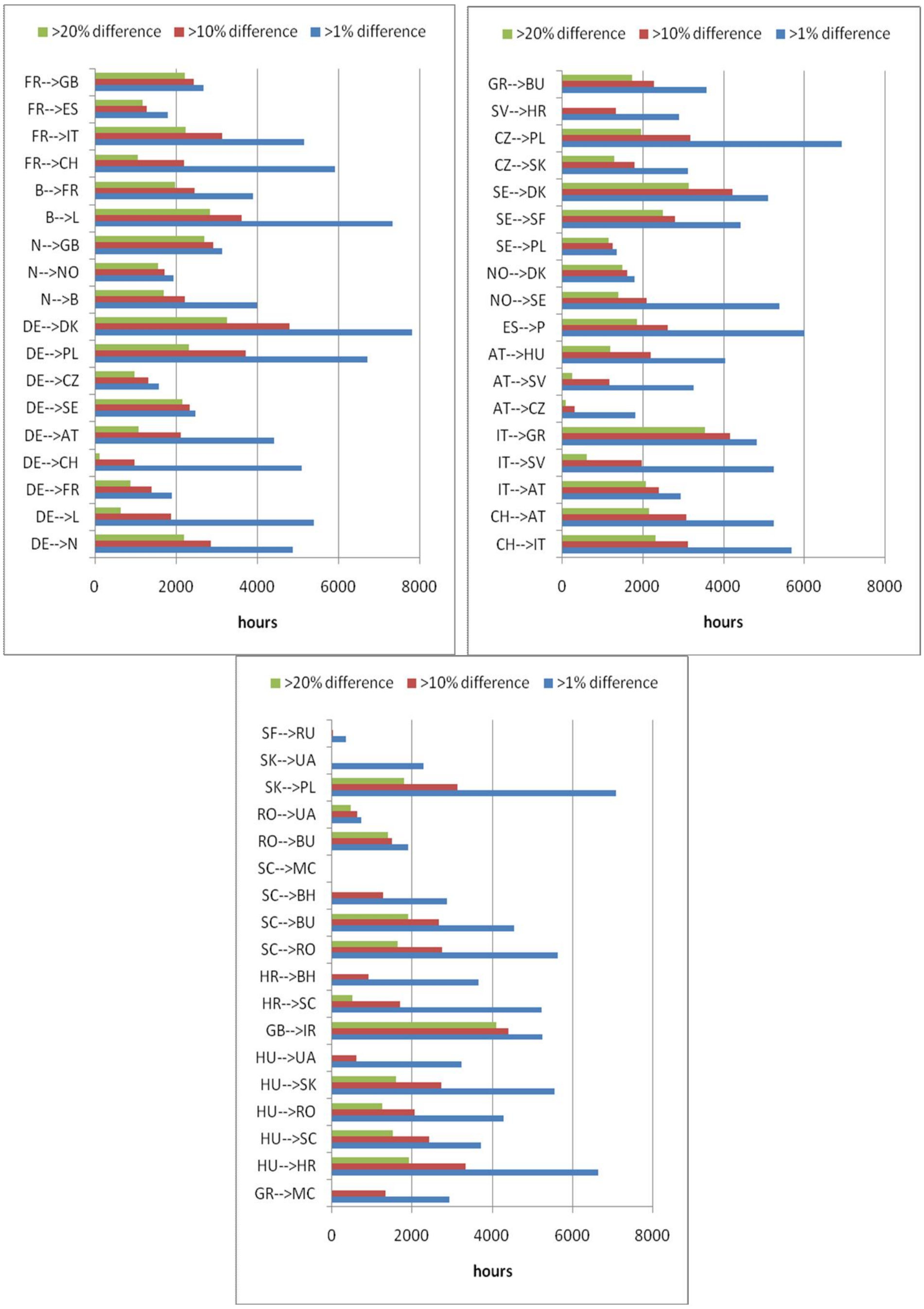


Figure 26. Flow difference in % of total time (day-ahead forecast horizon)

The wind power development scenario does not have an important impact on the hours of cross-border power flow difference (Figure 27).

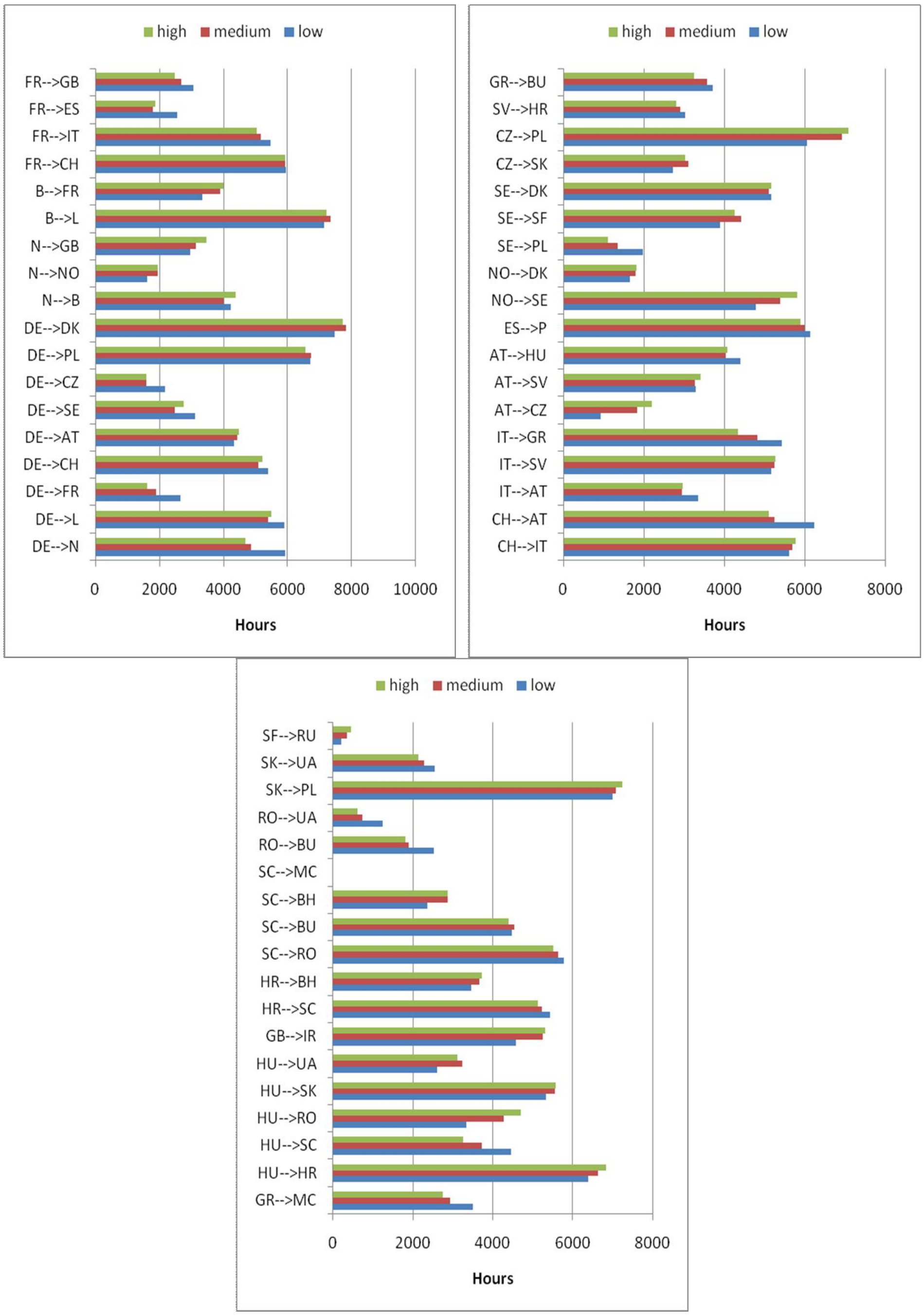


Figure 27. Hours of cross-border power flow difference for wind power development scenarios in 2015 (day-ahead forecast horizon)

When intra-day forecast horizon is considered, calculated with wind standard deviation of 1 m/s and the scaling factors being 1, 1.6 and 1.4, respectively and resulting in the country-wide errors presented in Figure 28, the number of hours when the actual power flow is different than the predicted does not change significantly, see Figure 29.

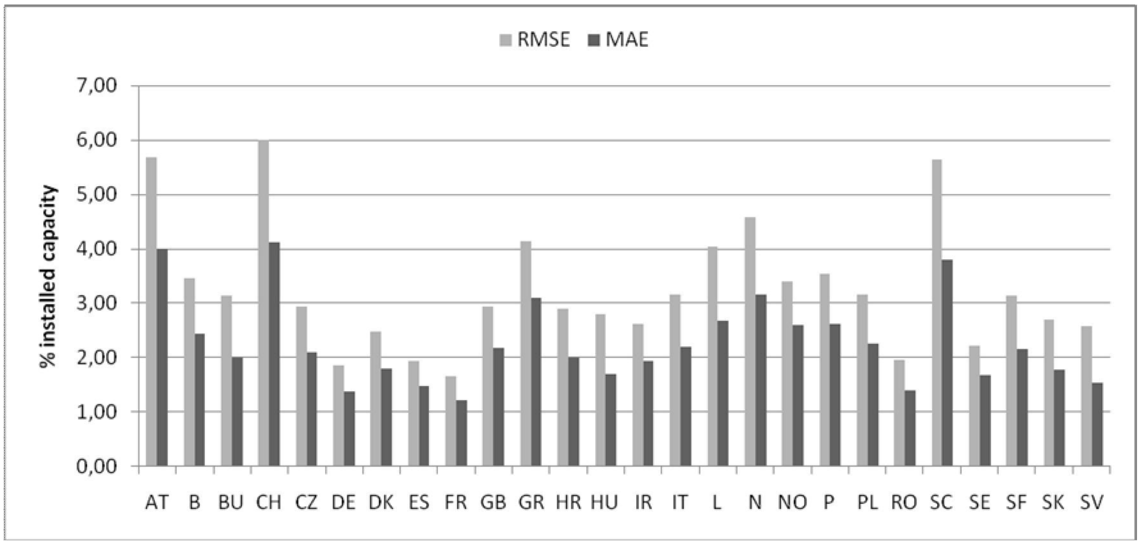


Figure 28. Simulated forecast errors, intra-day forecast horizon

The wind power forecast errors have an important influence on the hourly cross border power flow, leading to flow different than the planned one for period of times over 80 % of a year for some AC lines. Most of the power flow differences lie in the range between 0-20 % of the line rating.

Wind power forecast errors should be taken into account in large scale wind integration studies. They contribute to deviations from the hourly planned cross border power flows for large amounts of time.

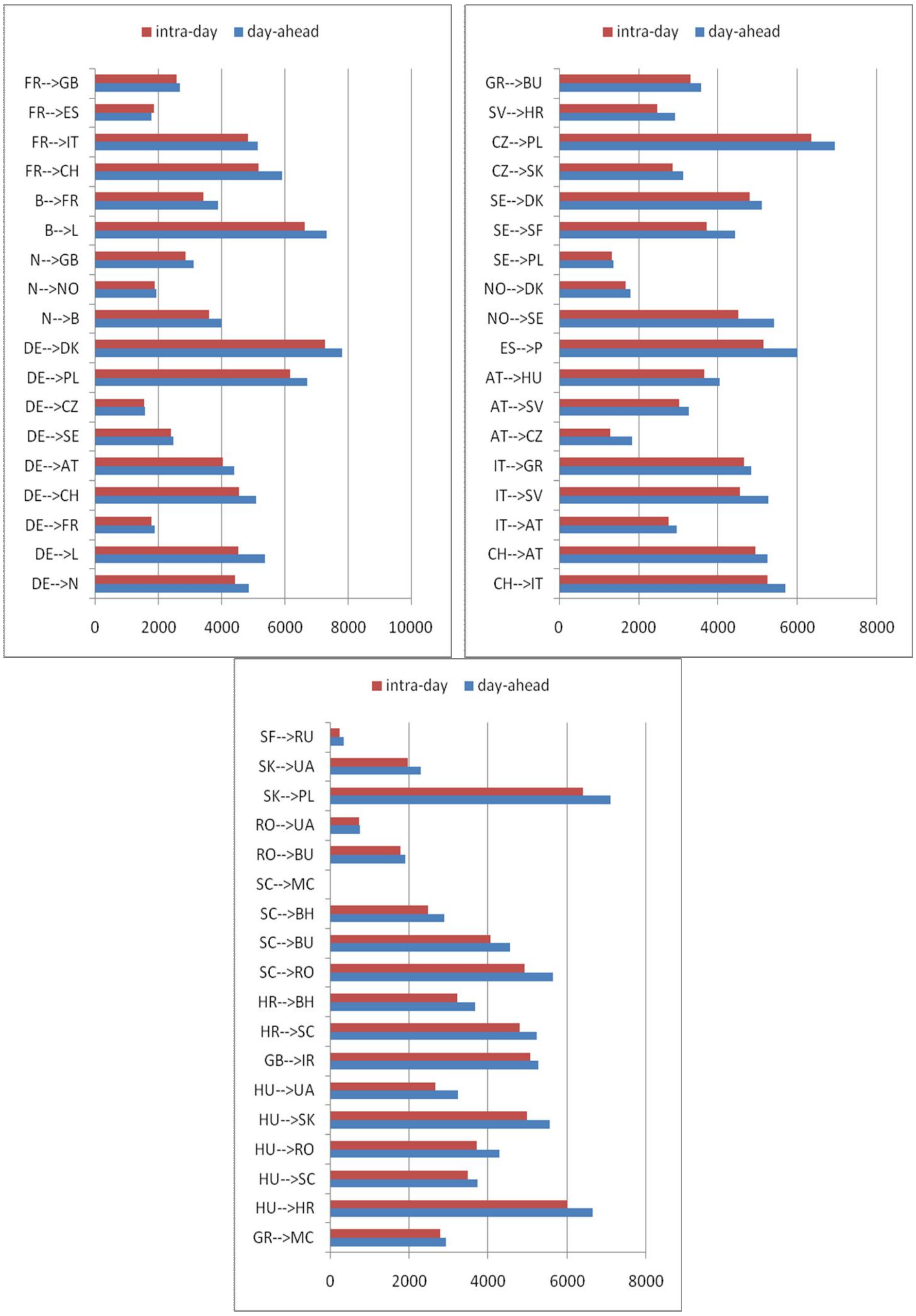


Figure 29. Forecast horizon impact on power flow difference hours

5 MOVING WEATHER EFFECTS

This Chapter deals with moving meteorological events and their effect on regional and national power balance and cross-border flows. Events that are the most challenging in terms of power flow variations for large power systems are deep, moving low pressure systems causing high wind power production, and storms that cause sudden shut-downs of wind farms.

5.1 Low pressure systems

Low pressure systems that Europe experience are mid-latitude low pressures that evolve on the Atlantic Ocean as a result of interaction of cold and warm air masses. The atmospheric pressure of low pressures is lower than in the surrounding area. The winds blow inwards and counter-clockwise around the low pressure's centre. Very low pressures can develop to storms. The diameter of a low pressure area is 1000 – 4000 km. The lows over Europe move from West to North-East with a velocity of up to 150 km/h. In the beginning they move faster, at the end they normally slow down or stagnate.

Cold fronts move faster than warm fronts due to higher air density. In the warm sector between the two fronts there is a risk of severe thunderstorms caused by the sharp difference of the cold and warm air. When the cold front overtakes the warm front an occluded front is formed, the low pressure is mature and begins to dissipate. The life time of low pressures is usually 3 to 7 days. During their lifetime low pressures move over distances of 1000 – 8000 km. [26]

The Atlantic low pressures make landfall in Europe typically North of 45^{th} latitude. Portugal and Spain are located South of the ordinary low pressure routes. An exceptional situation was experienced in October 2005 when a peculiar tropical storm named Vince reached the Iberian Peninsula [27]. Vince was, however, short lived and dissipated soon over South of Spain without causing damage. In the South of Europe there are Mediterranean cyclones but these span over smaller areas and last a shorter time (average 28 hours) than the Atlantic low pressures [28]. Hence they are not so interesting in a European power flow context.

5.2 Storms in the period 2000 – 2006

For some countries public lists or descriptions of storms can be found. In Denmark and Finland the meteorological institute lists storms. In Germany the reinsurance company Deutsche Rückversicherung AG issues yearly since 1997 a report on storms in Germany.

The Danish publication lists 8 storms in the period of 2000 – 2006 [29]. One event is classified to be of class 4 (10 min mean wind speed more than 28,5 m/s), one event to class 3 (more than 26,5 m/s), two events to class 2 (more than 24,5 m/s) while the four remaining are of class 1 (more than 21 m/s). The storm of class 3, named Gudrun, caused severe damage in Sweden on 8.1.2005. No storms were reported in 2001.

Finnish Meteorological Institute counts up to seven storms caused by low pressures in 2000 – 2006 [30]. In addition there were local cyclones in summer time. The definition for *storm* is events where the 10 min mean wind speed exceeds 21 m/s. In Finland most of the storms occur in the autumn.

Deutsche Rückversicherung AG presents in its publication all low pressure storms that cause damage in Germany [31]. There is no absolute wind speed according to which the events to report are chosen. Altogether 16 storms are reported in the period 2000 - 2006. All but one occurs in the period October to March. No storms were reported in 2001.

The time of occurrence of the storms reported in Denmark, Germany and Finland is shown in Figure 30. Autumn and winter is clearly dominating. Four low pressures caused storms both in Germany and Denmark:

- 29-31.1.2000 Kerstin
- 28-29.1.2002 Jennifer
- 27-28.10.2002 Jeanette
- 8.1.2005 Gudrun/Erwin.

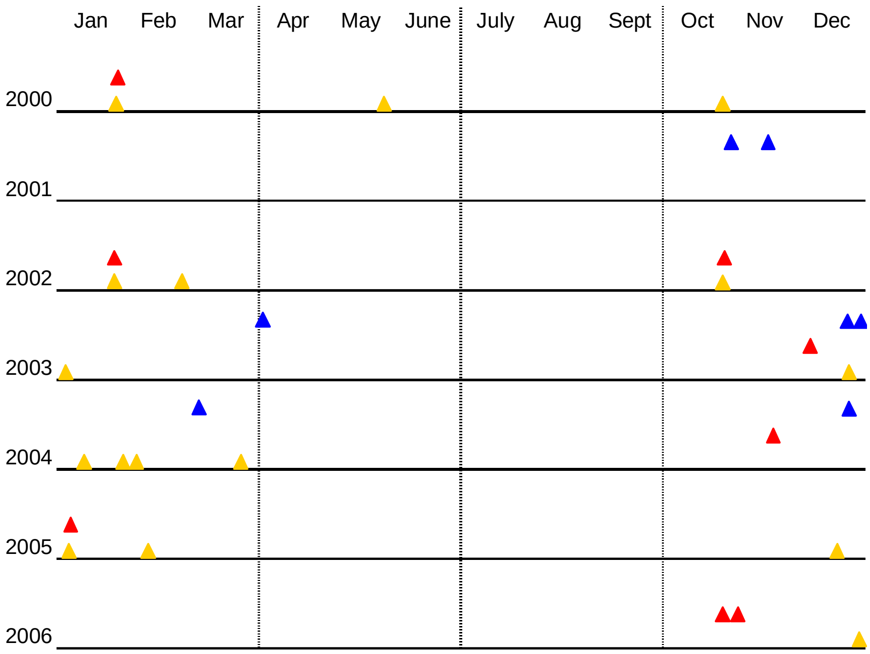


Figure 30. Date of storms in Denmark (red), Germany (yellow) and Finland (blue). Data from [29, 30, 31].

The routes of eight low pressures causing winds reaching storm level at some stage are shown in Figure 31. For comparison also the significantly different route of the tropical storm Vince is plotted. The daily location of the centre of the low pressure is indicated with a dot in order to illustrate the speed of the low pressures. These low pressures moved, with some exceptions, 1000 to 3000 km in a day, which is equivalent to 40 – 125 km/h.

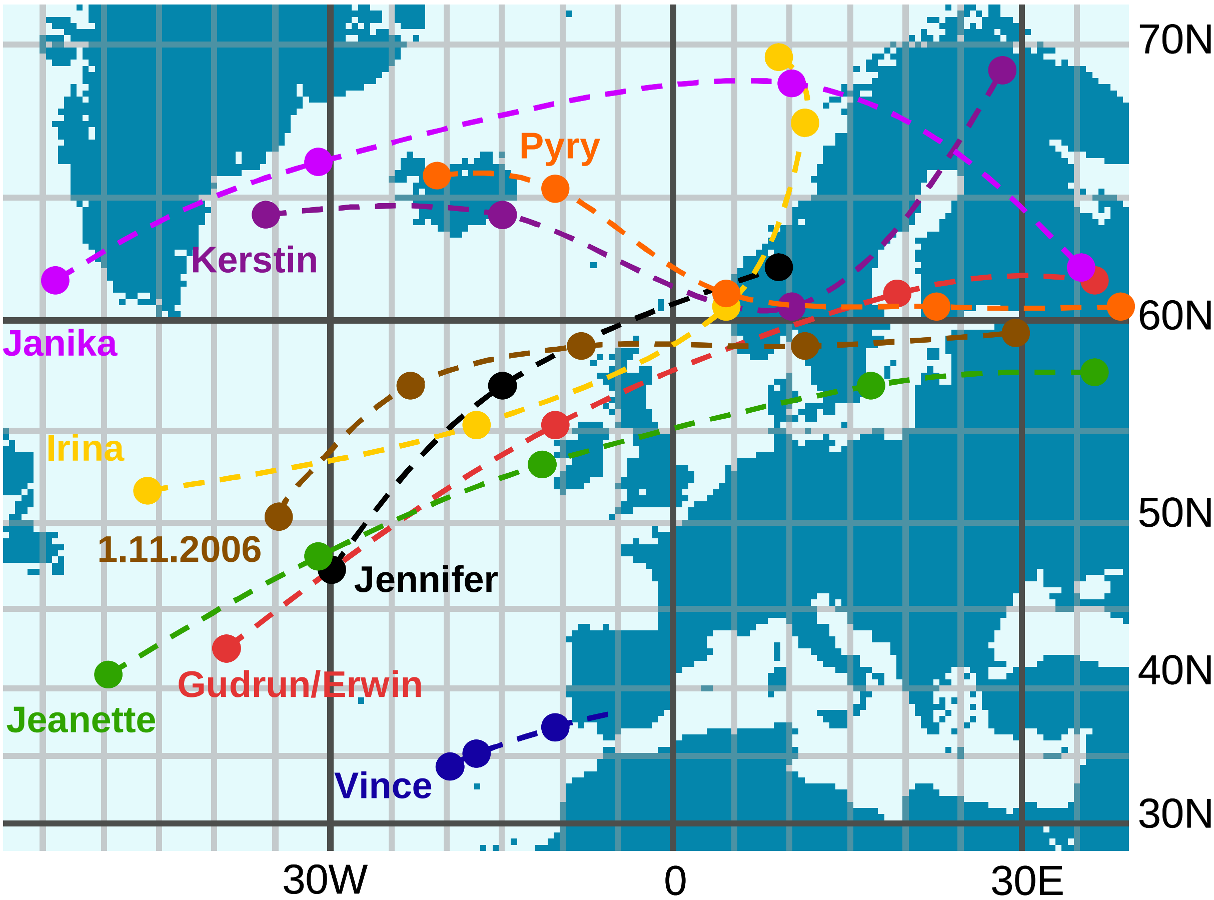


Figure 31. Routes of selected low pressures. Dot indicates daily position of the centre of the low pressure.

In this study a few moving low pressures were chosen to study the effect of wind speeds and changes in them to wind power production and power transfer changes caused by increasing/decreasing wind power production. The low pressures chosen to be studied are Janika, Jennifer and Gudrun/Erwin.

5.3 Moving weather front simulations

The moving weather front, i.e. low pressure, effects on wind power production, national power balance and cross-border power flows were studied by using the Reanalysis wind data of the periods of the occurrence of the moving weather phenomena. To see the influence of the phenomena on wind power, the year 2015 with reasonably large amount of wind power was chosen to be studied. The wind power amounts for each country for the chosen 2015 medium wind power scenario can be found in Appendix 1. The grid model, however, is the same as at present except for those HVDC's scheduled. The load and other-than-wind production are those estimated for the year 2015.

5.3.1 Gudrun/Erwin

Gudrun (named by the Norwegian Meteorological Institute) a.k.a. Erwin (named by German Weather Service) took place on January 8th 2005 in Denmark and Sweden. The centre of low pressure passed first Ireland and Great Britain the same day before entering Scandinavia. There was quite much wind a couple of days before and after the storm taking place also, as well as in the vicinity of the low pressure centres path. Total wind power capacities in the countries most concerned with the Gudrun/Erwin low pressure phenomenon in 2015 medium scenario are;

- Ireland 3257 MW
- Great Britain 10813 MW
- Denmark 4318 MW
- Sweden 3600 MW

Wind power production and thus the propagation of the low pressure is seen in Figure 32. It is noticeable that the low pressure has some effect on wind power production in Ireland and Great Britain, and the effect has some similarities in both countries. In Figure 32, the wind power production drop to the lowest point just after mid-night on January 8th is due to the centre of low pressure approaching the countries.

The shape of the wind power production curves, i.e. kind of arcs connected to each other, is so apparent because of the relatively large grid spacing of the Reanalysis wind speed data. Thus the countries are represented by only a few Reanalysis data points in the simulations. In reality this arcing feature may be more difficult to detect. The reason behind this arc shape is the power curve itself and its shape around maximum power production.

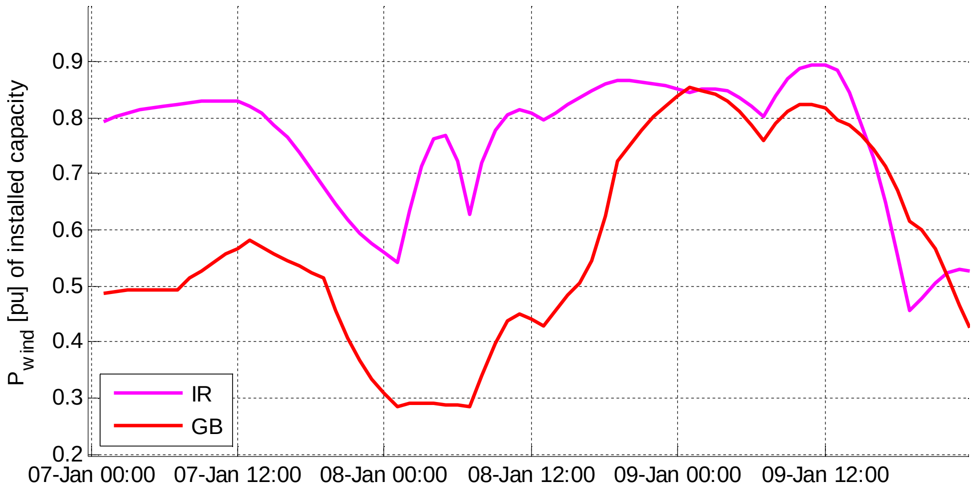


Figure 32. Wind power production during Gudrun/Erwin low pressure passing through Ireland and Great Britain.

The Figure 33 weather map shows that there are large pressure differences especially in the south of Great Britain at the time. Although the wind power production decrease is not very severe – only under 30 percentage units of capacity in both countries, compared to that in Denmark in 2005 real case (Figure 5) – the absolute wind power production changes in MW:s are still large, especially in Great Britain (see Figure 34). It can be seen in Figure 6 that although the January 8th production drop is the most severe, there still are quite many large changes in wind power production, which are not caused by any storms and do not cause any shut-downs of wind power plants from full power (see definition of a storm in section 5.2 and occurrences of storms in Denmark in Figure 30).

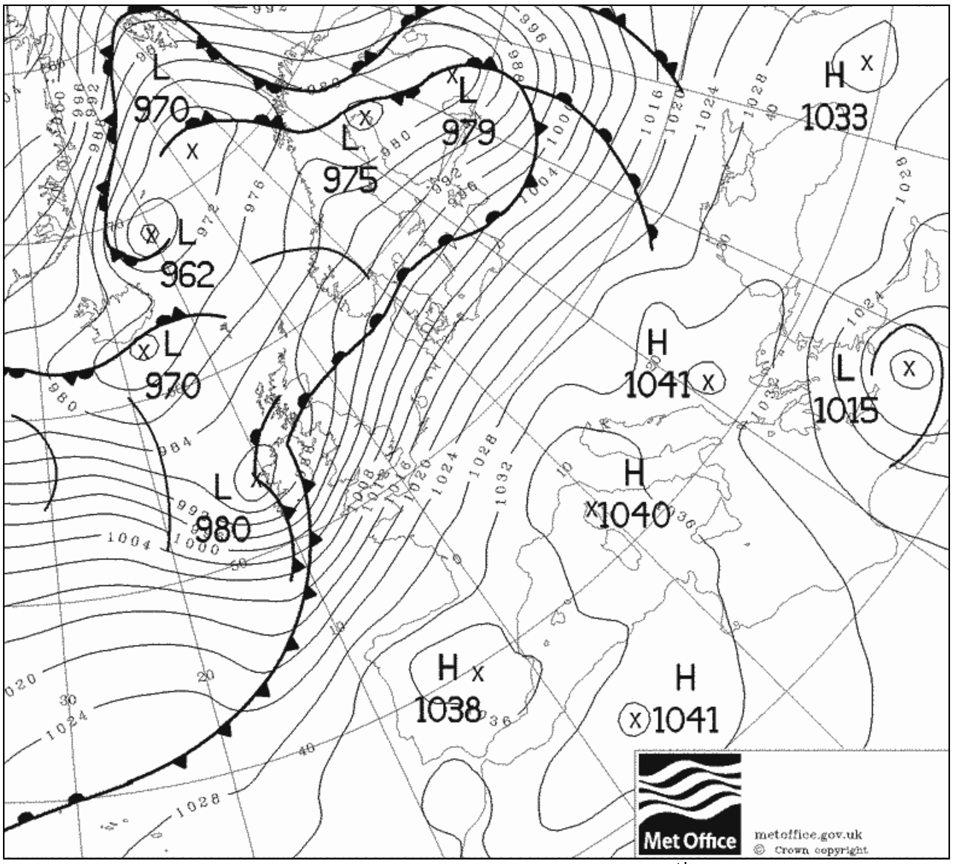


Figure 33. Weather map of Europe January 8th 2005 at midnight. [32]

There are two reasons for fast dropping of wind power production, too low wind (below cut-in) speeds and too high wind speeds (above cut-out). In Figure 34 the wind speeds of Reanalysis data points are plotted for wind power grid connection points in Great Britain. These wind speeds give some idea of what is causing the wind power production variations.

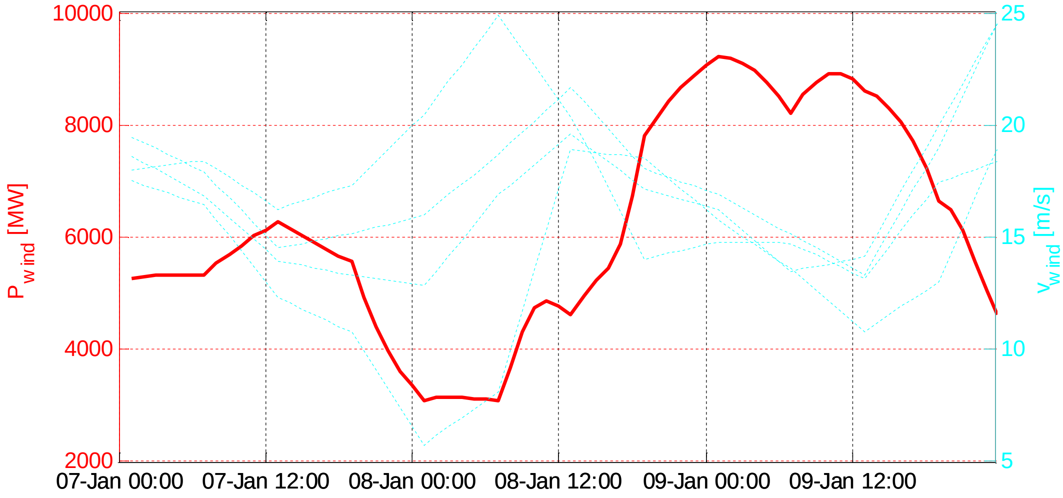


Figure 34. Wind power production in Great Britain and wind speeds at those Reanalysis data points where wind power grid connection points are located.

Figure 34 shows that there are high wind speeds due to Gudrun which cause some wind farms to stop so that the total wind power production reduces to a lower level, and as the wind speeds decrease from storm values sufficiently, the wind power production increases again.

In Figure 35 and Figure 36 the wind power production in Denmark and Sweden and corresponding wind speeds at Reanalysis data points of grid connection points are shown. In Denmark shut-down of huge part of wind power production takes place, just as in the 2005 case discussed in section 3.1.1 and shown in Figure 5. In Sweden the shut-down due to high wind speeds is more moderate. At some locations, i.e. in the South of Sweden, the wind speeds do increase above that of maximum wind power production and shut-down occurs. However, in other locations wind speeds first decrease, and later increase but not enough to cause shut-down so wind power production keeps increasing. Thus the total wind power production remains within smaller variation range than in Denmark, also because Sweden is a larger geographical area.

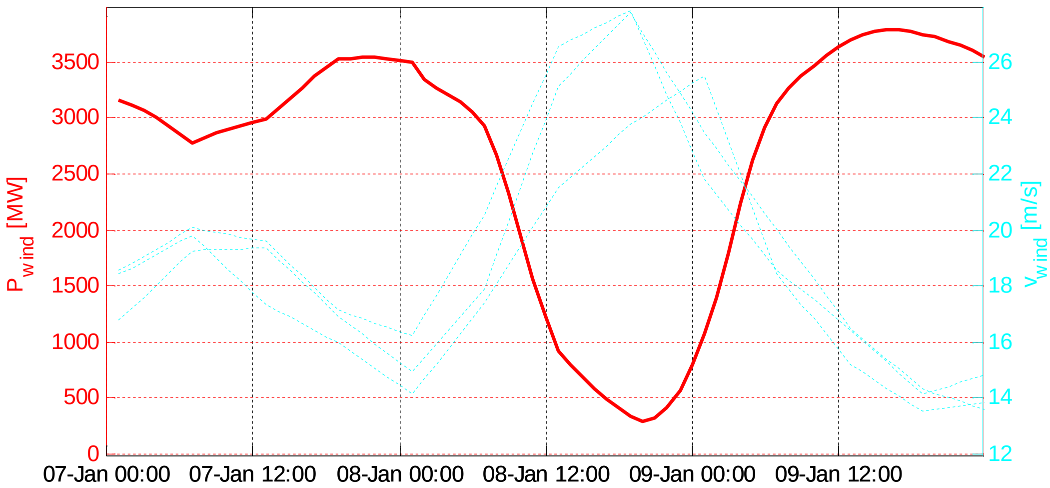


Figure 35. Wind power production in Denmark and wind speeds at Reanalysis data points where wind power grid connection points are located.

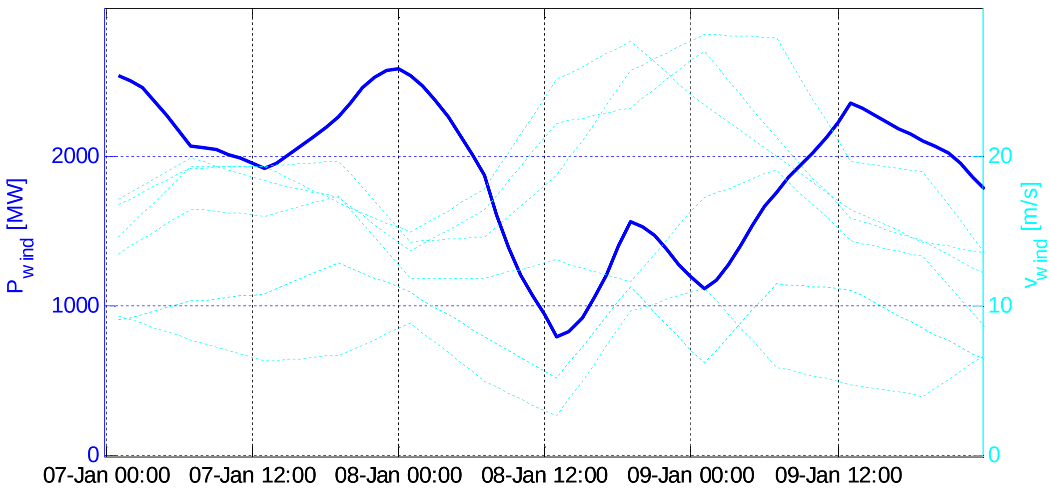


Figure 36. Wind power production in Sweden and wind speeds at Reanalysis data points where wind power grid connection points are located.

5.3.2 Janika

The Janika storm took place on 14-16.11.2001 and passed through Norway, Sweden and Finland. In Figure 37 the weather map over Europe is shown.

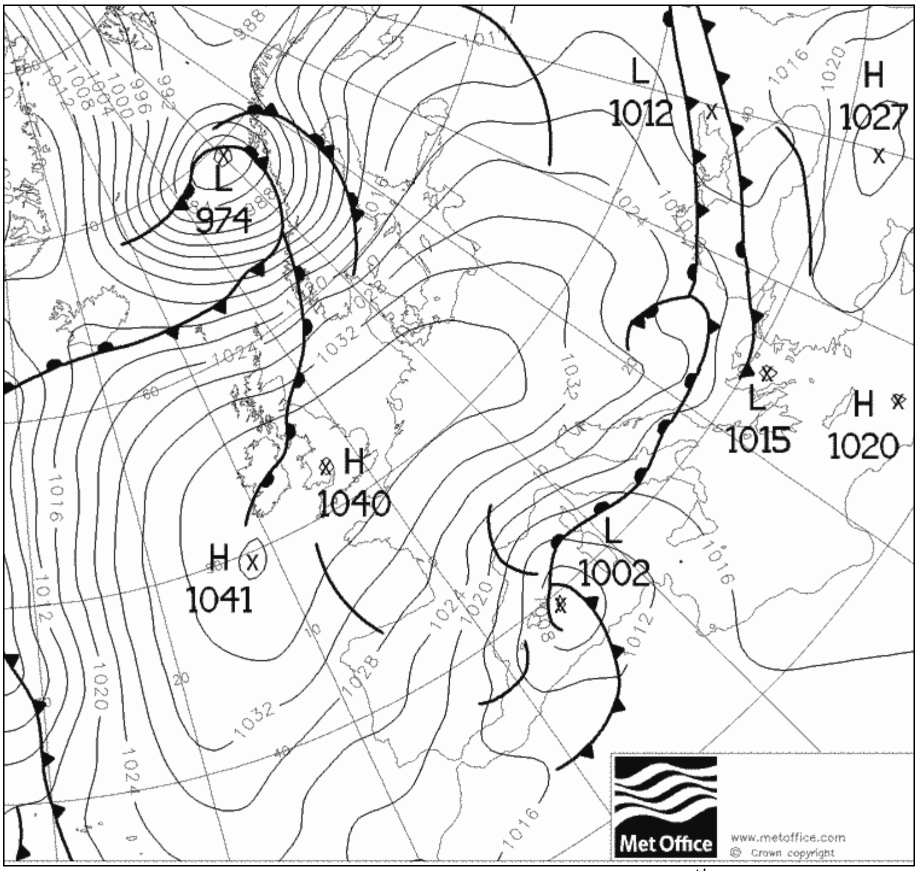


Figure 37. Weather map of Europe October 15th 2001 at midnight. [32]

The 2015 case wind power production in the three countries is shown in Figure 38. Total wind power capacity in these three countries in 2015 medium scenario are;

- Norway 2350 MW
- Sweden 3600 MW
- Finland 900 MW

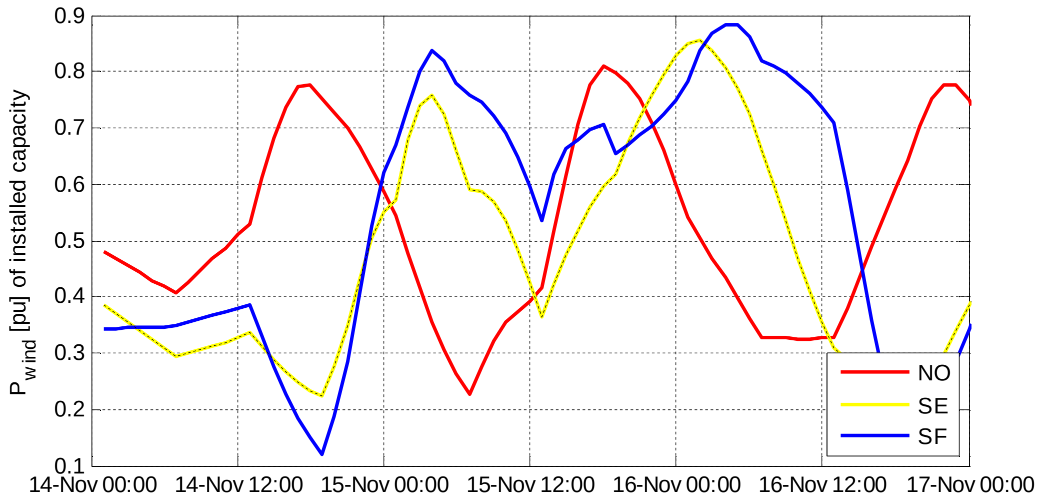


Figure 38. Wind power production during Janika passing through Norway, Sweden and Finland in 2015 medium wind power scenario.

The propagation of the centre of low pressure Janika is seen in Figure 38 as it passes the counties from west to east. The centre of low pressure passed Norway in the morning of the 15th.

The drop in Swedish and Finnish production seems to be at the same time just after noon on the 15th. The reason of production drop, however, is not the same. In Sweden, just as in Norway a few hours earlier, the drop is due to high wind speeds causing shut-down of wind turbines. In Finland, the production drop taking place simultaneously with Sweden, is due to decreasing wind speed. The highest wind speeds in Finland occur in the evening before midnight, and cause only some shut-down of wind turbines. This example shows that unless the wind power production curves are studied with wind speeds, it is not possible to determine if the increase or decrease of wind power production is due to shut-down because of too high increasing wind speeds, or due to decreasing wind speeds. It is also interesting to note that simultaneous decrease of wind power production in neighbouring countries can occur due to a storm effect in one country and decreasing wind speed in the other country.

Overall the proportional changes in wind power production were not that large in Sweden and especially not in Finland, as in Norway.
In Finland during Janika passing, the production is lowest when there is less wind – not because of shut-down of turbines due to too high wind speeds. This is because the wind speeds have already decreased when the low pressure arrives to Finland and begins to dissipate.

The power transfers between Sweden and other countries are shown in Figure 39. The cross border power transfer is not in this case significantly affected by the changes in wind power production caused by the moving low-pressure. The power transfer changes seem to be lost in normal daily variation – the storm occurred during weekdays (Wednesday-Friday, November 14th-16th).

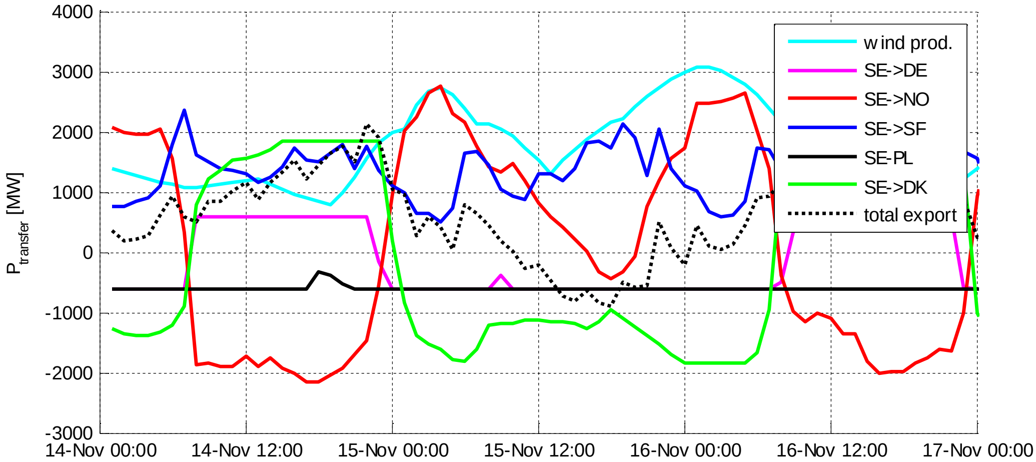


Figure 39. Wind power production and power exchange of Sweden with neighbouring countries during Janika in 2015 medium wind power scenario.

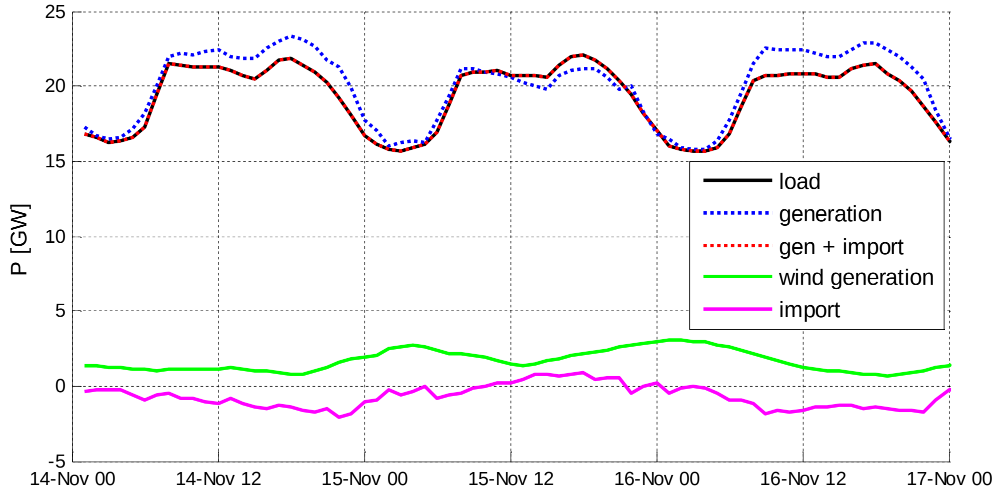


Figure 40. Total power generation, wind power, import and consumption in Sweden during Janika in 2015 medium wind power scenario generation.

5.3.3 Jeannette

Jeannette took place on 27.-28.10.2002 and passed through Ireland, Great Britain, Denmark and south of Sweden. It also affected the Benelux countries and Germany (Figure 41).

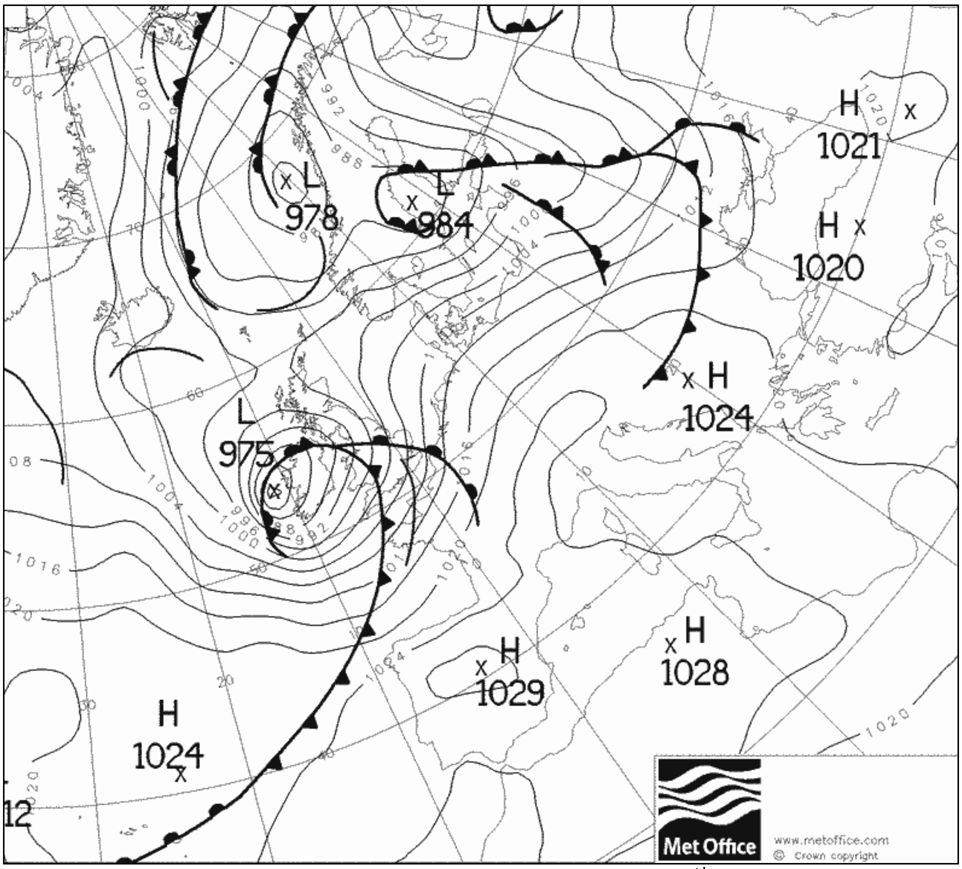


Figure 41. Weather map of Europe October 27th 2002 at midnight [32].

The 2015 case wind power production in some of these countries are shown in Figure 42. In 2015 medium scenario, the total wind power capacities in the countries concerned are;

- Ireland 3257 MW
- Great Britain 10813 MW
- Denmark 4318 MW
- Sweden 3600 MW
- Germany 36004 MW
- Belgium 1286 MW
- The Netherlands 5250 MW
- Luxemburg 96 MW

From the wind power production curves in Figure 42 it is not totally clear which effects are caused by the storm Jeannette and whether it has similar effects on neighbouring countries. Before Jeannette, there were two deep low pressures, Irina and Kyle, moving the same direction, and because of those, there is high wind power production on the 26th in almost all the countries shown in the figure. Jeannette centre of low pressure just reached Ireland after midnight between 26th and 27th and had just passed Denmark and south of Sweden at midnight between 27th and 28th. By midnight between 28th and 29th there were quite little pressure differences, and it was still calming down and the following midnight there is hardly any wind power production in all of Europe as seen in the Figure 42.

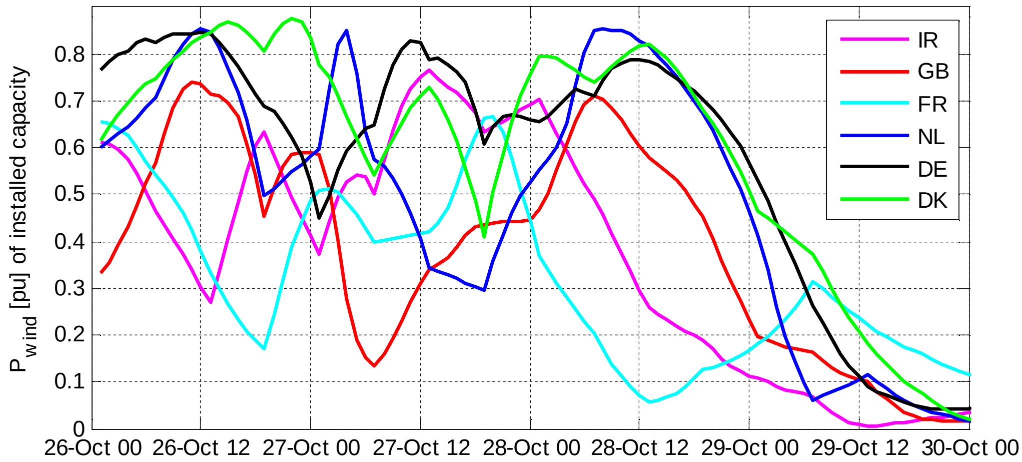


Figure 42. Wind power production during Jeannette passing through Ireland, Great Britain, Netherlands and Denmark in 2015 medium wind power scenario.

Making a similar comparison of wind power production and wind speed curves as in previous examples, it can be determined that there were storm induced wind power shut-down in Great Britain (all 24 hours on 27th), France (a few hours around noon 27th), the Netherlands (about 24 hours from night 27th to 28th), Germany (about 24 hours from the afternoon on 27th to afternoon 28th), whereas there were no shut-down or hardly any in Ireland and Denmark.

In Figure 43 and Figure 44 the power generation, wind power generation, import and electricity consumption in Germany and Great Britain are shown. Wind power production seems to be more significant than net import in Germany. It seems like there is not strong correlation between wind power production and power exchange. Only on 29th import increases as wind power production significantly decreases, but import replaces only a small portion of decreased wind power production. It seems like neither increase nor decrease in wind power generation in Great Britain has influence on net import.

Daily load variations are much more significant than wind power production variations in Great Britain. In Germany, according to this case study, the wind power variations are of about the same magnitude as the daily load variations, but slower, at least in this case. The wind power production increase turns to decrease at noon on 28th when power consumption also does the same. During the evening load peak the wind power production still continues to decrease, as well as for the night and still the following morning when consumption turns back up again.

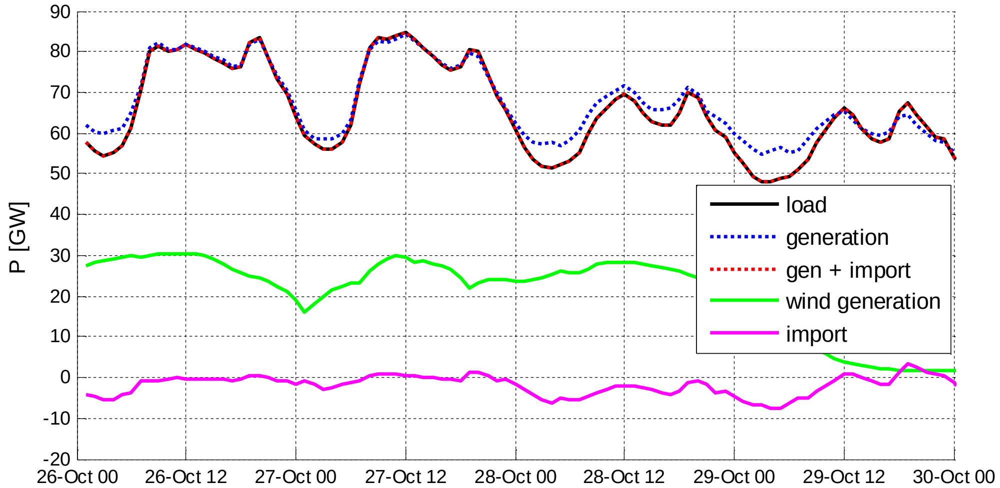


Figure 43. Total power generation, wind power, import and consumption in Germany during Jeannette in 2015 medium wind power scenario generation (36 GW wind power production capacity).

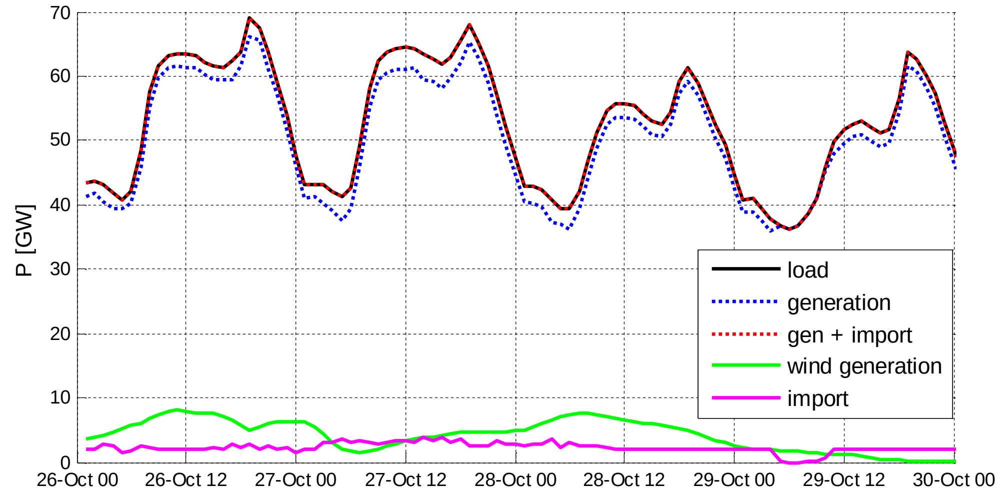


Figure 44. Total power generation, wind power generation, import and consumption in Great Britain during Jeannette in 2015 medium wind power scenario (10.8 GW wind power production capacity).

For scenario 2015 medium installed wind power cross-border power transmission does not seem to be significantly affected by the large changes in wind power production that Jeanette causes. Firstly, the wind power variation is still relatively small compared to load variation. Secondly, wind power replaces partly other domestic generation and only partly import. Thirdly, some cross-border connections are and will remain congested.

5.3.4 Conclusions – moving weather front study

The effect of deep low pressures passing was less noticeable and less straightforward than expected by the authors of this report. There are several reasons to this:

- The time scale of moving low pressures is in the same order of magnitude as diurnal load variation. It is hence difficult to detect the effect of moving low pressures on cross-border transmission.
- Wind power capacity and hence the absolute production variations, are relatively small compared to national load and its variation in the case studied here for scenario 2015 medium installed wind power.
- Wind power replaces partly other domestic generation and only partly power exchange.
- Cross-border connections might be and remain congested despite the wind power. In this case moving low pressures have no impact on the cross-border transmission itself, only on the severity of the congestion.

The analysis and results in this section illustrate that when studying large scale wind power production from a large area, it is not straightforward to see whether a dip in the production is caused by storm induced wind farm shut-downs. In several cases the wind farms were shut down only in one part of the country or region. Also basic variability due to decreasing wind speeds was causing part of the production reductions.

What is not well seen in the simulations described and illustrated above, due to the nature of used wind speed data, is the variation of wind speeds during the centre of low pressure passing. It is possible that there are high wind speeds on all sides of the centre of low pressure, in the direction towards the centre of low pressure. However, at the centre of low pressure there might be only little wind, which might be seen as reduction in wind power production – or maybe as increase if the highest wind speeds ahead the centre of low pressure caused shut-down. Because the area of low pressure centre is rather small, the influence of centres low speeds may also be lost in total variation when observing wind power production of a larger area, such as a small or medium size country.

In moving weather studies, a higher sampling of wind speed data should be used instead of interpolated data. With 6 hour initial sampling rate data only indicative simulation results can be shown.

Although the simulation results implied that even large changes in wind power production do not significantly affect cross-border transmission, this conclusion can not be drawn to apply in general. More detailed simulations need to be done to study short time scale wind power production change influence on power transmission with simulation models targeted for solving that particular task.

6 CAPACITY CREDIT OF WIND POWER

Capacity credit/value of wind generation can be broadly defined as the amount of firm conventional generation capacity that can be replaced with wind generation capacity, while maintaining the existing levels of security of supply. Sometimes the capacity credit is defined as the amount of additional load that can be carried by the system with wind power, without decreasing the level of the security of supply for the power system. In practice the first definition leads to a procedure where we increase the level of security of the system without wind energy by adding generation units. We count the amount of capacity that has to be added to a system in order to obtain the same security of supply as in the system with wind energy. The second definition leads to a procedure where we add load to the system with wind energy in order to decrease the level of security until we reach the same level of supply of the system without wind energy.

This topic has been the subject of much study and debate in recent times and several methodologies have been proposed to calculate the capacity credit of wind power [33].

With the TradeWind project data some analyses have been made to see the effect of clustering larger areas than single countries on results of capacity value. The methodology used is not a full capacity credit methodology with loss-of-load calculations so the results of the analyses cannot be stated as capacity value. However, the effect of larger geographical area can be seen in the results.

Hourly wind power production data from years 2000-2006 was combined with hourly data for electricity consumption (load) for year 2006. The same load profile was used for all the years as we only had the hourly consumption numbers from year 2006.

Installed wind power capacities were taken from wind power scenario year 2020 Medium. The clustering was made according to the UCTE areas now used in UCTE (UCTE1, UCTE2 etc). The results also produce results for the whole of UCTE as well as for the whole of Europe including also Nordic countries and GB.

6.1 Capacity factor method

Capacity factor wind power production during times of high load can be used as an indication of the capacity credit for wind power in low penetration levels [34]. This is because the actual capacity credit calculations are sensitive to wind power production during the highest peak load hours.

However, the capacity factor does not take into account the fact that capacity value will decrease as the penetration levels of wind power increase – the capacity factor will be the same for the first hundred megawatts and then tens of gigawatts of wind power.

Thus, the capacity factor cannot be taken as capacity value, but merely an indication of capacity value at low penetration levels of wind power. A high capacity factor during peak load hours demonstrates a strong correlation between wind and load which can be regarded as a pro-wind argument.

6.1.1 Method description

First, hourly wind power production time series were calculated for each country. Then, data for each country were combined with country load data. Wind power production during 1, 10 and 100 hours with highest consumption was taken from the data for each year separately. Average capacity factor of wind power was calculated from the seven yearly results.

Then both wind and load hourly data were summed up to make clusters (Nordel, UCTE1, UCTE2 etc) and to even larger clusters (UCTE, UCTE+Nordel+GB). Again wind power production during the highest peaks was taken and average production calculated.

In addition to average production also the range of production (from the seven years) was calculated and year 2006 results are indicated separately as this was the year with synchronous wind and load data.

6.1.2 Results

The results for single countries and their clusters are presented in Figure 45 - Figure 47. The rest of the results are in Appendix 6.

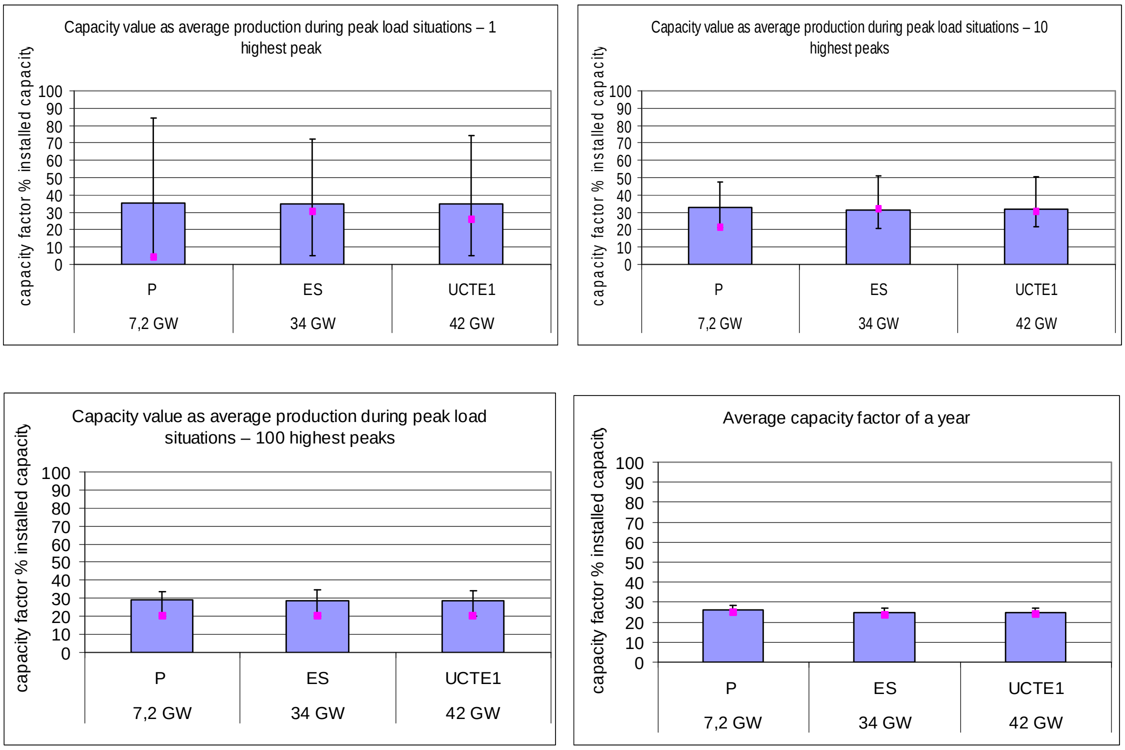


Figure 45. Wind power production during 1, 10 and 100 highest peak load hours for UCTE1. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.

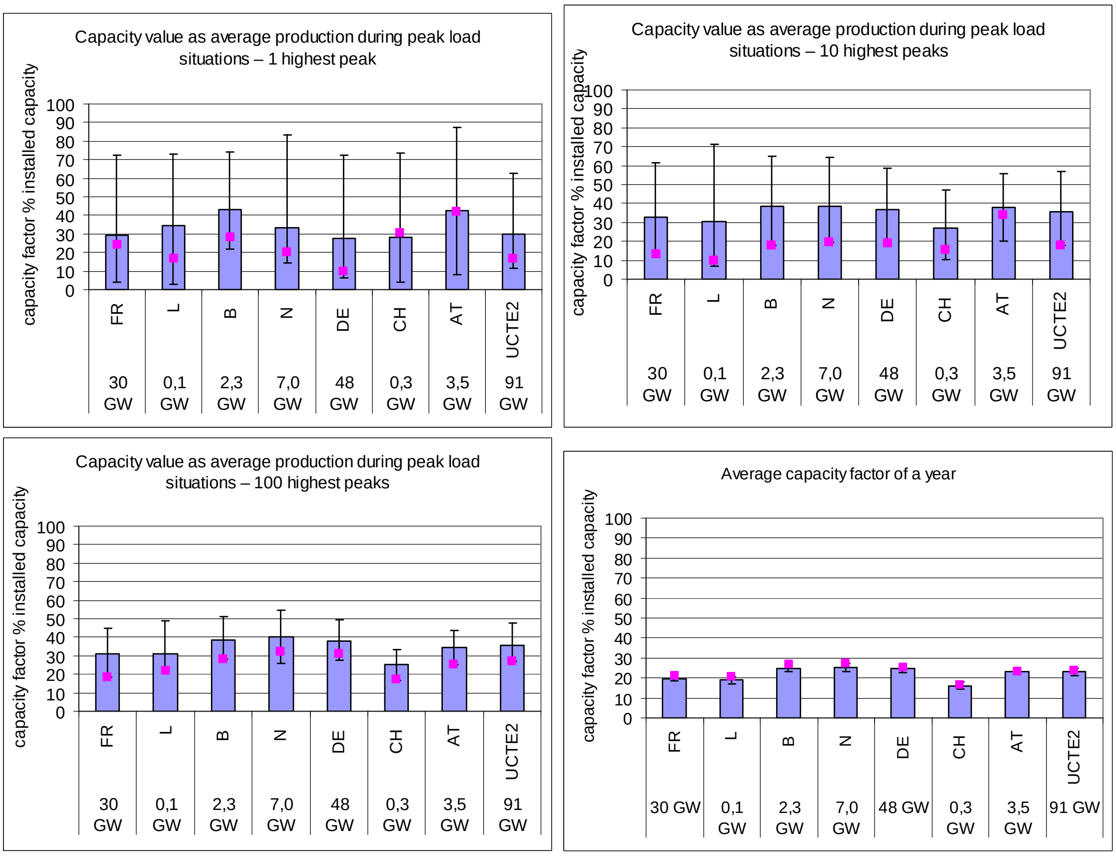


Figure 46. Wind power production during 1, 10 and 100 highest peak load hours for UCTE2. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.

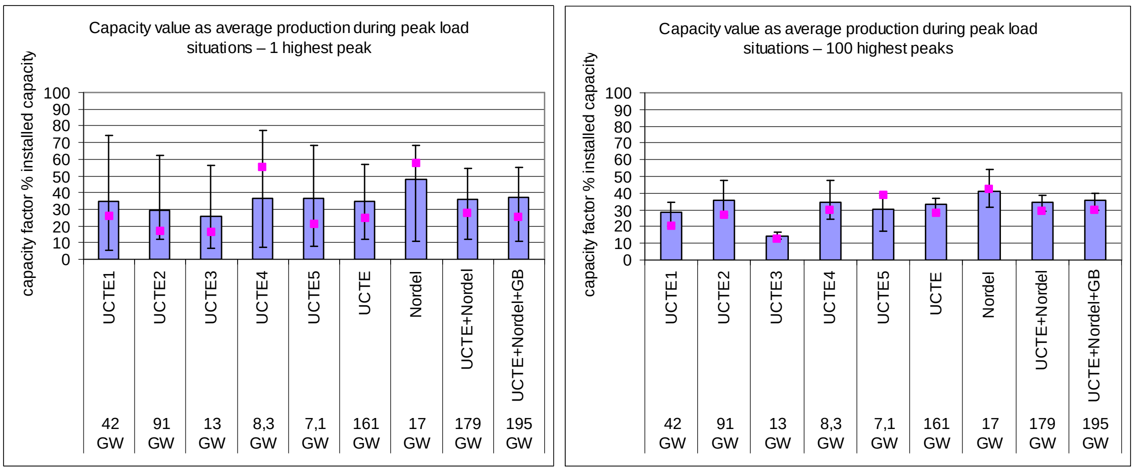


Figure 47. Wind power production during 1 and 100 highest peak load hours for clusters and the whole of Europe. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data.

The results show that when taking a single year, and single highest peak load situation, the result of wind power production during the peak load has large range. The effect of clustering is most clearly seen in the range of single year values becoming smaller. The result as the average value of seven years is not necessarily the highest of single country results, but somewhere in the middle.

Taking the 100 highest peak load hours, with the lowest year results, the capacity factors indicate that at low penetrations of wind power the capacity value of wind power can be of the order of 20 % in UCTE1/5, 25 % for UCTE2/4, 10% for UCTE3, and 30 % for Nordic countries. For the whole of UCTE, and the whole of Europe, the capacity value of wind power at low penetrations of wind power can be of the order of 30 %.

It has to be taken into account that we use the installed capacity scenario of 2020 Medium, this means that German wind power is dominating the other countries.

According to the data, in nearly all cases, the wind power production during peak load hours is on average higher than the yearly average production.

6.2 Probabilistic method

6.2.1 Method description

For TradeWind the capacity credit of wind energy was calculated by applying the approach of probabilistic recursive convolution. This considers the generation capacities of a country and combines the reliability of the power fleet with that of wind power during high load situations.

The power fleet of a country or a region must be capable of reliably carrying the load at any given time. A certain part of the power fleet may be subject to scheduled maintenance or repair status. Repairs and maintenance can be scheduled for periods when the load is relatively low (for instance, during the summer in Germany). Apart from this planned unavailable capacity, some outages from generation units are unplanned. Every generation unit is available during peak load times with the probability p. The secured capacity of the conventional power fleet without wind energy is calculated by recursive probabilistic convolution. Based on this data, the secured capacity at a certain level of supply security can be determined.

In the next step, wind energy is integrated into the system and the secured capacity is calculated once more. The wind energy generates a certain electricity output with a probability that can be determined from the yearly wind time series. This allows it to be integrated into the power fleet as a “virtual” wind energy plant.

The difference between the secured capacity of the system without wind energy and with wind energy, at a certain level of supply security, is referenced as the capacity credit of wind power.

In order to include the correlation between wind power production and load profile, the power probability density curve for wind power is generated by using only the power production data of a set number of peak load hours. The comparison of the results for different numbers of peak load hours should show regardless of whether load and wind are indeed correlated. In this analysis, we have taken the wind production during 30 % of peak load hours with the highest consumption. This means that wind energy during the remaining period is disregarded because the load is low, there is enough redundant conventional power to meet the consumption demands, and wind generation is not of principle importance regarding the power supply.

The methodology is described in detail in Appendix 7.

Capacity Credit of Individual Countries and Country Groups

Capacity credit calculations for the TradeWind project analyzes the benefit of better European interconnections between countries. As wind power is distributed to wider areas, the wind energy production of the system becomes steadier. In the European context, distribution covers different weather systems; while there is a high-pressure weather system over Spain there may be simultaneously a low pressure weather system over Germany.

We investigated how much the capacity credit can increase when the calculations are based on a smoothed wind energy generation curve, which we assume will be created when the exchange of wind energy between countries occurs.

In the following paragraphs, two procedures regarding the generation of smoothed wind energy curves will be discussed. Firstly, the simple smoothing effect of the country grouping is described (referenced simply as the, “smoothing effect”). Secondly, we integrate the load profiles of selected countries; note that the peak load hours of some countries are somewhat shifted and that wind energy may be distributed from one country during low load periods to another country at high load periods (referenced simply as, “redistribution of wind energy”).

In this analysis the capacity credit is always calculated for an individual country respectively based on the power fleet of individual countries. It is not based on the power fleet of the country group. Only the wind energy is exchanged between the countries in the group which results in smoothed wind energy curves for the individual countries. If the capacity credit was calculated based on the power fleet of the group, this would assume that the country group is carrying the load together, which is not in line with the current practice.

Smoothing Effect

The capacity credit for individual countries is based on wind energy curves of each country. In order to determine the smoothing effect of country groups,
individual country wind energy series are summed up and the cumulated wind energy curve is scaled down to represent the correct annual wind energy output of the country in order to make sure that every country integrates the same amount of wind energy as before the countries were grouped together. The result is smoothed wind energy curves, for each country individually.

Based on these curves, the capacity credit of individual countries can be recalculated. In the following, the values derived on the basis of theses smoothed wind energy curves will be referenced as the *smoothing effect* values.

Redistribution of Wind Energy

The smoothing effect approach discussed above does not yet regard that load profiles in Europe are different and the peaks may be slightly shifted. When determining the capacity credit of country groups, this may be of great importance as the wind energy produced in the country group may be redistributed to individual countries according to load profiles.

As discussed above, we have only taken into account the wind production during 30 % of the hours with highest consumption. Consequently, the wind energy produced during low load hours will be disregarded in the calculation and does not contribute to the capacity credit. As discussed in the Appendix 7 Chapter 2, this is allowed as the load during these times can be easily met by the conventional generation. The wind energy during low load periods may be transferred to another country, where the load is high and additional wind energy is beneficial.

Figure 48 illustrates the procedure of redistributing wind energy according to load profiles with an example involving two countries. First, wind energy is summed up (Figure 48a) and subsequently scaled to the annual output of each country (Figure 48b). This generates the smoothed wind curves as already discussed before when describing the “smoothing effect”. In addition, Figure 48b displays the load profiles of each country. As only 30 % of the peak load hours are taken into account in the capacity credit calculations, as explained above, the wind energy for one country can be redistributed if the load is lower than the so-called load threshold line. For the hours when the load is higher, the threshold line belongs to the 30 % of hours of highest consumption. In order to simplify the example, we assume that the threshold line is identical for both countries. In this example, the load of country II in hour 2 is lower then 70 GW and the wind energy can be redistributed to country I.

If there are more than two countries, there may be times when the wind energy from different countries will be redistributed to several countries. In this scenario, wind energy would be redistributed according to the share of annual wind energy production from an individual country based on annual wind energy production of the whole country group.

Later we will refer to this procedure as the *wind energy redistribution* methodology.

It is important to note that also after the redistribution the wind energy production of the country group is not higher than before. It is ensured that the redistributed wind energy is only used once and not in several countries when calculating the capacity credit.

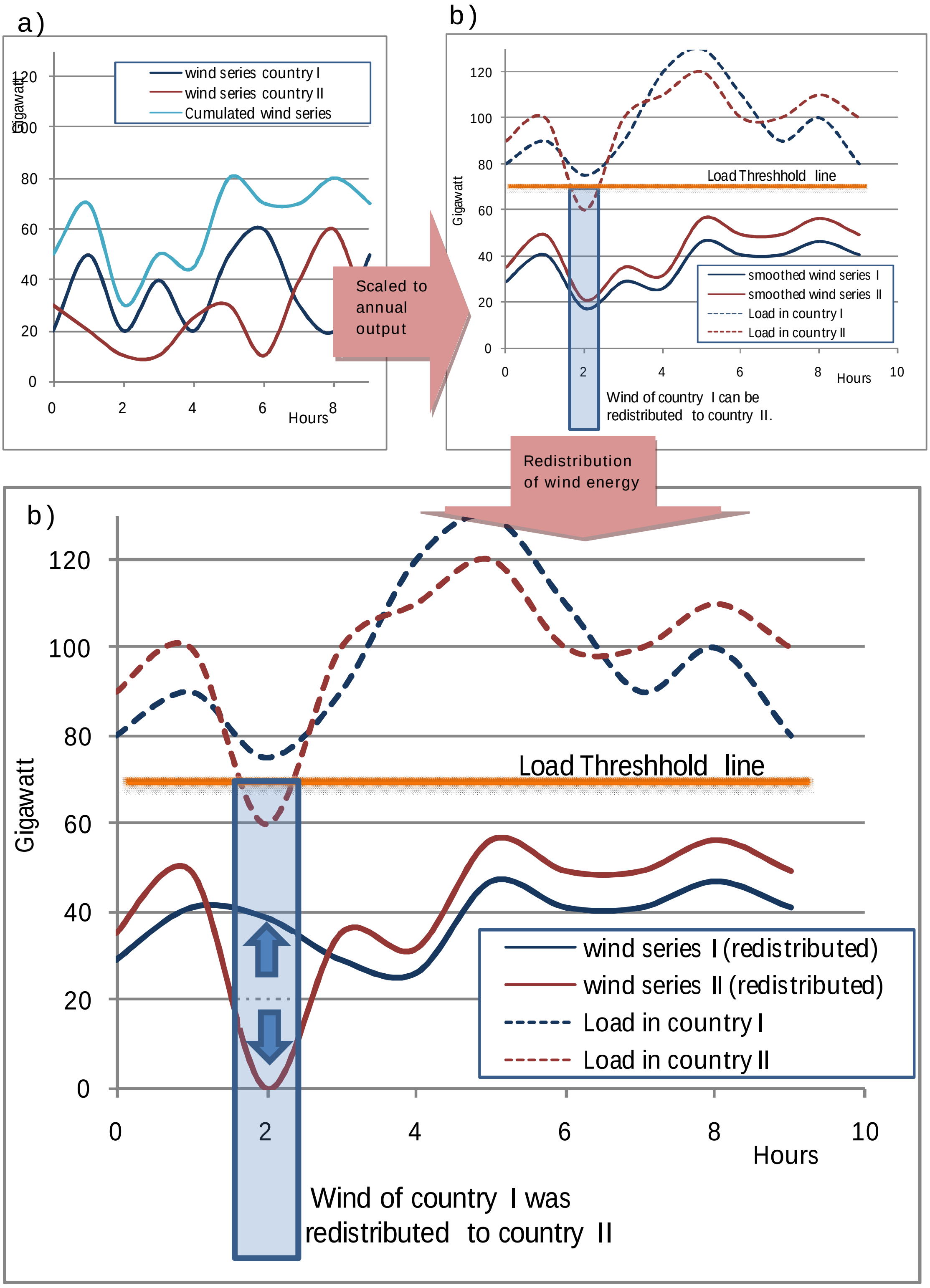


Figure 48: Redistribution of wind energy in country I to country II when the load is lower then the load threshold line of country I. The threshold line is defined by the fact that the capacity credit is based on wind energy production during 30 % of the hours of highest consumption.

Wind generation data

The analysis is based on the reanalysis data wind years 2000 till 2006 for the 2020 medium scenario. The capacity credit was calculated for each of these wind years and the minimum value was considered the final result. The average value of the seven wind years would be misleading because the capacity credit is directly linked with the system security and only the worst case reflects a robust result.

Generation unit data used for the calculations

The data of the generation units for the European countries is based on the UDI WORLD ELECTRIC POWER PLANTS DATA BASE (Dated June 2008).

The rate of the unplanned outages is assumed in accordance with the values listed in Table 5 [35].

Table 5: Assumptions for unplanned, non-disposable plant outages. [35]

Power plant technologies	Unplanned, non-disposable outages
Nuclear power stations	3%
Lignite fired power stations	3,2%
Hard coal fired power stations	3,8%
Natural gas and steam fired power plants	1,8%
Gas fired steam turbines	1,8%
Gas turbines	3,0%
Oil fired power station	1,8%
Storage power station	0%
Pumped storage hydro power stations	0%

Level of Supply Security

Values of 97 % for a single balancing zone can be confirmed in relevant literature [36, 37, 38], meaning that the annual peak load cannot be covered without electricity importation from neighbouring regions in 3 out of 100 cases. Considering Germany as a whole, which consists of four distinct balancing zones, justifies a level of 99 % [35]. In Appendix 7, a sensitivity analysis for values ranging from 95 % to 99 % is conducted and demonstrates that the sensitivity in this range is rather low.

All further calculations for the different European countries are based on the 99 % value. Assuming the same level of supply security for all countries allows the comparison of the results.

6.2.2 Results

Effect of increasing installed capacity and turbine distribution

The most important input for the calculation of the capacity credit for wind energy is the wind power time series. If there are a lot of periods with low wind power, the capacity credit decreases. The characteristics of the wind power dispatch depend on the wind turbine distribution. In the the investigation period 2008-2020, the regional distribution of onshore wind turbines changes and offshore wind turbines become more important. This results in higher wind energy during peak load hours and higher capacity credit.

In order to show this effect, the capacity credit was calculated for Germany with the specific distributions of the 2020 and 2008 medium scenario. For each distribution the production series was scaled from 1 GW to 50 GW of the installed capacity. Figure 49 shows the relative and absolute capacity credit for the different distributions in Germany (the calculation was based on the wind year 2004). The distribution of the 2020 medium scenario results in a higher capacity credit. The effect is stronger for Germany which is perfectly aligned with high offshore wind energy penetration in the year 2020.

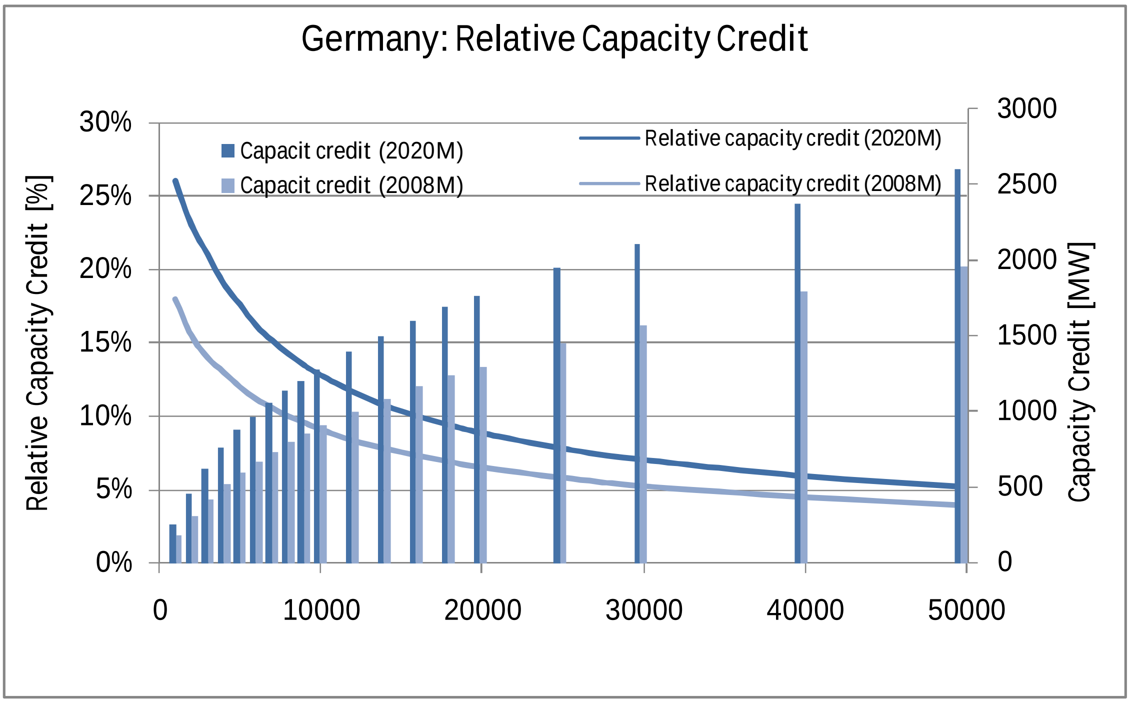


Figure 49: Germany - Relative and absolute capacity credit of increasing installed capacity and changing wind turbine distribution.

While the overall capacity credit increases, the relative capacity credit decreases. This effect has to be taken into account when looking at countries with a low total installed capacity and a high relative capacity credit. The relative capacity credit does not remain constant when more wind energy is installed.

These characteristics, as illustrated by the example of Germany, are applicable for any country. It is important to keep this in mind when comparing the capacity credit of countries with different wind energy penetration.

Capacity Credit of Individual Countries and Country Groups for UCTE 2 in the 2020 Medium Scenario

The following discusses how the grouping of wind energy production in the UCTE 2 zone increases the capacity credit. Table 6 displays the capacity credit that is calculated for the different countries in the UCTE 2 zone in the 2020 medium scenario. First, the capacity credit is calculated based on the individual wind energy series; second, the capacity credit is based on the smoothed wind energy curves that result when grouping the wind energy production in the UCTE 2 zone. Last, the calculations are based on smoothed wind energy curves when the wind energy is distributed with consideration to the load profiles of individual countries.

Table 6: Capacity credit in the UCTE2 zone in the 2020 medium scenario.

	Total installed capacity	Individual Capacity Credit		Smoothing Effect - Capacity Credit		Wind Energy Redistribution - Capacity Credit	
Country	[MW]	[MW]	Relative	[MW]	Relative	[MW]	Relative
D	48202	2580	5.4%	3360	7.0%	3810	7.9%
F	30000	2370	7.9%	2960	9.9%	3400	11.3%
B	2289	440	19.2%	510	22.3%	600	26.2%
NL	6950	490	7.1%	820	11.8%	990	14.2%
LUX	126	30	23.8%	30	23.8%	50	39.7%
CH	300	30	10.0%	40	13.3%	60	20.0%
AUS	3500	260	7.4%	360	10.3%	410	11.7%
Total	91367	6200	6.8%	8080	8.8%	9320	10.2%

As anticipated, the capacity credit for each individual country increases when the country is grouped with all UCTE2 countries. The highest capacity credit is seen when “wind energy redistribution” methodology is applied. In Germany, for instance, the relative capacity credit increases from 5.4 % (or 2580MW) to 7.9 % (or 3810 MW). Similarly, in France wind energy of the country considered alone is 7.9 % (2370 MW) and this value increases to 11.3 % (or 3400 MW) when the wind energy production is grouped with the other UCTE2 countries.

In Figure 50, the results for the capacity credit in the whole UCTE zone are summarized. By redistributing the wind energy "intelligently" with consideration of individual load profiles of each country, the capacity credit increases from 6.8 % to 10.2 %, which correspondingly equals an increase from 6200 MW to 9320 MW.

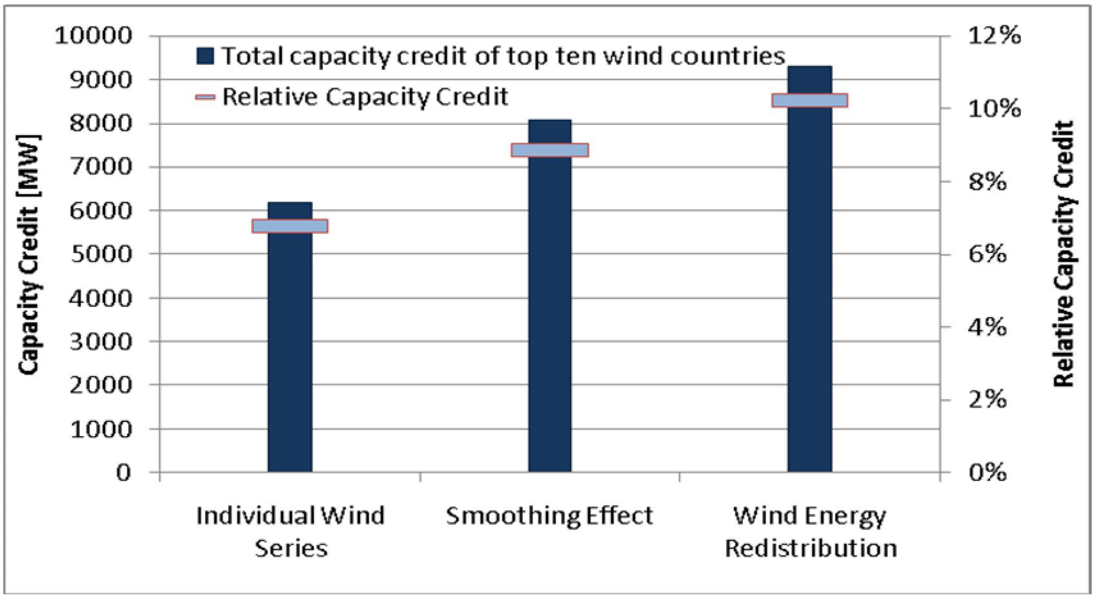


Figure 50: Total and relative capacity credit of wind energy in the UCTE2 zone in the 2020 medium scenario.

<u>Capacity Credit of Individual Countries and Country Groups for the Top Ten Wind Countries of the 2020 Medium Scenario</u>

The following section will investigate the capacity credit increase when the wind energy production of the top ten wind countries in the 2020 medium scenario is grouped. The results for the different top ten wind countries are displayed in Table 7. The figures display the capacity credit when only the wind energy of each country is considered and the capacity credit is determined when smoothing effects between these ten countries are taken into account. The highest capacity credit is observed when the redistribution method is applied.

In the case of Germany the relative capacity credit increases from 5.4 % to 12.5 %, which equals a respective increase of 2580 MW to 6030 MW when the wind energy redistribution method is applied. In France the capacity credit of wind energy in the individual country is

7.9 % (2360 MW) and goes up to 15.8 % (4730 MW) when France is grouped with the other UCTE2 countries and. The capacity credit in the other countries increases similarly.

Table 7: Capacity Credit in the top ten wind countries in 2020 medium scenario.

	Total installed capacity	Individual Capacity Credit		Smoothing Effect - Capacity Credit		Wind Energy Redistribution - Capacity Credit	
Country	[MW]	[MW]	Relative	[MW]	Relative	[MW]	Relative
DE	48202	2580	5.4%	4770	9.9%	6030	12.5%
ES	34477	2330	6.8%	2650	7.7%	3620	10.5%
F	30000	2360	7.9%	4100	13.7%	4730	15.8%
GBR	16278	1920	11.8%	2830	17.4%	3310	20.3%
I	11620	610	5.2%	850	7.3%	1150	9.9%
POR	7211	660	9.2%	710	9.8%	1280	17.8%
NL	6950	490	7.1%	1060	15.3%	1350	19.4%
SWE	6500	1110	17.1%	1560	24.0%	1800	27.7%
POL	6000	520	8.7%	1090	18.2%	1280	21.3%
DK	5309	470	8.9%	850	16.0%	1070	20.2%
Total	172547	13050	7.6%	20470	11.9%	25620	14.8%

Figure 51 sums up the capacity credit in the top ten wind countries. When the capacity credit is based on the individual of all top ten wind countries results in 25.6 GW capacity credit and 14.8 % relative capacity credit when the wind energy redistributed according to the load profiles.

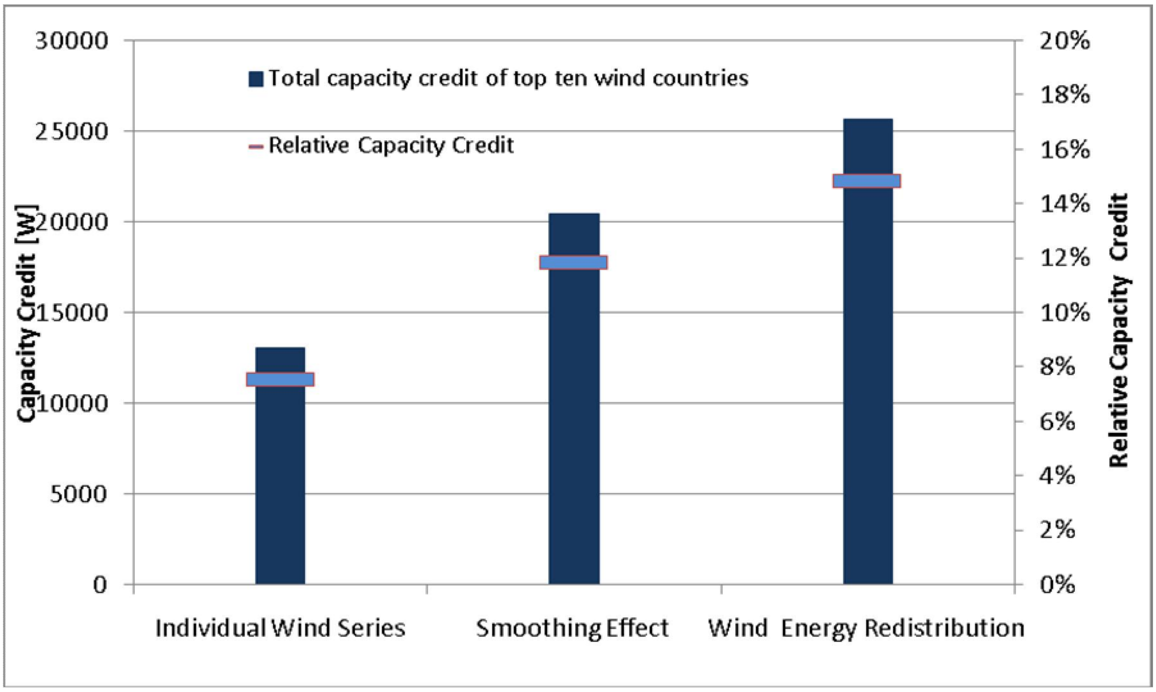


Figure 51: Total and relative capacity credit of wind energy in the UCTE zone in the 2020 medium scenario.

Capacity Credit of Individual Countries and Country Groups for Europe

Finally it is investigated how the capacity credit increases when the wind energy of all European countries is grouped. The results observed when applying the different smoothing procedures are displayed in Table 8. Again the capacity credit increases significantly when the capacity credit calculations are based on the grouped wind energy production and again the highest capacity credit is seen when the redistribution method is applied.

Table 8: Capacity Credit in Europe in 2020 medium scenario.

	Total installed capacity	Capacity Creedit based on individual wind series		Smooting Effect - Capacity Credit		Wind Energy Redistribution - Capacity Credit	
Country	[MW]	[MW]IM	Relative IM	[MW]SM	RelativeSM	[MW] DM	Relative DM
Aus	3500	260	7.4%	500	14.3%	620	17.7%
Bel	2289	370	16.2%	570	24.9%	740	32.3%
Bul	875	90	10.3%	130	14.9%	230	26.3%
Cro	1400	60	4.3%	120	8.6%	170	12.1%
Cze	1200	170	14.2%	230	19.2%	340	28.3%
Den	5309	470	8.9%	910	17.1%	1200	22.6%
Fin	1700	250	14.7%	390	22.9%	540	31.8%
Fra	30000	2360	7.9%	4650	15.5%	5270	17.6%
Ger	48202	2580	5.4%	5290	11.0%	6740	14.0%
GBR	16278	1920	11.8%	3100	19.0%	3770	23.2%
Gre	3640	350	9.6%	490	13.5%	760	20.9%
Hun	850	70	8.2%	80	9.4%	120	14.1%
Ire	4537	340	7.5%	730	16.1%	930	20.5%
Ita	11620	610	5.2%	1080	9.3%	1540	13.3%
Lux	126	30	23.8%	30	23.8%	50	39.6%
Net	6950	490	7.1%	1150	16.5%	1520	21.9%
Nor	3660	500	13.7%	770	21.0%	880	24.0%
Pol	6000	520	8.7%	1200	20.0%	1380	23.0%
Por	7211	660	9.2%	770	10.7%	1020	14.1%
Rom	2500	260	10.4%	390	15.6%	520	20.8%
Ser	80	20	25.0%	20	25.0%	30	37.5%
Slovakia	280	40	14.3%	40	14.3%	90	32.1%
Slovenia	430	20	4.7%	30	7.0%	50	11.6%
Spa	34477	2330	6.8%	2870	8.3%	4040	11.7%
Swe	6500	1110	17.1%	1730	26.6%	1980	30.5%
Swi	300	30	10.0%	50	16.7%	80	26.7%
Total	199915	15910	8.0%	27320	13.7%	34610	17.3%

Figure 52 sums up the results. The figure displays the capacity credit when only the wind energy of each country is considered and the capacity credit is determined when smoothing effects between these ten countries are taken into account. The overall capacity credit can be increased from 8.0 % to 17.3 % when the European wind energy is grouped. This corresponds to an increase from 15.9 GW to 34.6 GW.

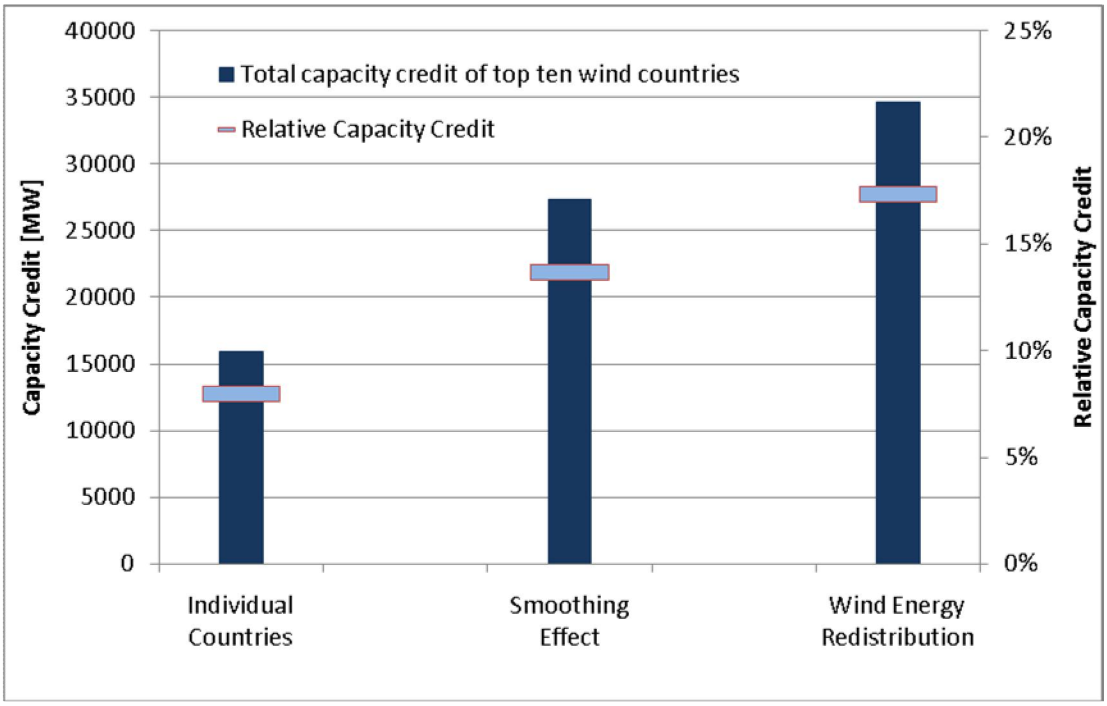


Figure 52: Total and relative capacity credit of wind energy in European wind countries.

7 CONCLUSIONS

Identification of wind power induced bottlenecks

The impact of wind power on electricity exchange and cross-border congestions have been studied for all TradeWind scenarios by the use of a flow-based market model. The model represents the European power system as a single market, and cross-border flow is restricted by individual tie-line capacities and NTC values.

It is important to model transmission restrictions well (correct values for NTC and line capacities), because cross-border connections are often fully in use in one direction or the other, consequently incorrect capacity values impact power flow widely in meshed networks. Not all the information needed was available in desired detail for the study, but Tradewind consortium is reasonably satisfied with the data and model. In comparison of year 2005 simulation results to actual transmission and bottleneck situation in the European power system, there was found quite good correspondence in some issues, and some others there were somewhat differing results. The differing results are due to modelling issues; using ideal market model and single NTC value for all the time for all cases, as well as general imperfections in the modelling due to lack of more precise information of the system.

The simulations have identified that many bottleneck situations are rather independent of the wind capacity scenario, but changes significantly for the different simulation years. This is due to the different country-wise scenarios used for load growth and development of other power generation. For the simulation years 2008, 2010 and 2015, wind power generally has low impact on congestion situations. For the later simulation years (2020 and 2030) increased wind integration would impact more significantly to congestion occurrences, especially for:

France - Spain
France - Switzerland
France - Belgium
France – Great Britain
Great Britain - Ireland
Austria - Germany
Germany - Sweden
Sweden - Finland
Sweden - Poland
Greece - Bulgaria

On some connections, increased wind power leads to less, and in others to more, congestion occurrences according to the simulations.

It is not only important to analyse how many hours lines are congested but also how severe the congestion is. As measure on severity of congestion a "sensitivity value" is used in this project, and results with these measures are shown in the report on cross-borders as well.

Wind power prediction errors have an impact on the hourly cross-border power flow. The results obtained indicate that most of the time the differences between the actual and predicted power flow are in the range of 1-20 % of line capacity. In some cross-border connections, this could lead to more congestion. The wind power development scenarios do not have an important impact on the uncertainty on the cross-border power flows. Based on the simulations wind power forecast should be included in large scale integration studies.

Moving weather effects

The effect of moving weather fronts, especially storms, passing was discovered less noticeable and less straightforward in terms of wind power production influence in cross-border transmission than expected. Several reasons were identified for this. First, the low pressures movement and influence is not easy to distinguish from diurnal load variation. Secondly, the wind power capacities and hence the absolute production variations are still relatively small compared to national loads and their variations (studied 2015 medium scenario). Thirdly the wind power replaces partly other domestic generation and only partly power exchange, and in addition cross-border connections might be and remain congested despite the wind power.

Capacity credit issue

Based on capacity credit data analysis, in almost all cases wind power production during peak load hours is higher than the yearly average production. Capacity factor of wind power during peak loads can be used as an indication of capacity value of wind power at low wind power penetration level. Clustering the countries with the 2020M scenario installed wind power capacity improves the capacity factor of total wind power, in the whole study area UCTE+Nordel+GB it is 30 % during 100 highest peaks even in lowest wind year.

The probabilistic capacity credit calculation confirms the capacity factor analysis: load and wind energy production have some beneficial correlation, which increases the capacity credit of wind energy. The results for the 2020 medium scenario show that grouping wind energy production from multiple countries strongly increases the capacity credit and the more geographic area the grouped countries represent, the higher it is. For instance for the top ten wind countries, the capacity credit is 8 %, when the wind energy is not grouped and increases to 15 % when grouped among wind energy from multiple countries. The smoothing effect of the wind energy is strongest when we base the calculations on the wind energy production of all European countries. In the case when no wind energy is exchanged between the European countries, the capacity credit in Europe is only 8 %, which corresponds to 15.9 GW. Lastly, when Europe is calculated as one wind energy production system and wind energy is distributed across multiple countries according to individual load profiles, the capacity credit increases to nearly 17.3 %, which corresponds approximately to 34.6 GW. It is important to consider that 34.6 GW represents a maximum value for the capacity credit, which could be achieved when the transmission capacity between countries is sufficient enough.

REFERENCES

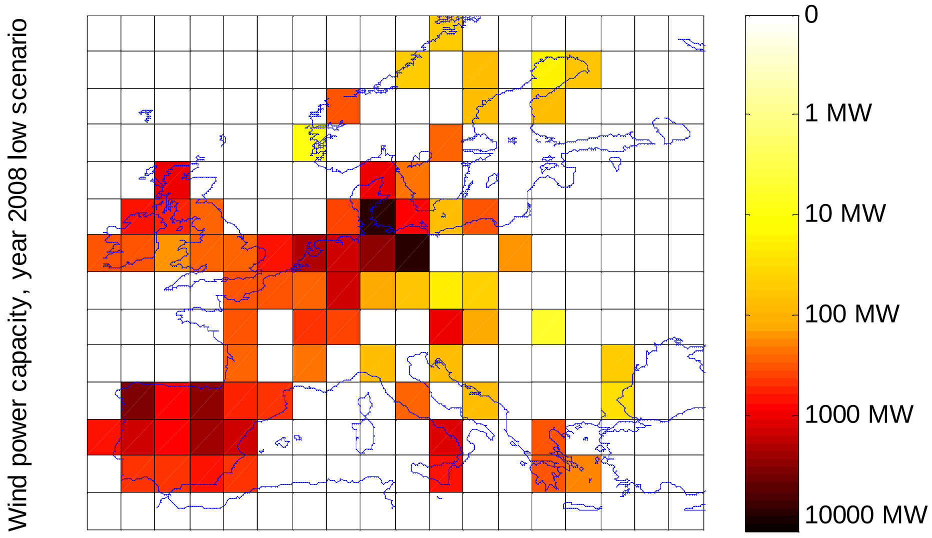
1. Tradewind deliverable D2.3 “Time series wind speed data”
2. Tradewind deliverable D2.4 “Models for conversion of of wind speed data”
3. G. van der Toorn, WP2.1 Wind power capacity data collection. TradeWind Deliverable 2.1, Garrad Hassan 11914/GR/01B, 2007.
4. J.R. McLean, WP2.6 Equivalent wind power curves. TradeWind Deliverable 2.4, Garrad Hassan 11914/BT/02B, 2007.
5. Tradewind deliverable D3.2 “Grid modelling and power system data”
6. UCTE, System Adequacy Forecast 2007-2020, January 16th, 2007. Available at http://www.ucte.org/_library/systemadequacy/saf/UCTE_SAF_2007-2020.pdf Visited at 8.6.2008.
7. Union of the Electricity Industry. Statistics and prospects for the European electricity sector (EURPROG), 2005 and 2007.
8. Tradewind deliverable D3.1 “Grid equivalents – numerical data”
9. Tradewind deliverable D3.2 “Grid modelling and power system data – Appendix: Model updates”
10. NTC Values Winter 2007-2008 (Created 5.12.2007) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
11. Energinet.dk. http://www.energinet.dk/da/menu/Marked/Udtr%c3%a6k+af+markedsdata/Udtr%c3%a6k+af+markedsdata.htm Visited at 1.7.2008.
12. UCTE Transmission Development Plan, edition 2008. UCTE http://www.ucte.org
13. Tradewind deliverable D7.1 “List of significant interconnectors”
14. Tradewind deliverable D6.1 “Assessment of increasing capacity on selected transmission corridors”
15. NTC Winter 2004-2005 (Created 22.9.2004) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
16. NTC Winter 2005-2006 (Created 12.12.2005) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
17. http://www.ucte.org/services/onlinedatabase/exchange Visited at 4.6.2008.
18. Nordel Annual Statistics 2005. Available at http://www.nordel.org/content/Default.asp?PageID=213 Visited at 4.6.2008.
19. http://www.berr.gov.uk/files/file45407.pdf Visited 6.6.2008.
20. Tradewind deliverable D2.1 “Scenarios of installed wind capacity in each region for each of the targets”
21. G. Giebel, G. Kariniotakis, R. Brownsword, ”The State-of-the-Art in Short-Term Forecasting of Wind Power”, Position paper for the Anemos project, to be downloaded from www.anemos.cma.fr , 2003.
22. Boone A, “Simulation of Short-term Wind Speed Forecast Errors using a Multi-variate ARMA(1,1) Time-series Model”, Royal Institute of Technology, Stockholm, 2005
23. G. Giebel, P. Sørensen, H. Holttinen, ”Forecast error of aggregated wind power”, TradeWind Deliverable 2.2, April 2007.
24. K. Rohrig, F. Schlögl, B. Ernst, Ü. Cali, R. Jursa, J. Moradi, Wind Power Prediction in Germany – Recent Advances and Future Challenges, EWEC06, Athens, Greece, 2006
25. G. Gonzalez, Wind Power Prediction in the Spanish System Operation (peninsula and islands) Sipreolico, POW’WOW, Workshop on Best Practice in Short-term Forecasting, 28 May 2008, Madrid,

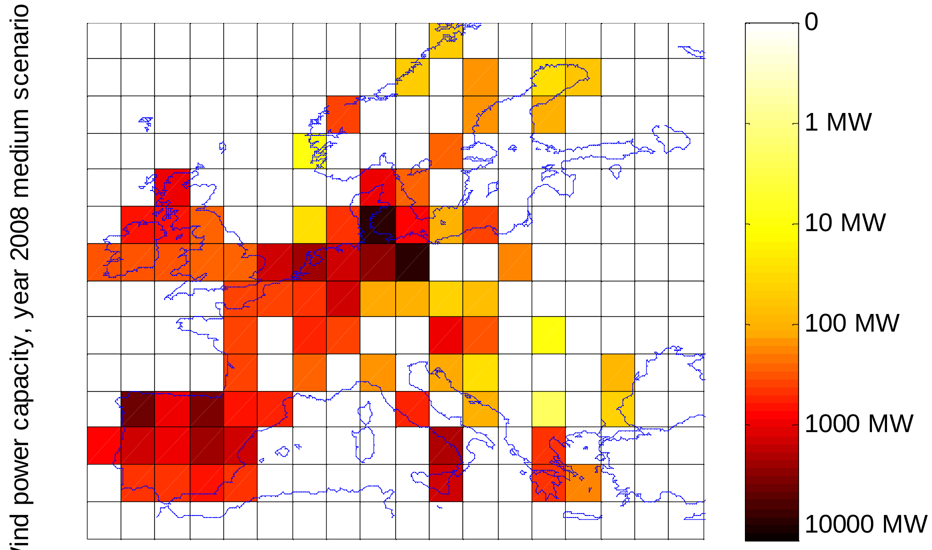
http://powwow.risoe.dk/publ/GGonzalez_(REE)-WindPowPredInSpanishSystemOp_BestPractice-2_2008.pdf
26. H. Karttunen, J. Koistinen, E. Saltkoff, O. Manner. Ilmakehä ja sää. Ursan julkaisuja 62, Tähtitieteellinen yhdistys Ursa.
27. J.L. Franklin, Tropical Cyclone Report: Hurricane Vince. National Hurricane Center, National Oceanic and Atmospheric Administration. http://www.nhc.noaa.gov/pdf/TCR-AL242005_Vince.pdf
28. Cyclones in the Mediterranean. April 2006, World Climate Research Programme http://www.wmo.ch/pages/prog/wcrp/pdf/WCRPnews_LionelloMedCLIVAR_Final.pdf
29. J. Cappelen & S. Rosenørn (editors), Storms in Denmark 1891 – 2008. DMI Danmarks Meteorologiske Institute. http://www.dmi.dk/dmi/storme-2.pdf Visited at 7.5.2008.
30. Matalapainemyrskyt 1959 lähtien. http://www.ilmatieteenlaitos.fi Visited at 27.5.2008.
31. Sturmdokumentation Deutschland, Deutsche Rückversicherung Aktiengesellschaft. http://www.deutsche-rueck.de/web/export/sites/dr/das_unternehmen/veroeffentlichungen/sturmdokumentation/index.html Visited at 7.5.2008.
32. Wetterzentrale http://www.wetterzentrale.de Visited at 7.5.2008.
33. Holttinen, H, Lemström, B, Meibom, P, Bindner, H, Orths, A, Van Hulle, F, Ensslin, C, Tiedemann, A, Hofmann, L, Winter, W, Tuohy, A, O'Malley, M, Smith, P, Pierik, J, Tande, J O, Estanqueiro, A, Gomez, E, Söder, L, Strbac, G, Shakoor, A, Smith, J C, Parsons, P, Milligan, M, Wan, Y. Design and Operation of Power Systems with Large Amounts of Wind Power. State-of-the-art report. VTT Working Papers 82, 2007. VTT, Espoo, Finland. Available at http://www.vtt.fi/inf/pdf/workingpapers/2007/W82.pdf.
34. Milligan, M. & Porter, K. 2005. The Capacity Value of Wind in the United States: Methods and Implementation. Electricity Journal, Vol. 19, Issue 2. March 2006. Elsevier, Inc. Pp. 91–99.
35. dena grid study 2005
36. G. Dany, Kraftwerksreserve in elektrischen Verbundsystemen mit hohem Windenergieanteil. Aachener Beitrage zur Energieversorgung Band 71, Klingenberg Verlag (2000)
37. Th. Hartkopf, B. Hagenkort, Kapazitätskredit der Windkraftanlagen in Hessen (1998)
38. H. Bouillon, R.-D. Machate, G. Tetzlaff, Leistungseffekt von Windkraftanlagen, Elektrizitätswirtschaft Heft 24 (1989)

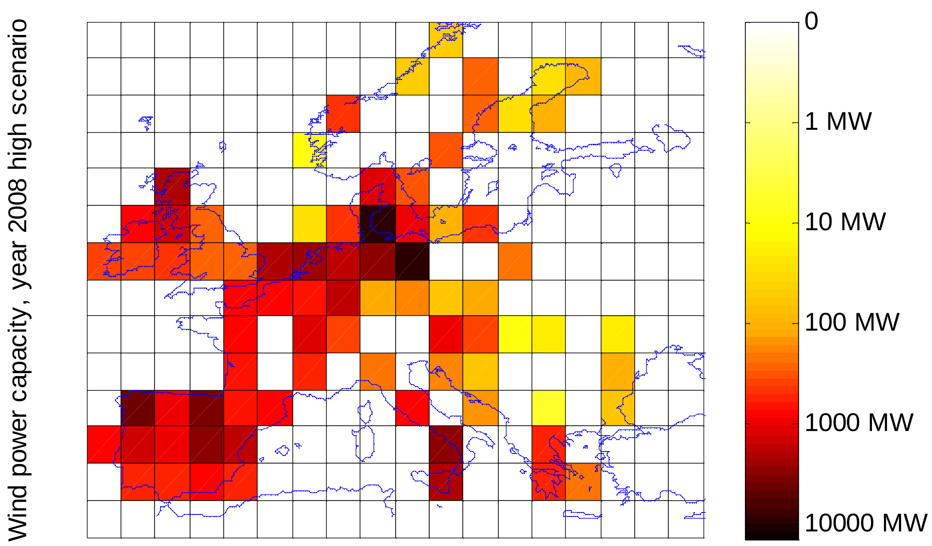
APPENDIX 1. INSTALLED WIND POWER PER COUNTRY (MW) AND ITS GEOGRAPHICAL DISTRIBUTION IN THE SCENARIOS

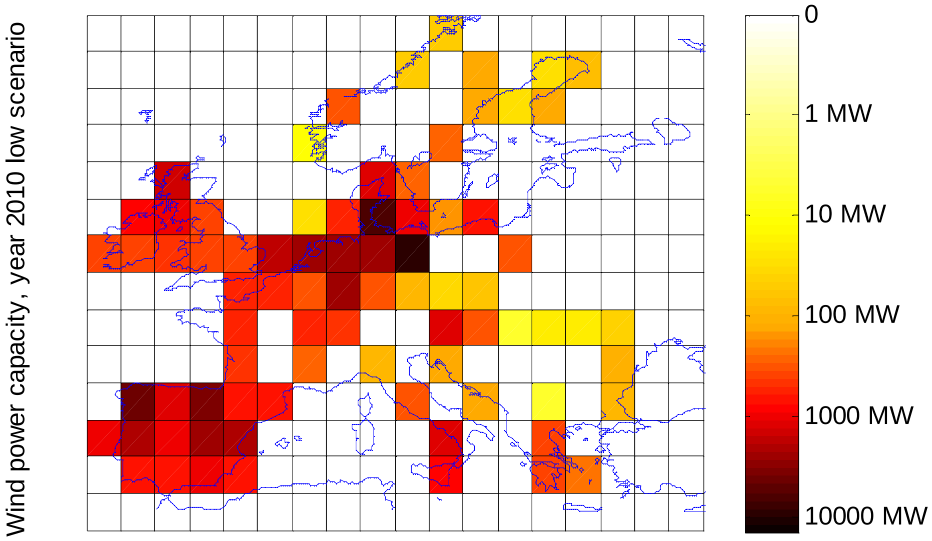
Installed wind power in different scenarios and years (MW)

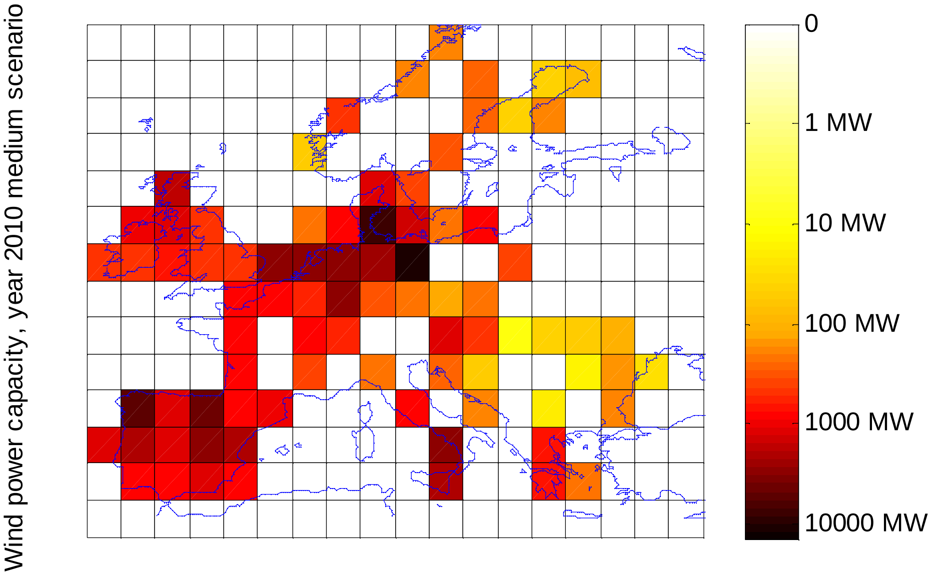
		Actual 2005	Low 2008	**Medium 2008**	High 2008	Low 2010	**Medium 2010**	High 2010	Low 2015	**Medium 2015**	High 2015	Low 2020	**Medium 2020**	High 2020	Low 2030	**Medium 2030**	High 2030
AT	**Austria**	819	990	**1015**	1045	1100	**1160**	1250	1400	**3000**	3400	1700	**3500**	4900	2300	**4300**	7900
B	**Belgium**	167	357	**571**	834	469	**750**	1119	986	**1286**	1952	1218	**2289**	3034	2262	**4983**	6086
BU	**Bulgaria**	10	30	**40**	55	90	**183**	245	300	**540**	650	680	**875**	1150	1495	**2160**	3450
HR	**Croatia**	6	150	**230**	360	250	**400**	600	370	**580**	1150	700	**1400**	2800	1200	**3000**	5600
CZ	**Czech republic**	29	120	**220**	350	180	**580**	1100	220	**900**	1800	230	**1200**	2500	250	**1500**	4000
DK	**Denmark**	3130	3129	**3129**	3286	3329	**3629**	4229	3886	**4318**	4750	4778	**5309**	5840	6562	**7291**	8020
SF	**Finland**	82	150	**200**	250	250	**350**	500	500	**900**	1600	1000	**1700**	3000	2000	**3200**	6000
FR	**France**	702	2100	**2700**	5100	3098	**4840**	9680	12313	**16745**	23000	23000	**30000**	37000	38000	**45000**	49950
DE	**Germany**	18428	21622	**22900**	24063	22665	**25291**	28466	27383	**36004**	42612	34170	**48202**	56640	44857	**54244**	63587
GB	**Great Britain**	1460	2822	**4086**	6400	5550	**7512**	8900	6864	**10813**	16979	9995	**16278**	26087	11059	**18136**	29183
GR	**Greece**	573	845	**1098**	1350	958	**1479**	2000	1988	**2744**	3500	2280	**3640**	5000	3126	**5628**	8130
HU	**Hungary**	17	105	**250**	325	250	**325**	330	330	**450**	500	330	**850**	900	330	**900**	1600
IR	**Ireland**	583	1246	**1326**	1525	1478	**1955**	2858	1747	**3257**	4444	2993	**4537**	5344	3295	**4998**	5891
IT	**Italy**	1381	2075	**4233**	5810	2490	**5893**	8300	3403	**9130**	12865	4150	**11620**	15770	6640	**15355**	19090
L	**Luxembourg**	35	45	**54**	53	54	**66**	66	78	**96**	98	102	**126**	132	117	**184**	206
N	**Netherlands**	1224	2058	**2228**	2328	2528	**2950**	3400	4100	**5250**	6700	5100	**6950**	10100	5150	**7050**	10200
NO	**Norway**	274	454	**544**	595	508	**1057**	1458	940	**2350**	4070	1380	**3660**	6660	1990	**5980**	11970
PL	**Poland**	83	450	**550**	650	1000	**1200**	1500	3000	**3500**	4000	5000	**6000**	7000	10000	**12000**	14000
P	**Portugal**	1014	2699	**2841**	2983	3894	**4099**	4304	5365	**5647**	5930	6850	**7211**	7572	8516	**8964**	9412
RO	**Romania**	1	50	**80**	120	160	**345**	460	600	**1100**	1350	1600	**2500**	3100	2300	**3300**	4000
SC	**Serbia**	0	0	**2**	5	5	**10**	30	20	**40**	80	40	**80**	150	100	**200**	500
SK	**Slovakia**	5	20	**55**	90	100	**175**	410	160	**245**	545	177	**280**	545	205	**303**	545
SV	**Slovenia**	0	0	**20**	40	0	**85**	130	102	**220**	340	205	**430**	560	310	**540**	860
ES	**Spain**	11482	13929	**15477**	17025	17528	**19475**	21423	23028	**26476**	30924	29029	**34477**	39425	40031	**48479**	53427
SE	**Sweden**	493	750	**1050**	1350	1100	**1600**	2150	2150	**3600**	5600	4000	**6500**	10000	6500	**10000**	17000
CH	**Switzerland**	12	15	**18**	20	15	**40**	100	50	**150**	300	100	**300**	600	300	**600**	1100
	Total	42011	56212	**64917**	76012	69047	**85449**	105007	101282	**139342**	179139	140807	**199915**	255808	198895	**268295**	341707

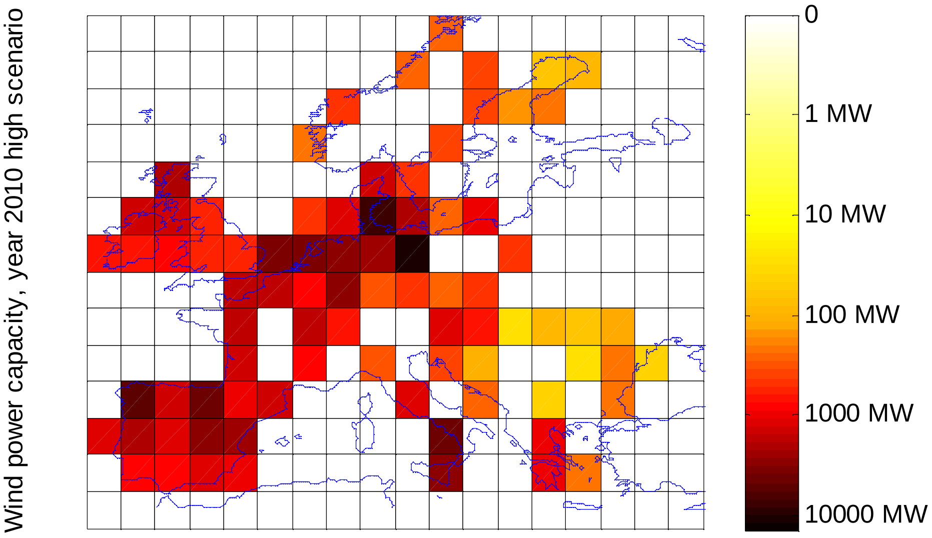

Wind power capacity, year 2008 low scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

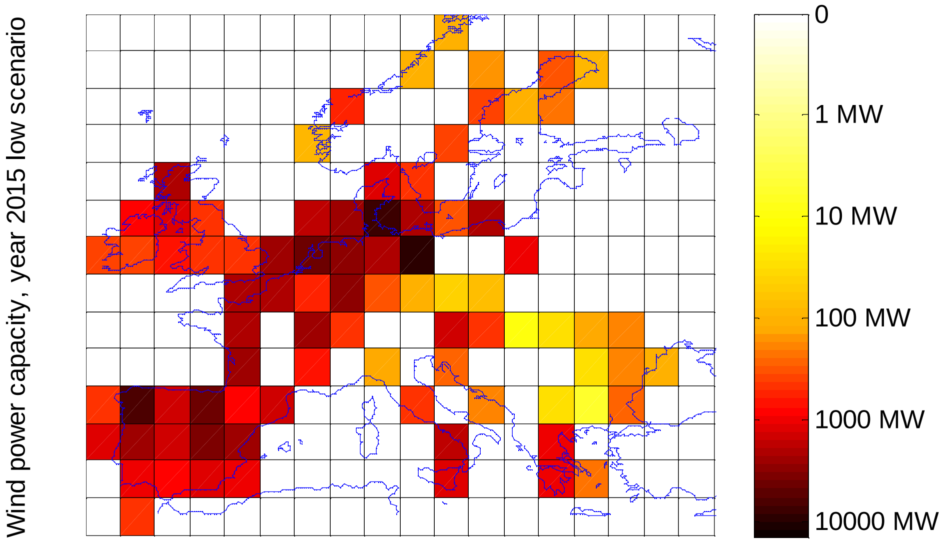

Wind power capacity, year 2008 medium scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

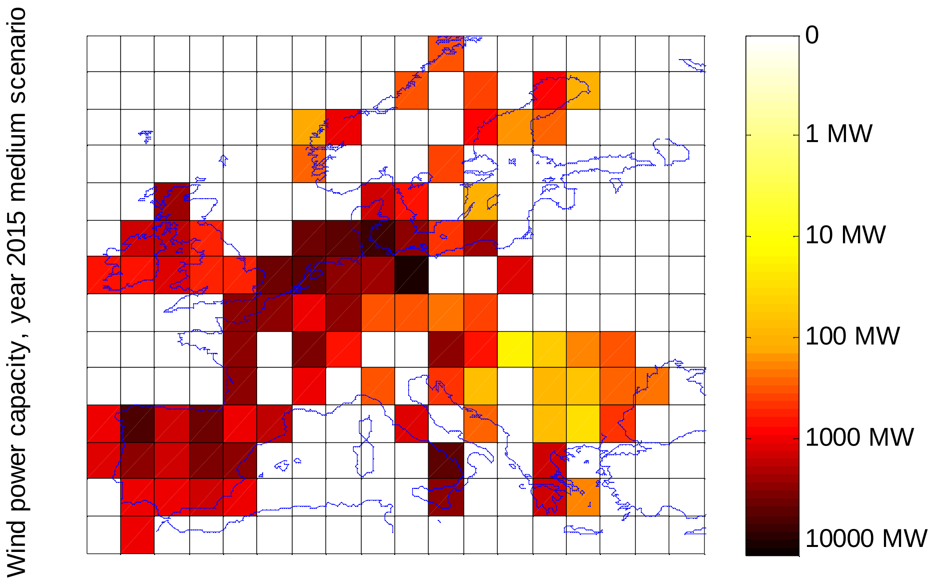

Wind power capacity, year 2008 high scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

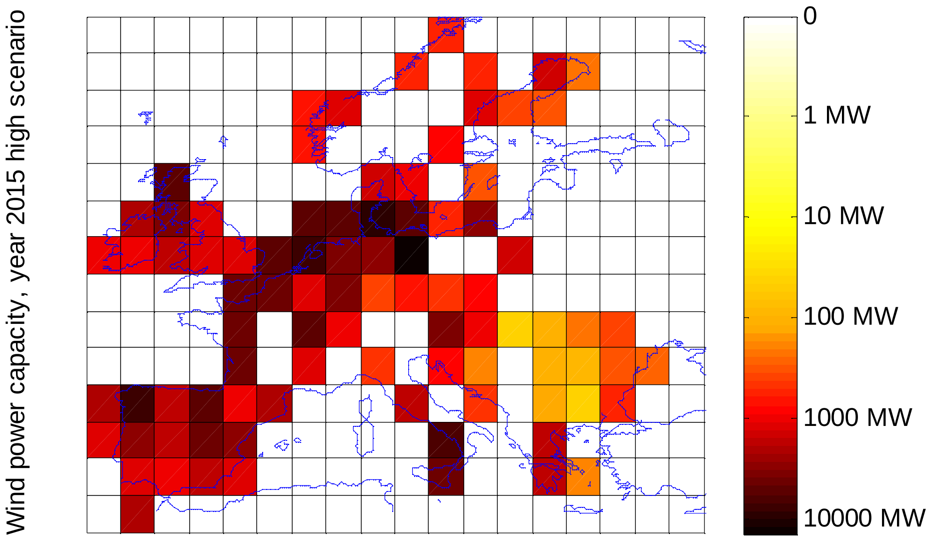

Wind power capacity, year 2010 low scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

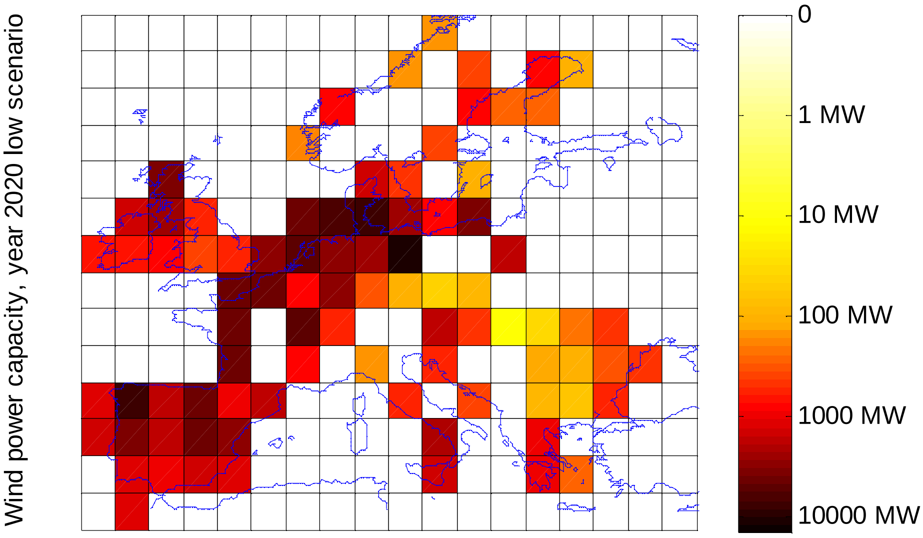

Wind power capacity, year 2010 medium scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

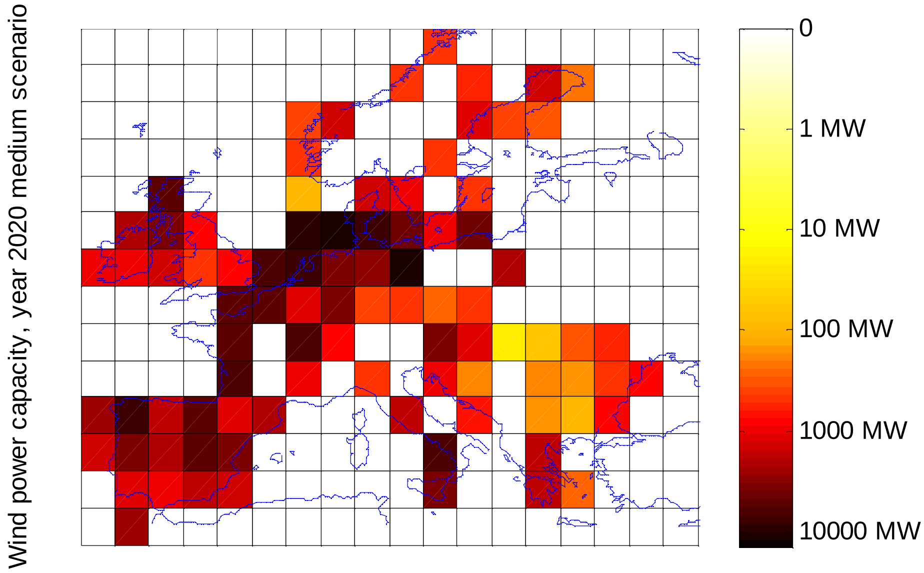

Wind power capacity, year 2010 high scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

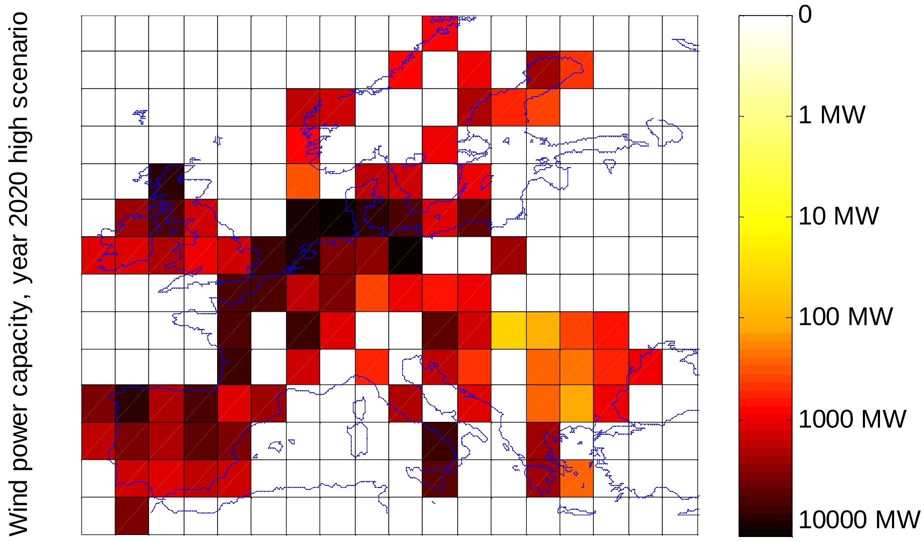

Wind power capacity, year 2015 low scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

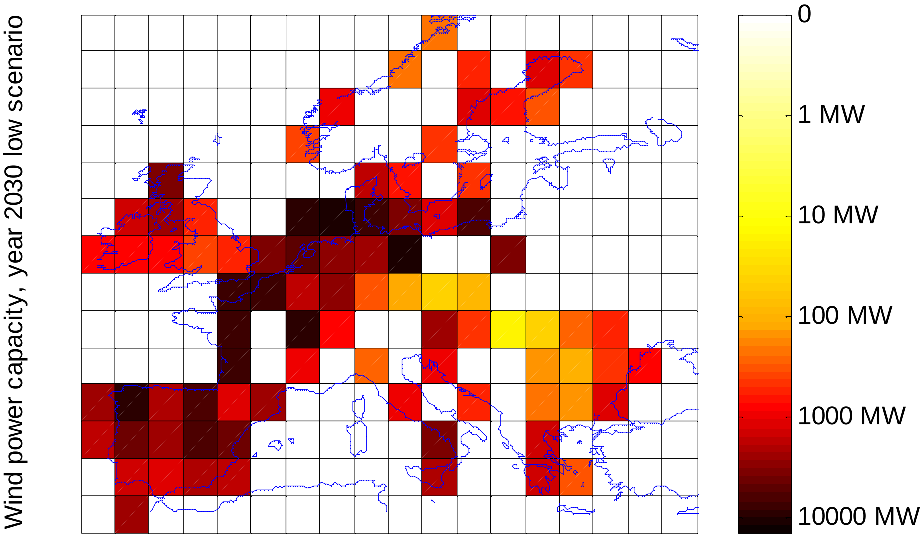

Wind power capacity, year 2015 medium scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

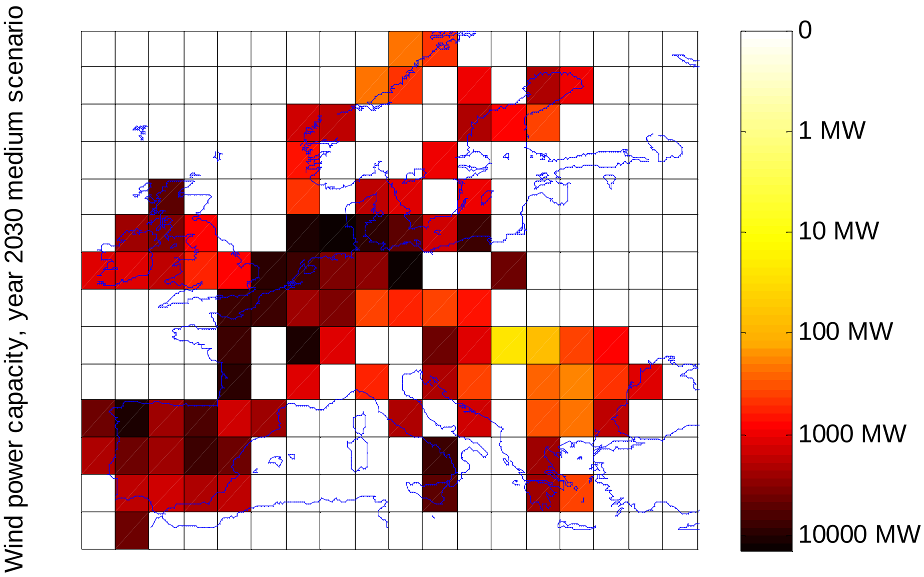

Wind power capacity, year 2015 high scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

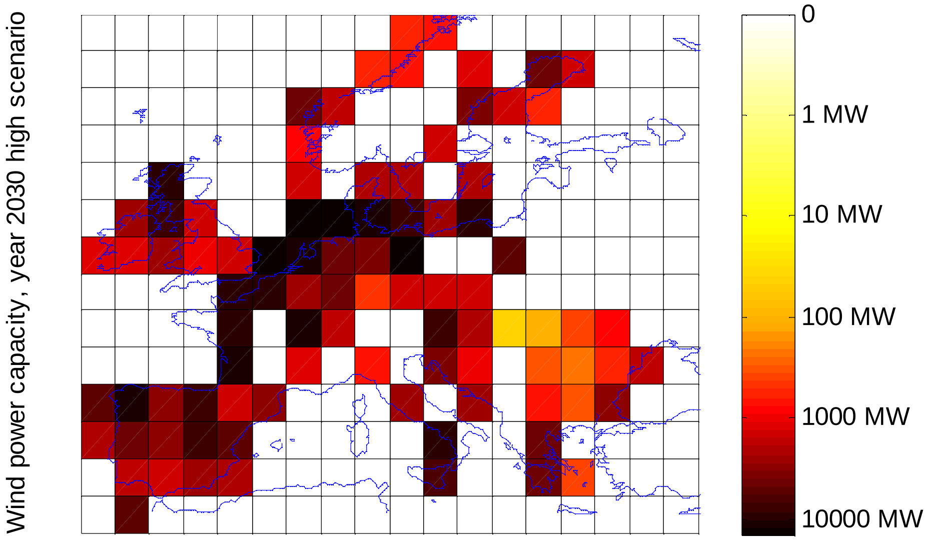

Wind power capacity, year 2020 low scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW


Wind power capacity, year 2020 medium scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

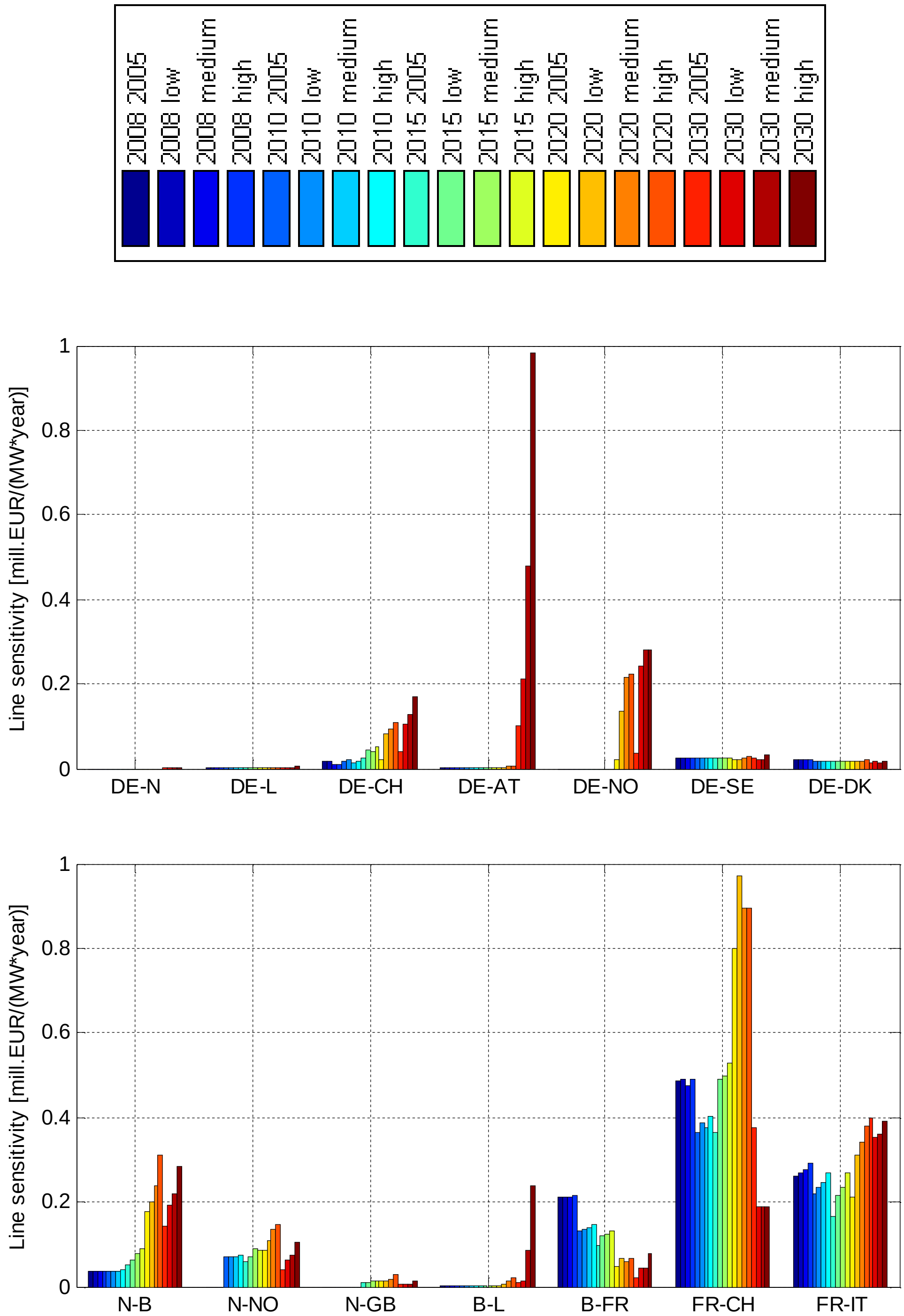

Wind power capacity, year 2020 high scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

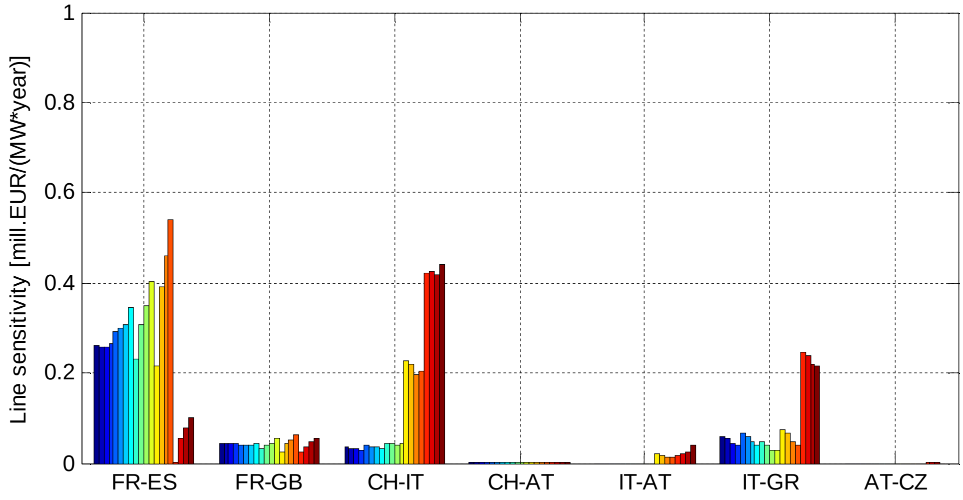

Wind power capacity, year 2030 low scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

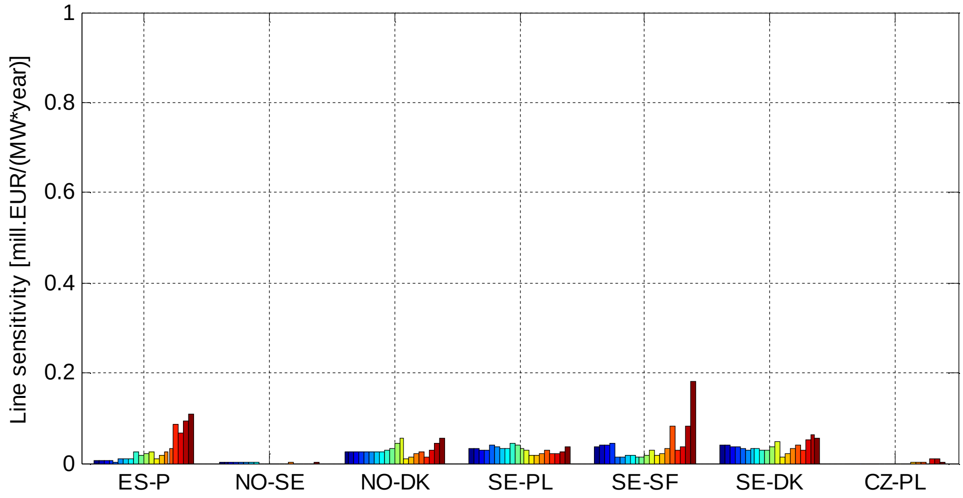

Wind power capacity, year 2030 medium scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

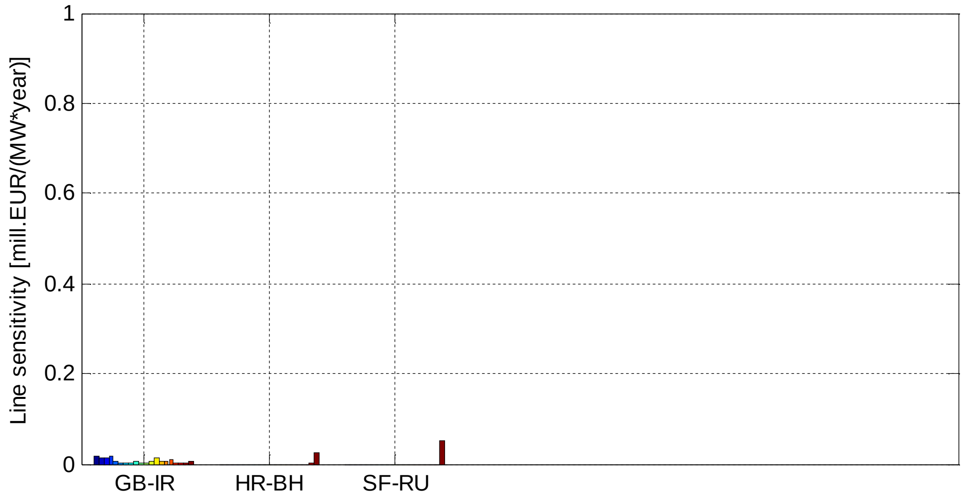

Wind power capacity, year 2030 high scenario
0
1 MW
10 MW
100 MW
1000 MW
10000 MW

APPENDIX 2. SIMULATION RESULTS; POWER LINE CONGESTION SENSITIVITIES BETWEEN COUNTRIES.

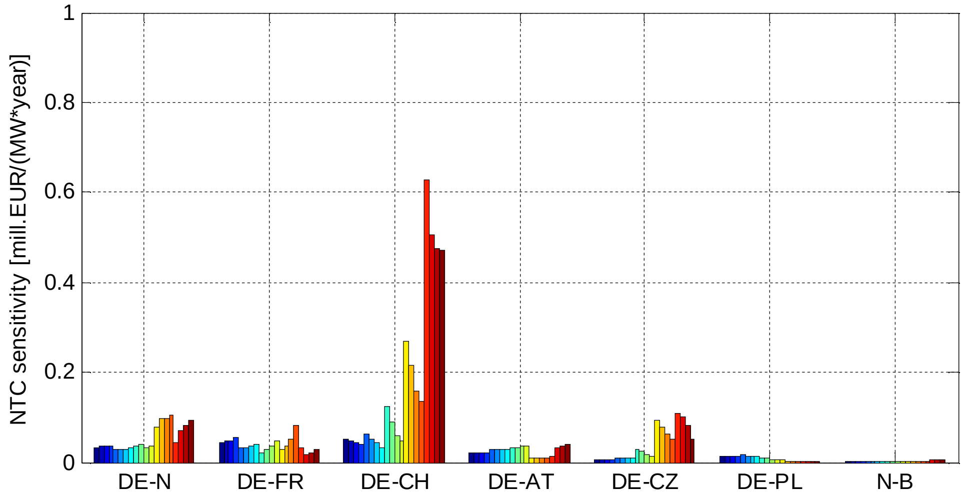


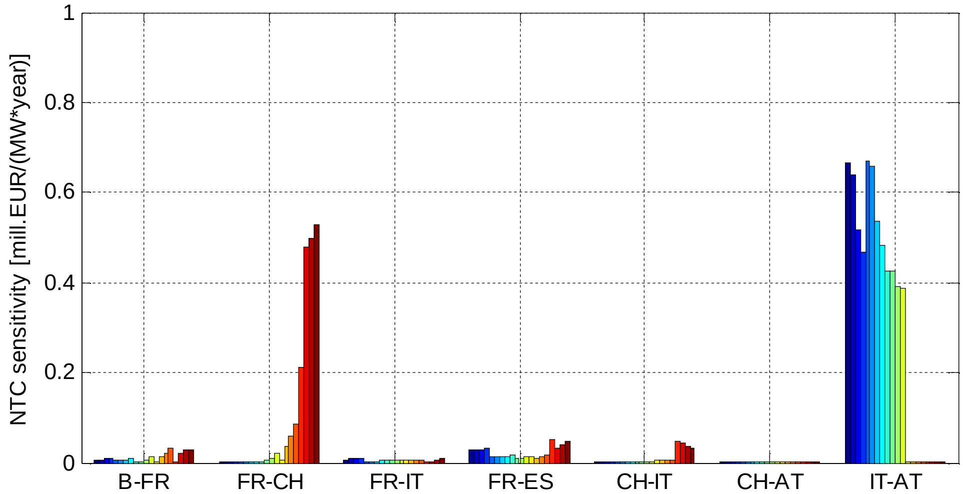

Line sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
FR-ES
FR-GB
CH-IT
CH-AT
IT-AT
IT-GR
AT-CZ

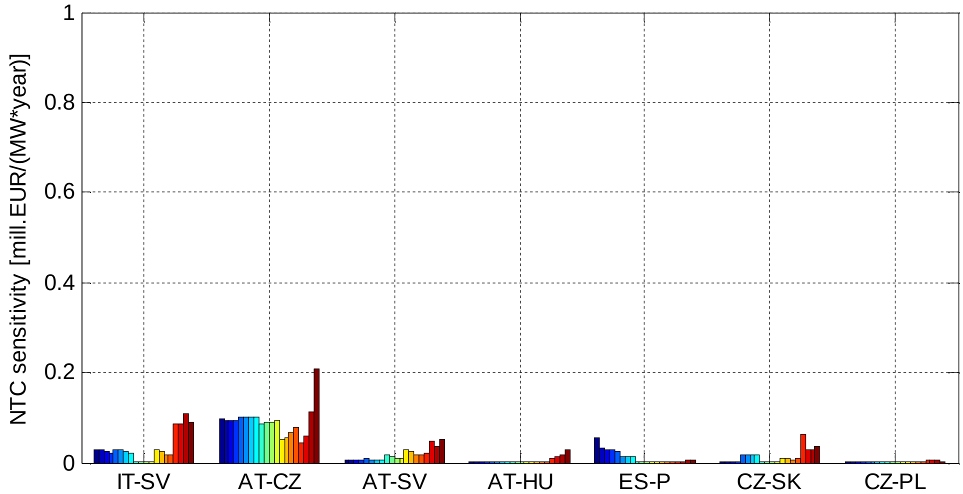

Line sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
ES-P
NO-SE
NO-DK
SE-PL
SE-SF
SE-DK
CZ-PL

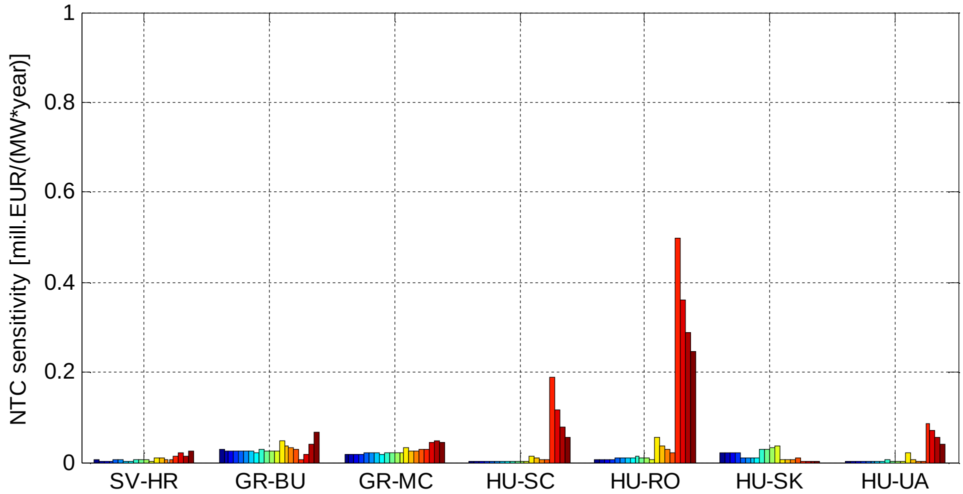

Line sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
GB-IR
HR-BH
SF-RU

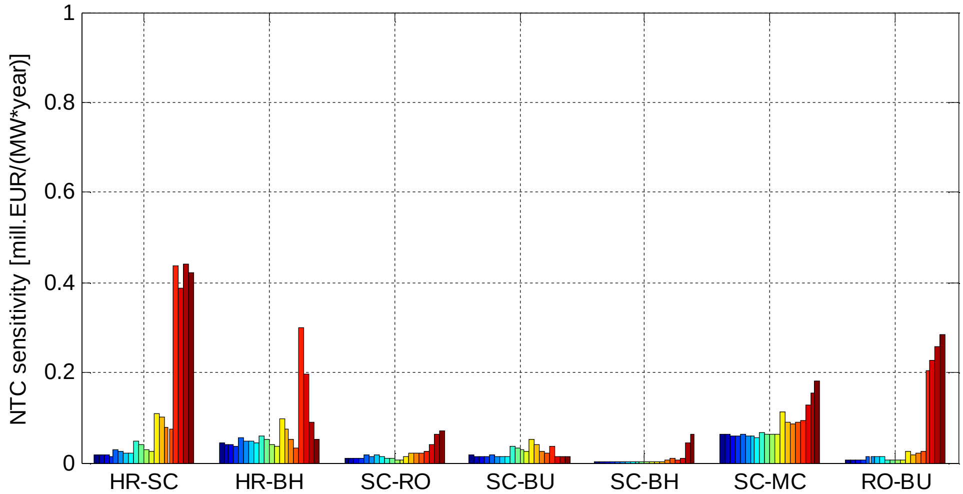
APPENDIX 3. SIMULATION RESULTS; INTERCONNECTION CONGESTION SENSITIVITIES BETWEEN COUNTRIES DUE TO NTC. *SEE FOR LEGEND AP 2.*

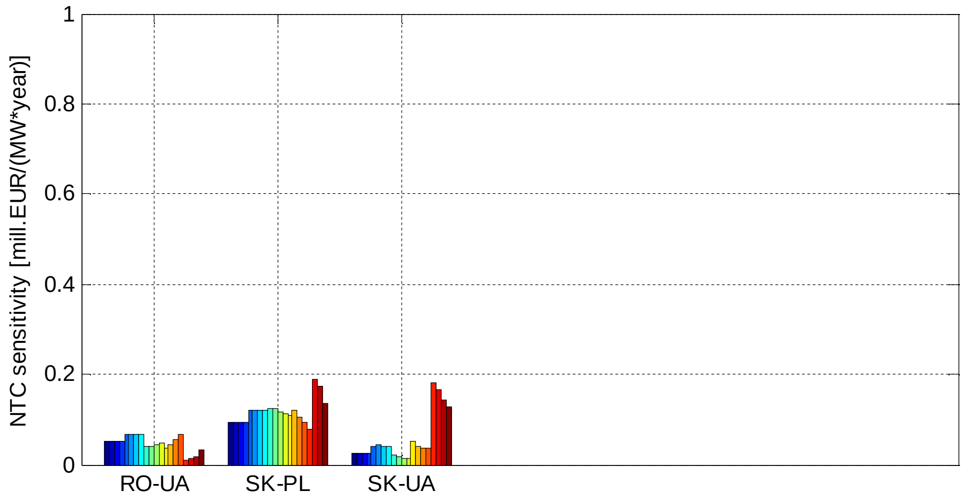




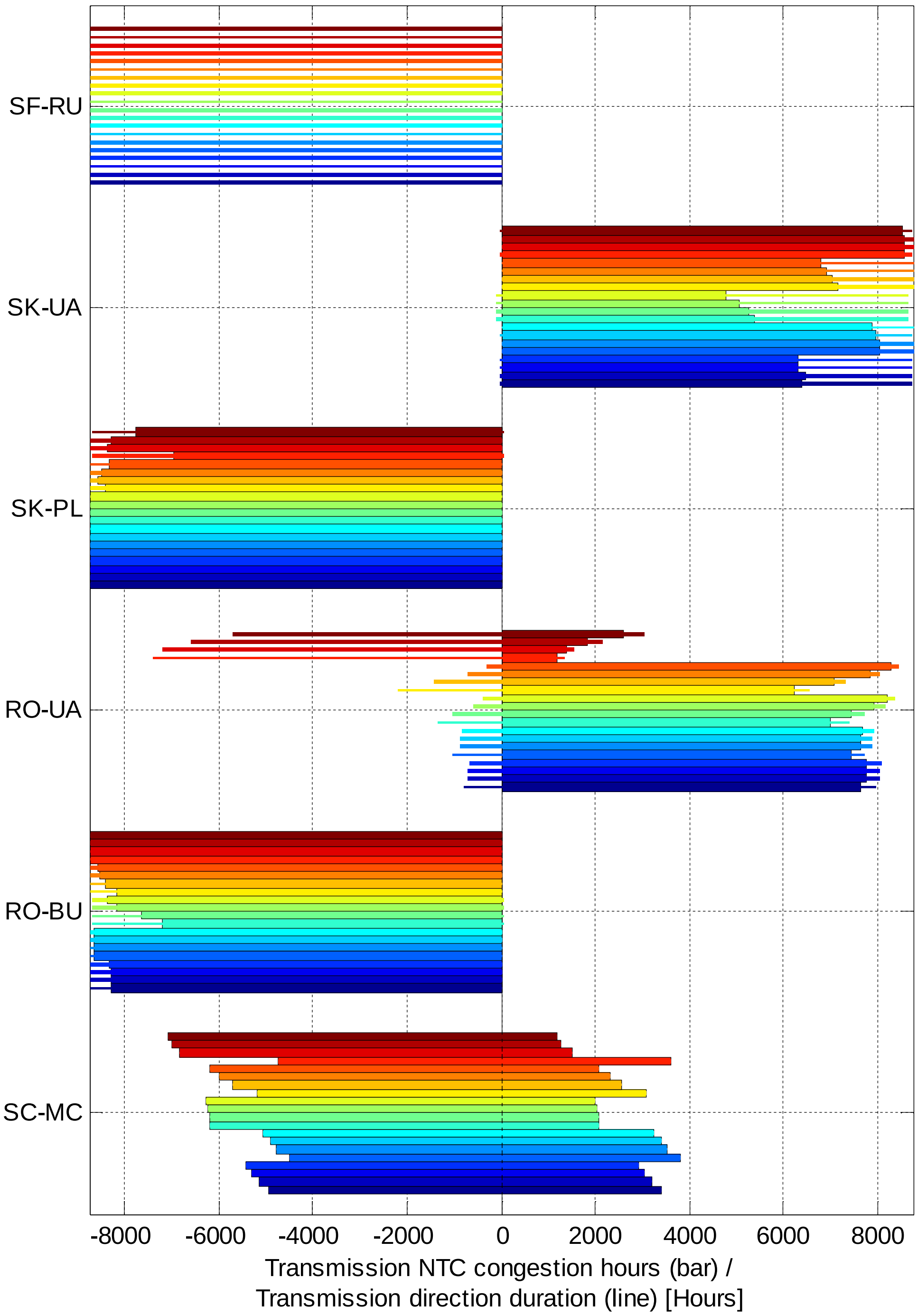


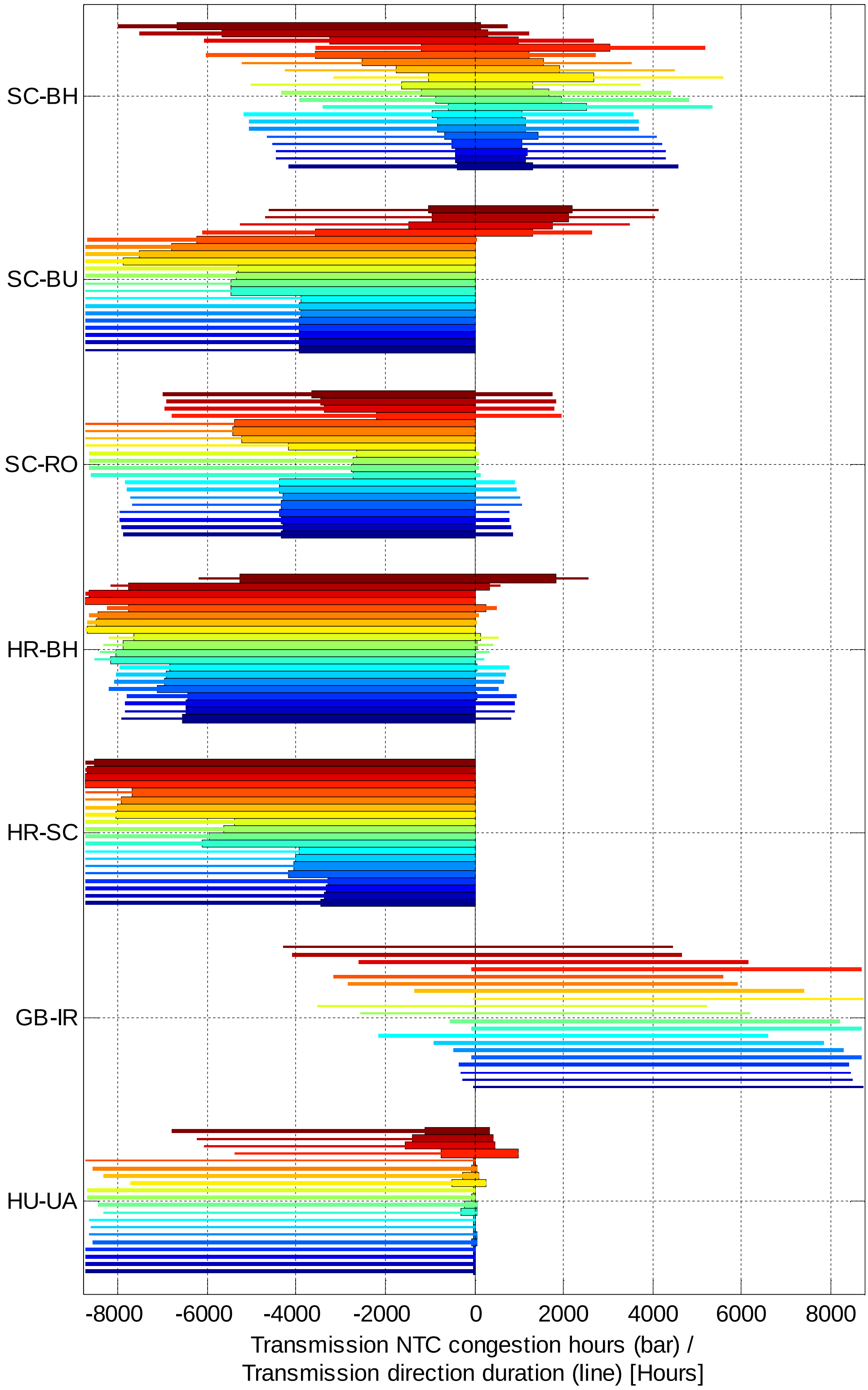

NTC sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
SV-HR
GR-BU
GR-MC
HU-SC
HU-RO
HU-SK
HU-UA

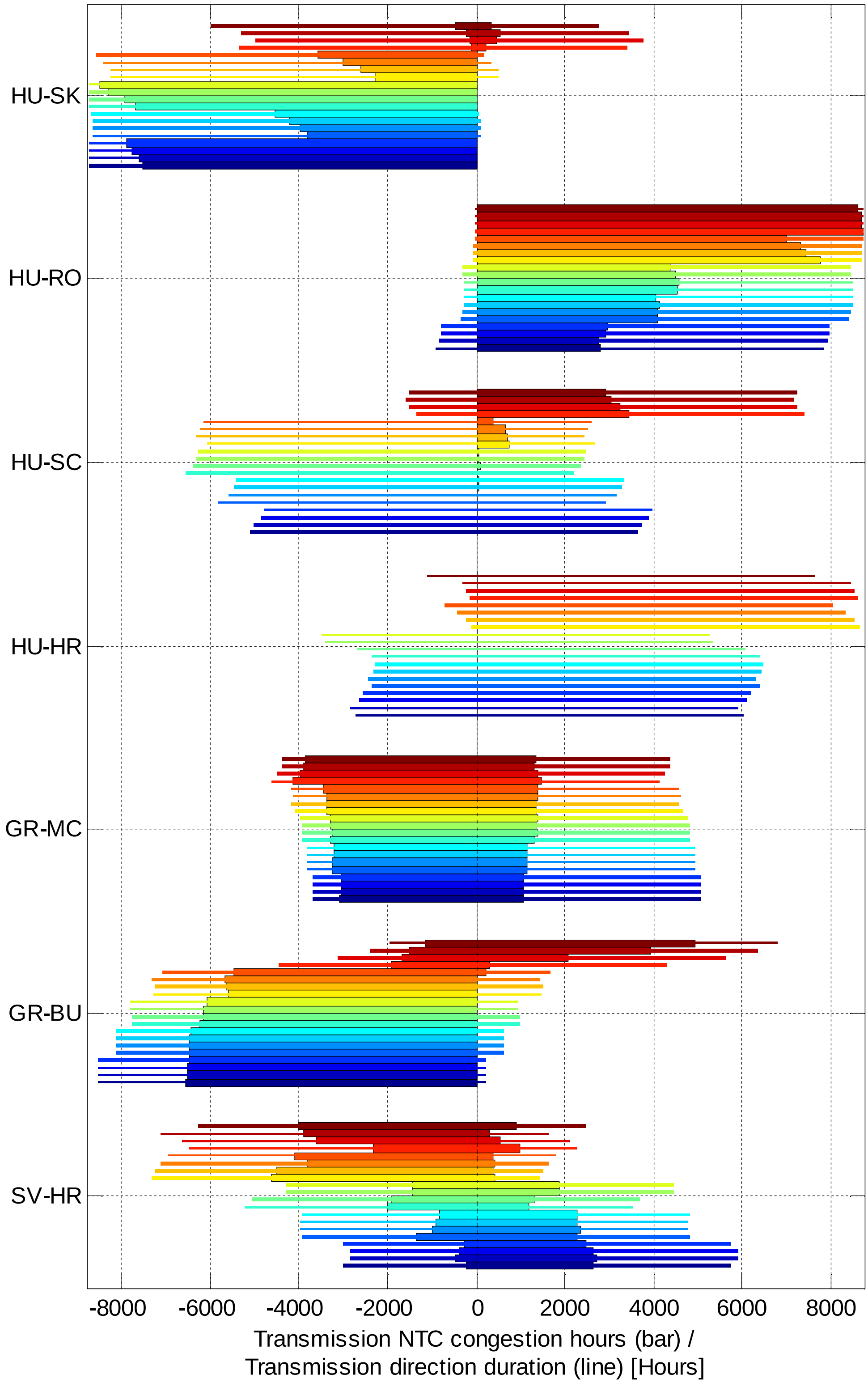

NTC sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
HR-SC
HR-BH
SC-RO
SC-BU
SC-BH
SC-MC
RO-BU

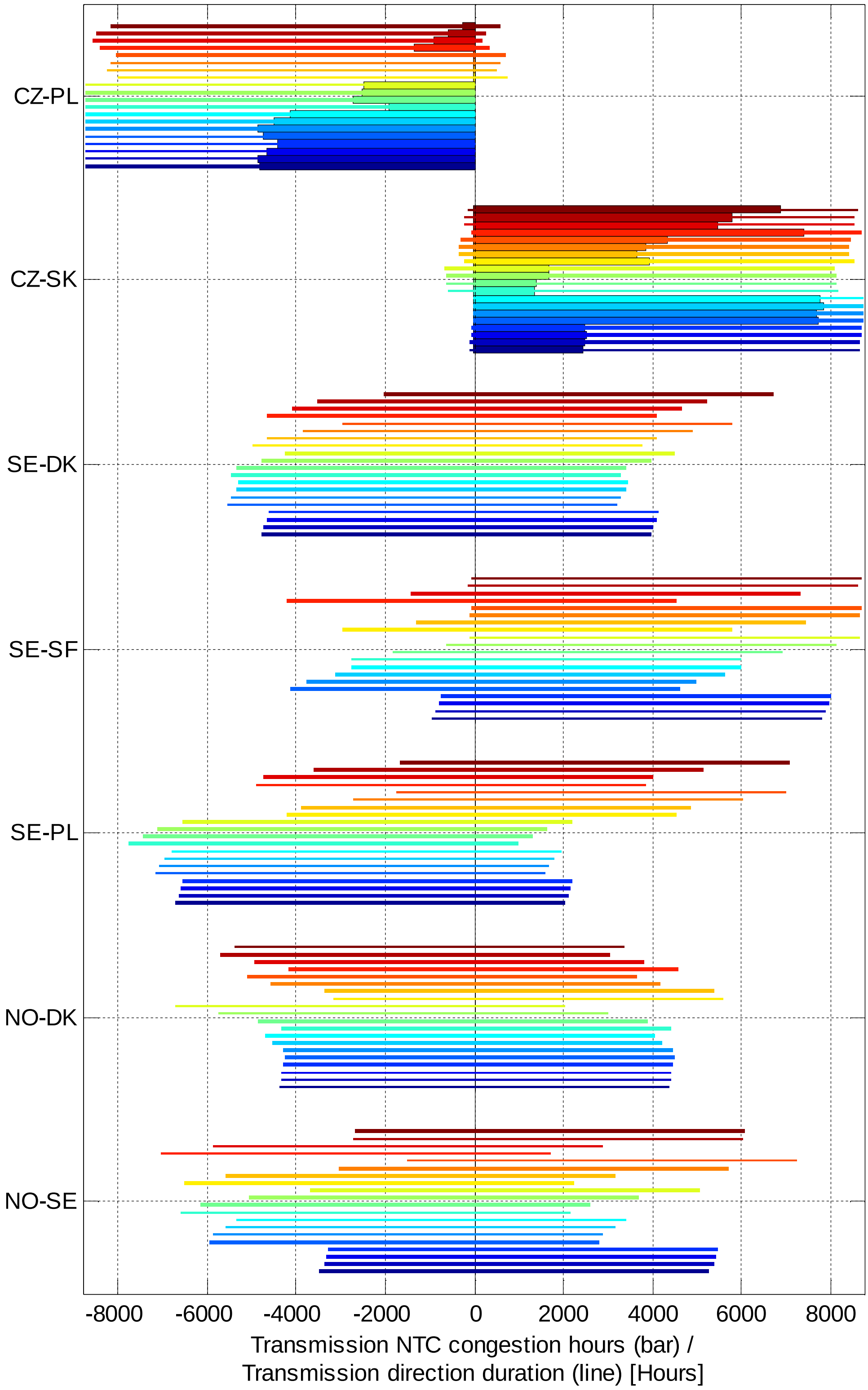

NTC sensitivity [mill.EUR/(MW*year)]
1
0.8
0.6
0.4
0.2
0
RO-UA
SK-PL
SK-UA

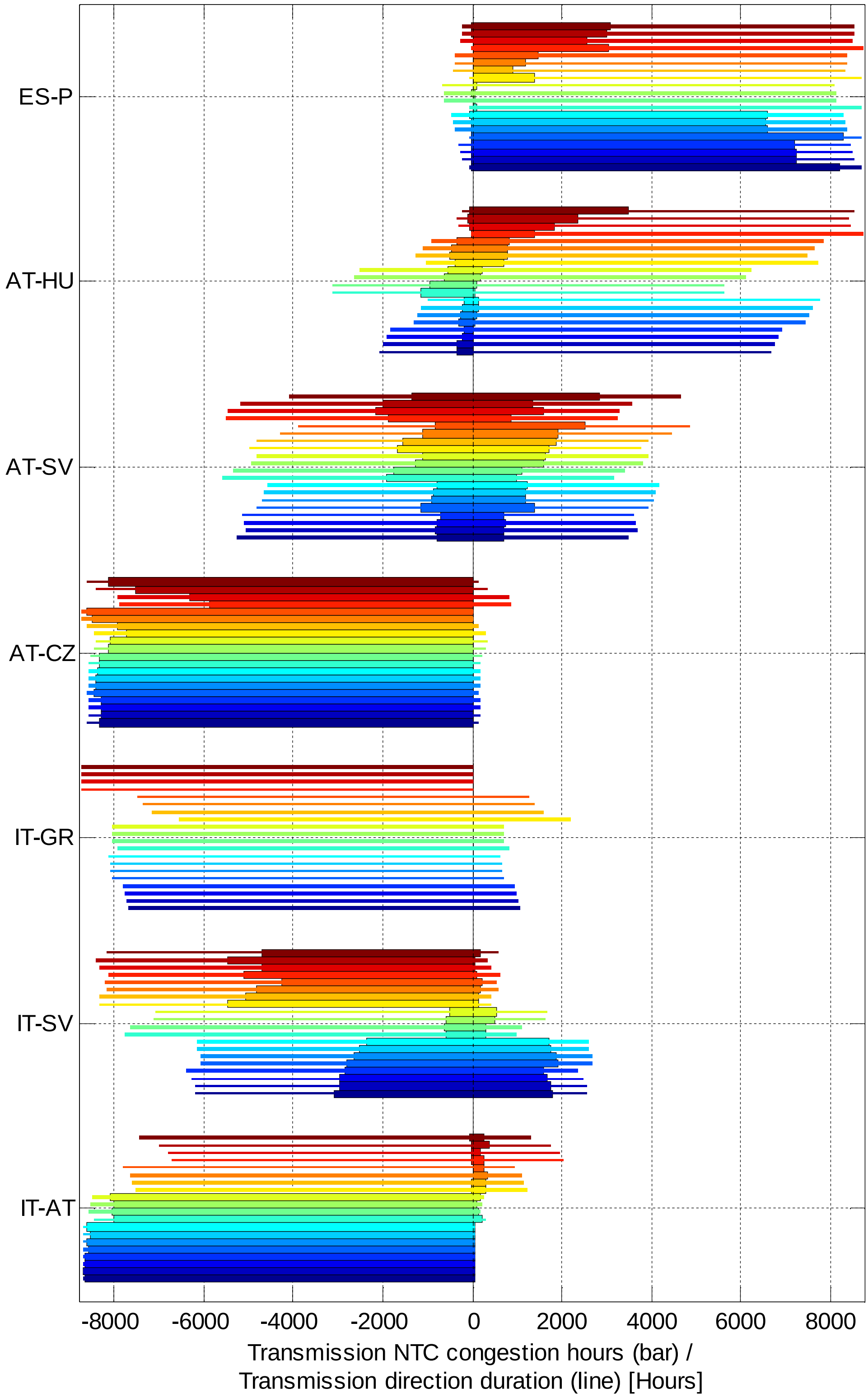
APPENDIX 4. SIMULATION RESULTS; POWER EXCHANGE CONGESTION (DUE TO NTC) HOURS AND POWER FLOW DURATION HOURS BETWEEN COUNTRIES. ALL COUNTRY-TO-COUNTRY CONNECTIONS SHOWN. SEE FOR LEGEND APPENDIX 2.

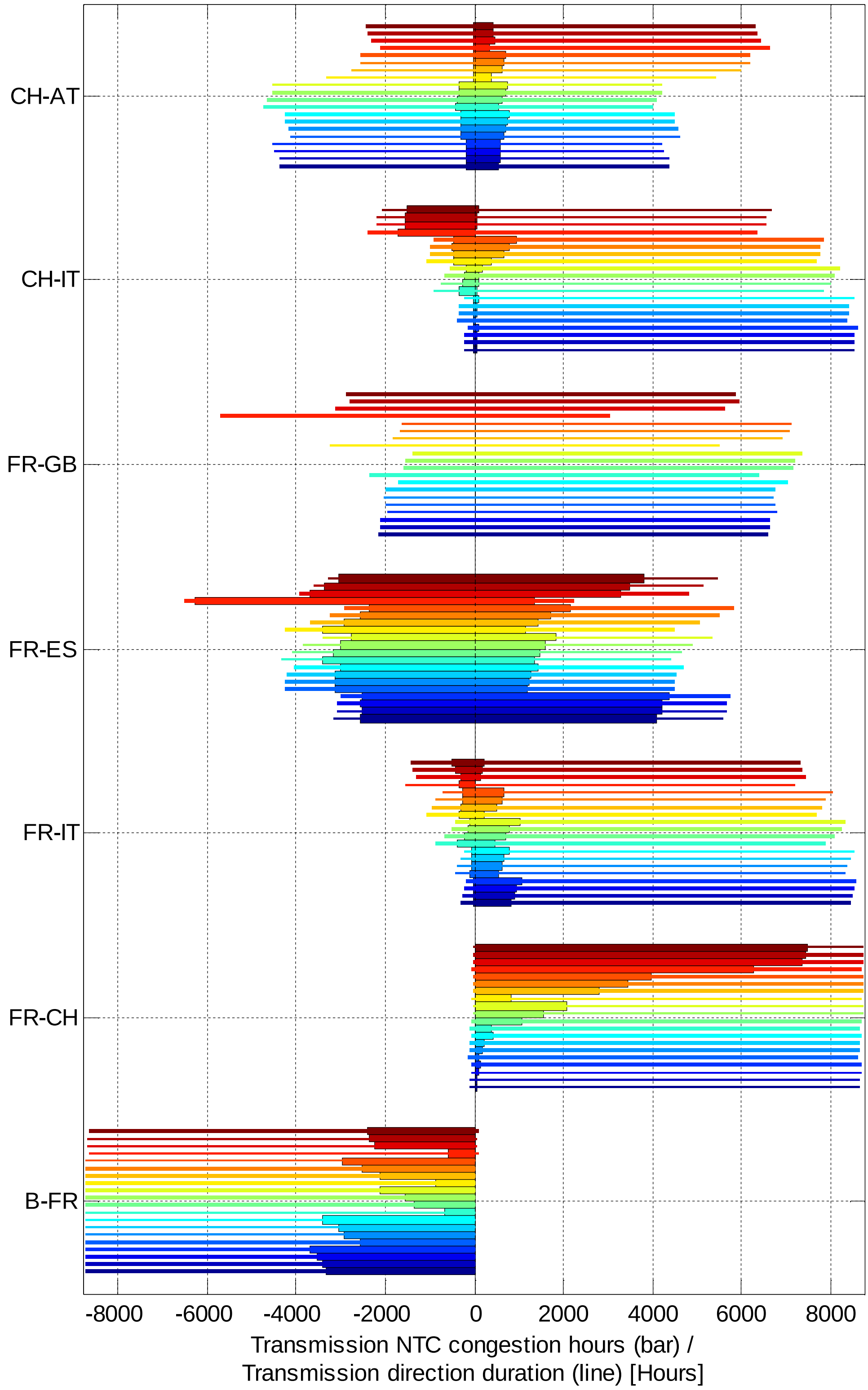


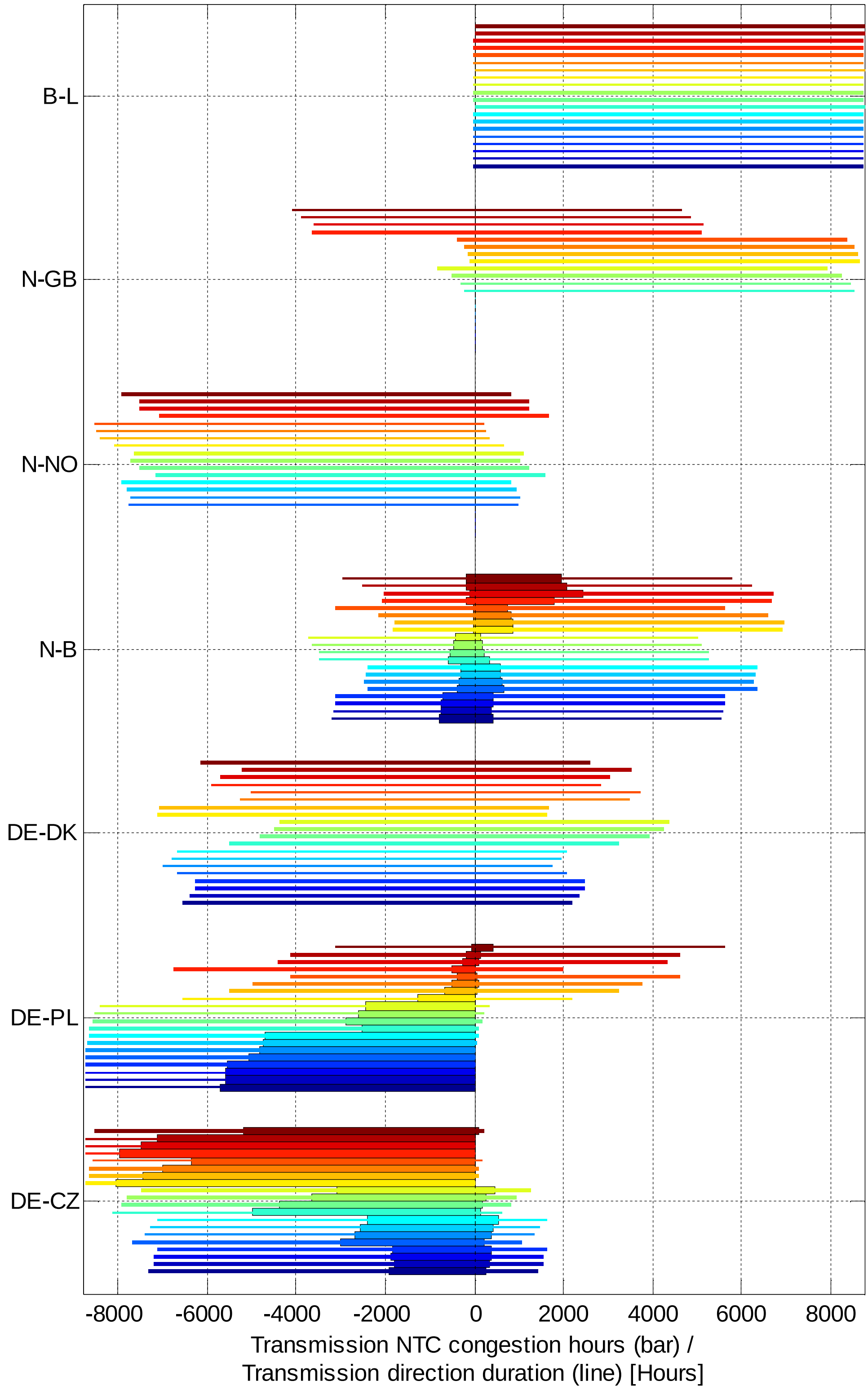

SC-BH
SC-BU
SC-RO
HR-BH
HR-SC
GB-IR
HU-UA
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

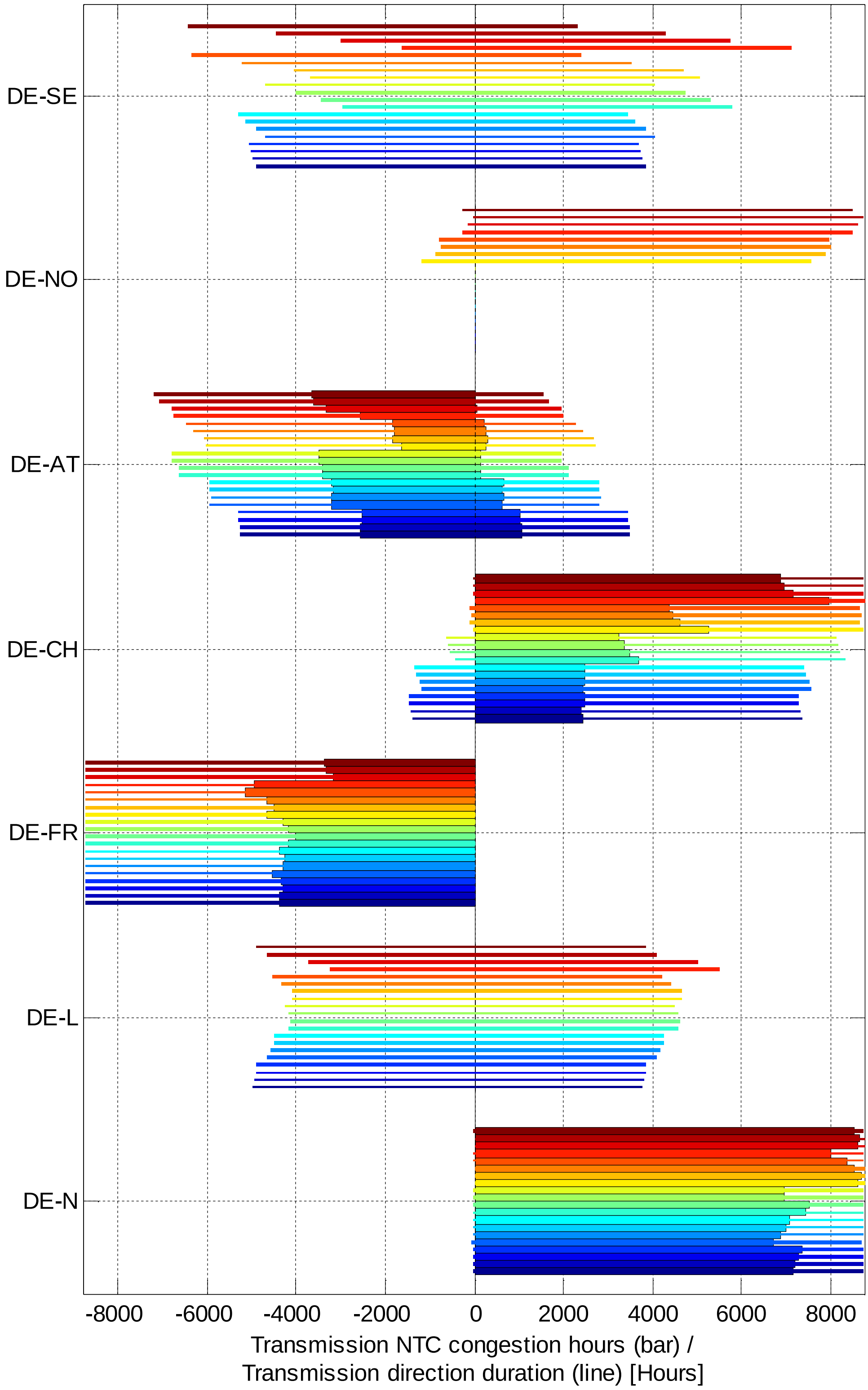

HU-SK
HU-RO
HU-SC
HU-HR
GR-MC
GR-BU
SV-HR
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]


CZ-PL
CZ-SK
SE-DK
SE-SF
SE-PL
NO-DK
NO-SE
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

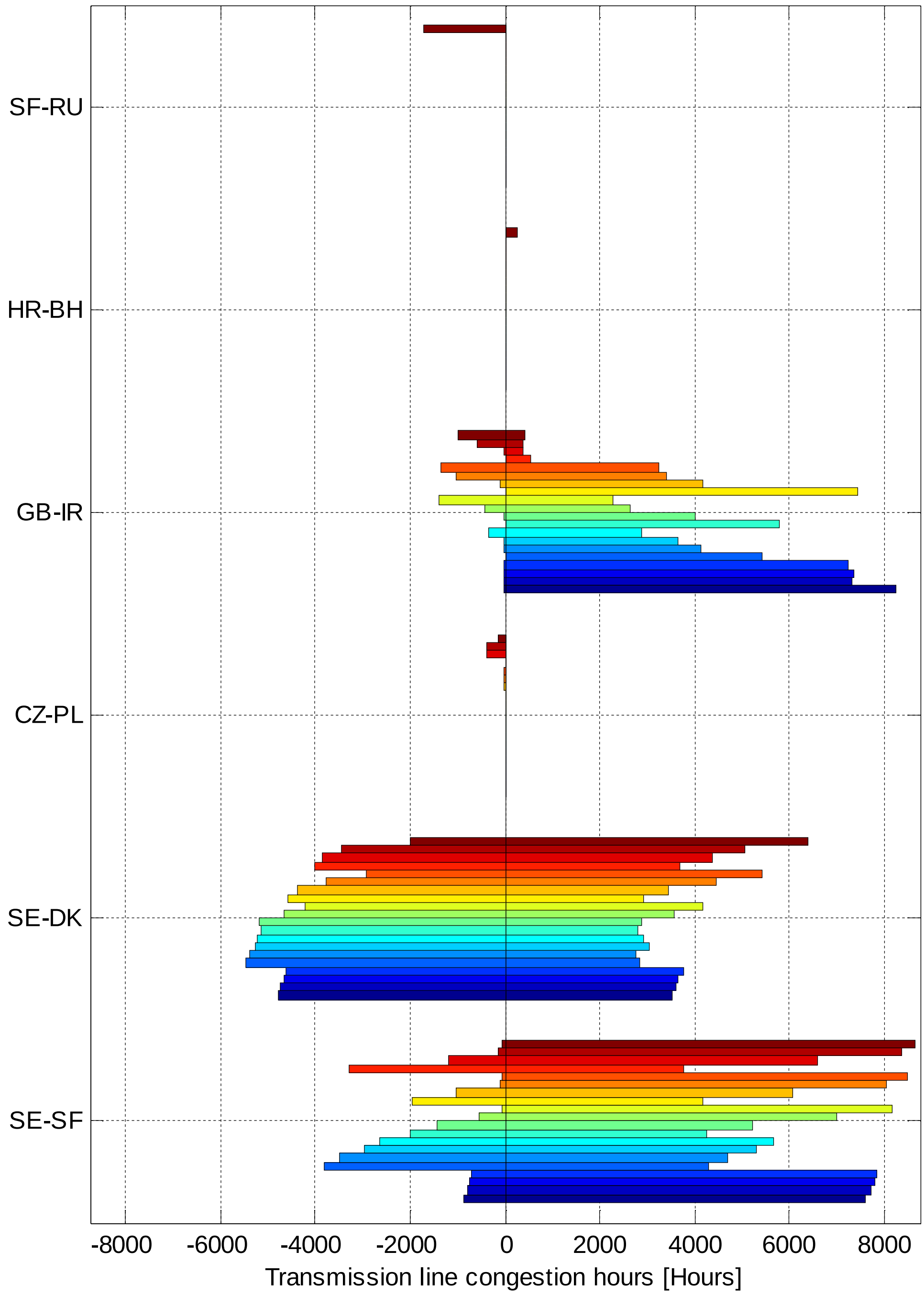

ES-P
AT-HU
AT-SV
AT-CZ
IT-GR
IT-SV
IT-AT
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

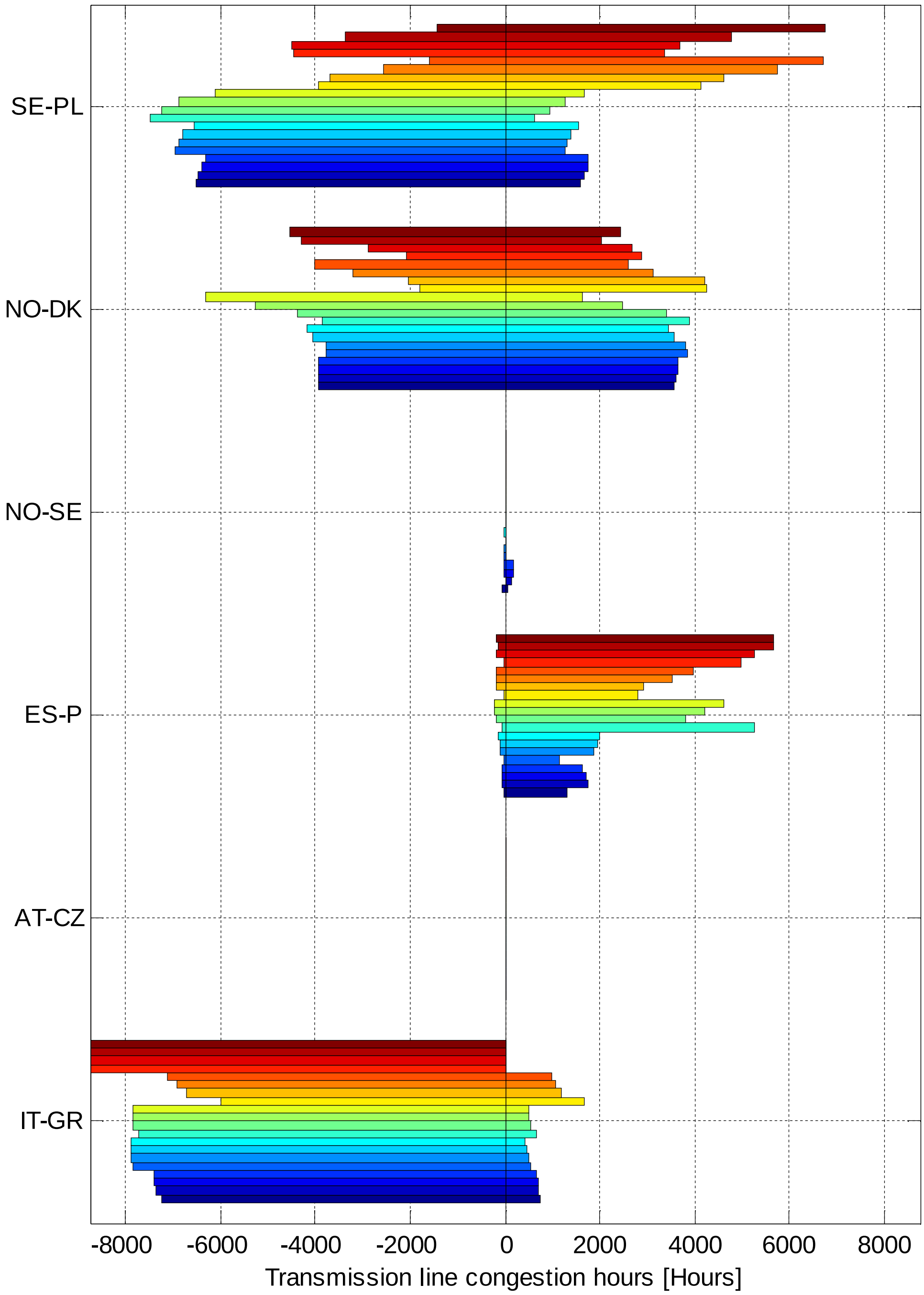

CH-AT
CH-IT
FR-GB
FR-ES
FR-IT
FR-CH
B-FR
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

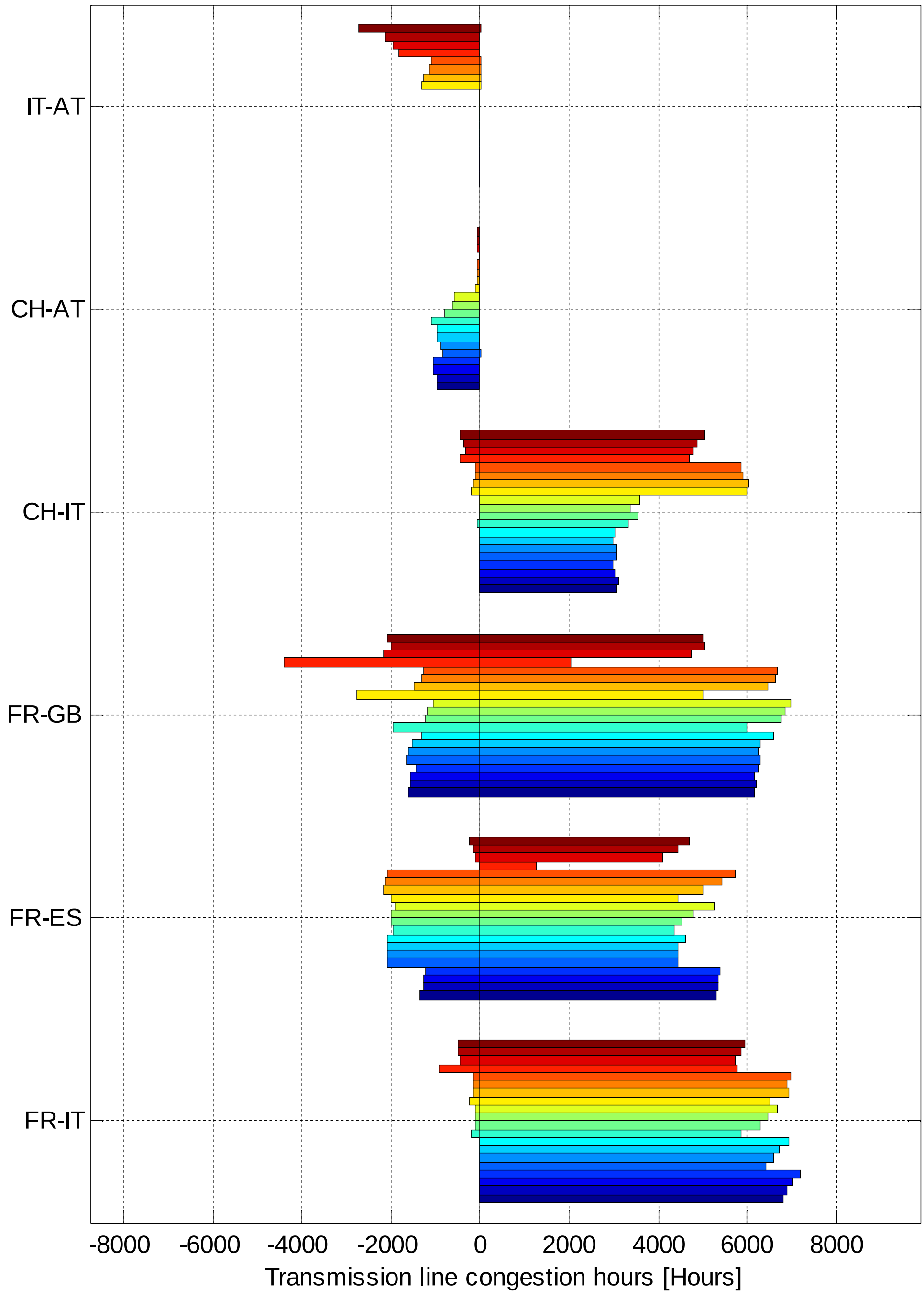

B-L
N-GB
N-NO
N-B
DE-DK
DE-PL
DE-CZ
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

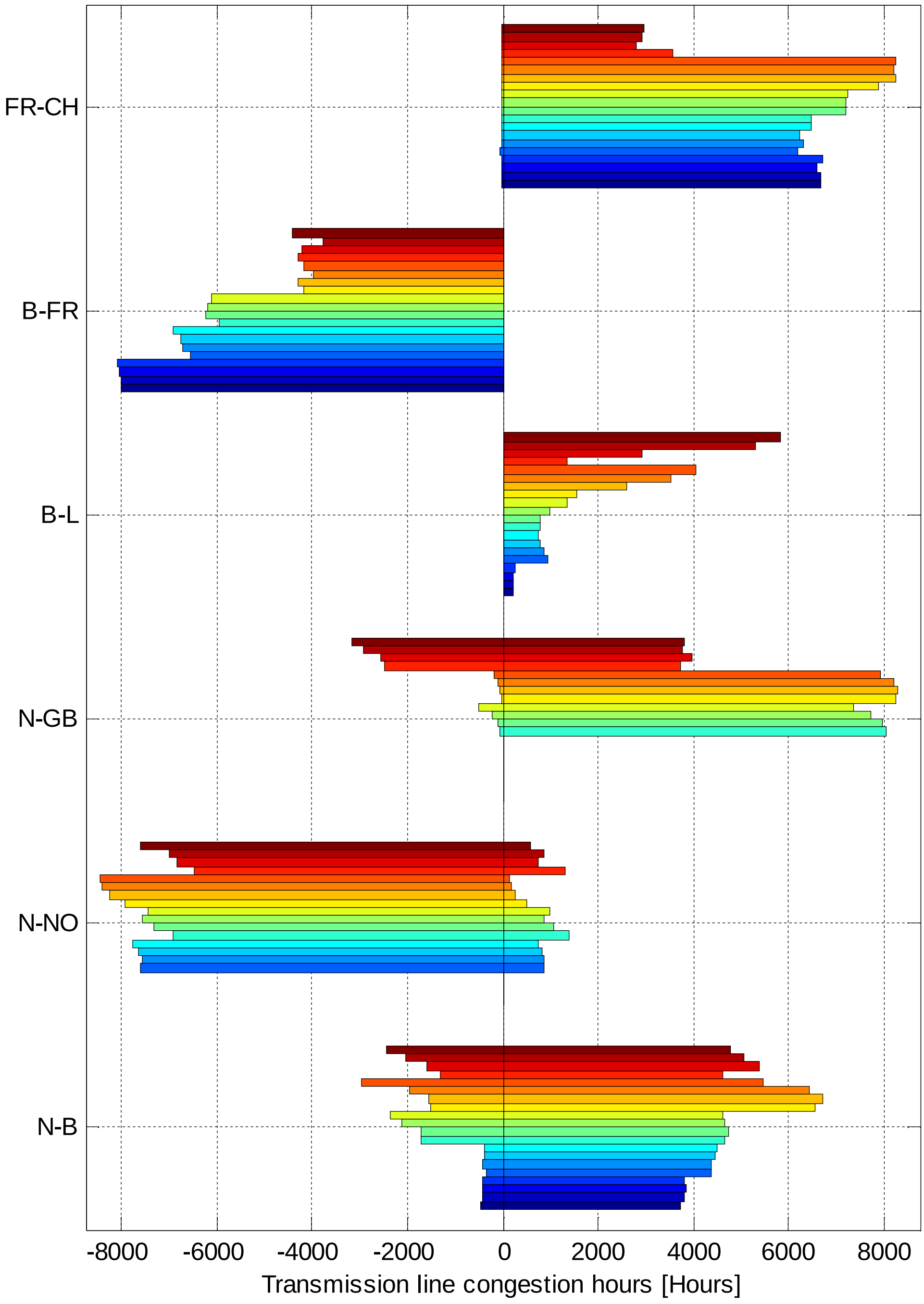

DE-SE
DE-NO
DE-AT
DE-CH
DE-FR
DE-L
DE-N
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission NTC congestion hours (bar) /
Transmission direction duration (line) [Hours]

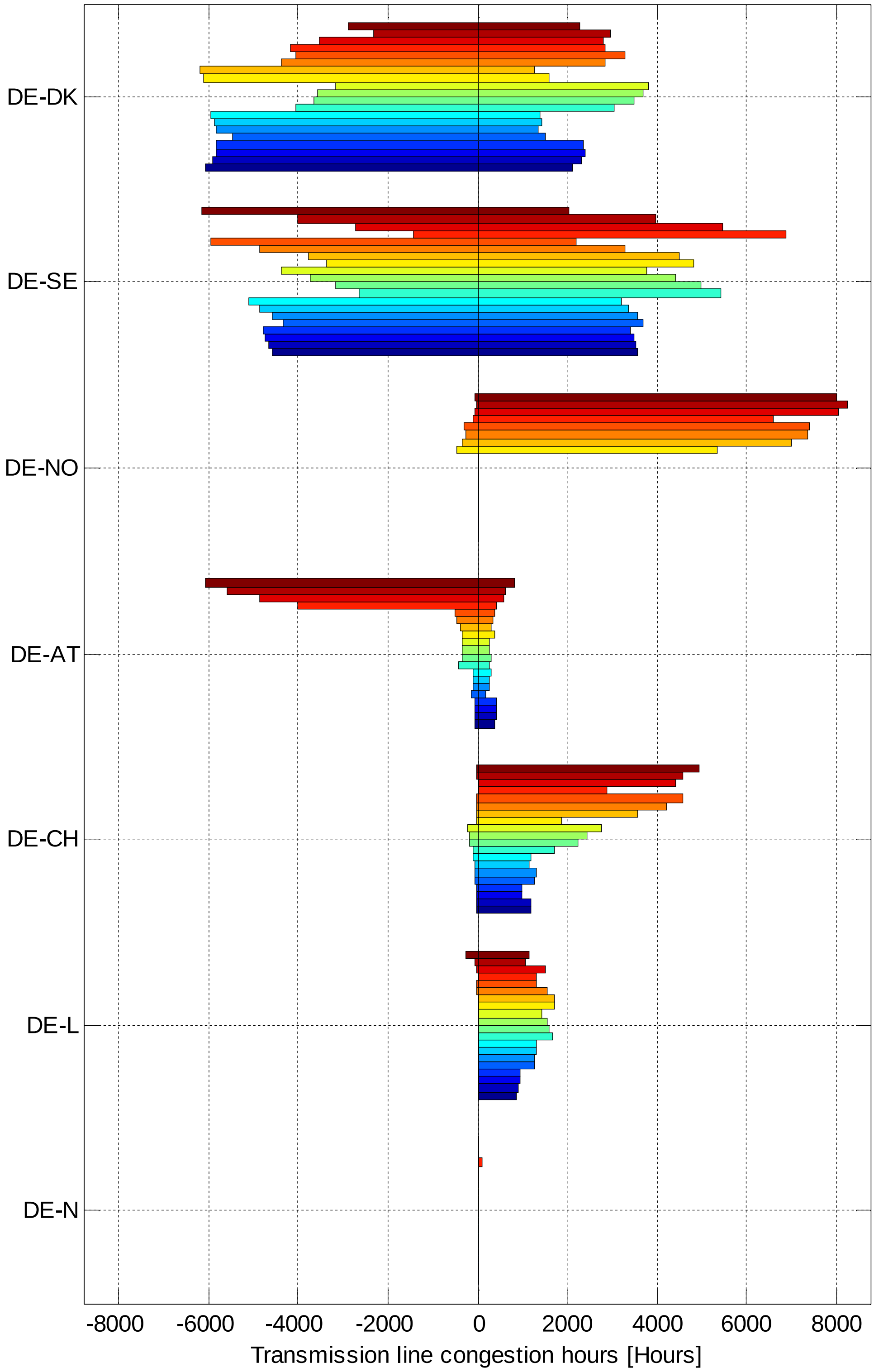
APPENDIX 5. SIMULATION RESULTS; POWER EXCHANGE CONGESTION (DUE TO LINE RATINGS) HOURS. SHOWN ONLY THOSE CONNECTIONS THERE OCCURS ANY CONGESTION IN AT LEAST ONE SIMULATION. SEE FOR LEGEND APPENDIX 2.



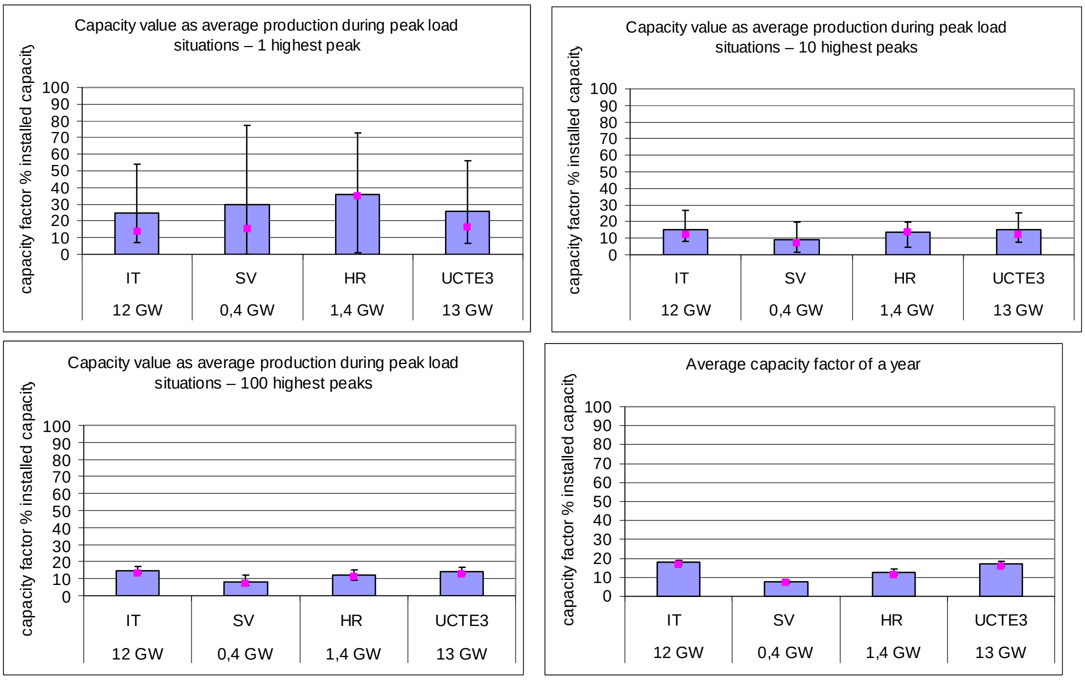

SE-PL
NO-DK
NO-SE
ES-P
AT-CZ
IT-GR
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission line congestion hours [Hours]


IT-AT
CH-AT
CH-IT
FR-GB
FR-ES
FR-IT
-8000 -6000 -4000 -2000 0 2000 4000 6000 8000
Transmission line congestion hours [Hours]

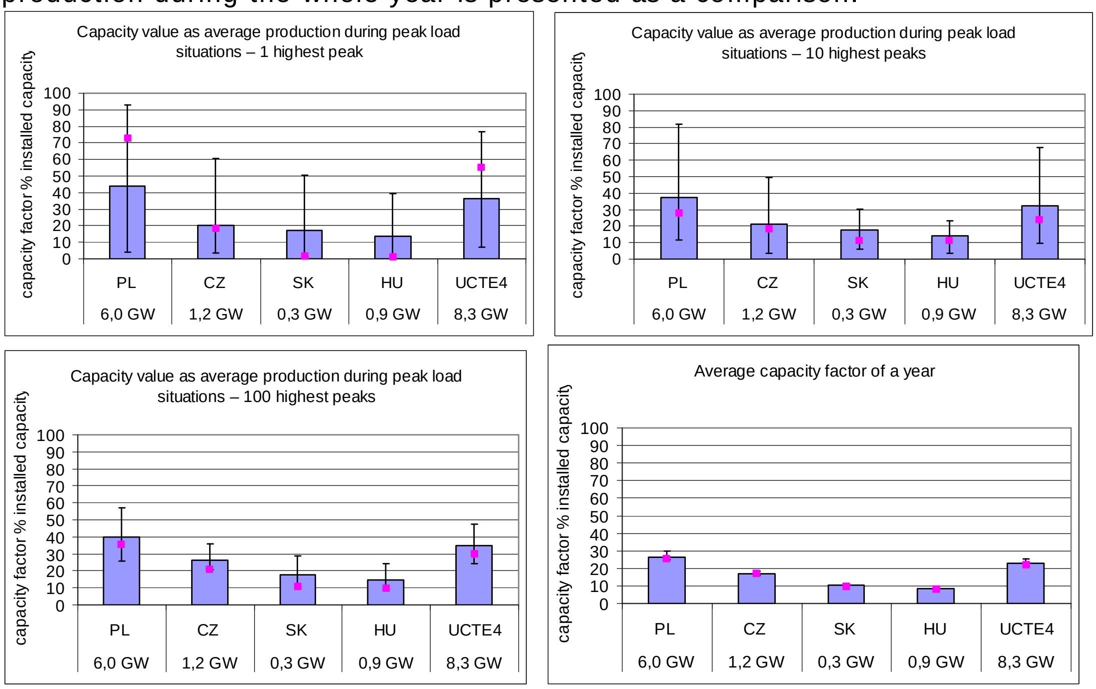

FR-CH
B-FR
B-L
N-GB
N-NO
N-B
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission line congestion hours [Hours]


DE-DK
DE-SE
DE-NO
DE-AT
DE-CH
DE-L
DE-N
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
Transmission line congestion hours [Hours]

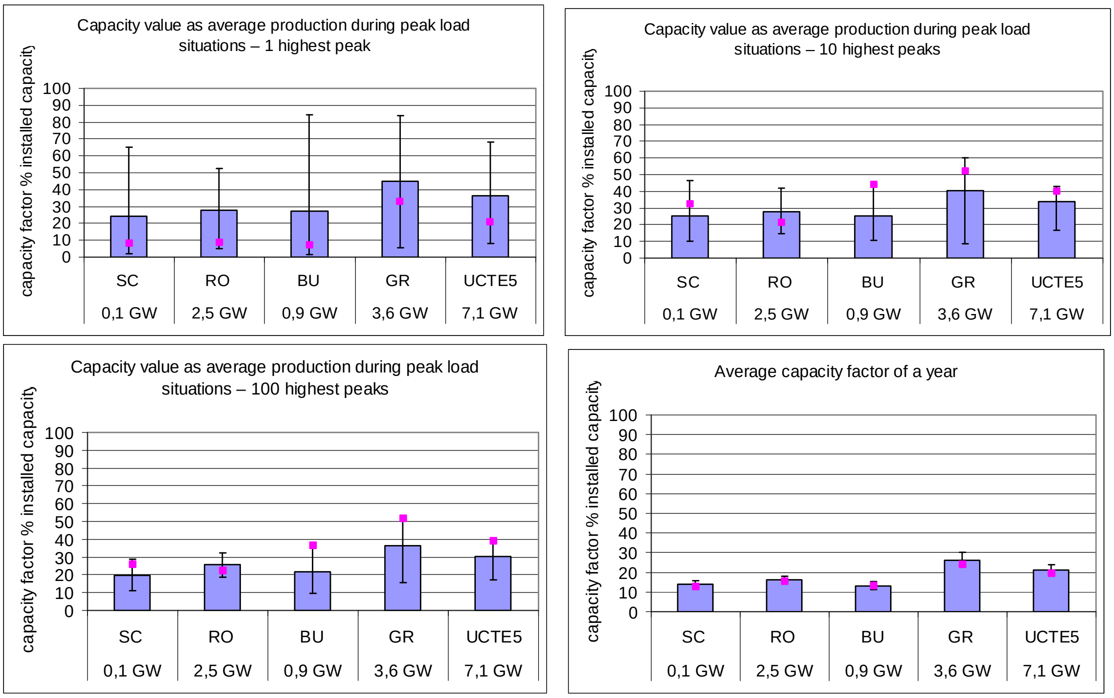
APPENDIX 6. CAPACITY FACTORS DURING PEAK LOAD SITUATIONS



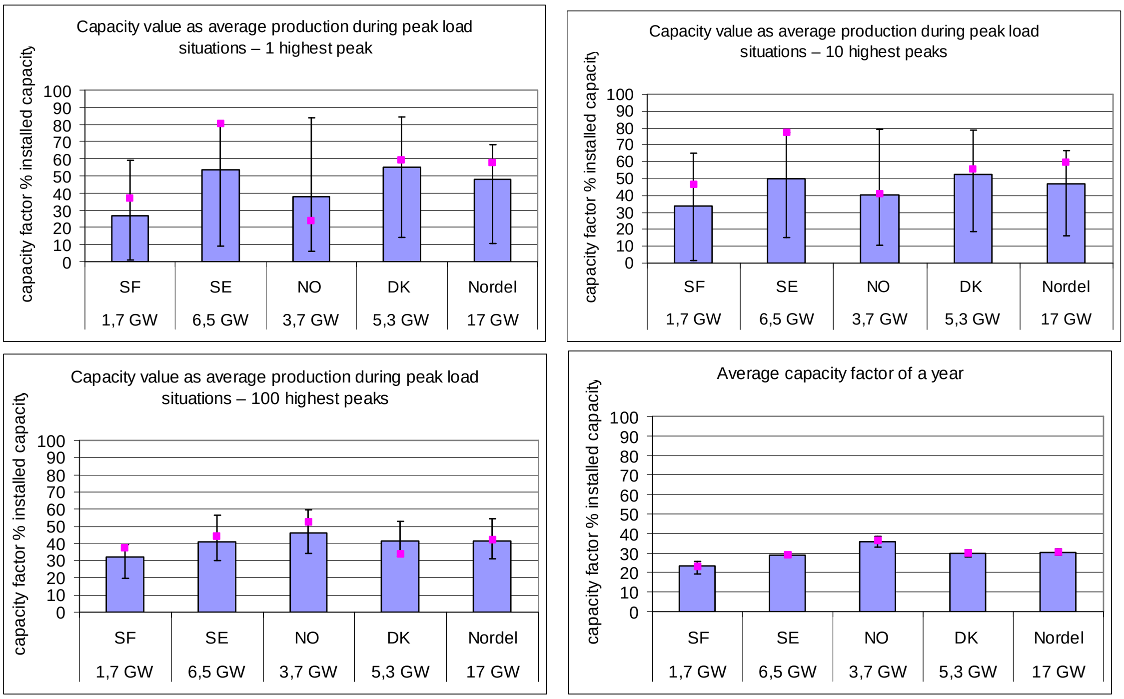
UCTE3: Wind power production during 1, 10 and 100 highest peak load hours. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.



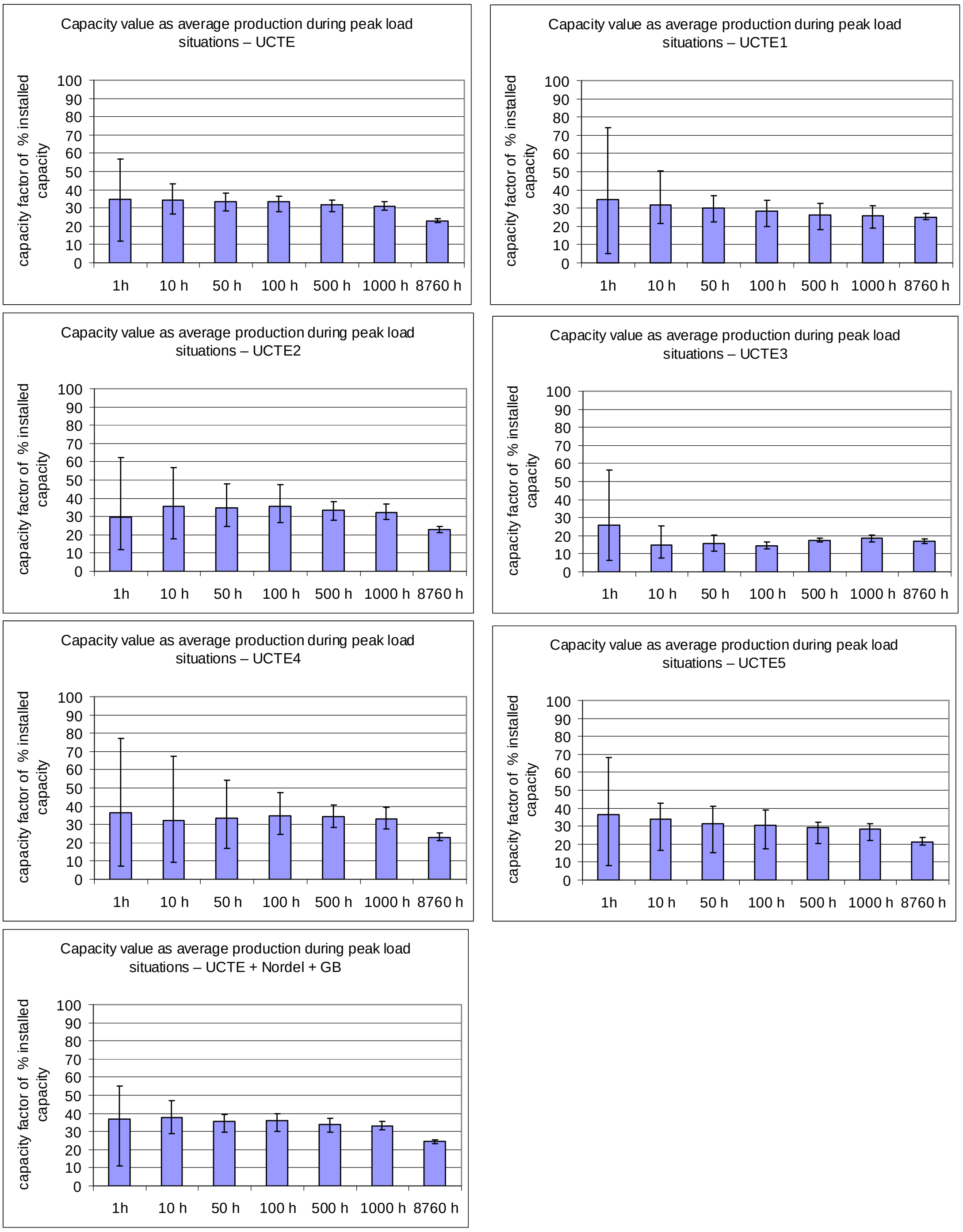
UCTE4: Wind power production during 1, 10 and 100 highest peak load hours. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.



UCTE5: Wind power production during 1, 10 and 100 highest peak load hours. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.



Nordel: Wind power production during 1, 10 and 100 highest peak load hours. Average and range of results for 7 years are presented, year 2006 result is marked separately as that year has synchronous wind and load data. Wind power average production during the whole year is presented as a comparison.

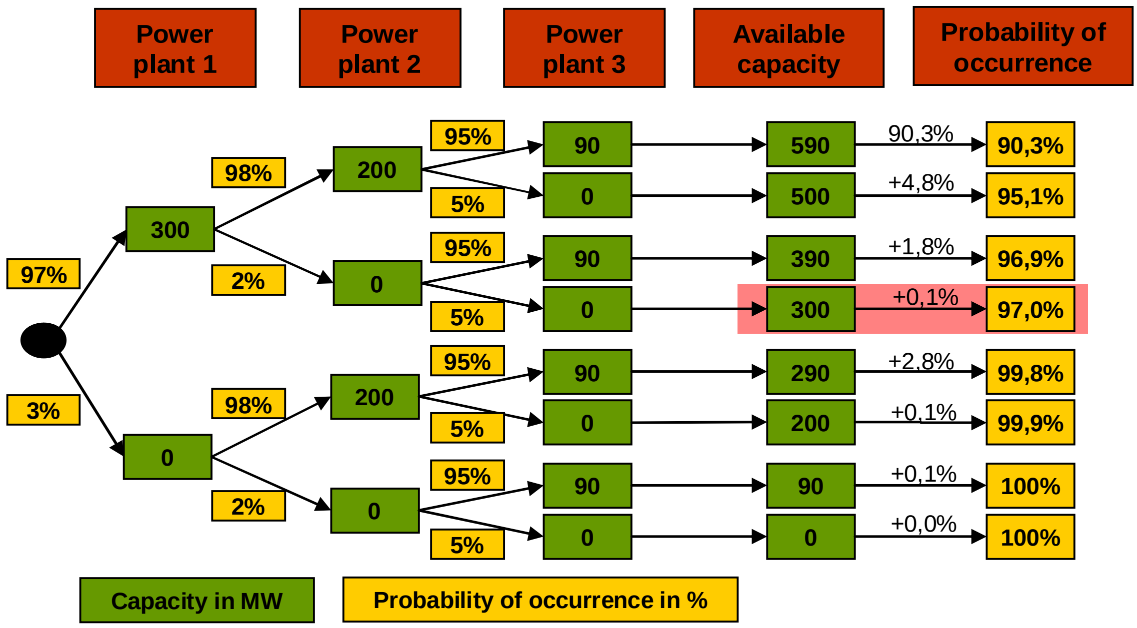


Wind power production during peak load hours for clusters and the whole of Europe. Average and range of results for 7 years are presented.

APPENDIX 7. DETAILED DESCRIPTION OF THE CAPACITY CREDIT CALCULATIONS USING THE PROBABILISTIC APPROACH

1 DESCRIPTION PROBABILISTIC RECURSIVE CONVOLUTION[3]

The probabilistic recursive convolution described in this chapter is based on data of the generation units within a power system, specifically the unit's forced outage rates and the wind power production series over several wind years.



Source: dena Grid Study I, 2005

Figure 53: Calculation of the cumulative probability of the capacity availability by recursive convolution.

The capacity credit of wind energy is calculated in three steps.

First, the power system without wind energy is evaluated and the available capacity provided that a certain system security is maintained. For this calculation step the forced outage rates[4] of each generation unit is needed. It is assumed that the outage probabilities of the generation units are independent events. System status is defined by the collective status of the single generation units which

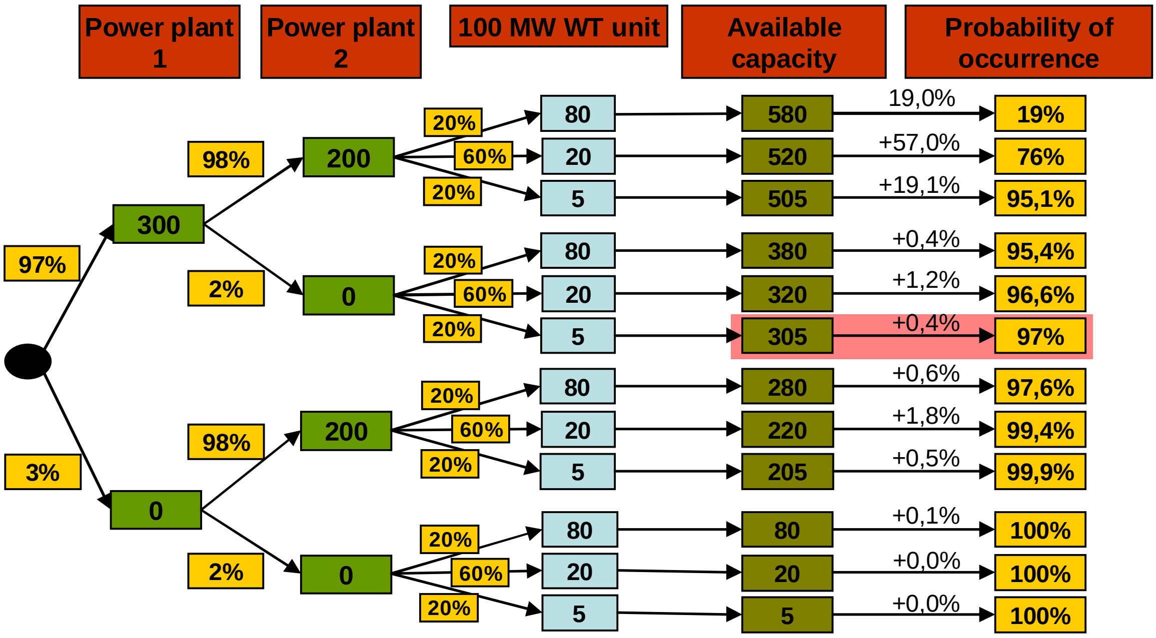
[3] dena Grid Study I, 2005

[4] Forced outage is an unplanned, non-disposable power plant shutdown or failure to deploy power to the grid.

may or may not be available at a given time. Based on this view, it is possible to assign the system status based on the amount of available capacity (i.e. the sum of the capacity of available generation units). The probability of the system status is simply the product of the individual probability of whether a unit is or is not available at a given time within the system. In the next step, the system statuses are sorted by the amount of available capacity. The probability that a certain capacity is available equals the sum of all probabilities of system statuses with a higher available capacity, as shown in Figure 53. If 300 MW are available in one system status, this value is also available in a system status with 390, 500 and 590 MW. In other words, the cumulative probability is calculated to express a certain level of available capacity.

In a second step, the wind power production series are integrated into the system. In this step, the wind energy of the whole system is regarded as one power plant. This wind “power plant” has more states than a combustion power plant that can only be “available” or “not available”. The total installed wind power will produce a certain amount of energy depending on how much wind blows. The outage time of one single turbine can be disregarded considering its relatively small capacity compared to the capacity of the total installed wind power. The total wind power production is thereby defined by its wind power probability density function. For practical reasons a discrete power probability distribution is used and consequently can be incorporate the total wind power capacity as any other thermal power plant into the power system. As in step one, the probability and the available capacity of each system state is calculated (cp. Figure 54).

Finally, the available capacities of the system with wind and without wind are compared for the same target risk level. The difference is the effective load carrying capability (ELCC) of the total wind power capacity, that is, the capacity credit. In the case displayed in Figure 53 and Figure 54 this value is 5 MW.



Source: dena Grid Study I, 2005

Figure 54: Integration of the total wind power capacity as a 100 MW plant with power probability density distribution. In this case only three discrete states of wind energy power are displayed.

In order to include the correlation between wind power production and load profile, the power probability density curve could be generated by using only the power production data of a certain number of peak load hours. The comparison of the results for different numbers of peak load hours should show whether load and wind are indeed correlated.

Necessary Approximation

Time complexity is the principle problem in determining the described algorithm. The number of calculation steps increases exponentially with the number of generation units included. An average country with hundreds of generation units cannot be estimated without approximation to avoid time complexity problems.

The approximation based on dynamic programming is illustrated in Figure 55. The probability for the minimum outage of a certain capacity is calculated by increasingly adding generation units into the system. In the example shown in Figure 55, the system consists of five generation units with a capacity of 10 MW each and an outage rate of 4%. The probability of an outage of at least 20 MW in a system with three units is calculated as the sum of the probability of two states:

- State 1: In the system with two units 20 MW are already out and the (added) third unit is available.
- State 2: In the system with two units only 10 MW are out and the (added) third unit is out too.

The sum of the probability of the two states reflects the probability that in a system with three units at least 20 MW are out. Consequently, the complementary probability of this state means that the probability that at least 20 MW are available.

Number of generation units in the system

	1	2	3	4	5
0	100%	100%	100 %	100 %	100 %
10	4 %	7.84%	11.53%	15.07%	18.46%
20	0%	0.160%	0.467%	0.910%	1.476%
30	0%	0 %	0.006%	0.025%	0.060%
40	0%	0%	0 %	0 %	0.001%
50	0%	0%	0 %	0 %	0%

Outage rate 4%

Availability 96%

Sum of probability of both states

Shows the probability that in a system with 3 units at least 20 MW will be out. It is the sum of the probability of two states:

State 1: **Probability that in a system with 2 units 20 MW are out** times the outage rate of the third unit: 0,16 * 0,96 = 0,154 %

State 2: **Case that in the system with 2 units 10 MW are out** and that the third unit is out too: 7,84 * 0,04 = 0,314 %

Sum: 0,314+0,154=**0,467**

Figure 55: Approximation by dynamic programming. Example: 10 units with 10 MW capacity each. The outage rate is the same for every unit: 4 %.

Finally, the capacity that is available at a specific probability respective of the level of supply security may be deducted from the last column of the matrix.

The result of the approximation corresponds to the last column of Figure 53. The difference is simply the density of system statuses. For example, the profile of the power fleet in Germany features more than 4000 generation units the resolution is sufficiently high and the approximation error is insignificant.

Wind power will be integrated as additional generation with different wind power generation statuses, as already discussed above.

2 Sensitivity analysis of the security of supply level

The higher the level of supply security the lower is the secured capacity of the power system in the probabilistic approach. Consequently also the capacity credit of wind energy will decrease. In order to analyze the effect of different levels of supply security a sensitivity analysis was conducted. Figure 56 shows the capacity credit for France in the 2020 medium scenario (total installed capacity 30 GW) for different wind years and also shows supply security levels from 95% to 99%. As expected, the capacity credit is smaller when the calculations are based on higher supply security levels. The greatest difference between the capacity credit for 99% and 95% is found during wind year 2006, when the capacity credit falls from 7.7% to 6.8%. The average difference is 0.8%. The selected level of supply reliability influences the values for the specific secured capacity of wind turbines at the time of the annual peak load only slightly. (However it is wrong to deduce, that the secured capacity of the whole power fleet is not reduced significantly by a higher security level.)

The calculations of the capacity credit with in the TradeWind project are based on a security of supply level of 99%.

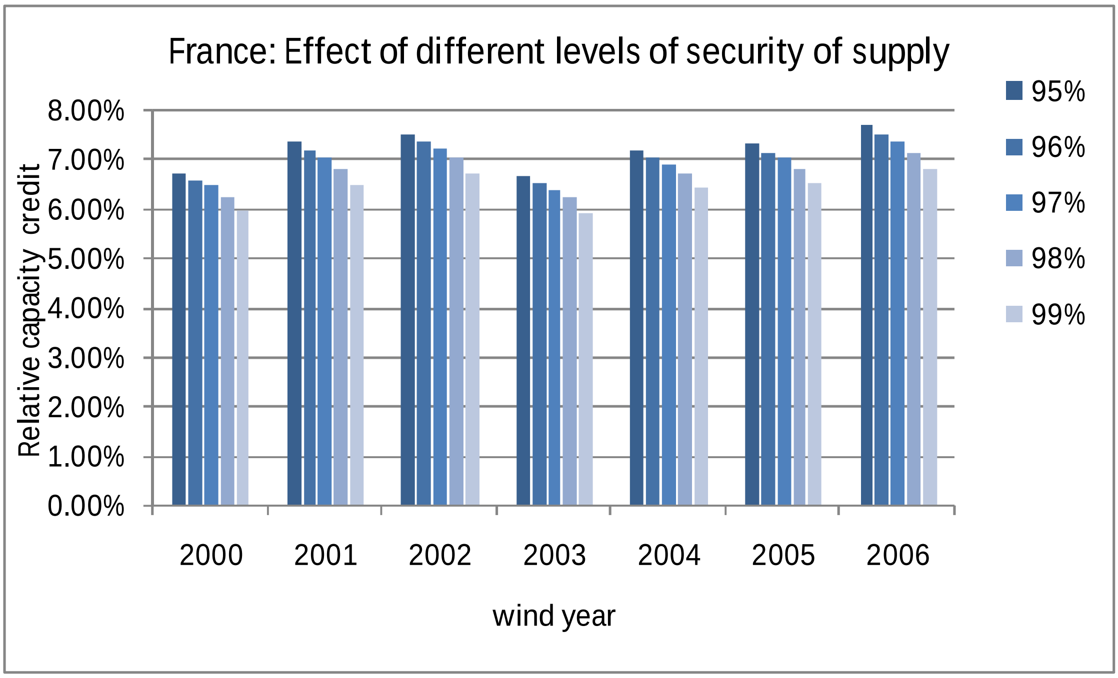


Figure 56: Sensitivities to rises in the capacity credit in relation to the level of supply reliability in the 2020 medium scenario.

3 Sensitivity Analysis of Load Wind Correlation and seasonal capacity credit analysis

The idea of the capacity credit calculations is to determine the capacity of conventional power that can be substituted by wind energy provided that the level of supply security is not decreased. While conventional power is available as long as there is not undisposable, unplanned outages, wind power depends on the wind conditions. As explained in chapter above, the capacity credit is the additional assured capacity at a certain supply security level that is available in the model run with wind energy.

For instance, in some countries the load is highest during summer days because the widespread use of air conditioning drives up electricity consumption. As a result, the capacity credit of solar energy is very large during these conditions, as hot temperatures, air conditioning, and improved solar performance are correlated (cp. Supplementary Report on Ontario IPSP, dena 2008). On the other hand, the peak load in Germany occurs in the evening during winter months when solar power is not available. Consequently, the capacity credit for photovoltaic energy sources in Germany is very low.

In Germany and other countries in Northern Europe, energy consumption may be correlated with actual wind energy production, which results in a higher capacity credit when calculations are based on the wind production during the peak load hours. A high capacity credit in Germany, for example, might correspond to a low or negative capacity credit value in Spain. Therefore, it is necessary to conduct a sensitivity analysis in order to determine the number of peak load hours upon which the calculations should be based.

Consequently, the evaluation of wind power production during the peak load hours demonstrates sound results because the supply security must be observe at peak load; supply security is not of high concern during off peak hours as the peak loads are to be met by assured generation. When load is low there is enough redundant conventional power to meet the consumption demands, and wind generation is not of principle importance regarding the power supply y as long the capacity credit is not higher than the offset between the annual peak load and the last peak load hour that is regarded during the calculation (cp. Figure 57).

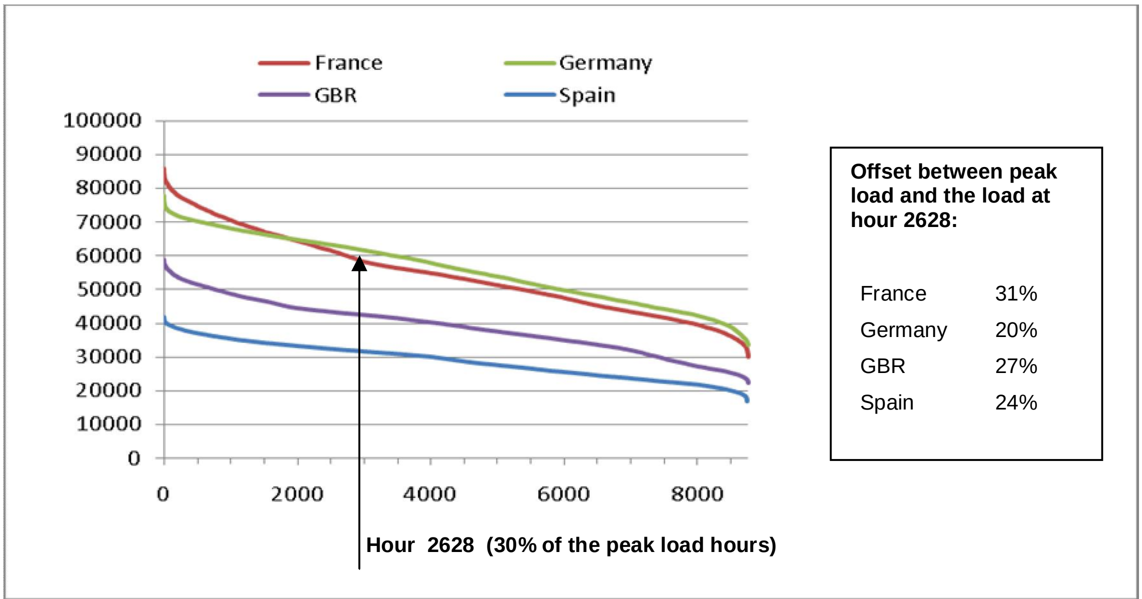


Figure 57: Load duration curves for France, Great Britain and Spain in 2006. Offset between the peak load and the load at hour 2628 (corresponds to 30% peak load hours).

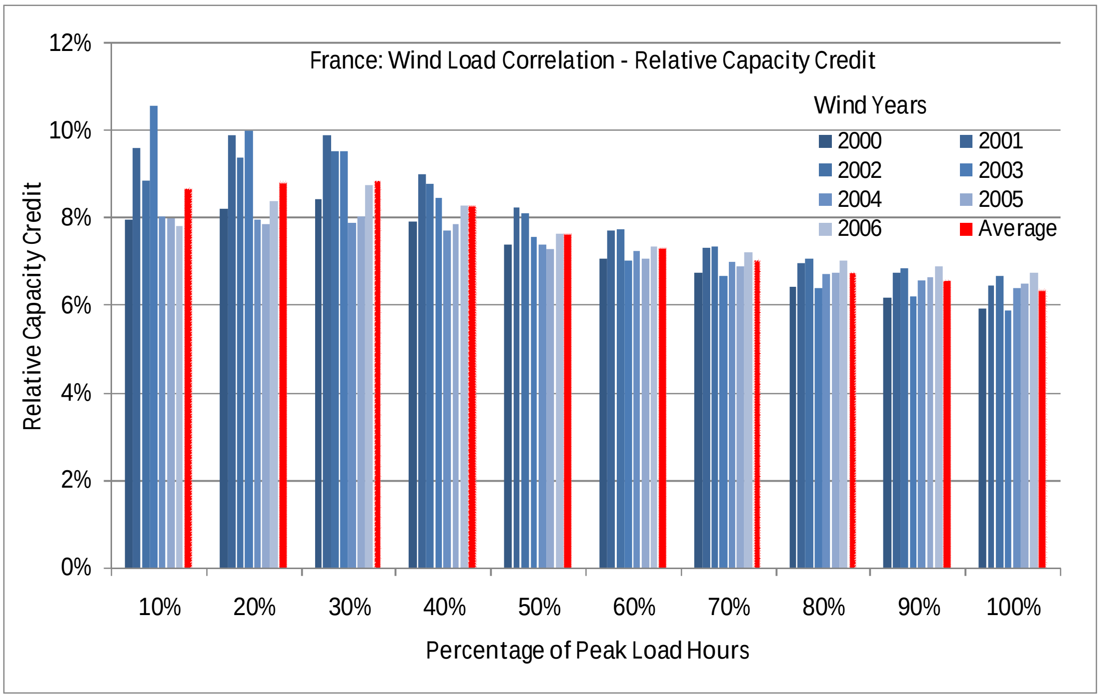


Figure 58: France - Capacity credit calculations based on the wind energy production during progressive percentages of the peak load hours in the 2020 medium scenario.

Figure 58 shows the relative capacity credit in France for the wind years 2000 through 2006, based on the wind production during 10% to 100% of peak load hours. The lowest average capacity credit is found when the wind production over the whole year is evaluated. The capacity credit increases if the calculations are based on a set percentage of peak load hours. This reflects a correlation between wind generation and the load profile in France. The capacity credit stagnates when the wind production during 30% of the peak load hours are evaluated.

Figure 59 shows the relative capacity credit in Germany for wind years 2000 through 2006 based on the wind production during 10% to 100% peak load hours. The average capacity credit is nearly constant if 50%to 100% of peak load hours are regarded and from there shows strong increases and is highest when the wind production during only 10 % of the peak load hours are taken into consideration. These findings demonstrate that wind energy production is higher and more steady during the peak load hours. The correlation between wind energy production and load is stronger in Germany than in France.

Note that the capacity credit is considered as the minimum and not the average of different years. The average value of the seven wind years would be misleading because the capacity credit is directly linked with the system security and only the worst case reflects a robust result.

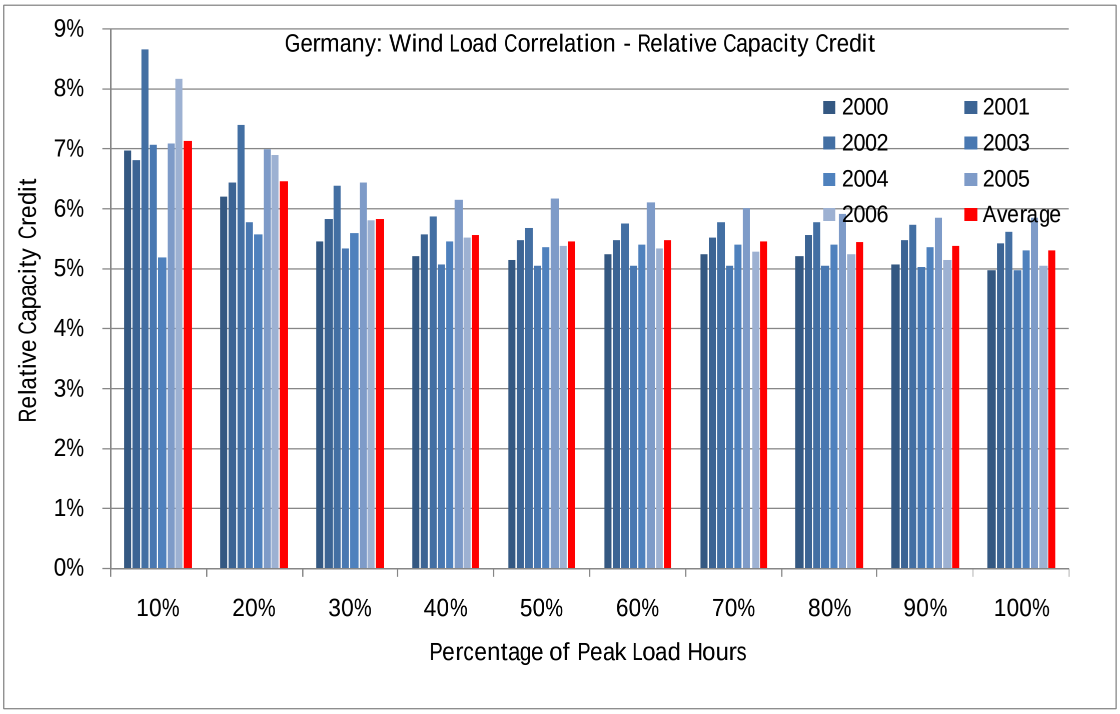


Figure 59: Germany - Capacity credit calculations based on wind energy production during a set percentage of peak load hours in the 2020 medium scenario.

As mentioned previously, the results based on fewer peak load hour give better results as long a the capacity credit is not higher then the offset between the annual peak load and the last peak load hour (cp. Figure 57) that is regarded during the calculation. In the case of Germany for instance the calculation based on ten percent of the peak load hours this means that we regard the production between hours when the consumption is up to 8 GW below the peak load. The average capacity credit in this case is about 3.6 GW. In this regard it may even be possible to further reduce the peak load hours regarded, but there is another trade off to be regarded: As shown in Figure 58 and Figure 59 the results for the different wind years are more variant the less peak load hours are considered. The less wind production hours are considered the more the results depend on the specifics of one wind year. In order to be on the save side we decided to base any further calculations on 30% of peak load hours.

Figure 60 for instance shows the difference between the capacity credit for the whole year and in the case when 30 % of the peak load hours are regarded. Again the results show that for all UCTE2 countries there is a load to wind correlation.

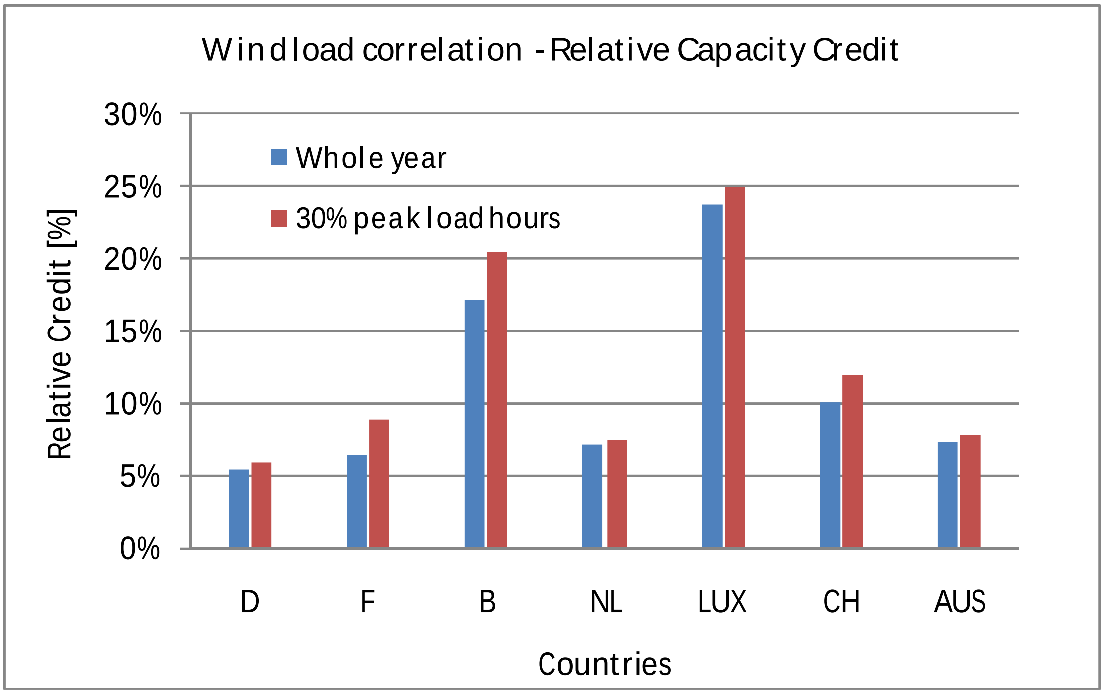


Figure 60: Capacity credit based on the wind energy production of the whole year and on the production during 30% peak load hours in the 2020 medium scenario.

In order to have further insight into the characteristics of the capacity credit in Figure 61 to Figure 63 the seasonal capacity credit for Germany, France and Spain is displayed for a range of wind years. As expected the capacity credit is highest during autumn and winter, which is owed to the fact that wind blows stronger and more steadily in these seasons. The capacity credit is hence lowest in summer. For Germany and France the capacity credit is significantly stronger in winter than in summer. This correlates with the results shown in Figure 58 and Figure 59. In Germany and France the highest peak load hours occur in winter when the capacity credit is likewise the highest. Consequently, Figure 58 shows a strong increase of the capacity credit, as less peak load hours are regarded.

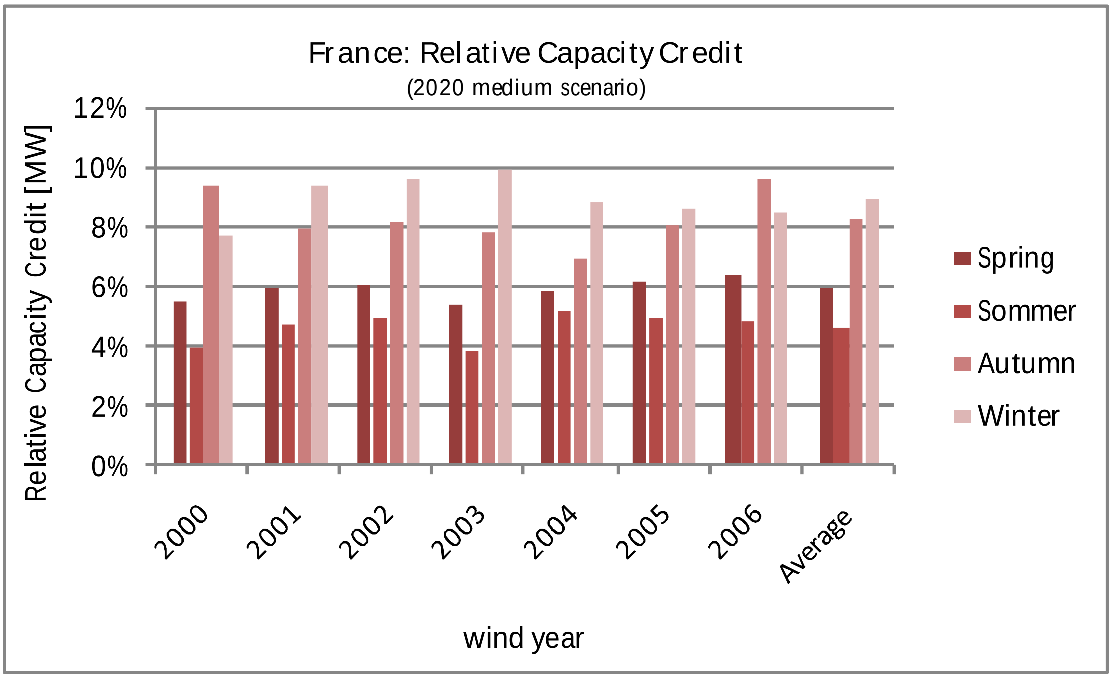


Figure 61: Capacity credit in France for the different wind years and seasons in the 2020 medium scenario.

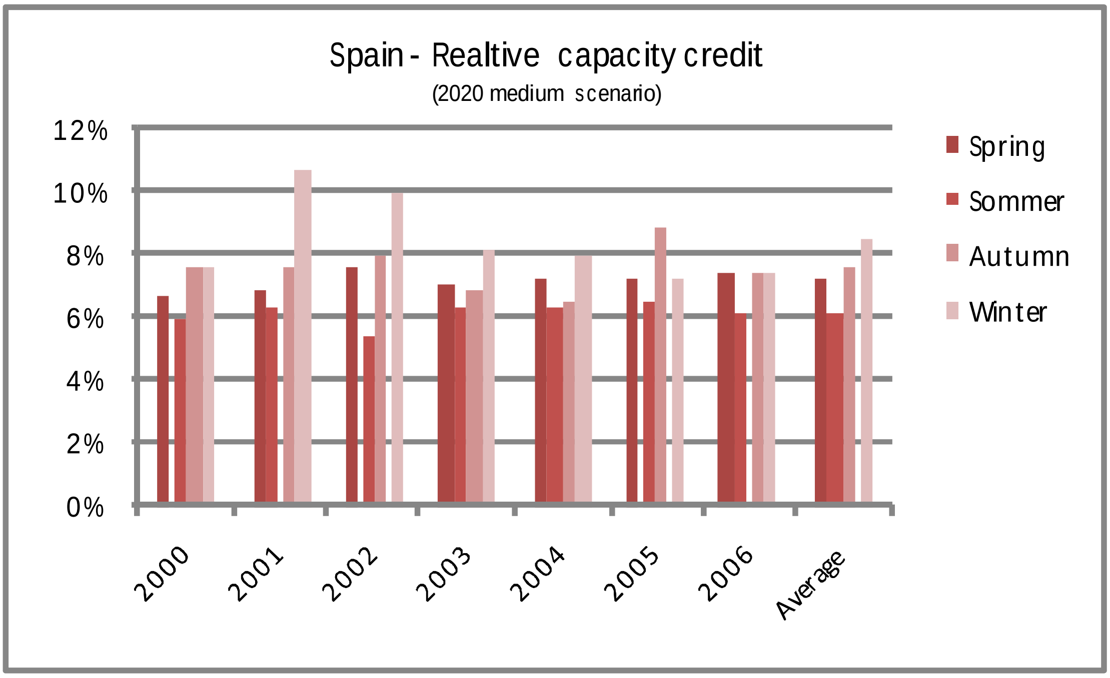


Figure 62: Capacity credit in Spain for the different wind years and seasons in the 2020 medium scenario.

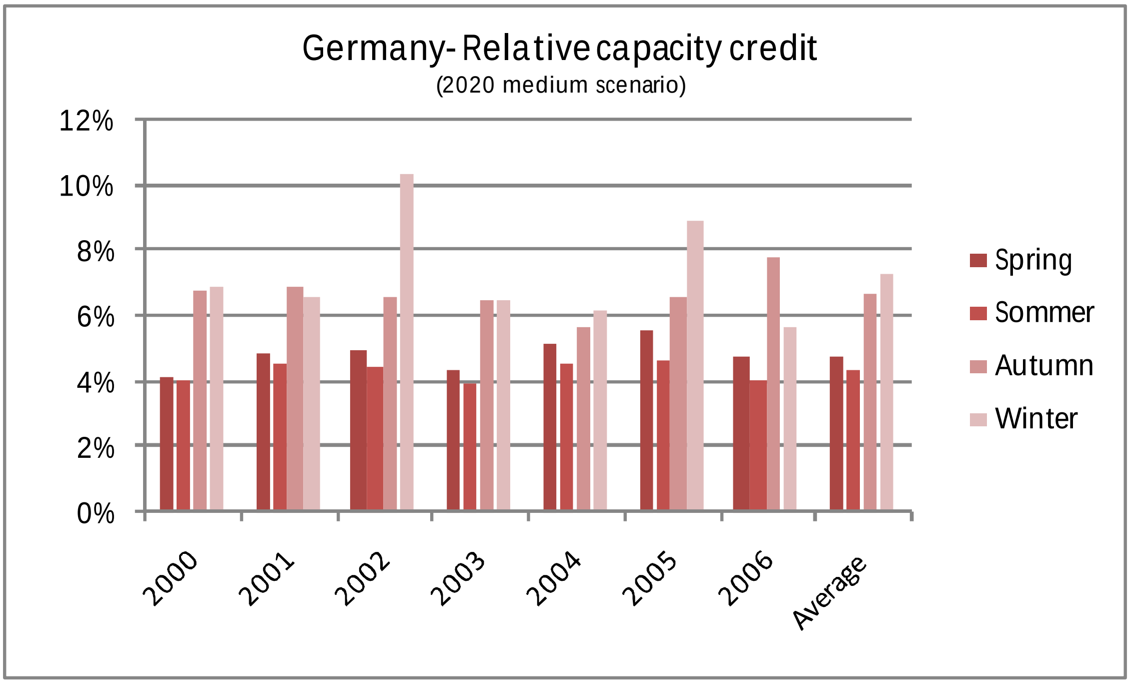


Figure 63: Capacity credit in France for the different wind years and seasons in the 2020 medium scenario.

[1] Tradewind deliverable D2.3 “Time series wind speed data”
[2] Tradewind deliverable D2.4 “Models for conversion of of wind speed data”
[3] G. van der Toorn, WP2.1 Wind power capacity data collection. TradeWind Deliverable 2.1, Garrad Hassan 11914/GR/01B, 2007.
[4] J.R. McLean, WP2.6 Equivalent wind power curves. TradeWind Deliverable 2.4, Garrad Hassan 11914/BT/02B, 2007.
[5] Tradewind deliverable D3.2 “Grid modelling and power system data”
[6] UCTE, System Adequacy Forecast 2007-2020, January 16th, 2007. Available at http://www.ucte.org/_library/systemadequacy/saf/UCTE_SAF_2007-2020.pdf Visited at 8.6.2008.
[7] Union of the Electricity Industry. Statistics and prospects for the European electricity sector (EURPROG), 2005 and 2007.
[8] Tradewind deliverable D3.1 “Grid equivalents – numerical data”
[9] Tradewind deliverable D3.2 “Grid modelling and power system data – Appendix: Model updates”
[10] NTC Values Winter 2007-2008 (Created 5.12.2007) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
[11] Energinet.dk. http://www.energinet.dk/da/menu/Marked/Udtr%c3%a6k+af+markedsdata/Udtr%c3%a6k+af+markedsdata.htm Visited at 1.7.2008.
[12] UCTE Transmission Development Plan, edition 2008. UCTE http://www.ucte.org
[13] Tradewind deliverable D7.1 “List of significant interconnectors”
[14] Tradewind deliverable D6.1 “Assessment of increasing capacity on selected transmission corridors”
[15] NTC Winter 2004-2005 (Created 22.9.2004) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
[16] NTC Winter 2005-2006 (Created 12.12.2005) http://www.etso-net.org/NTC_Info/library/e_default.asp Visited at 18.10.2008.
[17] http://www.ucte.org/services/onlinedatabase/exchange Visited at 4.6.2008.
[18] Nordel Annual Statistics 2005. Available at http://www.nordel.org/content/Default.asp?PageID=213 Visited at 4.6.2008.
[19] http://www.berr.gov.uk/files/file45407.pdf Visited 6.6.2008.
[20] Tradewind deliverable D2.1 “Scenarios of installed wind capacity in each region for each of the targets”
[21] G. Giebel, G. Kariniotakis, R. Brownsword, ”The State-of-the-Art in Short-Term Forecasting of Wind Power”, Position paper for the Anemos project, to be downloaded from www.anemos.cma.fr , 2003.
[22] Boone A, “Simulation of Short-term Wind Speed Forecast Errors using a Multi-variate ARMA(1,1) Time-series Model”, Royal Institute of Technology, Stockholm, 2005
[23] G. Giebel, P. Sørensen, H. Holttinen, ”Forecast error of aggregated wind power”, TradeWind Deliverable 2.2, April 2007.
[24] K. Rohrig, F. Schlögl, B. Ernst, Ü. Cali, R. Jursa, J. Moradi, Wind Power Prediction in Germany – Recent Advances and Future Challenges, EWEC06, Athens, Greece, 2006
[25] G. Gonzalez, Wind Power Prediction in the Spanish System Operation (peninsula and islands) Sipreolico, POW'WOW, Workshop on Best Practice in Short-term Forecasting, 28 May 2008, Madrid, http://powwow.risoe.dk/publ/GGonzalez_(REE)-WindPowPredInSpanishSystemOp_BestPractice-2_2008.pdf
[26] H. Karttunen, J. Koistinen, E. Saltkoff, O. Manner. Ilmakehä ja sää. Ursan julkaisuja 62, Tähtitieteellinen yhdistys Ursa.

[27] J.L. Franklin, Tropical Cyclone Report: Hurricane Vince. National Hurricane Center, National Oceanic and Atmospheric Administration. http://www.nhc.noaa.gov/pdf/TCR-AL242005_Vince.pdf
[28] Cyclones in the Mediterranean. April 2006, World Climate Research Programme http://www.wmo.ch/pages/prog/wcrp/pdf/WCRPnews_LionelloMedCLIVAR_Final.pdf
[29] J. Cappelen & S. Rosenørn (editors), Storms in Denmark 1891 – 2008. DMI Danmarks Meteorologiske Institute. http://www.dmi.dk/dmi/storme-2.pdf Visited at 7.5.2008.
[30] Matalapainemyrskyt 1959 lähtien. http://www.ilmatieteenlaitos.fi Visited at 27.5.2008.
[31] Sturmdokumentation Deutschland, Deutsche Rückversicherung Aktiengesellschaft. http://www.deutsche-rueck.de/web/export/sites/dr/das_unternehmen/veroeffentlichungen/sturmdokumentation/index.html Visited at 7.5.2008.
[32] Wetterzentrale http://www.wetterzentrale.de Visited at 7.5.2008.
[33] Holttinen, H, Lemström, B, Meibom, P, Bindner, H, Orths, A, Van Hulle, F, Ensslin, C, Tiedemann, A, Hofmann, L, Winter, W, Tuohy, A, O'Malley, M, Smith, P, Pierik, J, Tande, J O, Estanqueiro, A, Gomez, E, Söder, L, Strbac, G, Shakoor, A, Smith, J C, Parsons, P, Milligan, M, Wan, Y. Design and Operation of Power Systems with Large Amounts of Wind Power. State-of-the-art report. VTT Working Papers 82, 2007. VTT, Espoo, Finland. Available at http://www.vtt.fi/inf/pdf/workingpapers/2007/W82.pdf.
[34] Milligan, M. & Porter, K. 2005. The Capacity Value of Wind in the United States: Methods and Implementation. Electricity Journal, Vol. 19, Issue 2. March 2006. Elsevier, Inc. Pp. 91–99.
[35] dena grid study 2005
[36] G. Dany, Kraftwerksreserve in elektrischen Verbundsystemen mit hohem Windenergieanteil. Aachener Beitrage zur Energieversorgung Band 71, Klingenberg Verlag (2000)
[37] Th. Hartkopf, B. Hagenkort, Kapazitätskredit der Windkraftanlagen in Hessen (1998)
[38] H. Bouillon, R.-D. Machate, G. Tetzlaff, Leistungseffekt von Windkraftanlagen, Elektrizitätswirtschaft Heft 24 (1989)