Topic: Smoothing out the wind power production patterns by connecting different countries within Europe.

Master Thesis (30 ECTs)

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Abstract

The increase in wind power production changes variability in the power system on a large scale. The smoothing out effect is the extent to which this variability can be changed. Wind output fluctuation is of a great importance for evaluating and assessing the impacts in a power system with a large number of wind turbines interconnected.

In this thesis two methods are used in order to investigate the extent to which wind power production patterns can be smoothed out by connecting different countries within Europe. The first one is a step change analysis based on time series of wind power production. The second one is based on the comparison of relative wind power production. Furthermore, the wind power variability is studied on all time scales in the period 2011-2013 for five European countries (Denmark, Germany, Ireland, France and Spain). Two indicators are used for the quantification of smoothing effect, the standard deviation of paired countries and of countries individually and the correlation coefficient of paired countries. Also, the distance, the size of area and the wind power capacity are important factors that affect the behavior of that effect.

In this study, logarithmic relations are identified between the factors taken into account and the two indicators. It can be noticed that the standard deviation of the change in power production per time step decreases asymptotically with the increase of the area and the wind power. For example, at hourly basis it drops by 15% and 18% from 600,000 km^2 to 800,000 km^2 area and from 30 TWh to 50 TWh wind energy, respectively. In a similar way, the distance seems to have an asymptotic effect on the correlation coefficient of paired countries. For instance, at hourly basis the indicator decreases by 56% from 500 km to 1000 km distance.

In overall, the relative variability of wind power decreases when considering a large inter-connected system composed of the five European countries. In this system, the aggregated hourly wind power variations are most of the time within ±2% of installed capacity.

Finally, it is recommended that the smoothing effect of wind power should be investigated combined with the load variability of each country.

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1. Introduction

In this day and age, wind energy is a mainstream source of electricity. Unlike conventional fuels, wind energy is a massive power source which will never run out. This kind of indigenous energy has no resource constraints: the 'fuel' is free and endless. Additionally, wind energy entirely avoids costs of carbon, geo-political risk associated with supply and infrastructure constraints, energy dependence on other countries. Europe is the leader in wind energy and has solidified its position in global market. (EREC, 2012)

In the European Union, a cumulative wind power of 106 GW is now installed. Germany remains the country with the largest installed capacity (31.3 GW), followed by Spain (22.8 GW). These two countries represent 52% of total EU capacity. The UK, Italy, France follow with 10.5 GW, 8.6 GW and 8.3 GW, respectively. Also, Dennmark has a production capacity of 4.2 GW and Ireland 1.7 GW. (EWEA, 2014)

Many wind turbines that are connected to the electric power transmission network compose a wind farm. In cases of new constructions, onshore wind is considered to be an enticing source of electricity since it is not expensive. In various places it can even be a more preferable solution compared to fossil fuel plants in monetary terms. (BusinessGreen, 2011)

On the other hand, offshore wind is steadier and stronger than onshore. Nevertheless, constructing and maintening wind farms at sea is much more costly than wind farms at land. (Gipe P., 1993)

Wind power production is characterized by variations on all time scales under the influence of meteorological fluctuations. Understanding the predictability of these variations is of key importance regarding the integration and optimal utilization of wind in the power system. Electric power systems are inherently variable in terms of demand and supply, but they have been designed in a way to cope effectively with these variations through their configuration interconnection. (Murtagh A., 2010)

Considering the different wind conditions around Europe, it is necessary to be able to transfer power from one area to another. Thus, we need to create a strong European and inter-connected grid without bottlenecks. Studies in the past have indicated that interconnecting wind plants by using transmission lines decreases the variability of their overall power output as the number of installed wind plants and the distance between them increases.(Katzenstein W. et al, 2010)

It is crucial to consider wind power as a continental power source in order to understand the integration challenges. The wind power production variability across the European countries is a big challenge. A main characteristic of wind generation is the movement of huge weather systems across Europe. In fact, meteorologically wind velocities across Europe are not correlated over distances corresponding to the scale of weather systems (1,000 Km). In other words, that means: wind is always blowing in some places. Thus, a well interconnected grid is necessary to use optimally this spatial de-correlation of wind power. Transfer of wind power across the countries enables to captivate the smoothing effect of geographical aggregation on wind power production variations. (EWEA, 2009)

In general, there are sites with higher wind power yields and those with lower ones. The local climate (mean wind speed, extreme weather events, long-term changes etc.) and the technical design of the wind farm (wind profiles, turbulences, roughness, hills etc.) are the main factors that influence the wind yield. (Scharff R., 2012)

Wind speeds vary across Europe. The weather systems in Northern and Southern countries are different to each other. For instance, in the Mediterranean countries wind blows in summer time, while on the other hand in the Northern countries the wind speeds are stronger during winter time according to Giebel G. et al. (2003). The Mediterranean zone includes the countries or regions of countries around the Mediterranean Sea (e.g. France, Spain). Northern countries such as Ireland, Denmark, and Germany are part of the North maritime zone.

1.1 Smoothing Effect

The output from wind turbines is highly changeable over all timescales. The smoothing out effect is the extent to which this variability can be changed. This effect concerns a lot the power sector as it is significant to explore various ways to smooth out the different fluctuations of wind power. This could be achieved, for instance, by integrating into the system conventional energy sources such as natural gas or even alternative renewable sources like solar power. Another way to contribute to the stabilization of wind power generation is, as mentioned before, by connecting various countries such that wind power can be transferred from one place to another.

Previous studies have shown that smoothing out wind power production patterns is feasible in some cases, while in some others it is difficult to be realised. This depends on the extent to which wind speed is correlated. Factors that influence wind velocities are temperature, atmospheric pressures and the terrain.

Adams T. et al. (2009) made an analysis to quantify the benefits of geographical diversity regarding the smoothing effect in wind power. Also, Bach (2012) carried out a statistical analysis in wind power in Denmark, Germany, Ireland, Great Britain, France and Spain evaluating the smoothing effect between them. In another study, Giebel (2001) analyzed the extent to which the geographic dispersion of generation smoothes the overall generation. Furthermore, Rosques F. et al. (2009) indicated that remote countries present low or negative correlations (e.g Spain and Denmark). Low or negative correlations in the wind power output of different European countries indicate the potential to reduce wind output variability by spreading capacities of wind power over several countries.

Apparently, no clarity exists about the potential of smoothing effect within Europe and, thus, this analysis is required. It is investigated whether smoothing out the patterns of the production of wind power across certain European countries is feasible. The variations from hour to hour are much more important for the system than larger time steps because wind power fluctuates a lot in that time scale. Locally the variations of wind power are widely equal to the diversity of the geographical characteristics. In general, the majority of local hourly variations remains within ±5 per cent of wind power installed capacity at the regional level that is a region within a country. (Wind Energy The Facts, 2014)

However, the long-term wind power variability is investigated as well. The slower variations of wind power that are relevant for integration in the power system include the weekly, monthly and seasonal variations. These kinds of variations are not particularly significant for the daily operation and management of the grid, but they play an important role in the strategic power system planning. Especially, monthly and seasonal variations are important for the European Network of Transmission System Operators as well as electricity traders. These traders deal with electricity forward contracts in areas that wind power volume influences energy price. It seems that for both system planning and electricity trading purposes, deviations of monthly and seasonal variations resulting from annual statistics of produced wind power can be sufficiently hedged. (Wind Energy The Facts, 2014)

1.2 Problem definition

1.2.1 Research question

"To what extent can wind power production patterns be smoothed out by connecting different countries within Europe?"

A variety of sub-questions linked to the main one are formulated. Thus, a more detailed, structured and complete understanding of the topic and the issues emerging from it can be achieved.

a) How does the smoothing effect change on different time scales (hourly, daily, weekly, monthly and seasonal basis)? Does the smoothing effect decrease or increase on long-term analysis?

b) To what extent the distance between the countries affects the smoothing effect?

c) In which way does the size of the area influence the smoothing effect?

d) How does the wind power capacity of each country affect the overall smoothing effect?

e) How is the smoothing effect expected to change according to future projections in wind energy?

1.2.2 Scope of the problem

In the present research, wind power production patterns are studied at a country level. One could argue that large countries could be divided into smaller parts and, therefore, these regions could be studied separately. Nevertheless, this is not done in this study, because the availability of data for some countries was limited. For instance, in Spain only the overall actual wind power production was found while the collection of data was not feasible in different regions within the country. For this reason, each country under investigation is considered as a unique system. In this manner, a clear picture can be drawn regarding the possibilities of wind energy transit among countries. Also, an attempt is made to depict the actual wind power production on an hourly, daily, weekly, monthly and seasonal basis and present the way this varies in time by drawing the respective graphs.

2. Methodology

The first step of our method is the selection of the countries to be investigated. This choice is based on the various weather conditions as well as the availability of data. Therefore, five European countries are chosen: Germany, France, Spain, Ireland and Denmark. The three of them are located in the northern part of Europe, while the rest are found in the South and West part of Europe. The fact that the countries under investigation are located in different climatic zones (as specified in introduction) renders the smoothing effect volatile. This means that there is a possibility, countries with different climate conditions to show high smoothing effect among them.

Moreover, Germany and Spain play a significant role in the production of wind power since they have the largest installed wind power capacity in Europe. The selection of Denmark is made based on the fact that it is a pioneer on the wind energy sector. Regarding Ireland, it is expected to have a good potential for wind power due to its location in Europe as it is exposed to high winds from the Atlantic Ocean and Irish Sea (WWEA, 2008). The last country selected is France having the second largest wind energy potential (the first is Great Britain) mainly with respect to offshore wind energy (EOLFI, 2013).

Wind power production is characterized by variations on all time scales. Therefore, the smoothing effect between the chosen countries is investigated regarding the wind power production on an hourly, daily, weekly, monthly and seasonal basis and for the period 2011-2013. Investigating a period longer than a year is important because in this way our analysis becomes more reliable. Moreover, using data in the recent period renders the study more realistic since the climate changes with time and, therefore, the various factors (e.g. temperature) are quite different in the recent years from the past.

For the analysis of our research two indicators are used. These are the standard deviation and the correlation coefficient. More specifically, in statistics, the standard deviation (σ) indicates how much variation or dispersion exists from the average value of wind power. Thus, standard deviation tells the researcher how spread out the values are around the mean. A low data deviation shows that the data points have the tendency to be very close to the mean value, whereas a high standard deviation indicates that the data points are spread out over a large range of values. (Bland J. A. et al, 1996)

In turn, the correlation coefficient (r) measures the strength and the direction of a linear relationship between two sets of data. Sometimes the correlation coefficient is referred to as the Pearson product moment correlation coefficient in honor of its developer Karl Pearson (Nicewander W. A. et al, 1988). “The value of r is such that $-1 \leq r \leq +1$. The signs + and – are used for positive and negative linear correlations, respectively. If x and y have a strong positive linear correlation, the value of r is close to +1. Positive values indicate a relationship between the two variables x and y such that as x values increase, values of y increase as well. On the other hand, if x and y values have a strong negative linear correlation, value r is close to -1. Negative values of x and y indicate a relationship between the two variables such that as values of x increase, values of y decrease. In case that value r is close to 0, there is no linear correlation or the linear correlation is weak between the two variables. That means that there is a random, non-linear relationship between x and y variables." (MathBits.com, 2014)

The following formulas are used in order to calculate the standard deviation (σ) and the correlation coefficient (r):

Equation 1

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

Where,

X_i = Individual value of wind power

$\bar{X}$ = Mean of individual values of wind power

n = Number of data points

Equation 2

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

Where X and Y (two data sets of wind power) and $\bar{X}$ and $\bar{Y}$ the mean values of these sets.

Two different methods are used for the analysis of our subject. The first one, called step change analysis, is the most common time domain method (where time is considered as an independent variable in the analysis) which is used in studies regarding wind power generation (Wan Y.H., 2001; Wan Y.H., 2004). In this method, an attempt is made to quantify the smoothing effect between the countries by comparing the standard deviations of each country with the standard deviations of a pair of countries as well as the correlation coefficient between the countries. The standard deviation of the series of time step changes is a good measure for the variability. The change in power for a given time step is calculated and reported as energy (e.g MWh) or as a percentage of the rated capacity of a country. In this study, step changes are calculated as a percentage of the maximum power produced by a whole country (Equation 3).

Equation 3

$$\Delta p = \frac{P(t+1) - P(t)}{Pmax} * 100$$

More specifically, relative step changes are calculated at 1-hour, 1-day and 1-week time intervals in order to investigate to what extent the wind energy production varies on each scale for the period 2011-2013 for each country. Next step is to calculate the standard deviation of the series of all hourly, daily and weekly relative step changes in one year and the correlation coefficients between two countries at each time interval. In turn, graphs are drawn in order to examine the smoothing effect in this period.

The second method is called relative difference. It is based on the comparison of the relative percentage differences of wind power generation among the countries. The term relative difference is used as a quantitative index for each country. In this method, capacity factors are calculated on different time scales during the period 2011-2013. The following formula is used:

$$\text{Hourly capacity factor} = \frac{\text{Generated wind energy per hour(MWh)}}{\text{Theoretical output per hour(MWh)}} * 100\%$$

The same formula applies to daily, weekly, monthly and seasonal time scales.

In Appendix B, graphs are illustrated for each country in the given period regarding the wind power generation (% of installed capacity). Thus, the data available for this research can be found in these graphs. The time series show the hourly, daily, weekly and monthly wind power capacity factor during the period 2011-2013.

The graphs of wind power production in time series (% of installed capacity) for the five countries are plotted to help to identify the countries between which the smoothing effect appears to be strong or weak. The question is whether or not it is possible to quantify this smoothing effect and present the percentages that reveal exactly this quantification. A reference point (24%) is used in order to convert all the capacity factors on a common scale. The value of the reference point is chosen to be 24% because it is approximately the average of the annual capacity factors of the five countries. Without this step, a comparison among capacity factors is hard to be made. The same method is used for all time scales taken into account in this research.

The time scale used for the analysis differs between the two methods. The first one is applied on hourly, daily and weekly basis, while the second one includes, in addition, monthly and seasonal. The reason for this is that it does not seem realistic to make an analysis using Δp for long time scales because this method applies better on small variations.

Also, the smoothing effect is studied based on the two indicators with respect to certain factors such as the area of the countries, the distance and the wind power capacity. Mathematical formulas are expected to be found that will reveal the relation between the two indicators and the factors mentioned above.

After the analysis is completed a scenario is presented where a quantitative analysis is made regarding the way the smoothing effect changes according to future projections on wind power production. In turn, a discussion takes place where a comparison is made between the results that are found in this research and the outcome of previous studies. In this way, all findings can be evaluated and better recommendations can be formed for future work. At the end, the conclusions of this research are formed and recommendations are made regarding fields that need further investigation.

2.1 Data set

At the beginning of the research an attempt was made to collect wind speed data concerning the five European countries to be studied. Nevertheless, the collection of this kind of data was difficult as not all of it was possible to be found for all five countries and especially for the particular time period, i.e. 2011-2013. At the same time, a certain program was used for the elaboration of the data. Unfortunately, the program did not work properly for certain reasons such as incompatibility of the program as well as the fact that a beta version was used.

Therefore, actual wind power data are harnessed for the desired countries during the period 2011-2013.The reason for using this kind of data is based on the fact that the outcome is expected to be more reliable and reasonable when actual wind power generation data is used as input. In this way, assumptions leading to uncertainties as well as possible mistakes made using mathematical formulas to calculate the wind power generation can be avoided.

During this procedure, a website is found where all wind power production data on an hourly time scale are collected for the countries and the period under investigation.

Bach (2012) had based his data on the following web sources with hourly data of actual wind power production:

- Denmark: hourly data for years, 2011-2013, via the system operator Energinet.dk (www.energinet.dk).
- Germany: hourly data for years 2011-2013, via the web page www.transparency.eex.com . The transmission system operators determine the wind power output fed in their balancing area by means of an extrapolation based on reference wind parks measured on-line. The data information is published on an hourly basis.
  The web pages of balance areas are the following:
  http://www.tennettso.de/
  http://www.50hertz-transmission.net/
  http://www.amprion.de/
  http://transnet-bw.de/
- France: hourly data for three years, 2011-2013. Data extracted from the eCO2mix/RTE web site.
- Spain: hourly data for two years, 2012-2013. Data extracted from http://www.ree.es/.
- Ireland: hourly data for three years, 2011-2013. Data extracted from http://www.eirgrid.com/ .

3. Statistics of wind power production in Europe

Figure 1 illustrates the spatial distribution of wind stations in the EU member states. It presents the installed capacity in MW of wind stations in operation and under construction at the end of August in 2011.

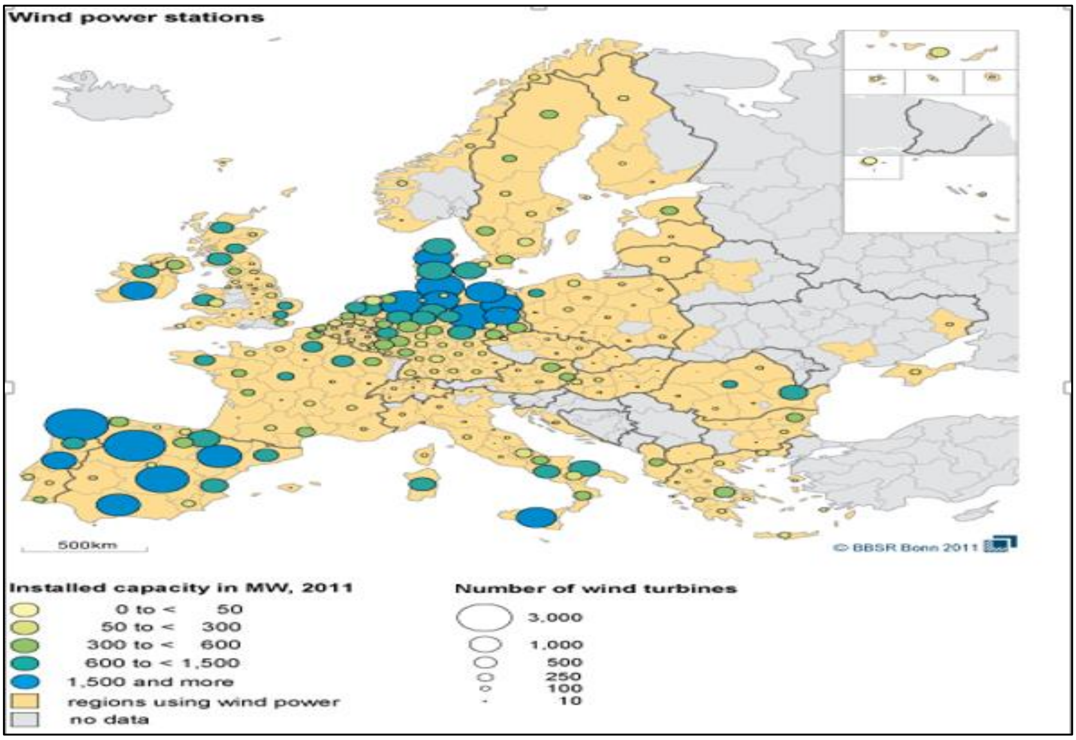


Figure 1: Wind power stations in operation and under construction in Europe (BBSR, 2011).

It is obvious that Germany and Spain have the highest installed capacities. In Denmark, Ireland and South Italy, quite high capacities can be detected as well. Most of the installed wind turbines can be found in places where the highest wind yields are achieved, for instance, close to the coast or on tablelands in the interior of Spain. Hence, it is quite surprising that on the French Atlantic Coast or the Baltic Sea area only few stations can be found. The reason for this is that France did not promote wind power until 2011 due to the policy that they followed. Very strict regulations were issued that did not enable wind power to be developed in the country. For example, environmental regulations and low feed-in-tariffs are the main issues for the low installed wind power. On the other hand, in Germany and, as mentioned before, in the interior of Spain rather high wind installed capacities can be detected. (BBSR, 2011)

Our statistical analysis is performed according to data used for three years, 2011-2013, for the five European countries (Denmark, Germany, Spain, France and Ireland). Table 1 shows the installed wind power capacity during the period 2011-2013 for the five countries. The source for this is the European Wind Energy Association (EWEA, 2014). A capacity factor of 100% is assumed meaning that the generated energy is as much as the installed and not less.

Table 1: Theoretical[1] yearly energy generation, assuming 100% capacity factor, in the five European countries at the end of each year from 2011-2013.

Year	Denmark (TWh)	Germany (TWh)	Ireland (TWh)	France (TWh)	Spain (TWh)
2011	34.40	254.70	14.14	59.57	189.86
2012	36.46	274.47	15.22	63.04	199.69
2013	41.80	295.47	17.84	72.31	201.12

Table 2 below illustrates the actual wind energy generation for the specific countries and time periods. Data was not available for Spain in 2011 and is, therefore, not presented in the table.

Table 2: Actual wind electricity generation in the five European countries at the end of each year from 2011-2013.

Year	Denmark (TWh)	Germany (TWh)	Ireland (TWh)	France (TWh)	Spain (TWh)
2011	9.75	43.01	4.26	11.25	-
2012	10.27	45.82	4.10	14.90	47.64
2013	11.13	47.18	4.64	15.79	54.03

The average yearly capacity factor of wind power for a country is simply defined. It is the ratio of its actual power output over a period of time divided by its maximum power output. Actual capacity factors vary significantly and are determined by multiple factors (e.g. height of territory, onshore/offshore installations) in different countries. Equation 4 is used in order to calculate the Capacity Factor during the period 2011-2013 for the five countries.

Equation 4 $$\text{Capacity Factor } (\%) = 100 * \frac{\text{Actual Energy Production(TWh)}}{\text{Theoretical yearly energy generation(TWh)}}$$

Table 3: Capacity factors in the five European countries at the end of each year from 2011-2013.

Year	Denmark	Germany	Ireland	France	Spain
2011	28,3%	16,9%	30,1%	18,9%	-
2012	28,2%	16,7%	30,0%	23,6%	23,9%
2013	28,5%	17,0%	30,0%	24,0%	24,0%

Using the following formula, the theoretical energy output is calculated per hour, day, week and month for each country and for the stated period. The results are presented in Table 4 below.

[1] Theoretical yearly wind energy generation refers to the maximum energy a wind turbine can provide assuming 100% efficiency. However, this is not realistic since wind turbines are not possible to work to its nominated wind capacity.

$$\text{Theoretical energy output per hour} = \frac{\text{Theoretical energy output per year(TWh)}}{8760 \text{ hours}}$$

The same formula applies to daily, weekly and monthly time scales.

Table 4: Theoretical energy output (TWh) assuming 100% capacity factor per hour, day, week and month for the five countries during the period 2011-2013.

Countries	Theoretical wind energy (TWh)	2011	2012	2013
Denmark	per hour	3.9	4.2	4.5
	per day	94.2	99.6	107.0
	per week	661.5	701.1	750.7
	per month	2866.7	3038.3	3253.2
Germany	per hour	29.1	31.3	31.7
	per day	697.8	752.0	760.4
	per week	4898.0	5278.2	5337.2
	per month	21224.8	22872.4	23128.0
Ireland	per hour	1.6	1.7	1.8
	per day	38.7	41.6	42.4
	per week	271.9	292.8	297.6
	per month	1178.2	1268.7	1289.5
France	per hour	6.8	7.2	7.5
	per day	163.2	172.2	180.3
	per week	1145.5	1212.2	1265.4
	per month	4964.0	5253.1	5483.6
Spain	per hour	-	22.8	25.7
	per day	-	545.6	616.8
	per week	-	3840.2	4329.6
	per month	-	16641.1	18761.8

4. Step change analysis

4.1 Hourly step change analysis

The time series of hourly step changes during 2012 for the five countries are presented in Figure 2 to Figure 6. The y-axis shows the hourly step change as a percentage of maximum power capacity, while the x-axis illustrates the hourly intervals.

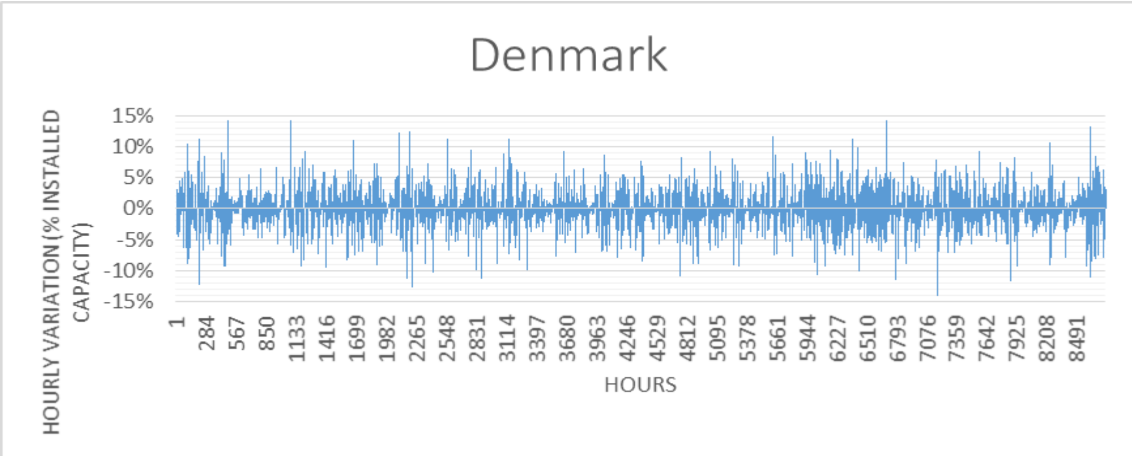


Figure 2: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

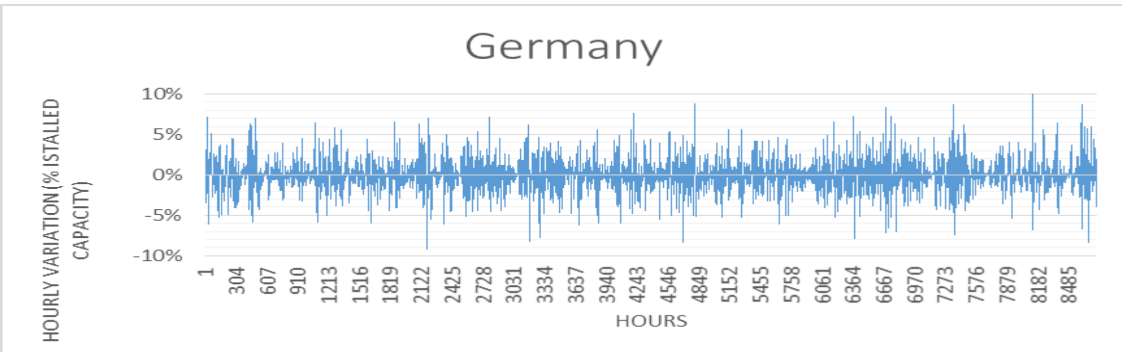


Figure 3: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

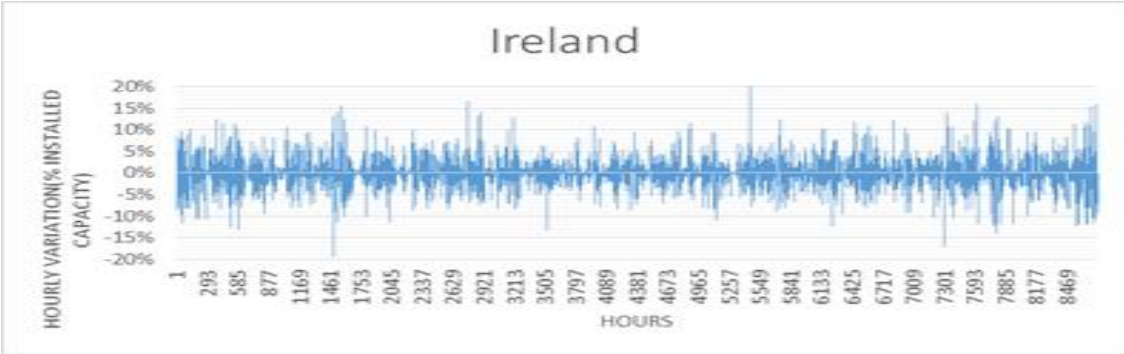


Figure 4: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

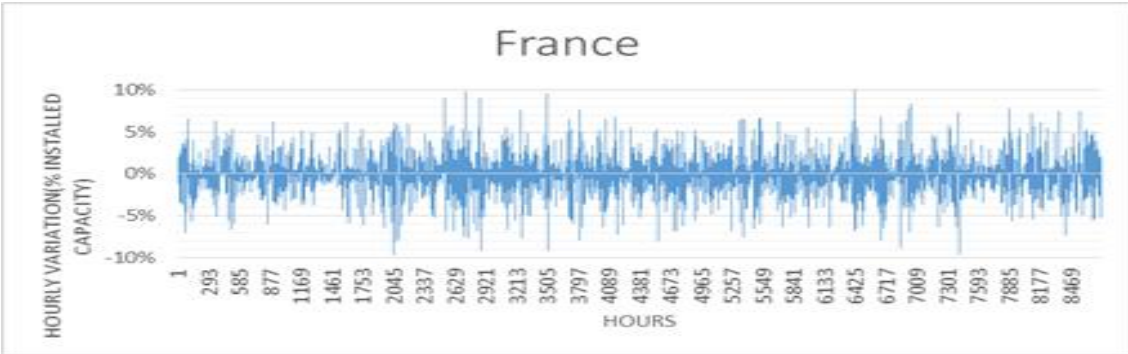


Figure 5: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

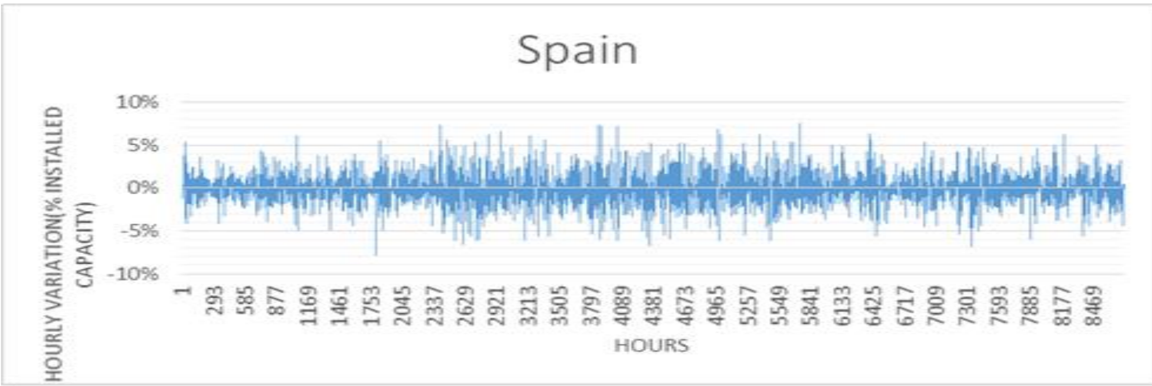


Figure 6: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

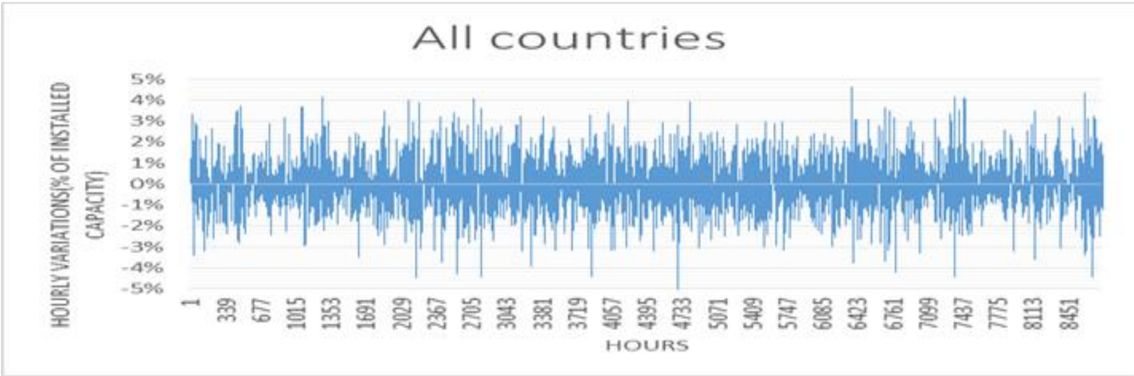


Figure 7: Hourly variation (difference in power output between two consecutive hours as % of installed capacity) in 2012.

Due to different spatial distribution of sites, the variations in both up or down are different between the five countries. In Spain and Germany the variability is smaller compared to Ireland and Denmark due to their larger area size. On the other hand, in Ireland the variability is larger than in Denmark even though the size of the country is larger. This can be explained by the fact that much more offshore wind parks are found in Denmark than in Ireland and the wind speed is steadier at the sea than at the mainland. Moreover, in France which is the largest of the five countries in terms of area size, the variability is bigger than in Germany and Spain because of its low wind power capacity. For instance, during 2012, the maximum hourly variation up is 14% in Denmark, 20% in Ireland, 10% in Germany and France, and 8% in Spain. Regarding the entire region of the five countries the maximum hourly up variability is less than 5% (Figure 7).

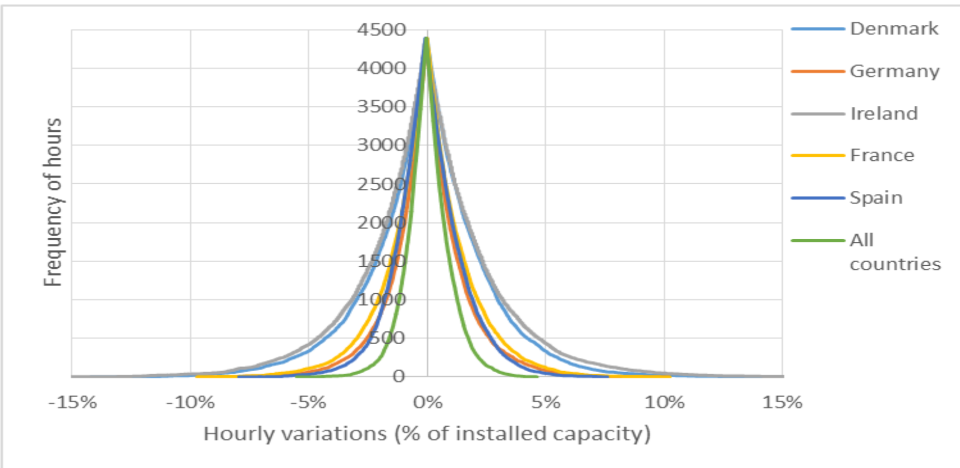


Figure 8: Histogram of hourly variations of wind power production in 2012.

Furthermore, the smoothing effect can be detected by comparing the curves of hourly relative step changes within each country and the entire region of all countries. More specifically, this smoothing effect is obvious when looking at the tails of the hourly distributions (Figure 8). In the entire European region under investigation, the variability from hour to hour is to a big extent within ±2% of installed wind capacity (97% of the samples). Additionally, in Spain, Germany and France (95.7%, 94.3% and 92.1% of the samples, respectively) it ranges within

±3% of installed capacity. At the end, in Ireland and Denmark the hourly variability lies within ±5% (92.5% and 94.1% of the samples, respectively).

The time series of hourly relative step changes in 2011 and 2013 for the five countries are presented in five figures in Appendix A (A.1 section). It can be noticed that, regardless few small differences, the variability in general is similar for all regions during the period 2011-2013. The hourly wind power variability is always smoothed when the power production is distributed into larger areas, combining the different countries. Additionally, looking at the histograms of the five countries, it can be concluded that when the area size is increased, the hourly relative wind variability is decreased. This can be seen especially at the tails where the variations of each country are larger than the total variation of the all countries together.

Looking at the graphs in Appendix A (A.1 section), it is noticeable that 2011 was a special year for France. The weather conditions seem to be stable, without extreme phenomena. The variability of hourly production is within ±5% of its installed capacity. This can be explained due to the fact that 2011 was remarkably dry and warm throughout France (About-France.com, 2014).

4.1.1 Standard deviation

Next step of this method is to calculate the standard deviations of each country individually and also when pairing countries together. The standard deviation is calculated according to hourly wind power variations as a percentage of installed capacity and then a comparison is made on the values in order to estimate the smoothing effect among the five countries. As already mentioned, the standard deviation shows how much variation there is from the average.

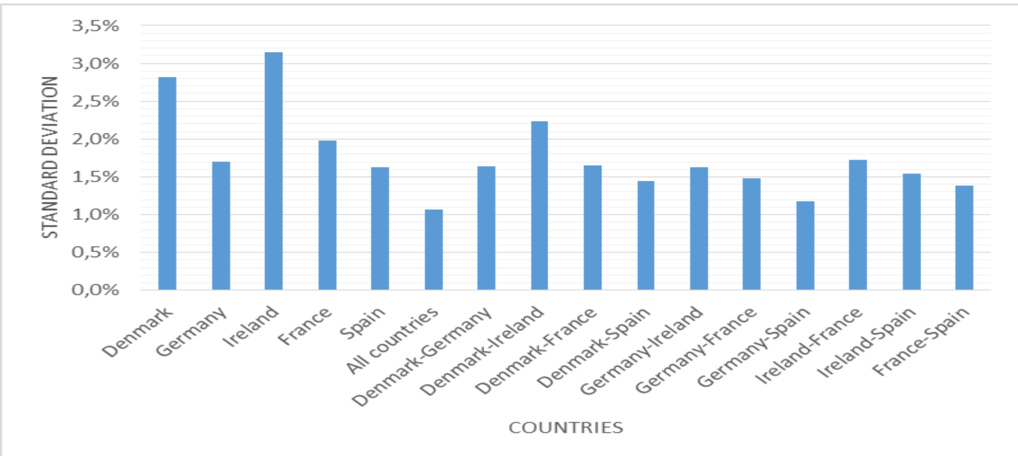


Figure 9: Relative standard deviation of the time series of hourly step changes in wind power averaged in period 2012-2013.

Figure 9 shows the relative standard deviations that are averaged for the period 2012-2013. Looking at this graph, it can be seen between which countries the smoothing effect is stronger at the current period. For instance, between Denmark and Germany there is a smoothing effect due to the fact that Denmark's standard deviation becomes quite smaller after the connection with Germany. It is more important for Denmark to connect with Germany because the smoothening then is more. On the other hand, for Germany, it matters less if there is a connection with Denmark as the reduction in standard deviation is very small.

It is noticeable that the connection between Germany and Spain which are the biggest wind power producers play the most significant role in decreasing the smoothing effect in the overall system. The standard deviation in this connection is similar to all countries together. Additionally, France also contributes to the smoothing effect due to its large area size. France is expected to play a key role in the near future since they will increase their wind power installation on a large scale, especially on offshore.

Table 5. The reduction in hourly relative standard deviation (%) when countries are paired compared to country by itself averaged for 2012-2013.

	Denmark	**Germany**	**Ireland**	**France**	**Spain**
Denmark	-	41,7%	19,6%	43,6%	47,8%
Germany	3,8%	-	4,1%	13,1%	29,8%
Ireland	31,6%	50,6%	-	50,3%	52,8%
France	13,8%	19,5%	10,6%	-	23,5%
Spain	11,5%	27,8%	5,8%	15,2%	-

Table 5 indicates how much the hourly standard deviation is reduced (in %) when the countries are paired compared to the country by itself. By looking at the table, one could deduce how important it is for a country to be connected with others. The bigger the reduction, the higher the importance of this connection.

In overall, as Table 5 shows, it is more important for countries which have small distribution areas and low wind power capacity (e.g. Ireland and Denmark) to connect with countries that have large spatial distribution and high capacity of wind power (e.g. Spain, Germany and France). Connection with wider countries decreases the smoothing effect significantly.

4.1.2 Correlation coefficient

In general, the smoothing effect of wind power variations is stronger when the production is not correlated well or when there is a negative correlation. The correlation coefficients regarding the hourly wind power variation between the countries in period 2011-2013 are illustrated in Table 6. The smoothing effect is strong between all countries even in neighboring countries such as Denmark and Germany. However, the strongest smoothing effect is observed between remote countries. For instance, between Spain and Germany the correlation is negative in period 2012-2013.

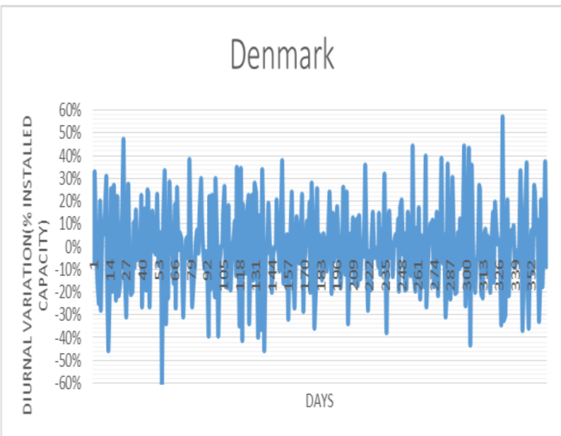
Table 6: Correlation coefficients of paired countries on hourly wind power production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.33	0.32	0.30
Denmark-Ireland	0.06	0.02	0.08
Denmark-France	0.06	0.03	0.02
Denmark-Spain	-	-0.04	0.01
Germany-Ireland	0.07	0.03	0.08
Germany-France	0.22	0.15	0.14
Germany-Spain	-	-0.03	-0.03
Ireland-France	0.06	0.02	0.05
Ireland-Spain	-	0.02	-0.02
France-Spain	-	0.12	0.12

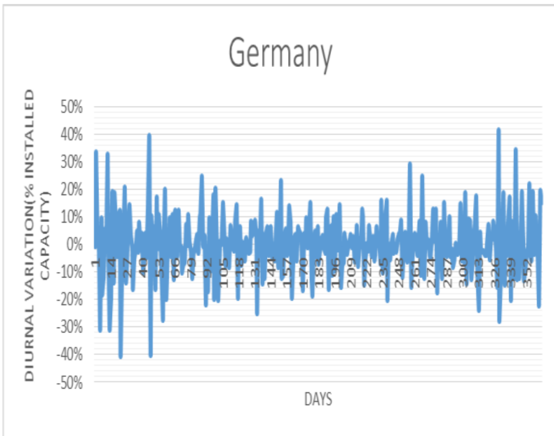
4.2 Daily step change analysis

After analyzing the hourly wind power variations, the next step is to analyze the diurnal wind power production variations.

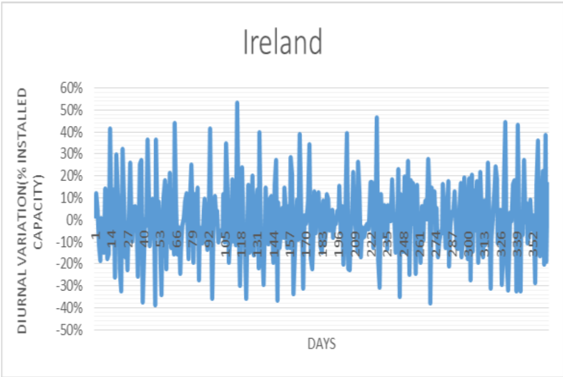
The time series of relative daily step changes during 2012 for the five countries are presented in Figure 10. The y-axis represents the daily step change as a percentage of installed capacity, while the x-axis illustrates the daily intervals.



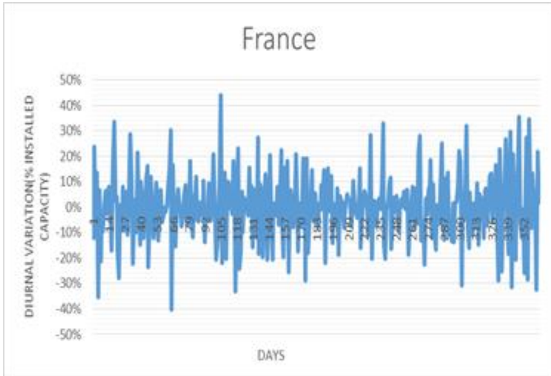
(a)



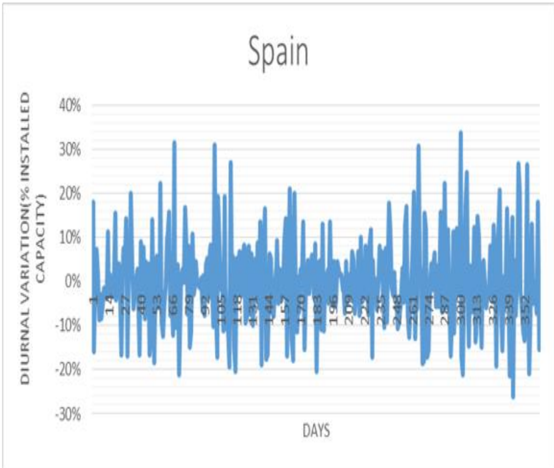
(b)



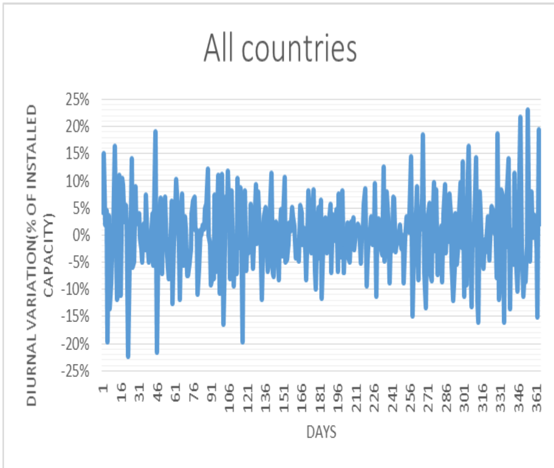
(c)



(d)



(e)



(f)

Figure 10: Daily variation (difference of two consecutive days as % of installed capacity) in 2012 in (a) Denmark, (b) Germany, (c) Ireland, (d) France, (e) Spain, (f) all countries.

The maximum diurnal step changes are within ±50 % of installed capacity for one country. Aggregating the five countries' variations (Figure 10(f)), we see that most of the daily variations are within ±15% of maximum power output regarding the overall interconnection of the five countries.

Due to wider distributions of sites, the scale of variations in Spain, Germany and France are smaller compared to Denmark and Ireland. For example, during 2012, the maximum daily variation is 33% and 41%, in Spain and Germany, respectively. On the other hand, it is 58% in Denmark and 54% in Ireland. Thus, there is a smoothing effect in these countries.

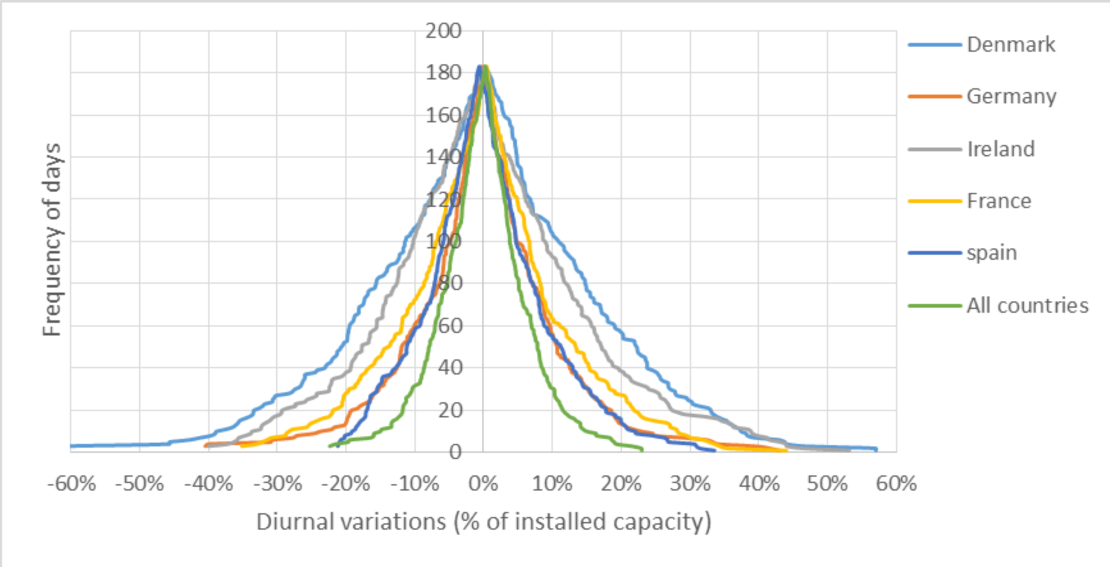


Figure 11: Histogram of daily variations of wind power production in 2012.

Additionally, the smoothing effect can be seen clearly by comparing the curves of the five countries in Figure 11. Especially the tails of these curves indicate the existence of smoothing effect. For instance, the variability from day to day is mainly within ±20% of the maximum power in Spain (92.6% of the samples) and in Germany (94% of the samples). Additionally, the variability in Denmark and Ireland most of the time lies within ±30% of their maximum power output (87.6% and 91.5% of the samples, respectively) and in France (94% of the samples) are within ±25%. On the other hand, the diurnal variability is mostly within ±10% of maximum power in the entire region of the five countries (86% of the samples).

The time series of diurnal step changes in 2011 and 2013 for the five countries are presented in figures in Appendix A (A.2 section). It is noticeable that the connection of Spain in the overall grid of the five countries is of high importance. This is obvious when comparing the curves of daily variation of wind power production in 2011 (excluding Spain due to unavailability of data) with 2012 and 2013 (all the countries). The histogram of wind power production for the five countries together changes significantly in 2012 and 2013 compared to 2011.

4.2.1 Standard deviation

The standard deviation is calculated according to the daily wind power variation as a percentage of installed capacity. Figure 12 illustrates the average standard deviation regarding the daily wind power variation for the period 2012-2013.

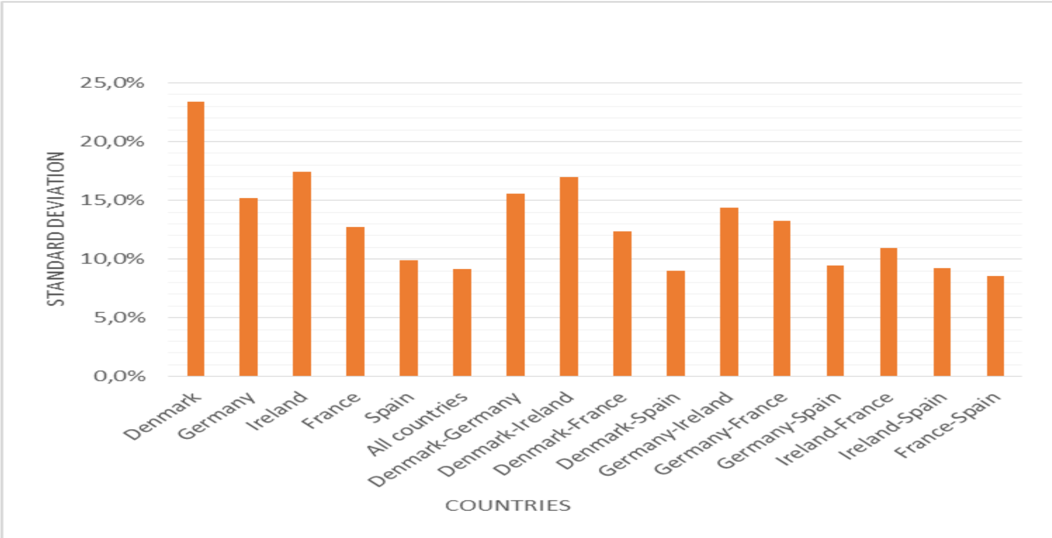


Figure 12: Relative standard deviation of the time series of daily relative step changes in wind power averaged in period 2012-2013.

Compared to hourly standard deviations, it can be seen that standard deviations increase significantly on a daily scale. Additionally, the countries to be more important for the system are again Spain and France instead of Germany. Moreover, there is also a change between Denmark and Ireland as the latter seems to be more important for the system on a daily scale than it is on an hourly scale. Furthermore, it is remarkable that the variability of Spain and France as a pair is smoother than the overall grid of the five countries.

Table 7. The reduction of daily relative standard deviation (%) when countries are paired compared to country by itself for the period 2012-2013.

	Denmark	Germany	Ireland	France	Spain
Denmark	-	35,8%	31,8%	51,8%	61,6%
Germany	1,2%	-	6,5%	14,9%	37,6%
Ireland	8,6%	18,5%	-	42,1%	47,2%
France	11,5%	1,6%	20,6%	-	32,9%
Spain	9,0%	3,9%	6,7%	13,4%	-

Similar to the hourly standard deviation, Table 7 shows the decrease of the daily standard deviation (in %) when the countries are connected to each other compared to the country itself. As far as the smoothing effect between the countries is concerned, again the interconnection is more important for smaller countries than with larger. For instance, when comparing the values in Table 7, it becomes clear that for Denmark the connection with Spain, France or Germany decreases its smoothing effect to a large extent. Furthermore, for Germany on a daily scale it is more important to connect with Spain compared to an hourly scale. Thus, all the countries change their characteristics on a larger time scale, except for Spain which seems to remain stable.

4.2.2 Correlation coefficient

The correlation coefficients of paired countries on daily wind power variation (% of installed capacity) are calculated between the five countries in period 2011-2013. Table 8 shows the correlation coefficients when pairing countries together.

Table 8: Correlation coefficients of paired countries on daily wind power production (% of installed capacity).

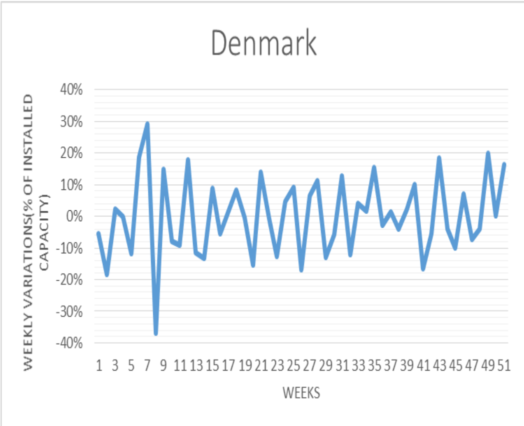
Countries	2011	2012	2013
Denmark-Germany	0.80	0.52	0.63
Denmark-Ireland	0.04	-0.12	-0.02
Denmark-France	0.03	0.10	0.09
Denmark-Spain	-	-0.06	-0.01
Germany-Ireland	0.07	-0.11	-0.01
Germany-France	0.24	0.37	0.32
Germany-Spain	-	-0.11	0.05
Ireland-France	0.04	0.05	0.04
Ireland-Spain	-	-0.04	-0.08
France-Spain	-	0.21	0.10

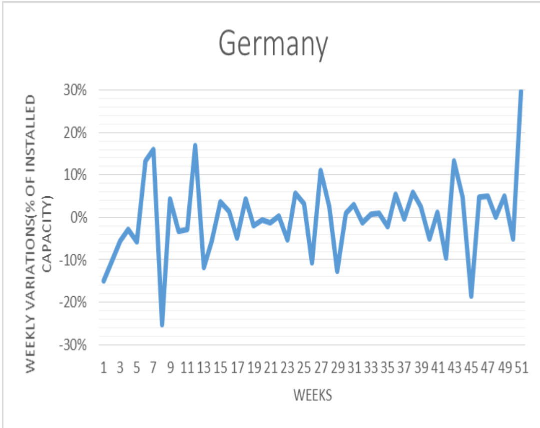
During the period 2011-2013, the correlation coefficients of daily variation between two countries vary significantly in some cases each year. For instance, in 2012 the correlation coefficient is negative between Germany and Spain, while in 2013 it is positive. In overall, again, remote countries show strong smoothing effect. Only the neighboring countries, Denmark and Germany appear to have a weak smoothing effect.

4.3 Weekly step change analysis

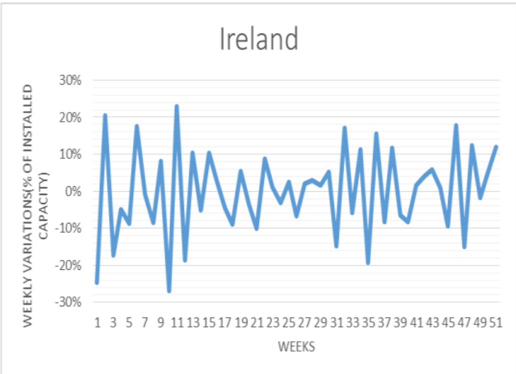
After analyzing the hourly and daily wind power variations, the next step is to analyze the weekly wind power production variations. The variations within a week are important mainly for the energy market. Analysis on long-term variability of wind power production is crucial in strategic power system planning as it is mentioned in the introduction.

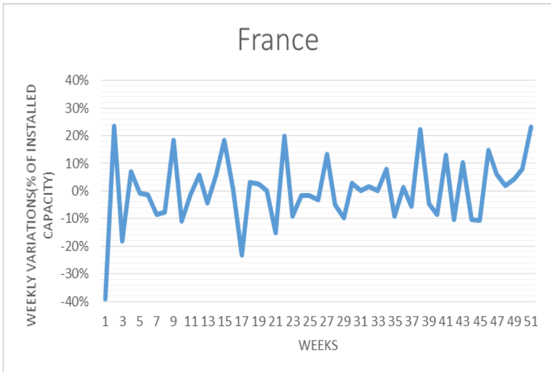
The time series of weekly step changes during 2012 for the five countries are presented in Figure 13.The y-axis shows the weekly step change as a percentage of installed capacity, while the x-axis illustrates the weekly intervals.



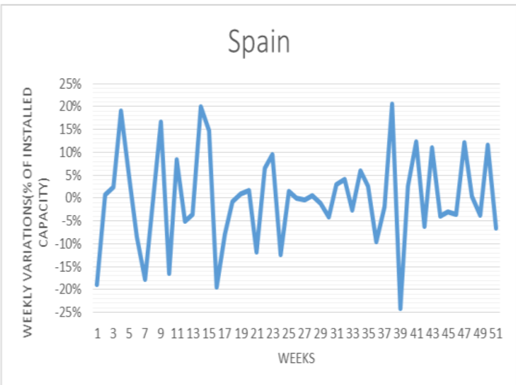


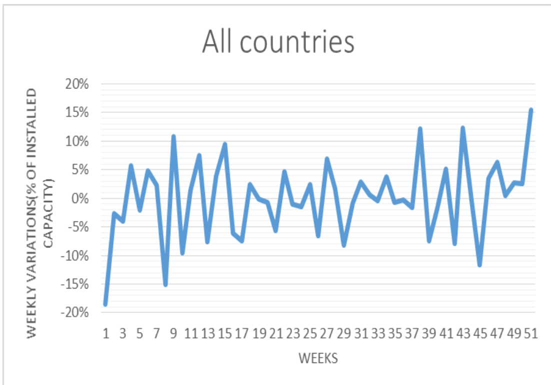
(a) (b)





(c) (d)





(e) (f)

Figure 13: Weekly variation (% of installed capacity) in Denmark, Germany, Ireland, France, Spain and all countries together in 2012.

The smoothing effect can be detected by comparing the maximum and minimum weekly variations in the five countries (Figure 13). For example, during 2012, the maximum 1 week up variation in France, Spain and Ireland is 22%, in Germany 30%, and 16% in the overall region of the five countries together. On the other hand, the minimum week down variation was approximately -40% in France and Denmark, about -25% in Spain, Ireland and Germany, and in the whole region of the five countries it was -19%.

The maximum weekly step changes are within ±40 % of installed capacity for a country. Spain and Germany appear to be the most stable regarding the weekly variations which lie within ±25% of maximum power output. Aggregating the five countries' variations (Figure 13(f)), it can be observed that almost all the weekly variations vary within ±15% of maximum power output.

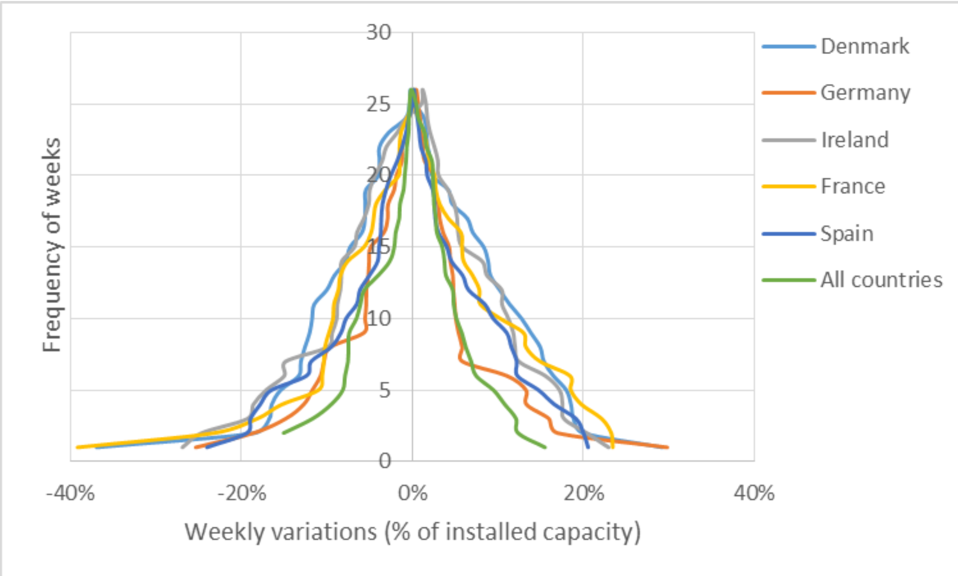


Figure 14: Histogram of weekly variation of wind power production in 2012.

Moreover, the smoothing effect can be clearly observed by comparing the curves in the histogram in each country with the overall region of all countries together (Figure 14). For instance, in Germany and in the whole region, the weekly variability is most of the times within ±10 of installed power capacity.

The time series of weekly step changes in 2011 and 2013 for the five countries are presented in figures in Appendix A (A.3 section). Observing the duration curves of weekly variation of wind power production in 2011(Appendix A.2), France's curve is smoother than the overall of all countries interconnected (excluding Spain due to lack of data). This can be clearly seen by the tails of the curves. For instance, the highest weekly variation in France is 18%, while in the four countries interconnected it is 22%. Finally, the curves of Germany and overall of countries almost coincide to each other.

4.3.1 Standard deviation

The standard deviations of each country are calculated individually and also when pairing countries together on a weekly time scale. The Figure 15 shows the standard deviations during the period 2012-2013.

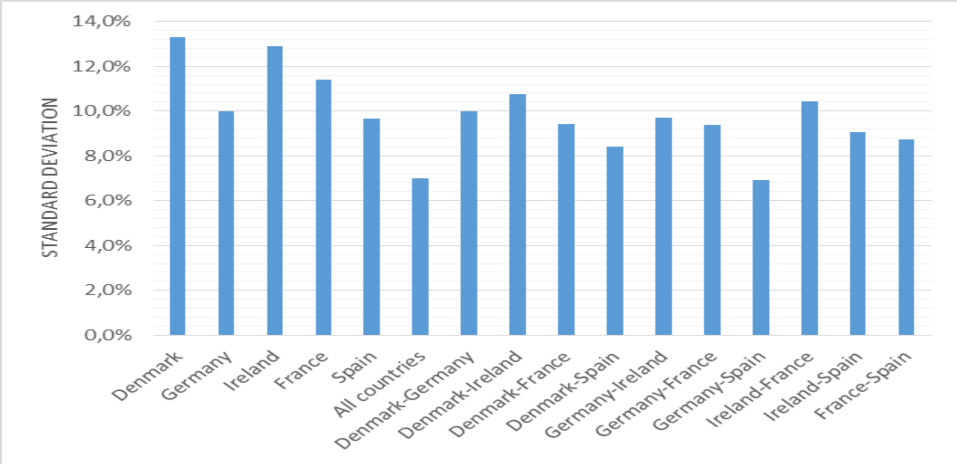


Figure 15: Relative standard deviation of the time series of weekly relative step changes in wind power averaged in period 2012-2013.

Compared to the values of daily standard deviations, the values on weekly scale drop significantly, except for Spain which remains the same. Spain and Germany play a key role for the overall smoothing effect, as the connection of these two countries help to decrease the overall smoothing effect on large scale. The standard deviation of all countries together is similar to the combination of Spain and Germany.

Table 9 below illustrates the significance of the connection between countries for the smoothening of the variability of wind power.

Table 9. The reduction of weekly standard deviation (%) when countries are paired compared to country by itself.

	Denmark	Germany	Ireland	France	Spain
Denmark	-	26,4%	15,7%	32,8%	36,6%
Germany	2,3%	-	5,3%	9,7%	30,7%
Ireland	13,0%	26,5%	-	27,6%	29,6%
France	21,7%	20,7%	18,2%	-	23,3%
Spain	12,7%	28,2%	6,0%	9,4%	-

According to Table 9, all countries are benefited from a connection with Spain or Germany. Again, countries with small size area it is more important to connect with larger areas. Also, it is remarkable that France seems to have the same benefit from a connection with any country (its standard deviation decreases about 20%). In addition, Spain and Germany are apparently the two key players since they present the lowest necessity to connect with the others.

4.3.2 Correlation coefficient

The correlation coefficients of paired countries on wind power variation (% of installed capacity) are calculated on a weekly scale in period 2011-2013 (Table 10).

Table 10: Correlation coefficients of paired countries on weekly wind power production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.74	0.73	0.66
Denmark-Ireland	0.38	-0.03	0.37
Denmark-France	0.25	0.10	0.25
Denmark-Spain	-	-0.16	0.14
Germany-Ireland	0.41	0.23	0.37
Germany-France	0.54	0.47	0.55
Germany-Spain	-	-0.06	0.00
Ireland-France	0.16	0.57	0.24
Ireland-Spain	-	0.23	-0.14
France-Spain	-	0.52	0.20

By comparing the values during the period 2011-2013, it is observed that in some cases the values are completely different in 2012. For instance, between Denmark and Ireland and between Denmark and Spain the values of correlation coefficient are negative and very different from other years. This can be explained due to extreme weather conditions in Ireland during 2012. According to data released by the UK's Meteorological Office, the year 2012 was the second wettest on record in the UK (Kinver M., 2013). Most areas were affected by the extreme weather with thousands of homes flooded.

The smoothing effect between remote countries is, again, strong, while between neighboring countries such as Denmark and Germany it is quite weak. Moreover, compared to the previous correlation coefficients on small-term period, the smoothing effect between France and Germany becomes less strong. It is noticeable that only between Spain and Germany the smoothing effect remains the same strong.

4.4 Quantification of smoothing effect with respect to distance, area and wind capacity

In Sections 4.1, 4.2 and 4.3 the smoothing effect was quantified among the countries under investigation. At this step another attempt is made to quantify the smoothing effect this time according to the factors that influence it (area of country, distance between countries and wind power capacity). The same two indicators are used as well in this case, the correlation coefficient of paired countries and the standard deviation of individual and paired countries. The manner these indicators behave in relation with these factors reveals the way the smoothing effect changes.

4.4.1 Output smoothing as a function of distance

To test how the smoothing effect is affected by the distance, the countries under investigation are considered as points reflecting certain cities which are located at the centre of each one of them (Figure 16). More specifically, these cities are Madrid (Spain), Kassel (Germany), Bourges (France), Aarhus (Denmark) and Clonmancois (Ireland).

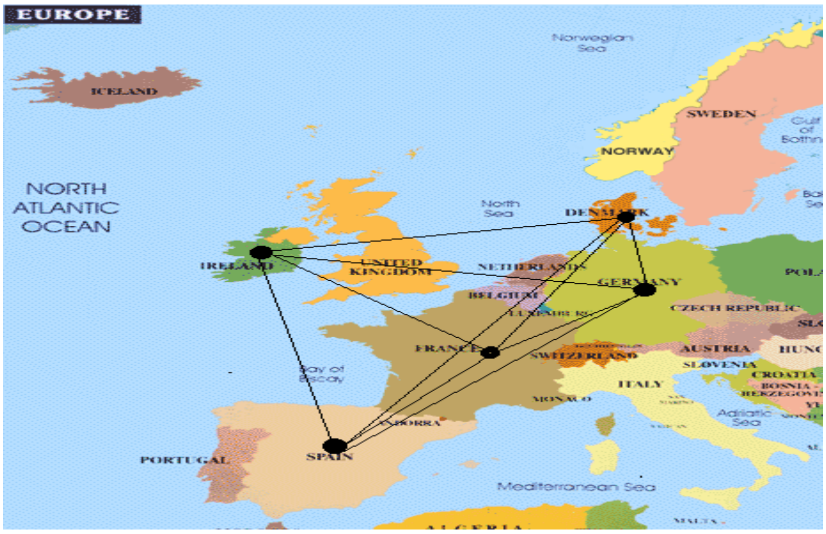


Figure 16. Map of the connection of the five countries (Spain, France, Germany, Denmark and Ireland) under investigation.

The website MapCrow Travel Distance Calculator (www.mapcrow.info) is used in order to calculate the distance between the countries. Table 11 shows the results of these calculations.

Table 11. Distance between the five European countries.

Countries	Distance (km)
Denmark-Germany	540
Denmark-Ireland	1204
Denmark-France	1141
Denmark-Spain	2021
Germany-Ireland	1204
Germany-France	697
Germany-Spain	1580
Ireland-France	1011
Ireland-Spain	1472
France-Spain	888

Based on the values on Table 11 and Tables 6, 8 and 10 the correlation coefficient is plotted against the distance on hourly, daily and weekly basis. The outcome of this is depicted in Figure 17.

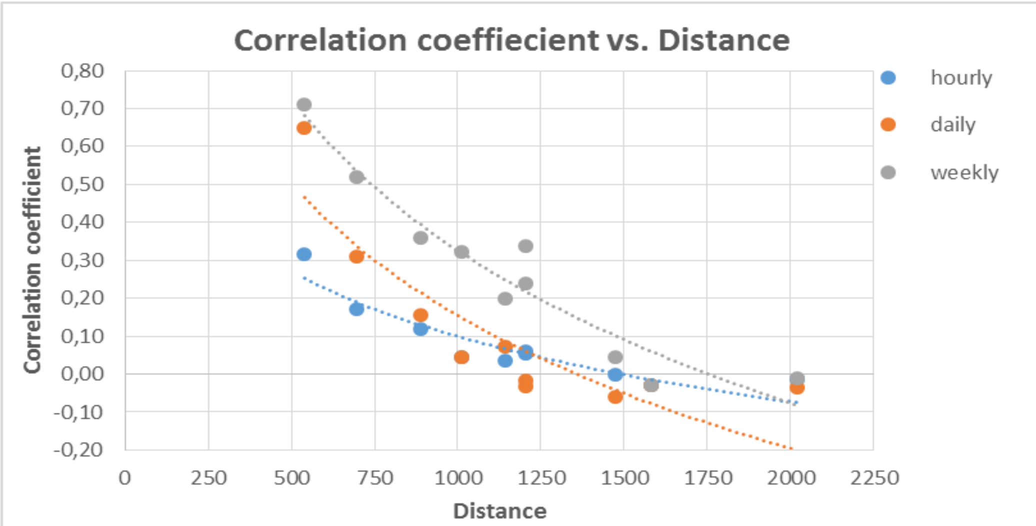


Figure 17. Average correlation coefficients against distance between the five countries based on hourly, daily and weekly outputs.

From the graph above it can be seen that distances of 310 km, 258 km and 394 km are required for the hourly, daily and weekly correlation coefficient, respectively, to drop by 50% when 750 km is taken as a starting point.

There is an exponential relation between the two variables. The mathematical functions connecting them are:

- $Y=-0.249 \ln(x)+1.8206$ with $R^2=0.8741$
- $Y=-0.506 \ln(x)+3.6490$ with $R^2=0.7879$
- $Y=-0.580 \ln(x)+4.3292$ with $R^2=0.9280$

on an hourly, daily and weekly basis, respectively.

Moreover, for a given distance, it can be observed that the decrease of the correlation coefficient is different on each time scale. For instance, for a distance of 500 km (starting point at 750 km to 1250 km), the correlation coefficient decreases by 74%, 86% and 61% on hourly, daily and weekly basis, respectively. In Appendix A4, Tables 27 and 28 show in more detail how the correlation coefficient behaves at different starting points. It can be noticed that at higher starting points the distance required for the correlation coefficient to drop by 50% decreases whereas, the reduction rate of the correlation coefficient increases.

4.4.2 Output smoothing as a function of area and wind capacity

In this section the smoothing effect is tested with respect to the area of country and wind power capacity. An assumption is made that the wind power is evenly distributed across the area. For this analysis, the standard deviation is used as an indicator for the quantification of smoothing effect. Table 12 presents the data regarding the size of area of the countries and the wind power capacity of them.

Table 12: Surface of area and wind energy output for the five European countries. (Eurostat, 2014)

Countries	Area (1000 km^2)	Wind Energy (Twh)
France	633	14.0
Spain	506	50.8
Germany	357	45.3
Ireland	70	4.3
Denmark	43	10.4
All countries	1609	124.9
Denmark-Germany	400	55.7
Denmark-Ireland	113	14.7
Denmark-France	676	24.4
Denmark-Spain	549	61.2
Germany-Ireland	427	49.7
Germany-France	990	59.3
Germany-Spain	863	96.2
Ireland-France	703	18.3
Ireland-Spain	576	55.2
France-Spain	1139	64.8

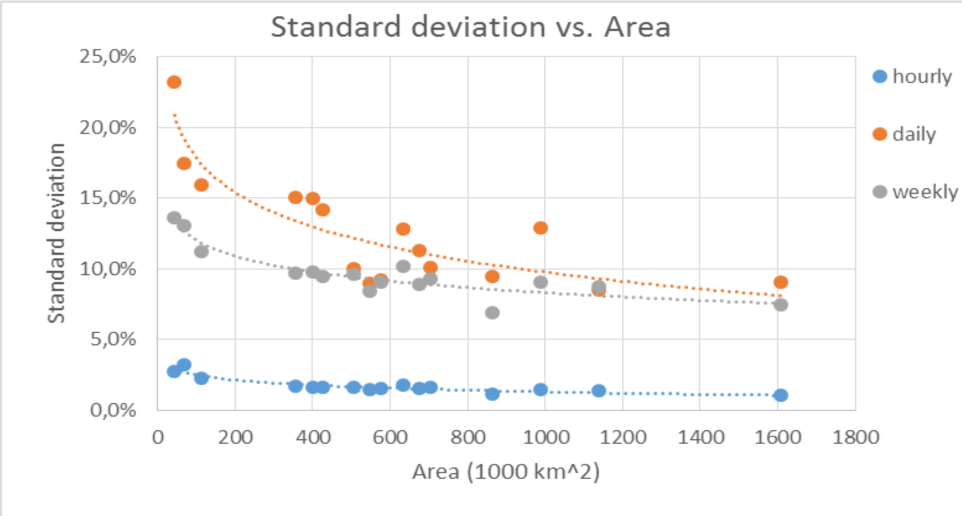


Figure 18. Relative standard deviations against area for the five countries based on hourly, daily and weekly outputs averaged for the period 2012-2013.

Figure 18 presents the standard deviation as a function of the area. It can be noticed that for an area of 200,000 km^2 (starting point at 200,000 km^2 to 400,000 km^2) the standard deviation decreases by 22%, 25% and 16% on hourly, daily and weekly basis, respectively. The area seems to have an asymptotic effect on the standard deviation. The functions connecting the two variables on the specific time scales of the graph above are the following:

- Y=-0.005 ln(x)+0.0491 with R^2=0.8575
- Y=-0.035 ln(x)+0.3403 with R^2=0.7762
- Y=-0.016 ln(x)+0.1947 with R^2=0.8573

on hourly, daily and weekly basis, respectively.

For the same starting point at 200,000 km^2, areas of about 419,000 km^2 are required in order for the standard deviation of hourly wind power output to decrease by 25%. Regarding the daily and weekly standard deviations to drop by 25%, areas of approximately 405,000 km^2 and 914,000 km^2 are required, respectively.

More examples can be found in Appendix A4 (Table 29 and Table 30). There it can be seen that for higher starting points larger area is required in order the standard deviation to fall by 25% on hourly, daily and weekly basis (Table 29). Additionally, the reduction rate of the standard deviation becomes lower for higher starting points (Table 30).

Wind power capacity is another factor influencing the smoothing effect. In order to quantify the smoothing effect according to this factor, an analysis is made testing the standard deviation as a function of wind power capacity. Figure 19 illustrates the average standard deviations against wind power capacity on hourly, daily and weekly basis.

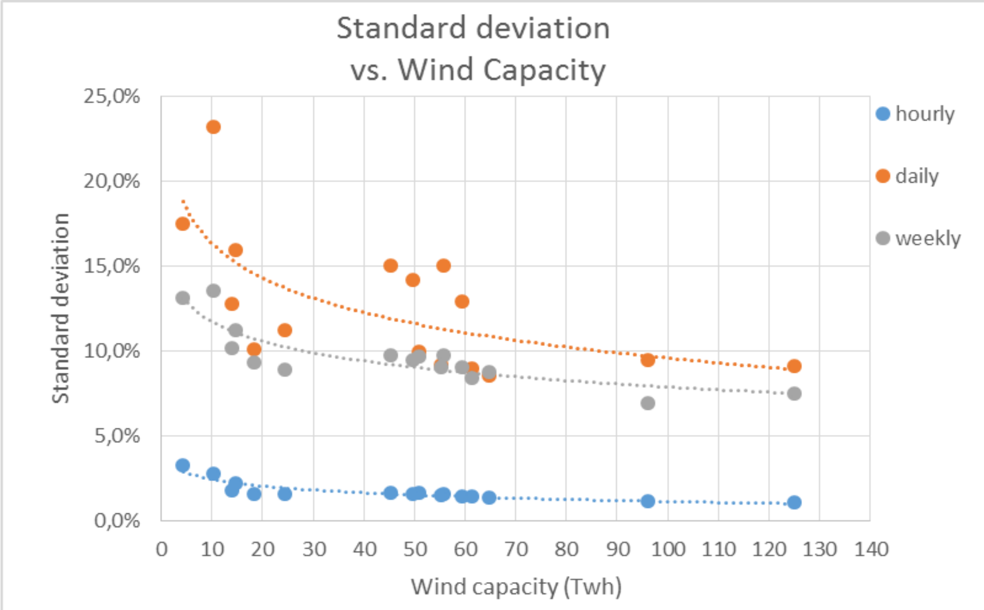


Figure 19. Relative standard deviations against wind capacity for the five countries based on hourly, daily and weekly output averaged for the period 2012-2013.

The following mathematical functions result from the graph of the Figure 19.

- Y=-0.006 ln(x)+0.0374 with R^2=0.8192 on hourly basis
- Y=-0.029 ln(x)+0.2310 with R^2=0.4437 on daily basis
- Y=-0.017 ln(x)+0.1559 with R^2=0.7531 on weekly basis

The standard deviation is reduced by approximately 28%, 19% and 16% on hourly, daily and weekly basis, respectively, for a certain wind energy output of 20 TWh (starting point at 10 TWh to 30 TWh). Additionally, it can be noticed that wind energy outputs of 16.7 TWh, 31.2 TWh and 45.7 TWh are required on hourly, daily and weekly basis, respectively, so that the standard deviation to drop by 25%. Furthermore, the standard deviation drops asymptotically with the increase of the wind energy generation.

Appendix A4 shows more details about the standard deviation as a function of the wind energy. It can be observed that the required wind energy for the standard deviation to decrease by 25% increases as higher starting points are chosen (Table 31). Also, for a specific wind energy of 20 TWh, the reduction of the standard deviation differs at different starting points (Table 32).

5. Relative Difference method

5.1 Hourly analysis

The hourly data available for this study is shown as time series in Appendix B (B.1 Section). Next step is to convert all the values of capacity factors according to the reference point which is equal to 24%, by using the following formula:

$$\text{Scaled hourly capacity factor} = \frac{\text{Ref point}}{\text{Average annual capacity factor of the country}} * 100\%$$

The average yearly capacity factors of the five countries are different (Table 3, Section3), thus we need to scale all the hourly wind power production data according to the reference point. The scaled capacity factor enables us to compare the countries in order to investigate the smoothing effect among them.

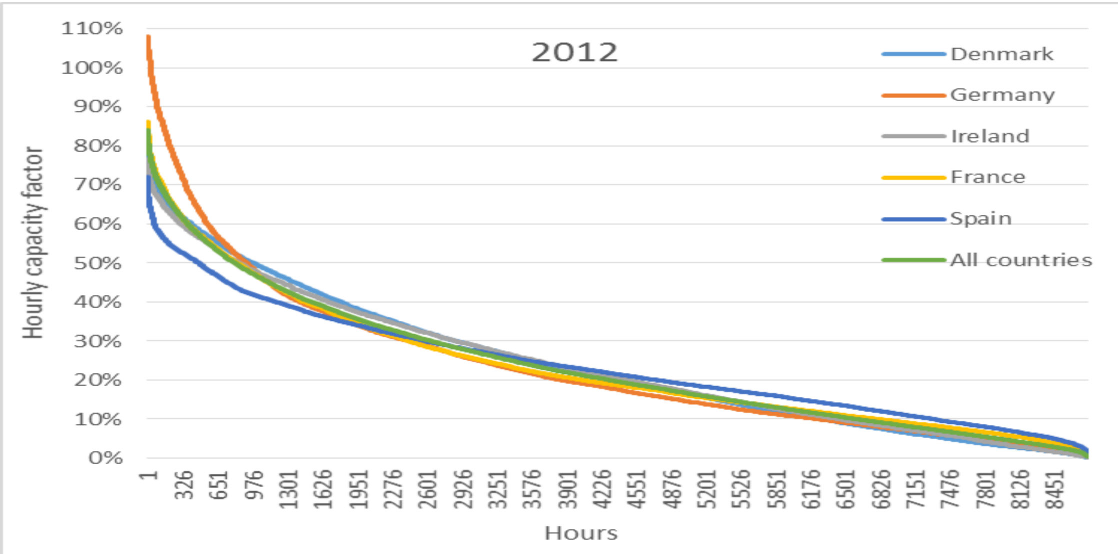


Figure 20. Duration curves of hourly capacity factors of wind power production in 2012 according to the reference point.

Variability of wind power will smooth out when production from different countries is combined. Figure 20 shows the duration curves of scaled hourly capacity factors of wind power production in each country and in the whole region of the five countries together, according to the reference point which is equal to 24%. The smoothing effect of hourly wind power production can be seen clearly by looking at the Figure 20. For instance, in Germany the maximum scaled hourly power is about 110% of installed capacity, while in Spain is 70% of installed power capacity. Moreover, the duration curve of the whole region of the five countries appears to be flatter compared to the other five duration curves.

The correlation coefficients of hourly wind power production between the five countries show if there is any smoothing effect. Table 13 presents the correlation coefficients of paired countries on relative hourly wind power production in period 2011-2013.

Table 13: Correlation coefficients of relative hourly production.

Countries	2011	2012	2013
Denmark-Germany	0.70	0.66	0.66
Denmark-Ireland	0.27	0.09	0.20
Denmark-France	0.21	0.15	0.26
Denmark-Spain	-	-0.07	0.12
Germany-Ireland	0.26	0.17	0.26
Germany-France	0.45	0.42	0.49
Germany-Spain	-	-0.12	0.12
Ireland-France	0.23	0.26	0.28
Ireland-Spain	-	-0.03	0.04
France-Spain	-	0.12	0.30

Wind power production in Denmark and Germany is correlated well. On the other hand, the correlation between Spain and Denmark, Germany or Ireland is non-existent. Again, in 2012, it is observed that Ireland presents completely different characteristics compared to the other years, but that can be explained due to extreme weather conditions occurred that year (Kinver M., 2013).

Compared with the correlation of hourly wind power variation in the step change analysis method, hourly power production is significantly more correlated between all countries. All the values of power production are higher compared to the values of production variability.

5.3 Daily analysis

The daily data available for this research is shown as time series in Appendix B (B.1 Section). At this point all the values are converted according to the reference point which is equal to 24%, by using the following formula:

$$\text{Scaled daily capacity factor} = \frac{\text{Ref point}}{\text{Average annual capacity factor of the country}} * 100\%$$

All the daily wind power production data of the five countries are scaled for visualization purposes. Thus, a comparison of the capacity factors among the countries can be easily made.

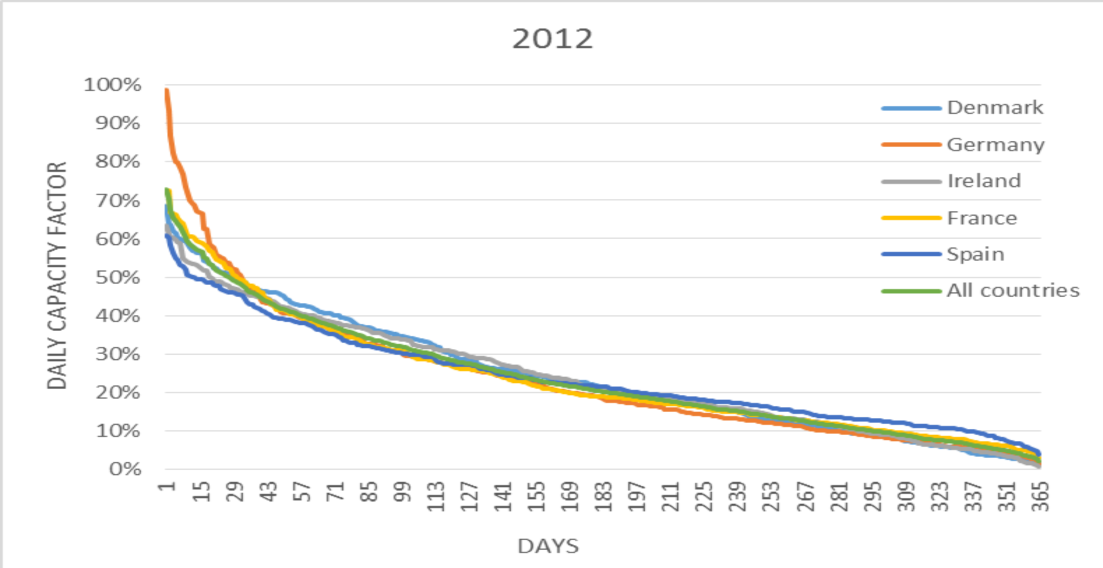


Figure 21: Duration curves of diurnal capacity factors of wind power production in 2012 according to the reference point.

The smoothing effect can be seen by comparing the duration curves in Figure 21. First of all, the maximum daily capacity factor is 100% in Germany, while in Spain is 60% during 2012. Additionally, the duration curve of five countries together is flatter compared to the others. The smoothing effect is clear when looking at some specific time periods. For instance, when comparing the daily capacity factors during the first 15, in Spain the daily capacity factor lies within 50-60%, while in France it is within 60-70%.

The smoothing effect of variations is, also, checked by calculating the correlation coefficients among the countries. Table 14 shows the relative daily wind power production in period 2011-2013 for the five countries.

Table 14: Correlation coefficients of paired countries on daily production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.82	0.60	0.71
Denmark-Ireland	0.29	0.12	0.23
Denmark-France	0.22	0.15	0.34
Denmark-Spain	-	0.06	0.14
Germany-Ireland	0.29	0.23	0.31
Germany-France	0.45	0.48	0.56
Germany-Spain	-	0.02	0.16
Ireland-France	0.27	0.36	0.33
Ireland-Spain	-	0.09	0.06
France-Spain	-	0.47	0.34

Again, Denmark and Germany are well-correlated, while remote countries, e.g. Spain-Ireland and Germany-Spain, show almost no correlation. Compared to the correlation coefficients regarding the relative hourly power production, smoothing effect on a daily scale decreases significantly. For instance, the smoothing effect of daily production (% of installed) between

Ireland and France is less strong than the relative hourly power production. In general, on a daily scale all the values are positive and not close to zero, which shows that smoothing effect decreases.

Compared to the correlation in step change analysis method, the smoothing effect is stronger in the relative daily wind power generation. In the first method, 50% of the paired countries have negative correlation to each other.

5.4 Weekly analysis

The weekly data available for this study is shown as time series in Appendix B (B.3 Section). Using the following formula all the values are converted according to the reference point which is equal to 24%:

$$\text{Scaled weekly capacity factor} = \frac{\text{Ref point}}{\text{Average annual capacity factor of the country}} * 100\%$$

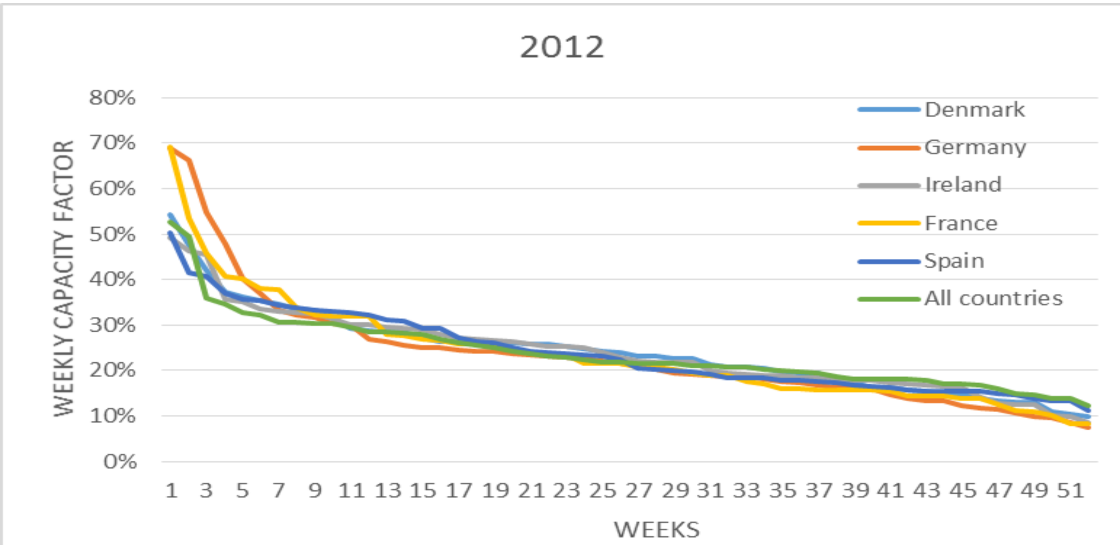


Figure 22: Duration curves of weekly capacity factors of wind power production in 2012 according to the reference point.

Figure 22 shows the duration curves of weekly capacity factors of the five countries according to the reference point in 2012. The smoothing effect is obvious when comparing the maximum values regarding the weekly capacity factors. For instance, in France and Germany the weekly capacity factor is equal to 70%, while in Spain and Ireland it is 50%. Also, looking at the initial duration curves, during the first five weeks it is observed that in the entire region of the five countries interconnected, and in Spain and Denmark, all the values of weekly capacity factors are within 30-50%, while in Germany and France it is 40-70%. Finally, the duration curve of five countries is smoother compared to other curves.

In turn, the correlation coefficients of the relative weekly wind power production are calculated. The Table 15 presents the results of these calculations. In general, the smoothing effect decreases significantly on a weekly scale compared to hourly and daily time scales. For instance, between remote countries such as Germany and Ireland, the smoothing effect is not so strong as the correlation coefficient is about 0.70, while on smaller time-scales it is approximately 0.30.

Table 15: Correlation coefficients of paired countries on weekly production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.82	0.81	0.79
Denmark-Ireland	0.51	0.41	0.55
Denmark-France	0.55	0.35	0.56
Denmark-Spain	-	0.04	0.35
Germany-Ireland	0.46	0.62	0.62
Germany-France	0.72	0.60	0.70
Germany-Spain	-	0.14	0.32
Ireland-France	0.41	0.68	0.57
Ireland-Spain	-	0.36	0.26
France-Spain	-	0.63	0.51

Furthermore, compared to the correlation coefficients on weekly power variations in the first method, production variability, again, is significantly less correlated among the countries. In some cases, the values vary so much that makes the investigation of the smoothing effect impossible. For instance, between Germany and Spain, the correlation coefficient is 0.32 in 2013 according to the second method, while in the first method it has the value of zero for the same year.

5.5 Monthly analysis

Figure 23 shows the monthly generated wind energy (% of maximum output) according to the reference point which is equal to 24% during 2012. The following formula is used in order to scale all the relative monthly wind power generation data:

$$\text{Scaled monthly capacity factor} = \frac{\text{Ref point}}{\text{Average annual capacity factor of the country}} * 100\%$$

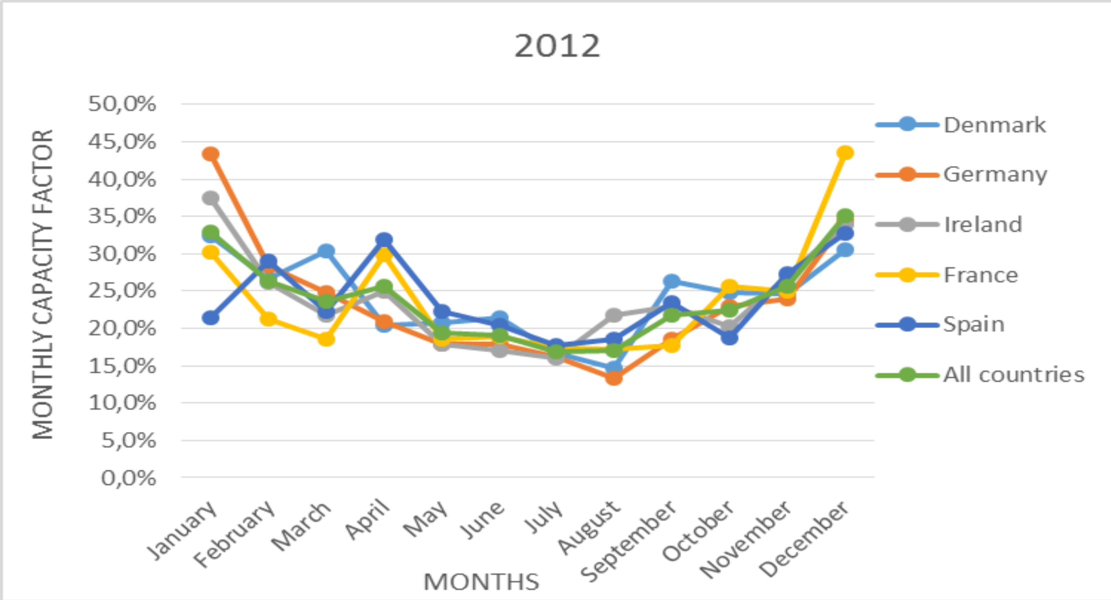


Figure 23: The vertical y-axis is the generated wind energy (% of maximum output) according to the Reference point. The horizontal x-axis illustrates the months.

A comparison among the curves of the five countries and the whole region of all countries interconnected can reveal possibilities of the existence of smoothing effect. For instance, in January, between Spain and Germany this effect is strong as the monthly scaled capacity factor is 20% and 44%, respectively. On the other hand, in July, the smoothing effect is almost non-existent, due to the fact that all the five countries and the whole region are on the same level, approximately 17%.

In general, December is the month with the highest wind power generation in all countries, while in July the wind power generation is very low. The smoothing effect between the five countries is expected to decrease on a monthly scale. Apparently, long-term variability has less strong smoothing effect compared to short-term variability even in remote countries.

Table 16: Correlation coefficients of paired countries on monthly production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.85	0.85	0.95
Denmark-Ireland	0.57	0.70	0.77
Denmark-France	0.69	0.52	0.78
Denmark-Spain	-	0.37	0.42
Germany-Ireland	0.47	0.89	0.85
Germany-France	0.81	0.69	0.81
Germany-Spain	-	0.38	0.52
Ireland-France	0.48	0.76	0.76
Ireland-Spain	-	0.54	0.54
France-Spain	-	0.67	0.65

Table 16 shows the correlation coefficients of monthly wind power generation between the five countries for the given period. Obviously, the smoothing effect decreases significantly in all paired countries, even between Spain-Denmark and Germany-Spain which are miles away from each other.

5.6 Seasonal analysis

Seasonal analysis is carried out in order to investigate if there is smoothing effect between the five countries on a long-term scale. As already mentioned, long-term analysis is very important especially for policy makers and energy traders.

Figure 24 and Figure 25 show the scaled seasonal relative wind energy generation (% of maximum output) according to the reference point which is equal to 24% during the period 2012-2013. The vertical y-axis is the scaled generated wind energy (% of maximum output), while the horizontal axis indicates the four seasons.

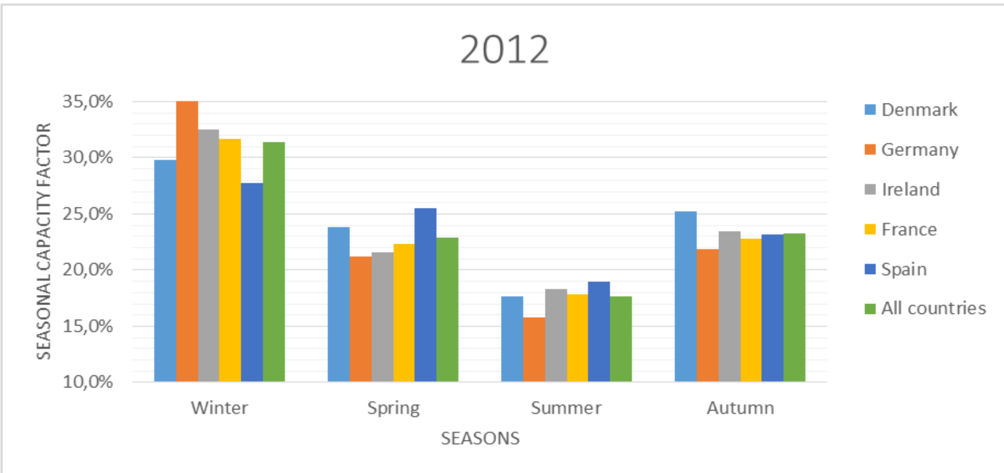


Figure 24: Scaled seasonal capacity factor in 2012 according to the reference point (24%).

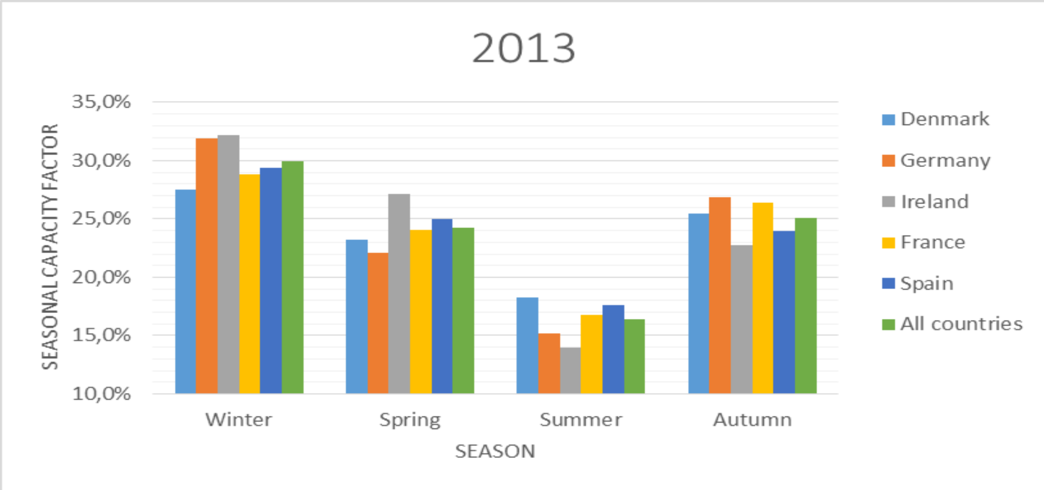


Figure 25: Scaled seasonal capacity factor in 2013 according to the reference point (24%).

Regarding the seasonal analysis, it is noticeable that all countries have the highest wind power production during winter. Especially Germany and Ireland are on the top in wind energy generation this season. During spring and summer, all the countries share the same percentage, except for Ireland's generation which varies between these two periods. In 2012 Ireland has greater energy production in spring compared to 2013, while in summer time, wind energy production is less in 2012 and larger in 2013.

Table 17: Correlation coefficients of paired countries on seasonal production (% of installed capacity).

Countries	2011	2012	2013
Denmark-Germany	0.90	0.99	0.99
Denmark-Ireland	0.70	0.89	0.89
Denmark-France	0.91	1.00	1.00
Denmark-Spain	-	0.95	0.95
Germany-Ireland	0.43	0.87	0.87
Germany-France	0.98	0.98	0.98
Germany-Spain	-	0.94	0.94
Ireland-France	0.58	0.91	0.91
Ireland-Spain	-	0.99	0.99
France-Spain	-	0.95	0.95

It is noticeable that countries which are in different climate zones and are miles away from each other, present similar characteristics regarding the seasonal wind power generation. This is also made clear by looking at the Table 17 which shows the seasonal correlation coefficients among the five countries. Most of the paired countries are almost perfectly correlated as the values of correlation coefficients are close to 1.00. Perfect correlation can be observed even between remote countries. This occurs due to fact that wind and solar power generation across Europe, besides short-term variations, follow the seasonal cycle of the weather. Wind power generation in winter is much stronger compared to summer (Bofinger S. et al., 2010).

5.7 Output smoothing as a function of distance

In this section, the correlation coefficient is used as an indicator in order to quantify the smoothing effect. Similar to Section 4.7, the relation between the correlation coefficient and the distance is analyzed now according to the relative wind power production. Using the Tables 13, 14, 15 and 16 as well as the Table 11, the correlation coefficient is plotted against the distance (Figure 26).

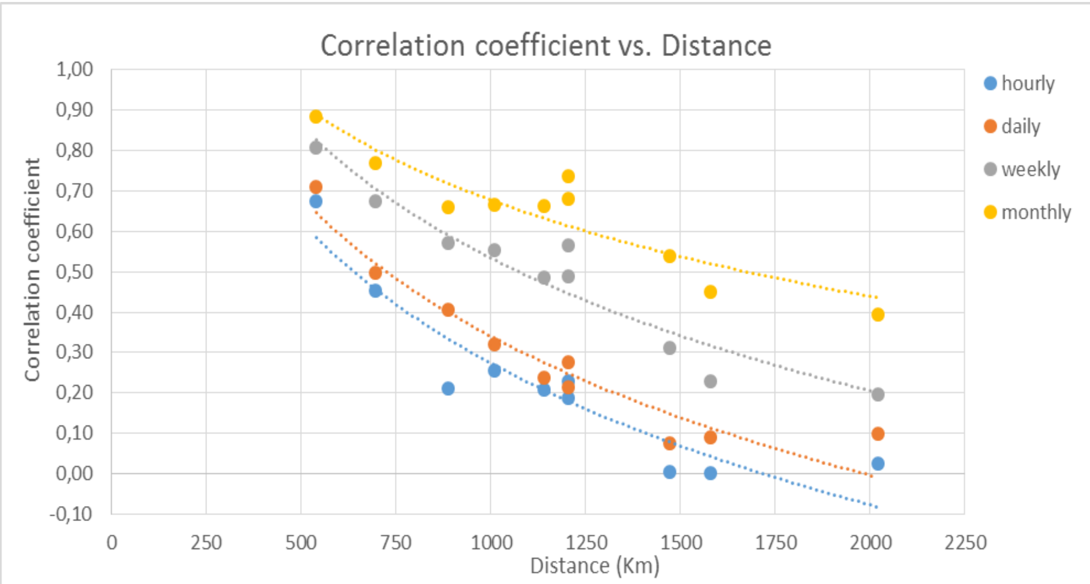


Figure 26. Average correlation coefficients against distance for the five countries based on hourly, daily, weekly and monthly outputs.

The mathematical equations relating the two variables are the following:

- $Y=-0.506 \ln(x)+3.7678$ with $R^2=0.8877$
- $Y=-0.497 \ln(x)+3.7716$ with $R^2=0.9283$
- $Y=-0.475 \ln(x)+3.8122$ with $R^2=0.9157$
- $Y=-0.345 \ln(x)+3.0600$ with $R^2=0.8377$

on hourly, daily, weekly and monthly basis.

Therefore, the correlation coefficient drops with the distance following the above exponential relations. For instance, for a distance of 500 km (starting point at 750 km to 1250 km), the correlation coefficient reduces by 62%, 53%, 36% and 23% on an hourly, daily, weekly and monthly basis, respectively. Moreover, when the correlation coefficient drops by 50% (starting point at 750 km), a distance of 383 km, 467 km, 764 km and 1,559 km is required on hourly, daily, weekly and monthly basis, respectively.

The way in which the correlation coefficient behaves in relation to the distance can be also seen in Appendix B5 (Table 33 and Table 34). It is observed that the distance required for the correlation coefficient to decrease by 50% differs depending on the starting point (Table 33). In general, this distance reduces for every increase by 250 km of the starting point. However, it is remarkable that the opposite happens on monthly basis. This can be explained by the fact that the respective graph is less steep compared to the others (Figure 26).

Additionally, for a distance of 500 km, the correlation coefficient seems to drop in a high rate as the starting point increases by 250 km (Table 34). This is not the case on the weekly basis where the decrease is realized on approximately the same rate and on the monthly basis where the reduction rate of the correlation coefficient happens on a smoother way.

6. Smoothing effect in 2020

6.1 Projections in wind energy generation at the end of 2020

In this section the projections in wind energy made by the European Renewable Energy Council (EREC, 2011) are used in order to identify how much the wind power is expected to be in 2020. These estimations are used in order to build a scenario of what the smoothing effect is expected to be in 2020. For this reason, a quantitative analysis is made again to check the way in which the standard deviation changes with the wind power in 2020.

Wind energy is expected to produce 495 TWh in order to achieve over 14% of the total electricity consumption in 2020 concerning the EU27 Members States as stated by the European Renewable Energy Council. Wind power installations will increase to over 213 GW in 2020, with an average annual growth rate of 9.7%. This projection is close to the European Wind Energy Association of 230 GW in 2020 forecast. The future action plans are based on the development of offshore wind power. It is estimated that at the end of 2020 there will be 43 GW of offshore cumulative capacity in the EU. More specifically, the overall installed wind power capacity in Germany, France, Denmark, Spain and Ireland will be 118.4 GW (EREC, 2011)

Table 18: Offshore and onshore installed wind power capacity at the end of 2013 and 2020.

	2013			2020		
Countries	Offshore Installed(MW)	Onshore Installed(MW)	Total (MW)	Offshore Installed(MW)	Onshore Installed(MW)	Total (MW)
Denmark	1271	3501	4772	1339	3621	4960
Germany	520	33210	33730	10000	35750	45750
Ireland	25	2012	2037	555	4094	4649
France	0	8254	8254	6000	19000	25000
Spain	5	22954	22959	3000	35000	38000

(Source for data of 2020: (EREC, 2011))

Table 19: Projections for offshore and onshore wind energy generation for five European countries at the end of 2020 based on the report and the actual wind power generation at the end of 2013. (EREC, 2011)

	2020			2013
Countries	**Onshore(TWh)**	**Offshore(TWh)**	**Total(TWh)**	**Total(TWh)**
Denmark	7.39	5.32	12.71	11.13
Germany	72.66	31.77	104.44	47.18
Ireland	10.23	1.74	11.97	4.64
France	39.90	18.00	57.90	15.79
Spain	70.50	7.75	78.26	54.03

At the end of 2013, the wind power variations of the five European countries, except for Denmark, depend mainly on onshore wind power generations. Thus, considering that offshore wind power generation will penetrate significantly in the wind energy sector, the characteristics of wind power variations will probably change significantly. The rate in which this offshore penetration will take place in each country will play an important role in the future.

Denmark, being a pioneer on the offshore wind power sector, is the only country among the others in our study which has high offshore wind installed capacity at the end of 2013. The share of offshore is 27% of its total wind capacity. Spain, France, Ireland and Germany produce electricity mainly from onshore wind power.

Germany's wind energy generation is based on onshore wind power as the statistics reveal (Table 18). The offshore is less than 2% of its total installed wind capacity. This is a main reason why Germany's average annual capacity factors are quite low, less than 18%. There are sufficient sites which, in combination with state-of-the art turbines, promise even more power production (Lutkehus I., 2013). Therefore, Germany, considering the great potential regarding the offshore wind energy (Rehfeldt K., 2007), will invest in offshore wind power.

It is noticeable that offshore wind power plants have not yet been realized in France. Potential does exist in the Mediterranean Sea, the Atlantic Channel and English Channel. Offshore wind energy is currently being introduced and the main goal is to install huge wind power capacity by the end of 2020 (Offshore-windenergie.net, 2013). In France, as well as in Germany, the share of offshore electricity generation will be approximately 30% of their total wind electricity production for each country, in contrast to current level of offshore which is almost negligible (Table 19).

Spain has small potential regarding the construction of offshore wind energy farms. Although, Spain has 5,000 miles of coastline, it is unlikely to boast wind farms at the sea in the near future because the surrounding areas are too deep (Phys.org, 2014).

Table 20: Yearly onshore and offshore wind capacity factors at the end of the year 2020 based on the report projections and the annual capacity factors at the end of 2020 and 2013. (EREC, 2011)

	2020			2013
Countries	**Onshore capacity factor**	**Offshore capacity factor**	**Annual capacity factor**	**Annual capacity factor**
Denmark	23.3%	45.4%	29.3%	28.5%
Germany	23.2%	36.3%	26.1%	17.0%
Ireland	28.5%	35.8%	30.4%	30.0%
France	24.0%	34.2%	26.4%	24.0%
Spain	23.0%	29.5%	23.5%	24.0%

It is obvious that the yearly capacity factors will change significantly according to the projections on offshore and onshore wind power generation. The estimated new capacity factors for each country are calculated in order to investigate the extent to which they are expected to change at the end of 2020 compared to the current level. For this reason, the mathematical equation for the capacity factor is used which is determined as the actual wind power generation divided by the installed wind power capacity for each country. Table 20 shows the estimated yearly capacity factors for the five European countries based on the projections for offshore and onshore wind energy generation at the end of 2020 and the actual annual wind capacity factors at the end of 2013.

It is noticeable that when comparing the countries' annual capacity factors in 2013 and 2020 Germany's yearly capacity factor presents a dramatic increase. More specifically, from 17% in 2013 it rises up to 26.1% in 2020. Additionally, an increment is noticed in case of Denmark where the capacity factor goes to 29.3% in 2020, from 28.5% in 2013. Moreover, as far as France is concerned, there is only a slight increase in the capacity factor. This is attributed to the fact that onshore wind power generation is expected to dramatically increase as well.

In general, offshore wind farms' capacity factor is larger compared to onshore since the wind speed at sea is higher than at land and, also, much more constant. Thus, the present high capacity factors for offshore wind projects compared to those for onshore that are lower, should be a sufficient reason to prioritize the development of offshore wind farms.

6.2 Quantitative analysis on smoothing effect in 2020

In turn, quantitative projections are made regarding the overall smoothing effect in 2020. These projections are based on the way the indicator standard deviation of relative step changes of wind power behaves according to the increase of wind energy in 2020 in the five countries under investigation. At this step, the wind power is assumed to be distributed exactly according the current locations.

An analysis is made regarding how the standard deviation changes at the end of 2020 on hourly, daily and weekly basis according to the increase of wind power capacity from 124.9 TWh to 265.3 TWh. At section 4.4.2, the following mathematical equations were found:

- $Y=-0.006 \ln(x)+0.0374$ with $R^2=0.8192$ on hourly basis
- $Y=-0.029 \ln(x)+0.2310$ with $R^2=0.4437$ on daily basis
- $Y=-0.017 \ln(x)+0.1559$ with $R^2=0.7531$ on weekly basis

According to these equations, we calculate the changes to the standard deviations with the wind power capacity from 2013 to 2020. Table 21 illustrates how the standard deviation changes in these two years.

Table 21.The standard deviation according to wind energy capacity in 2013 and 2020.

		Standard deviation		
	Wind energy	**hourly**	**daily**	**weekly**
2013	124.9 (TWh)	0.8%	9.1%	7.4%
2020	265.3 (TWh)	0.4%	6.9%	6.1%

In Table 21, it can easily be seen that at the end of 2020 the standard deviation will drop on all time scales. The increase of 140.4 TWh in the five European countries under investigation at the end of 2020 compared to 2013 will result in a decrease on the overall smoothing effect in those countries. This outcome can be observed especially by the hourly standard deviation which drops by 50%.

7. Discussion

An in depth investigation on the wind power variability helps to comprehend the integration challenges among countries. This research addresses the extent to which the wind power production patterns can be smoothed out when various European countries are connected to each other. It is found that the relative variability of wind power is decreased when considering a large interconnected system composed of the five European countries under investigation. Also, three factors having a great influence on the smoothing effect are the size of area, the wind power capacity and the distance. The more European countries connect to a possible energy system, the more this effect reduces. Especially, countries that combine a large area with a considerable wind power capacity constitute an optimal choice.

Certain mathematical formulas are formed as a result of our analysis. These formulas reveal the behavior of the two indicators (the correlation coefficient and the standard deviation) with respect to the area, the distance and the wind power capacity. A good comprehension of the relation between the indicators and the factors influencing the smoothing effect can lead to important decisions for policy makers. More specifically, these equations could be a useful tool for future strategy such as system planning.

It is remarkable that among the five European countries that are investigated, Spain and Germany are found to be key players for the reduction of the smoothing effect due to their high wind power capacity and their large size of area. Thus, these two countries should be included in a possible future system.

As mentioned in the introduction it is important for energy traders to understand how the wind power varies on long-time scale. Our research could be taken into account by these traders as it offers information about the weekly, monthly and seasonal wind power variability. For instance, this kind of information could be used for the estimation of future energy prices.

For the quantification of the smoothing effect, its country is treated as a unique system illustrated by a reference point at the center of the country (Figure 16, Section 4.4.1). The fact that countries are not divided into smaller parts could be considered as a limitation in our analysis. Investigating small regions within a country could give an added value in our study as the distribution of wind power differs across a country.

Actual wind power generation data are used in this specific study. Nevertheless, it would be interesting to examine the smoothing effect based on wind speed data. This could be useful especially for drawing a scenario about projections in the future.

As far as the scenario made in Chapter 6 is concerned, it is assumed that the distribution of wind power over locations in each country will remain the same. However, the distribution of wind farms is a factor that may affect the wind power variability and it should be further examined in future studies.

7.1 Comparison of the two methods used

Two methods are used in order to investigate the smoothing effect in wind power production. They measure two different aspects. The first method measures the change between two time steps, while the second method measures the power output per time scale compared to the wind capacity. The reason for using two different methods is to make this research more reliable by comparing the one outcome with the other. Table 22 below shows the correlation coefficients found in the two methods.

Table 22. Average correlation coefficient for 2011-2013 in the two methods on different time scales.

Methods	*1st*	*2nd*	*1st*	*2nd*	*1st*	*2nd*	*1st*	*2nd*
	hourly		daily		weekly		monthly	
Denmark-Germany	0.32	0.67	0.65	0.71	0.71	0.81	-	0.88
Denmark-Ireland	0.05	0.19	-0.03	0.21	0.24	0.49	-	0.68
Denmark-France	0.04	0.21	0.07	0.24	0.20	0.49	-	0.66
Denmark-Spain	-0.02	0.03	-0.04	0.10	-0.01	0.20	-	0.40
Germany-Ireland	0.06	0.23	-0.02	0.28	0.34	0.57	-	0.74
Germany-France	0.17	0.45	0.31	0.50	0.52	0.67	-	0.77
Germany-Spain	-0.03	0.00	-0.03	0.09	-0.03	0.23	-	0.45
Ireland-France	0.04	0.26	0.04	0.32	0.32	0.55	-	0.67
Ireland-Spain	0.00	0.01	-0.06	0.08	0.05	0.31	-	0.54
France-Spain	0.12	0.21	0.16	0.41	0.36	0.57	-	0.66

Obviously, the correlation coefficients are different on each time scale. The reason is that the variability of the relevant wind power (ΔP) is taken into account in the first method, while in the second one only the relative wind power (P) is considered. For instance, for a given time scale relative ΔP is lower than relative P which results in the capacity factor, and thus the correlation coefficient, being lower in the first method compared to the second one.

Table 23. Mathematical formulas taken by the two methods while plotting the correlation coefficient against the distance.

	Time scale	**Step change method**	**Relative difference method**
Equation	Hourly	$Y=-0.249 \ln(x)+1.8206$ ($R^2=0.8741$)	$Y=-0.506 \ln(x)+3.7678$ ($R^2=0.8877$)
	Daily	$Y=-0.506 \ln(x)+3.6490$ ($R^2=0.7879$)	$Y=-0.497 \ln(x)+3.7716$ ($R^2=0.9283$)
	Weekly	$Y=-0.580 \ln(x)+4.3292$ ($R^2=0.9280$)	$Y=-0.475 \ln(x)+3.8122$ ($R^2=0.9157$)
	Monthly	-	$Y=-0.345 \ln(x)+3.0600$ ($R^2=0.8377$)
Distance required to drop CC by 50% (Starting point 750 km)	Hourly	310 km	383 km
	Daily	258 km	467 km
	Weekly	394 km	764 km
	Monthly	-	1,559 km

Additionally, it can be seen in Table 23 above that the mathematical formulas are different in the two methods. As far as the distance required to drop CC by 50% is concerned, an unexpected result is found regarding the first method on daily time scale. Although the distance was expected to increase with the time scale (like in Method 2), a decrease is found instead on daily basis compared to hourly. Moreover, Table 23 presents the difference between the distances that are required to drop CC by 50% for a specific case (starting point 750km). In Appendices A4 (Table 27) and B5 (Table 33) further comparisons between the values can be made for other starting points.

Another difference is that the first method leads to mathematical equations showing the way the two indicators in question behave based on the distance, area and wind power capacity. Based on this, a scenario for the smoothing effect in the future is drawn. The scenario can be applied only in this method since there is a mathematical function involving the standard deviation with the wind power capacity. On the other hand, the second method examines only the correlation coefficient as a function of the distance.

7.2 Comparison with previous studies

Previous studies have been conducted in order to investigate to what extent wind power production patterns can be smoothed by connecting various European countries. Four similar studies are found in order to compare the results and the conclusions of this research with them.

To begin with, Rosques F. et al. (2009) indicated that remote countries present low or negative correlations (e.g Spain and Denmark). In this study, data are used from 2006 to 2007 for four European countries. Table 24 shows the correlation coefficients between the hourly variations of wind power production across the four countries as found in Rosques' study and in ours. The results to be compared are based on the the step change analysis method.

Table 24. Correlation coefficients of hourly step changes in wind power production.

	Rosques'study	Our study		
Countries	**2006-2007**	**2011**	**2012**	**2013**
Denmark-Germany	0.36	0.33	0.32	0.30
Denmark-France	0.05	0.06	0.03	0.02
Denmark-Spain	-0.06	-	-0.04	0.01
Germany-France	0.15	0.22	0.15	0.14
Germany-Spain	-0.03	-	-0.03	-0.03
France-Spain	0.06	-	0.12	0.12

When comparing our study with Rosques' analysis, the correlation coefficients present the same smoothing effect between the countries. These are approximately the same, especially in 2012. Only in one case, between France and Spain, our value is twice the value of the study it is compared to. Thus, our research shows a bit smaller smoothing effect between these two countries than Rosques' study.

To continue with, Bach P.F. (2012) carried out a statistical survey in order to quantify the smoothing effect between five European countries. The results of the correlation coefficients of hourly wind power are presented in Table 25. In this specific study, the statistical analysis is carried out by using the second method which is based on the comparison of the relative hourly wind power generation between countries. Thus, a comparison is made again, this time using the results of the second method of our study.

Table 25. Correlation coefficients of relative wind power production on hourly basis.

	Bach's study	**Our study**			
Countries	**2012**	**2011**	**2012**	**2013**	**Average for 2011-2013**
Denmark-Germany	0.66	0.70	0.66	0.66	0.67
Denmark-Ireland	0.10	0.27	0.09	0.20	0.19
Denmark-France	0.16	0.21	0.15	0.26	0.21
Denmark-Spain	-0.05	-	-0.07	0.12	0.03
Germany-Ireland	0.18	0.26	0.17	0.26	0.23
Germany-France	0.42	0.45	0.42	0.49	0.45
Germany-Spain	0.02	-	-0.12	0.12	0.00
Ireland-France	0.25	0.23	0.26	0.28	0.26
Ireland-Spain	0.07	-	-0.03	0.04	0.01
France-Spain	0.41	-	0.12	0.30	0.21

Due to the fact that ours and Bach's study are carried out using the same kind of data, the results of the comparison are expected to be similar. Thus, we can deduce that our study is a verification of Bach's study regarding the hourly wind power production. However, on Bach's study, there is no research at different time scales, only on hourly basis. Thus, our research has an added value because our analysis is based on the different time scales such as hourly, daily, weekly and monthly. As mentioned in the introduction, the wind long-term variability is important for the strategic power system planning as well as electricity trading purposes Moreover, our research is carried out for the period 2011-2013 while Bach's study is based on data for only one year (2012). Therefore, our analysis is more reliable than Bach's study as the data that is used cover a longer period of time. According to Table 25, the correlation coefficient of Bach's study in 2012 is different from the average for 2011-2013 of our study that indicates the importance to investigate the variability in more than one year.

Giebel (2001) quantifies the effect of distance on the wind power output between the wind farms that are located in the Northern and Central Europe. In Figure 27 the cross-correlation versus the distance between grid points on Giebel's study can be seen. It is found that the correlation coefficient decreases by 50% when the distance is about 580 km (starting point 500 km). However, there is no information about the time intervals. Assuming that Figure 27 is based on hourly time intervals, a big difference is found when compared to our results. In our research, a distance of about 365 km is required so that the correlation coefficient drops by 50% (starting point 500 km in step change method).

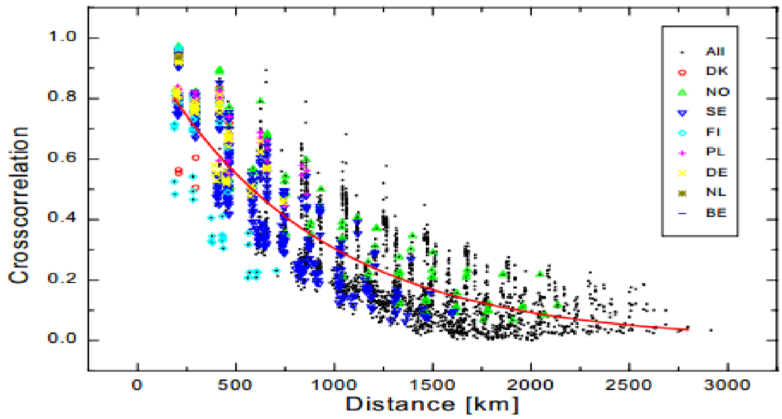


Figure 27. Cross-correlation versus distance between grid points. (Giebel, 2001)

At the end, Adams T. (2009) carried out a study in order to investigate the benefits of the geographical diversity for the mitigation of variability in wind power production. It is found that distances of about 230 km are required in order the correlation coefficient to drop by 50% on hourly basis, and 320 km regarding the daily output (starting point 500 km). Table 26 presents the results of the correlation coefficient as a function of the distance.

Table 26. Results of Adams's study and our study for the correlation coefficient (CC) as a function of the distance.

	Time scale	Adams'study	Our study
Mathematical formula	Hourly	$Y=e^{-0.003x}$ (R^2=0.9365)	Y=-0.506 ln(x)+3.7678 (R^2=0.8877)
	Daily	$Y=e^{-0.002x}$ (R^2=0.8867)	Y=-0.497 ln(x)+3.7716 (R^2=0.9283)
	Weekly	-	Y=-0.475 ln(x)+3.8122 (R^2=0.9157)
	Monthly	-	Y=-0.345 ln(x)+3.0600 (R^2=0.8377)
Distance required to drop CC by 50% (starting point 500 km)	Hourly	230 km	425 km
	Daily	320 km	493 km
	Weekly	-	736 km
	Monthly	-	1,385 km

Comparing the results of Adams' study with our study (the same starting point of 500 km), it can be noticed that there are differences on the hourly (205 km additonal) and the daily (173 km additional) time scale. Thus, the distance seems to have a far greater effect in Adams' study than ours. The reason for this may be due to the local topography and the different sites of wind farms. Adams' study refers to Ontario area while our study focus on European region. Finally, our study forms a further step as an analysis on weekly and monthly wind output is made.

8. General conclusion

The study was carried out to explore the smoothing effect in wind power production by connecting different countries within Europe. It has identified the factors such as the distance, the size of area and the wind power capacity and how they influence the smoothing effect as well as the extent to which the smoothing effect changes on different time scales. The importance of this research lies in the fact that no previous studies have been conducted regarding the countries selected as well as the analysis at different time scales such as daily, weekly and monthly. This study sought to answer the following question: “To what extent can wind power production patterns be smoothed out by connecting different countries within Europe?”

Wind power production is characterized by variations on all time scales. The correlation coefficient was found to increase with higher time scales. Even bigger values were found especially, on the weekly and monthly analysis. Thus, the smoothing effect is less strong on long-term wind power variability compared to short-term. **(Sub-question a)**

The distance between the five European countries plays a significant role on the smoothing effect. Remote countries show a strong smoothing effect regarding the wind power production; on the other hand, neighboring countries seem to be well-correlated. In Sections 4.4.1 and 5.7, the output smoothing has been analyzed as a function of the distance. The correlation coefficient was used as an indicator in order to quantify the smoothing effect. An exponential effect was identified between the wind output and the distance. **(Sub-question b)**

Additionally, another factor influencing the smoothing effect is the size of area. Large geographical distribution of wind power reduces variability and increases predictability. In Section 4.4.2, the smoothing effect was quantified according to the area. It was found that the standard deviation drops asymptotically with the increase of the area on different time scales. **(Sub-question c)**

The step change analysis was used to detect the relation of the smoothing output against the wind power capacity. Countries with large wind power capacity play important role on the decrease of the overall smoothing effect. In Section 4.4.2, it was found that the standard deviation drops as the wind energy generation rises on different time scales. There is an asymptotic effect between them. **(Sub-question d)**

To continue with, a scenario was formed as far as future estimations on smoothing effect are concerned. According to future projections an increase on wind power capacity is expected to take place in 2020. Due to this, the standard deviation seemed to decrease by 50%, 24% and 17% on hourly, daily and weekly basis, respectively, indicating a significant reduction on the overall smoothing effect by 2020 as stated in Section 7.2. **(Sub-question e)**

In overall, the relative variability of wind power decreases when considering a large interconnected system composed of the five European countries. In this system, the aggregated hourly wind power variations are most of the time within ±2% (97% of the samples) of installed capacity, while in Spain, Germany and France the hourly changes of the production are mostly within ±3%. Also, in Ireland and Denmark the hourly variability lies within ±5%.

The results of this research clearly indicate the benefits that the interconnection of countries has on smoothing effect within Europe. Consequently, a transmission grid should be created in the future including as many countries as possible.

8.1 Recommendations and future work

This study focuses mainly on macro-scale area investigation of smoothing effect between five countries. Our research was carried out by collecting hourly wind power generation data in each country during 2011-2013. Thus, our statistical analysis was performed by using aggregated hourly wind power data for a whole country. Therefore, an investigation especially on countries with large area size, for instance, in Germany, France and Spain, is required to identify further characteristics about smoothing effect. In order to achieve that, it is necessary each country to have more detailed data. Whereas, certain countries have in their possession such data, it is not publicly available.

Additionally, an investigation on smoothing effect is suggested using data on a time scale smaller than hourly. More specifically, the two methods exploited in this study could be carried out by using, for instance, 15-minute actual wind power data. However, this kind of data is not available in some countries (e. g in France) at the present period. This way could lead to a more in depth and, therefore, accurate analysis due to the fact that wind power varies on all timescales even on seconds and minutes.

Generally, it is recommended that future studies should focus mainly on the examination of offshore wind power generation. For instance, studies about extreme weather phenomena such as hurricanes, which occur more on coastal areas that affect the smoothing effect, could be carried out. This comes in accordance with future projections indicating that most European countries will invest in offshore wind power. Additionally, as mentioned before, offshore wind power has different characteristics from onshore and, thus, it will affect the wind power variability.

Also, an examination on the losses during energy transmission is advised and the way these can be minimized. This kind of losses are not taken under consideration in the present research, thus, a further research on this subject would lead to a more reliable outcome.

Finally, the smoothing effect of wind power should be investigated combined with the load variability of each country. In this manner, a clearer picture can be drawn regarding the way in which wind power variability is correlated to load variability in each country. Thus, the needs for possible transmissions of electricity produced by wind power could be identified for each country.

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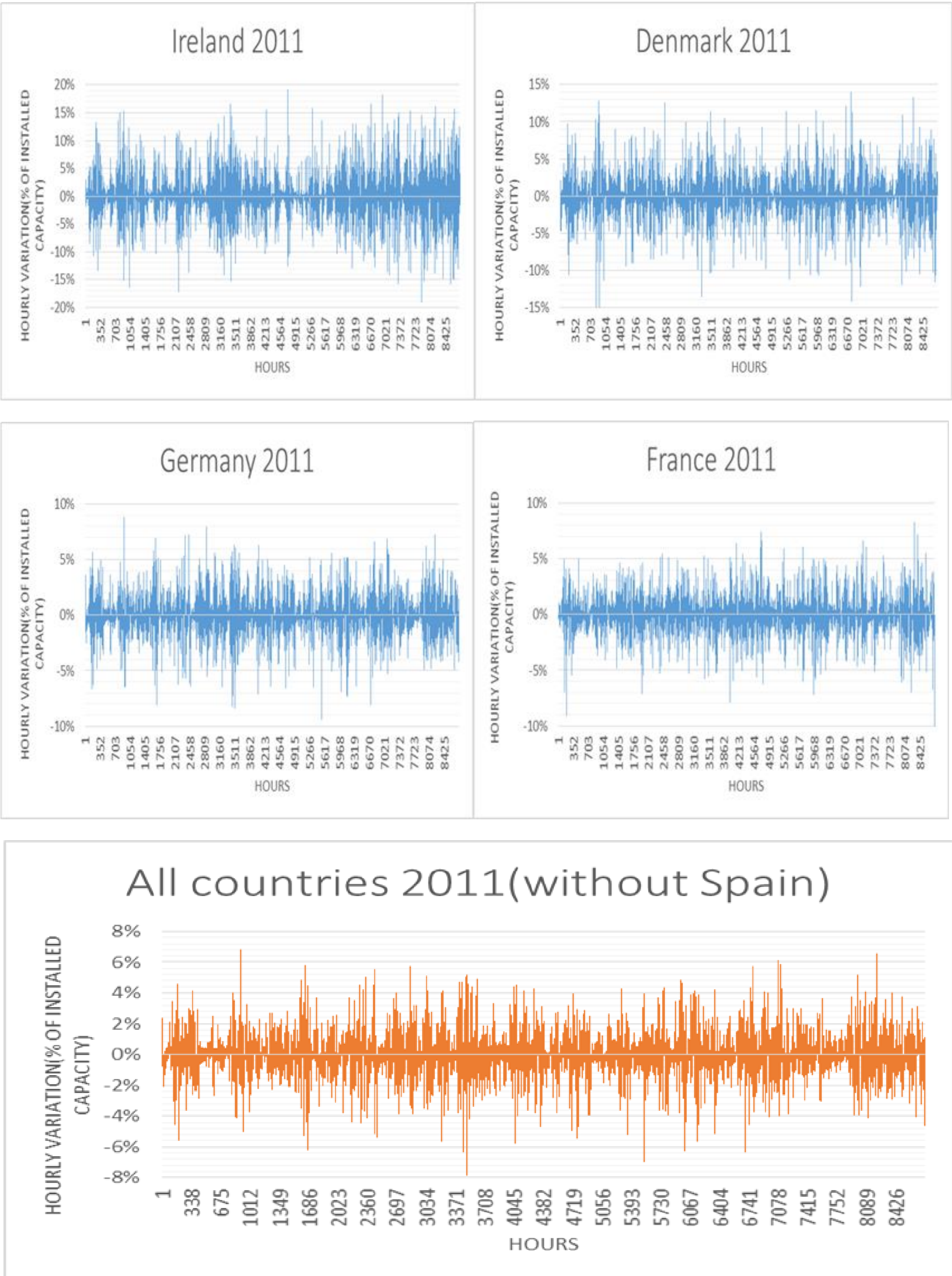
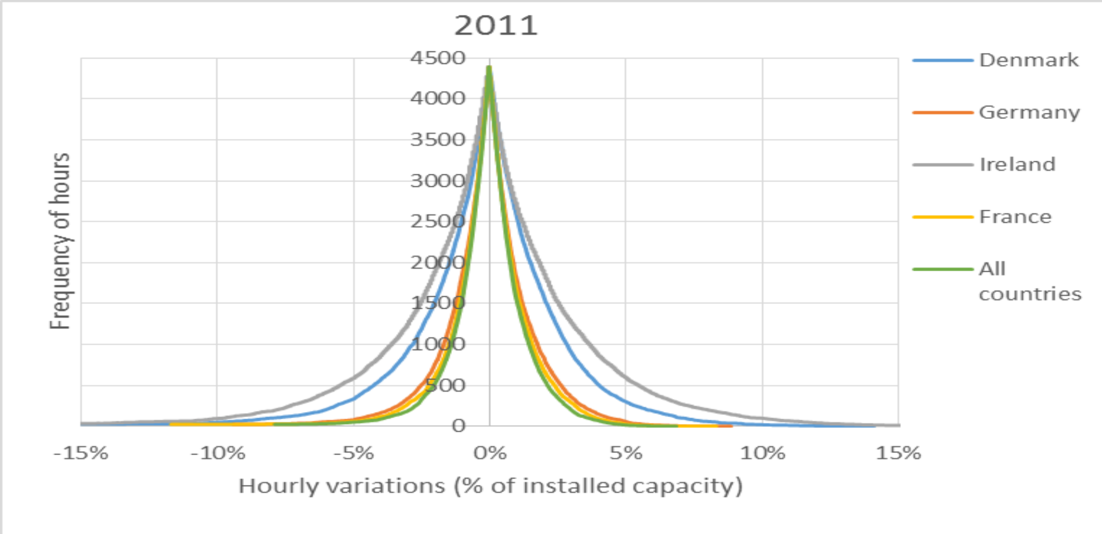
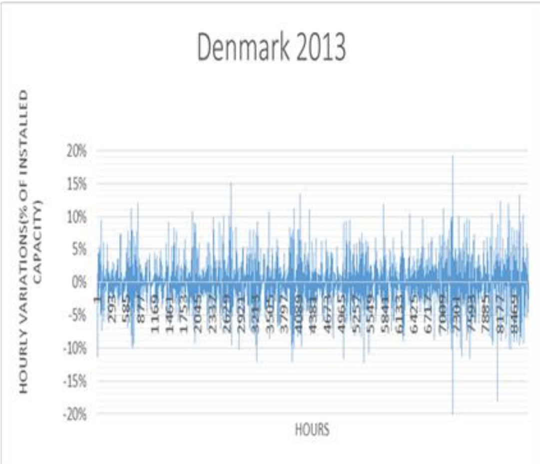
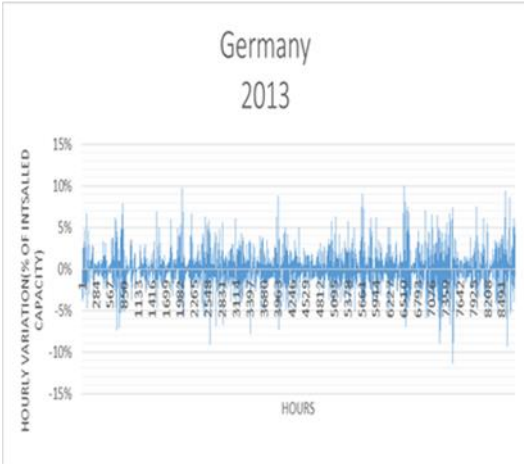
Appendix A: Time series of wind power production variation (% of installed capacity) in 2011-2013

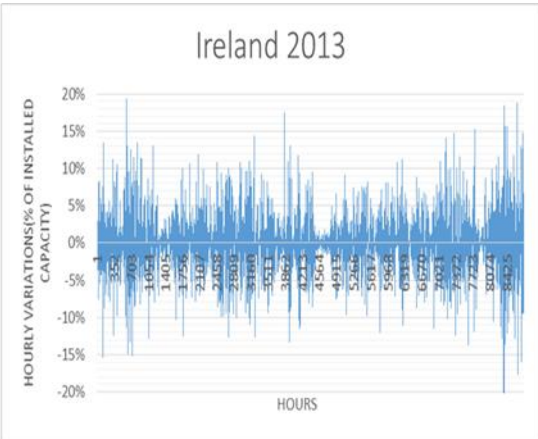
A1: Hourly time series of wind power production variation (% of maximum power output) for the period 2011-2013

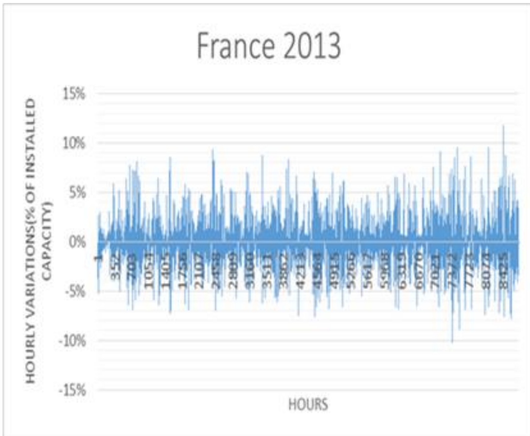


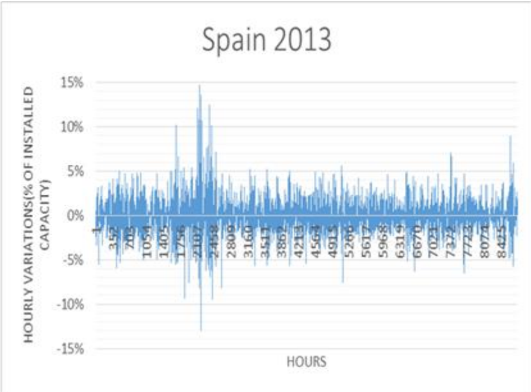

2011
Frequency of hours
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-15%
-10%
-5%
0%
5%
10%
15%
Hourly variations (% of installed capacity)
Denmark
Germany
Ireland
France
All countries

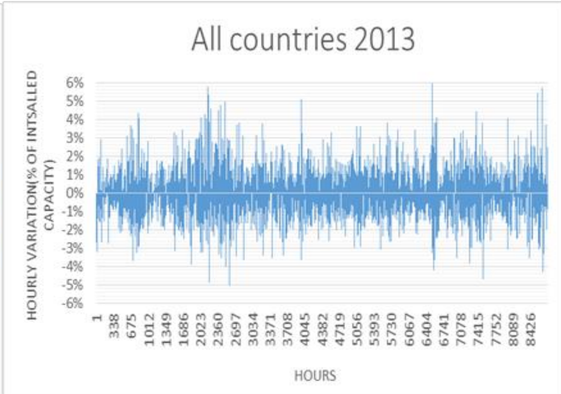

Denmark 2013
HOURLY VARIATIONS(% OF INSTALLED CAPACITY)
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
HOURS

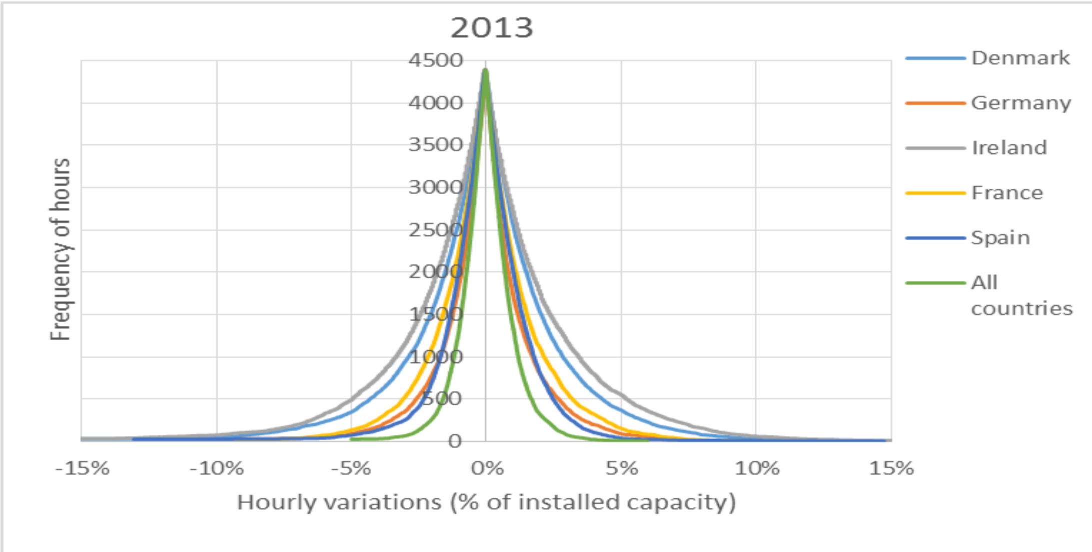

Germany 2013
HOURLY VARIATION(% OF INTSALLED CAPACITY)
15%
10%
5%
0%
-5%
-10%
-15%
HOURS


Ireland 2013
HOURLY VARIATIONS(% OF INSTALLED CAPACITY)
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
HOURS

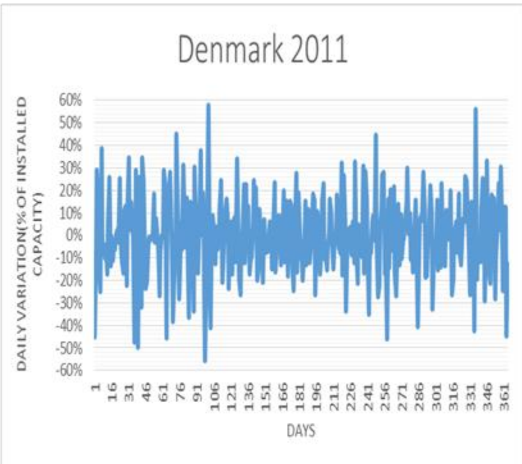

France 2013
HOURLY VARIATIONS(% OF INSTALLED CAPACITY)
15%
10%
5%
0%
-5%
-10%
-15%
HOURS

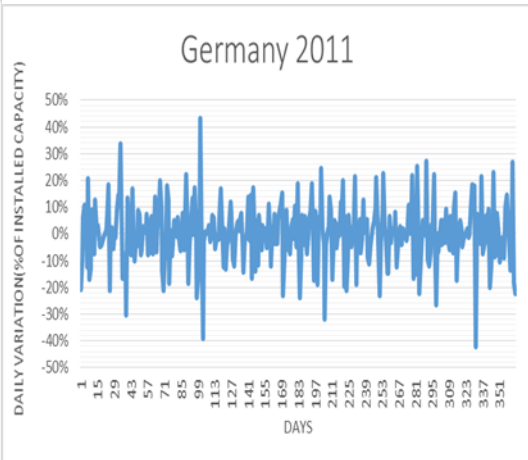


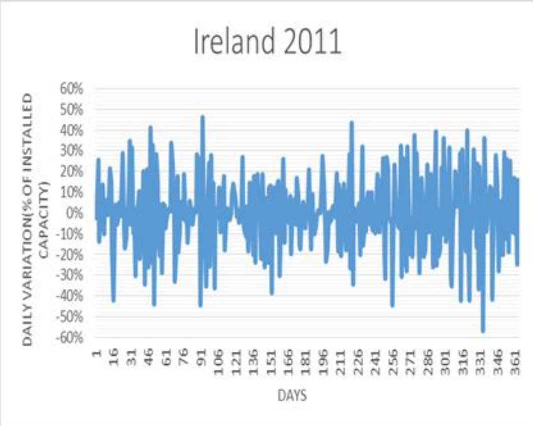


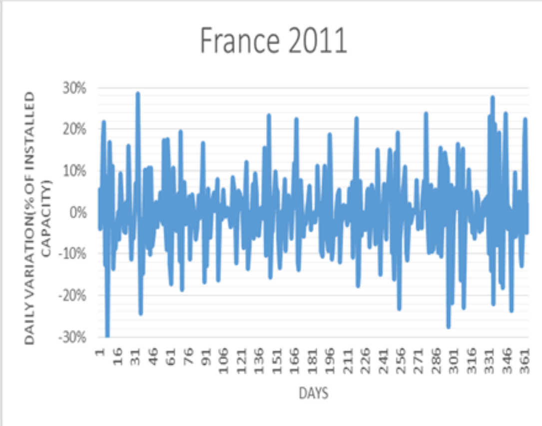


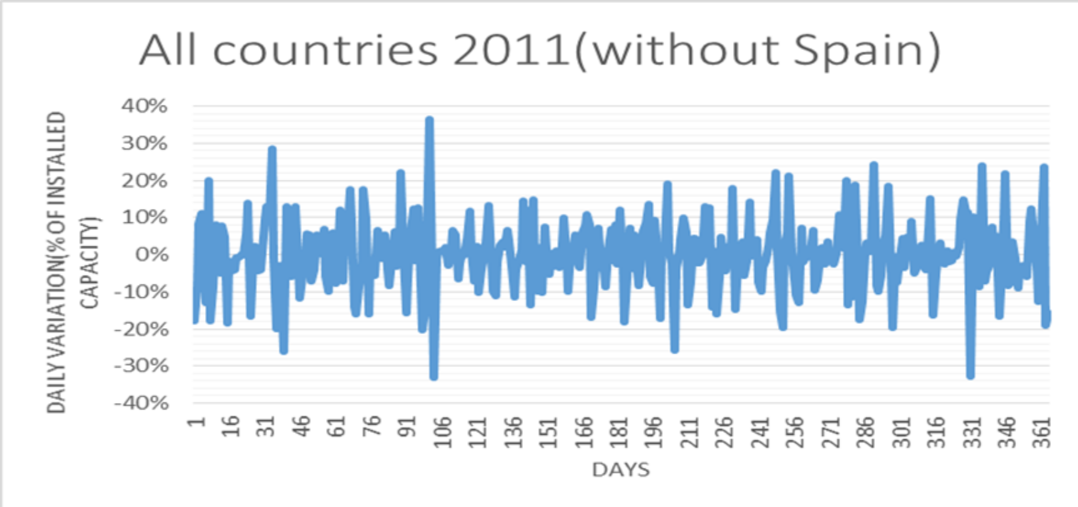
A2: Daily time series of wind power production variation (% of maximum power output) for the period 2011-2013

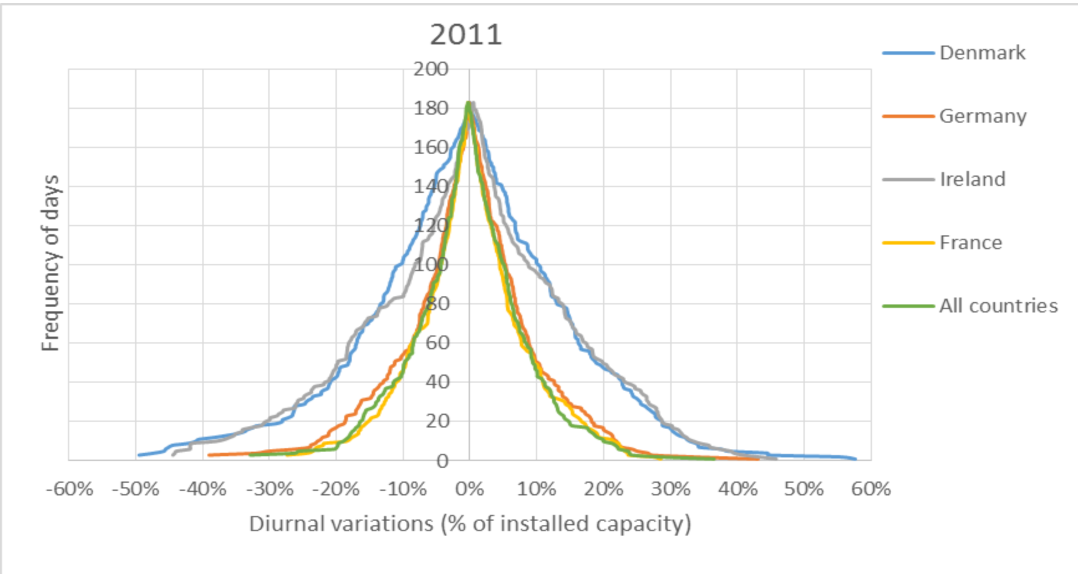


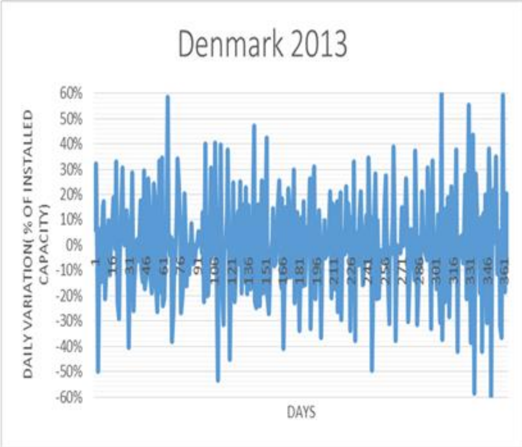


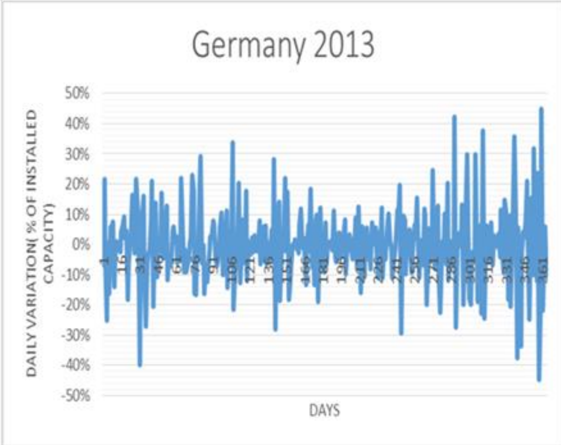

Ireland 2011
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

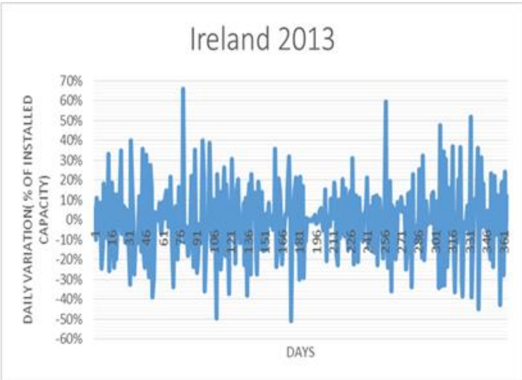

France 2011
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

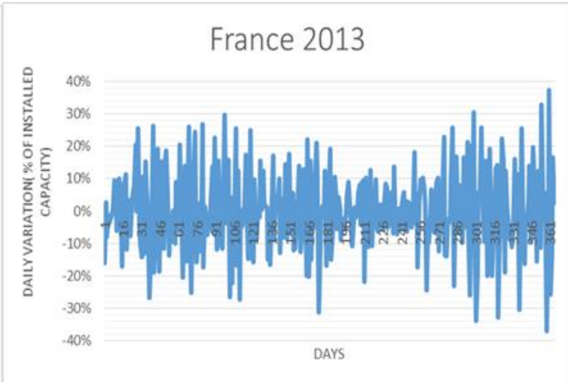

All countries 2011(without Spain)
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

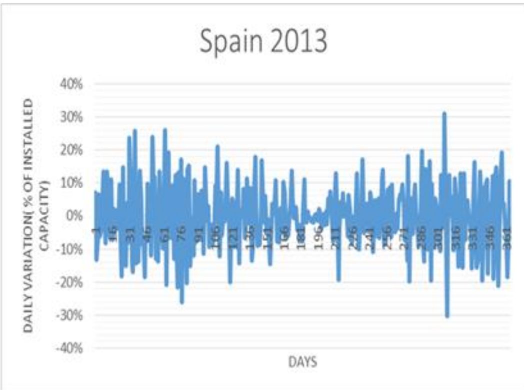

2011
Frequency of days
Diurnal variations (% of installed capacity)
Denmark
Germany
Ireland
France
All countries

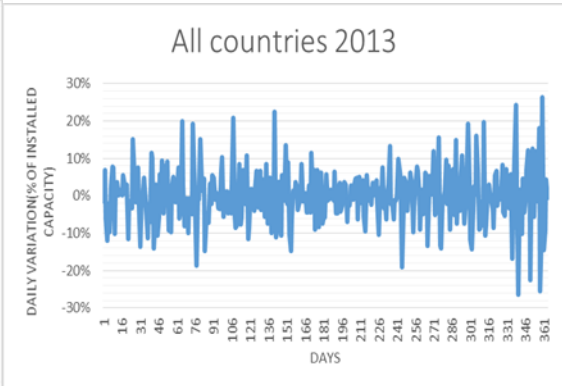

Denmark 2013
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

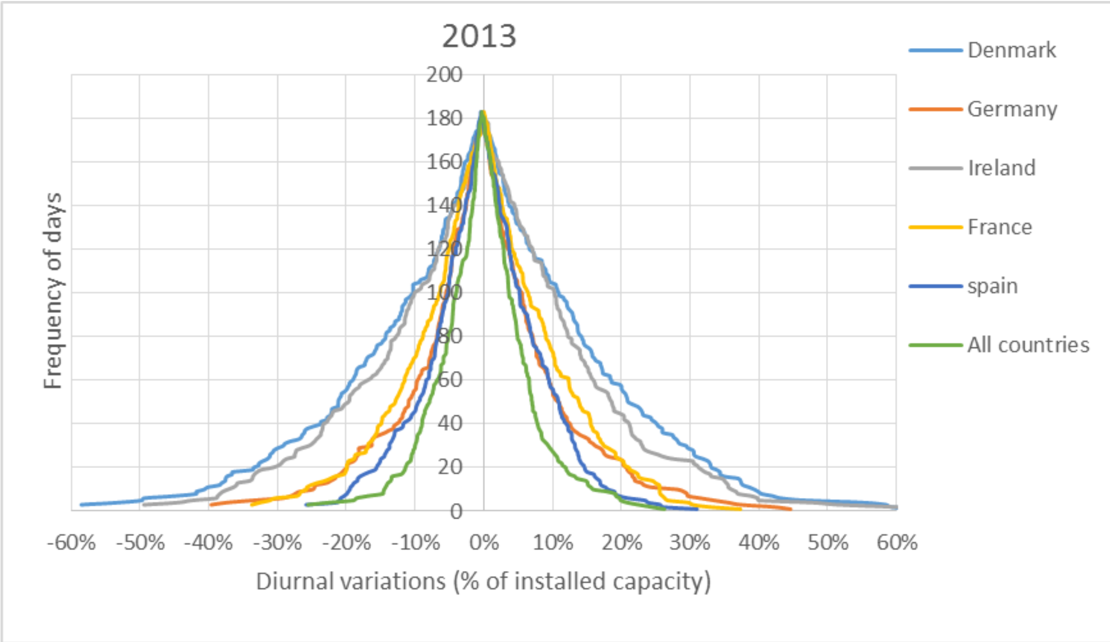

Germany 2013
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS


Ireland 2013
70%
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

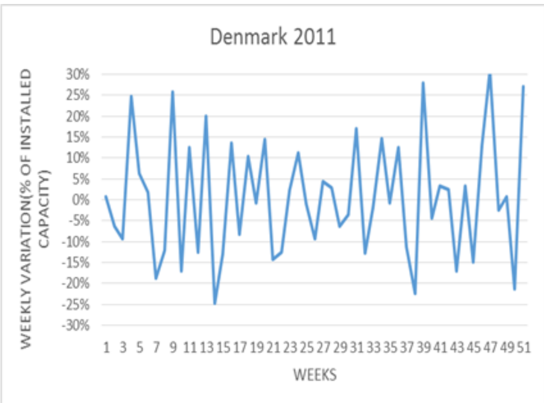

France 2013
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

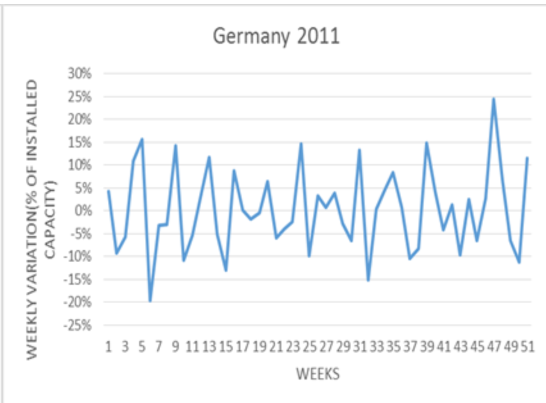

Spain 2013
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

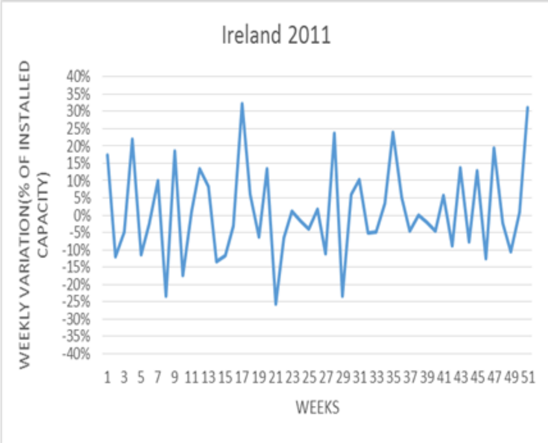

All countries 2013
30%
20%
10%
0%
-10%
-20%
-30%
DAILY VARIATION(% OF INSTALLED CAPACITY)
DAYS

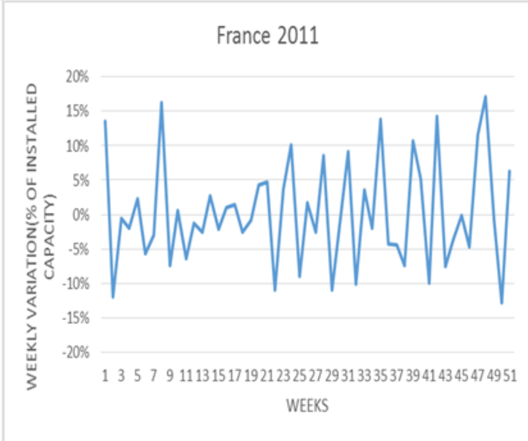


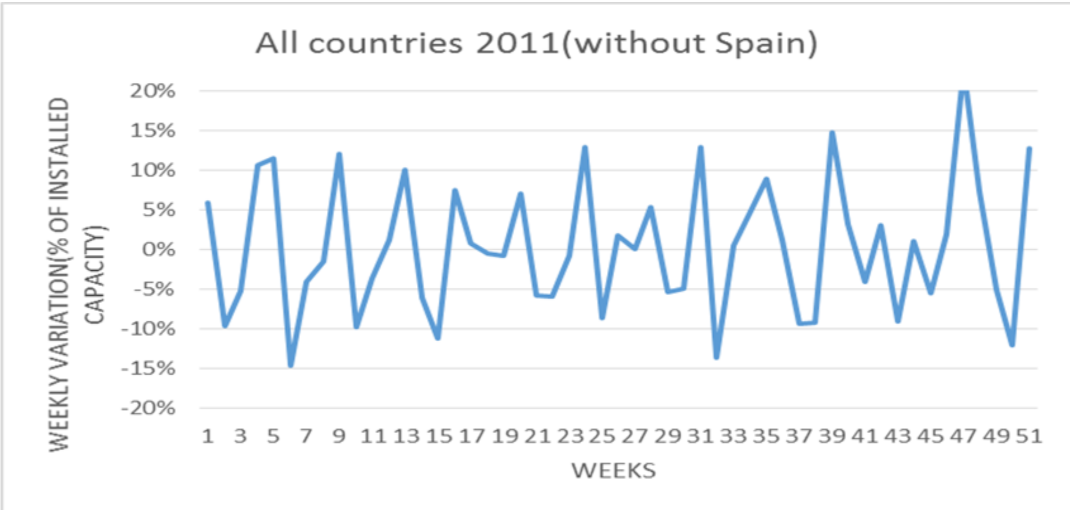
A3: Weekly time series of wind power production variation (% of maximum power output) for the period 2011-2013

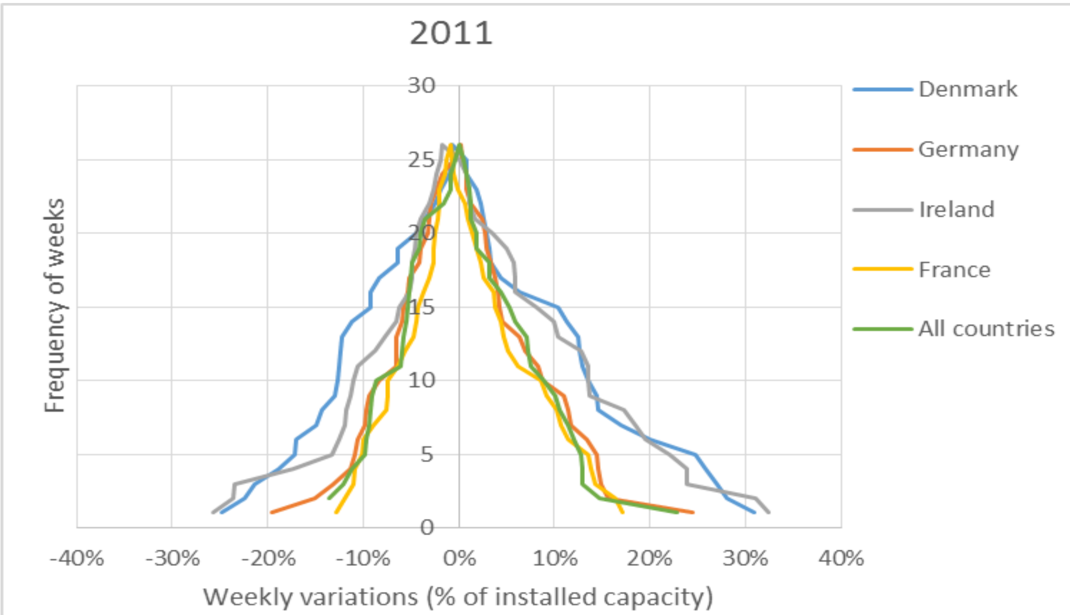


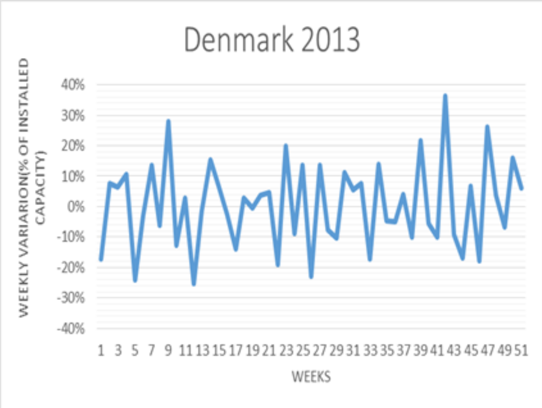


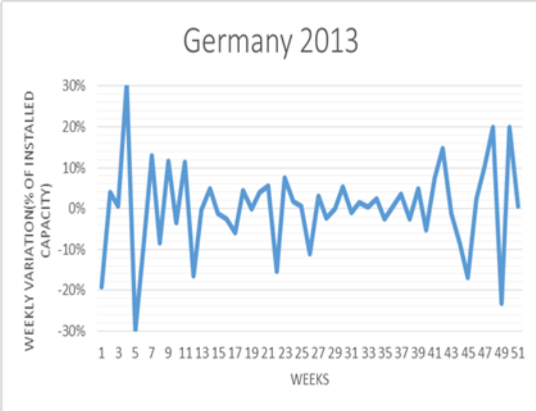

Ireland 2011
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
WEEKS

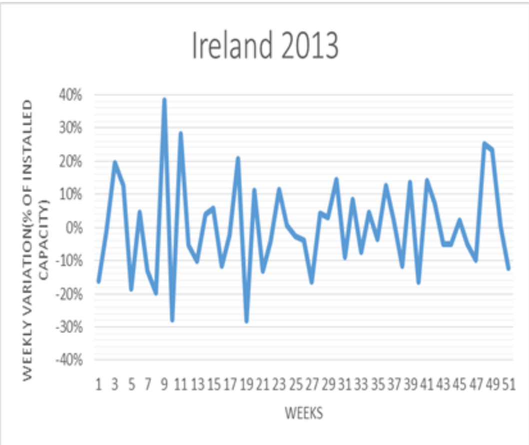

France 2011
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
WEEKS

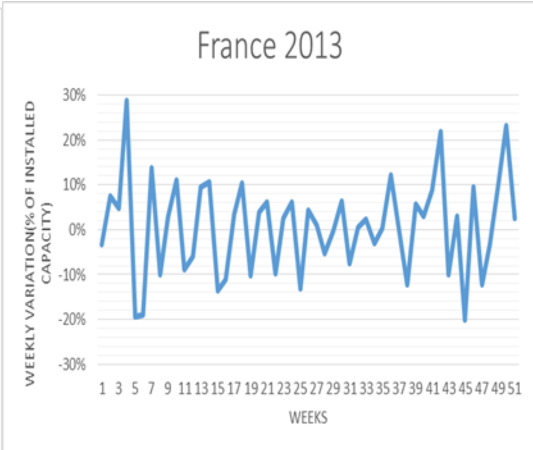

All countries 2011(without Spain)
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
WEEKS

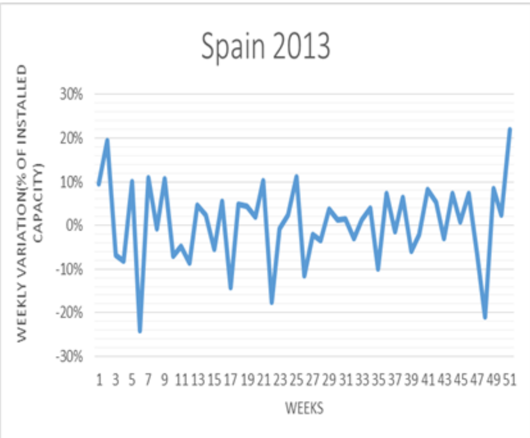

2011
Frequency of weeks
Weekly variations (% of installed capacity)
Denmark
Germany
Ireland
France
All countries

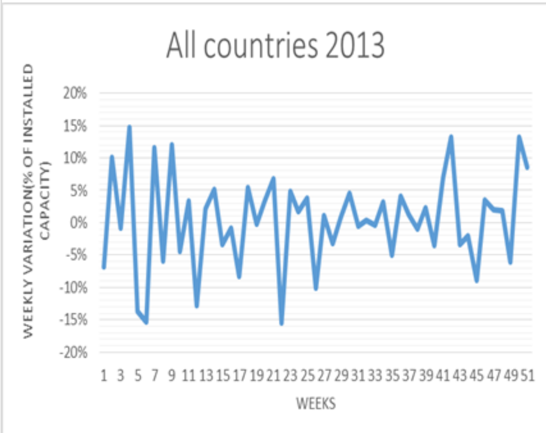

Denmark 2013
WEEKLY VARIARION(% OF INSTALLED CAPACITY)
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
WEEKS

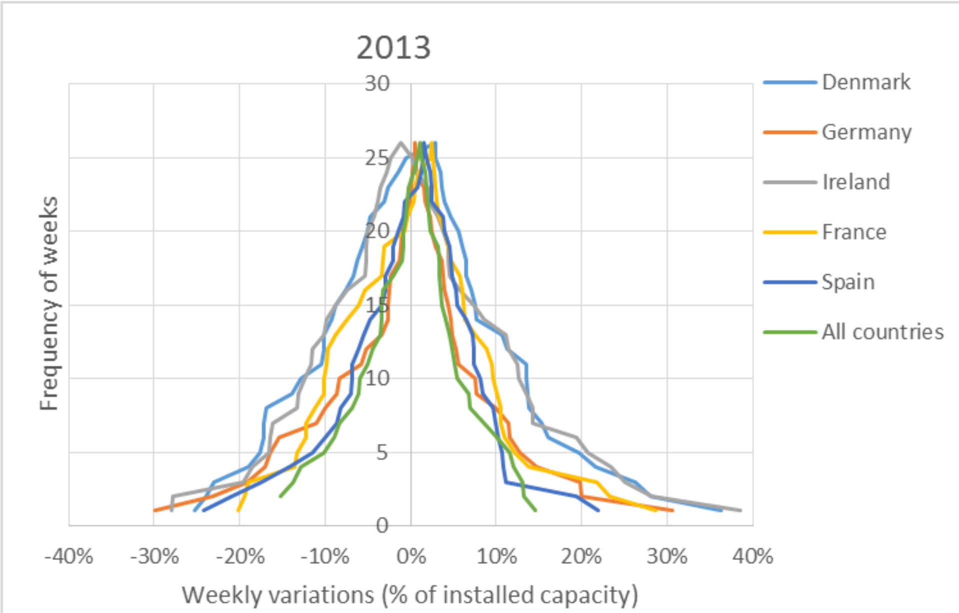

Germany 2013
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
30%
20%
10%
0%
-10%
-20%
-30%
WEEKS


Ireland 2013
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
WEEKS


France 2013
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
30%
20%
10%
0%
-10%
-20%
-30%
WEEKS


Spain 2013
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
30%
20%
10%
0%
-10%
-20%
-30%
WEEKS


All countries 2013
WEEKLY VARIATION(% OF INSTALLED CAPACITY)
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
WEEKS



A4: The correlation coefficient and standard deviation against the distance, area and wind power

Table 27. Distance (in km) required for the correlation coefficient to drop by 50% at different starting points (in km) on different time scales.

Starting point (km)	hourly	daily	weekly
500	365	323	434
750	310	258	394
1000	224	164	320
1250	118	51	227

Table 28. The reduction of the correlation coefficient (in %) for a distance of 500 km at different starting points on different time scales.

Starting point (km)	hourly	daily	weekly
500	63%	70%	55%
750	74%	86%	61%
1000	100%	134%	73%

Table 29. Area (in 1,000 km^2) required for the standard deviation to drop by 25% at different starting points on different time scales.

Starting point (1,000 km^2)	hourly	daily	weekly
200	419	405	914
400	642	617	1474
600	812	778	1940
800	952	910	2351
1000	1071	1021	2726

Table 30. The reduction of the standard deviation (in %) for an area of 200,000 km^2 at different starting points on different time scales.

Starting point (1,000 km^2)	hourly	daily	weekly
200	24%	25%	16%
400	18%	19%	11%
600	15%	15%	9%
800	13%	13%	7%
1000	12%	12%	6%

Table 31. Wind energy (in TWh) required for the standard deviation to drop by 25% at different starting points on different time scales.

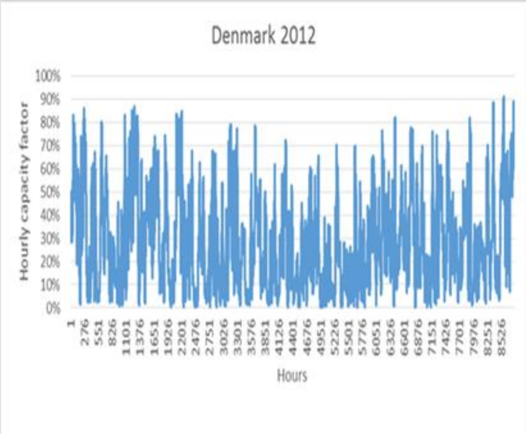
Starting point (TWh)	hourly	daily	weekly
10	16.7	31.2	45.7
20	24.9	49.3	73.6
30	30.9	63.9	96.9
40	35.6	76.5	117.5
50	39.3	87.7	136.1
60	42.4	97.9	153.5

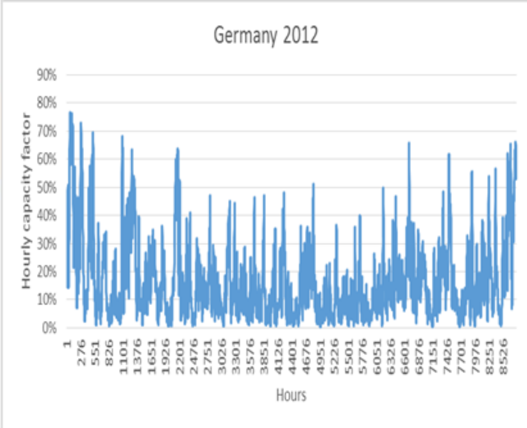
Table 32. The reduction of the standard deviation (in %) for a wind energy of 20 TWh at different starting points on different time scales.

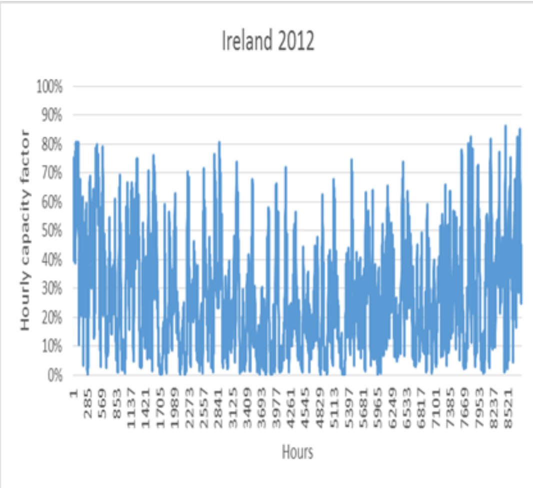
Starting point (TWh)	hourly	daily	weekly
10	28%	19%	16%
20	21%	14%	11%
30	18%	11%	9%
40	16%	9%	7%
50	14%	8%	6%
60	13%	7%	6%

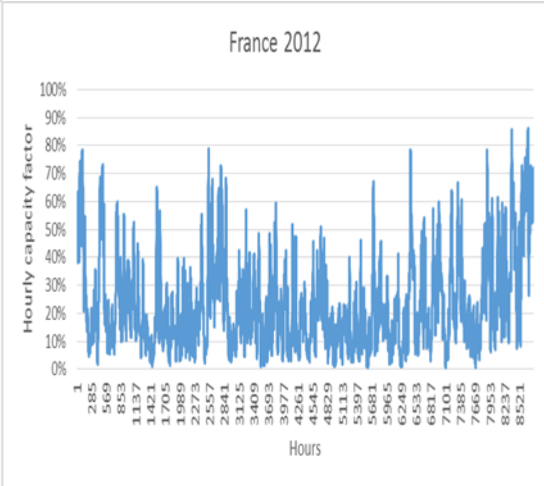
Appendix B: Time series of wind power production (% of installed capacity) in 2011-2013

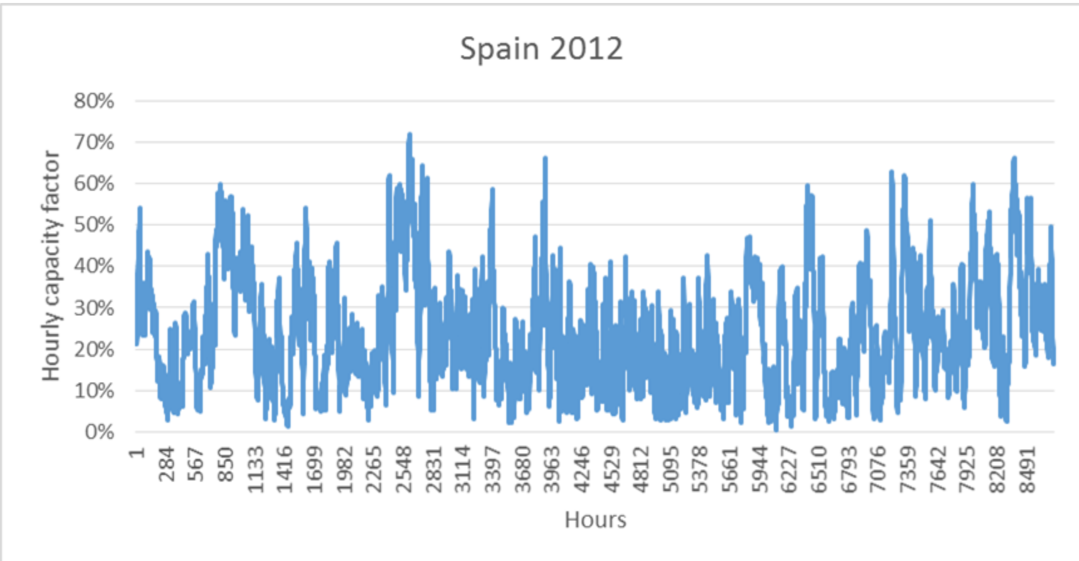
B1: Hourly time series of wind power production (% of maximum power output) for the period 2011-2013

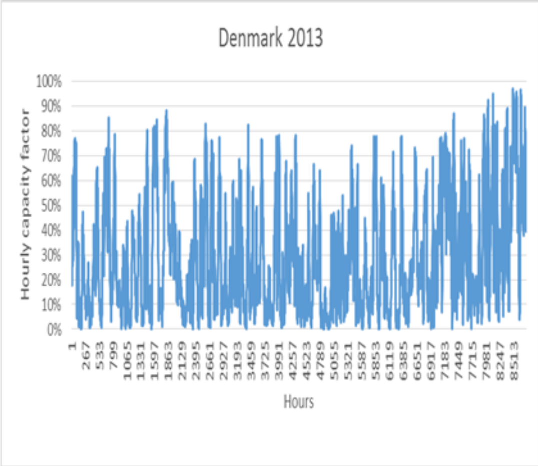


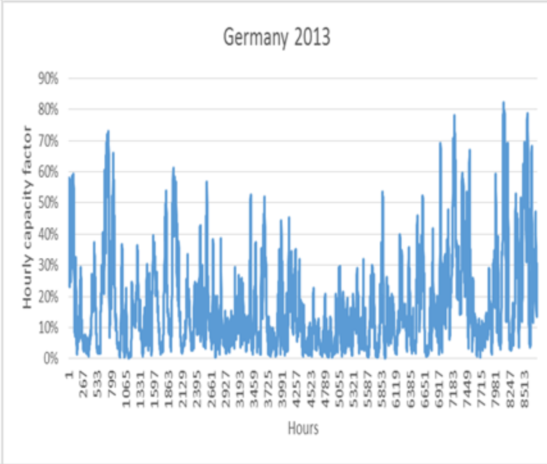


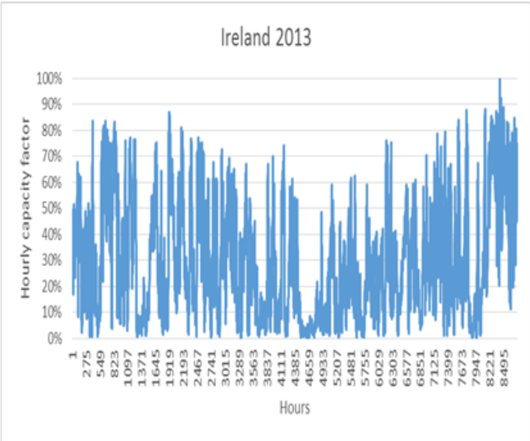


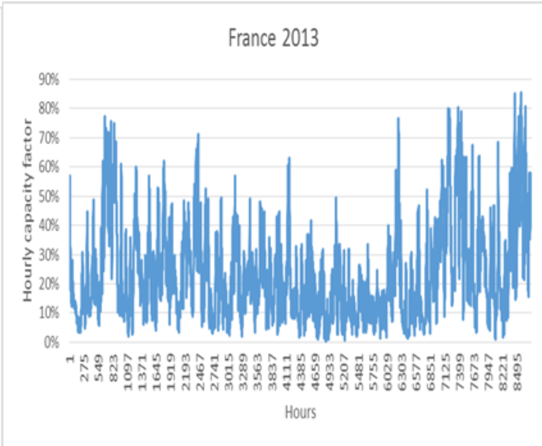


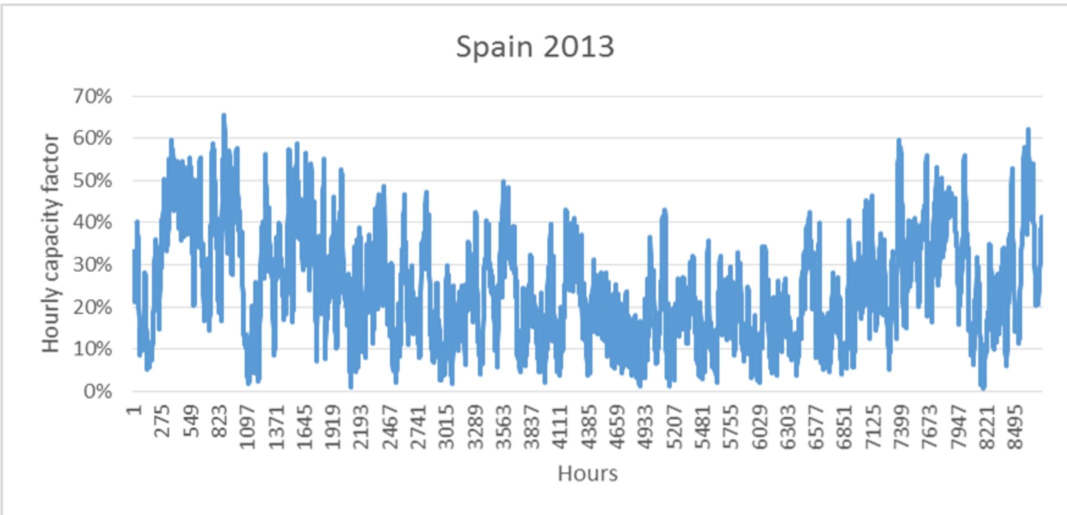



Denmark 2013
Hourly capacity factor
Hours

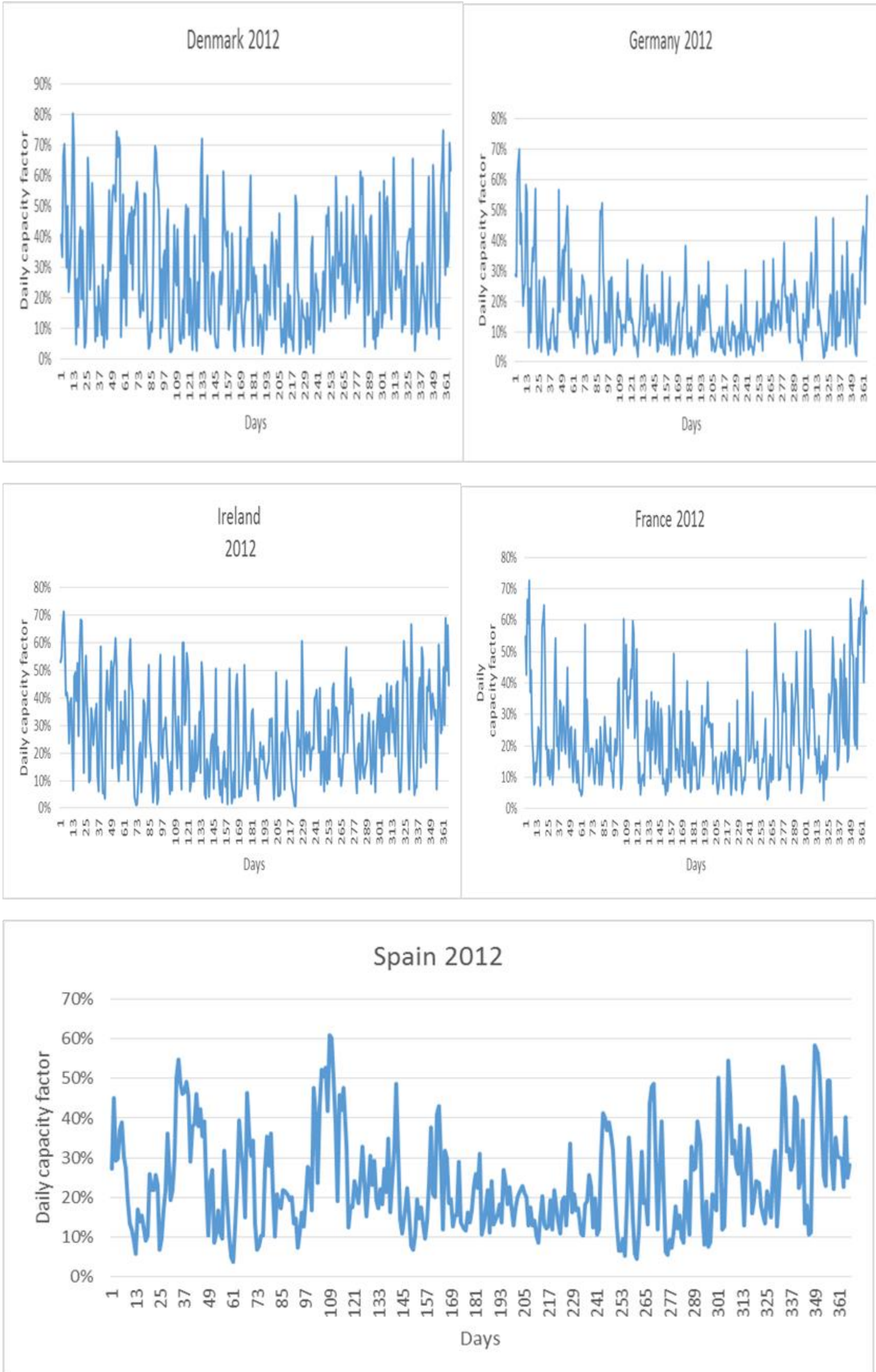

Germany 2013
Hourly capacity factor
Hours

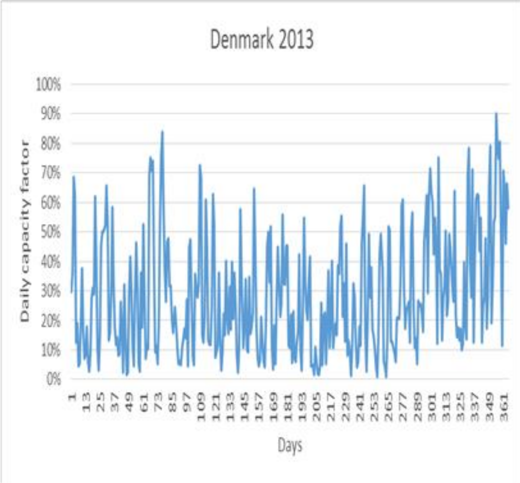

Ireland 2013
Hourly capacity factor
Hours

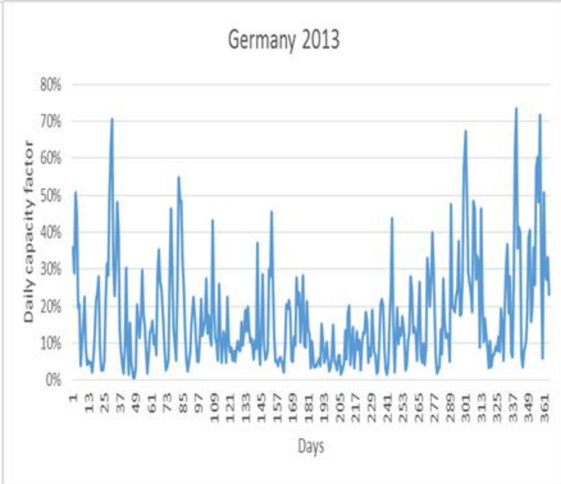

France 2013
Hourly capacity factor
Hours

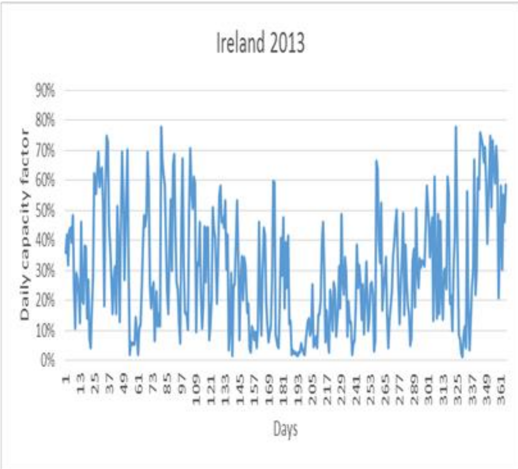

Spain 2013
Hourly capacity factor
Hours

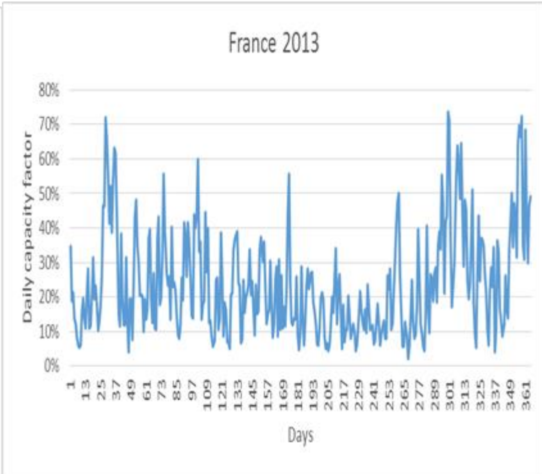
B2: Daily time series of wind power production (% of maximum power output) for the period 2011-2013

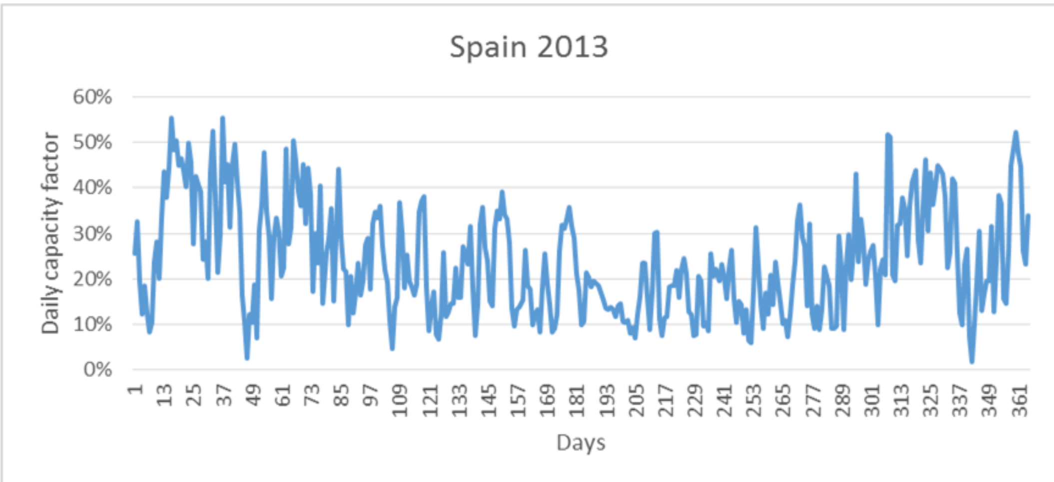



Denmark 2013
Daily capacity factor
Days

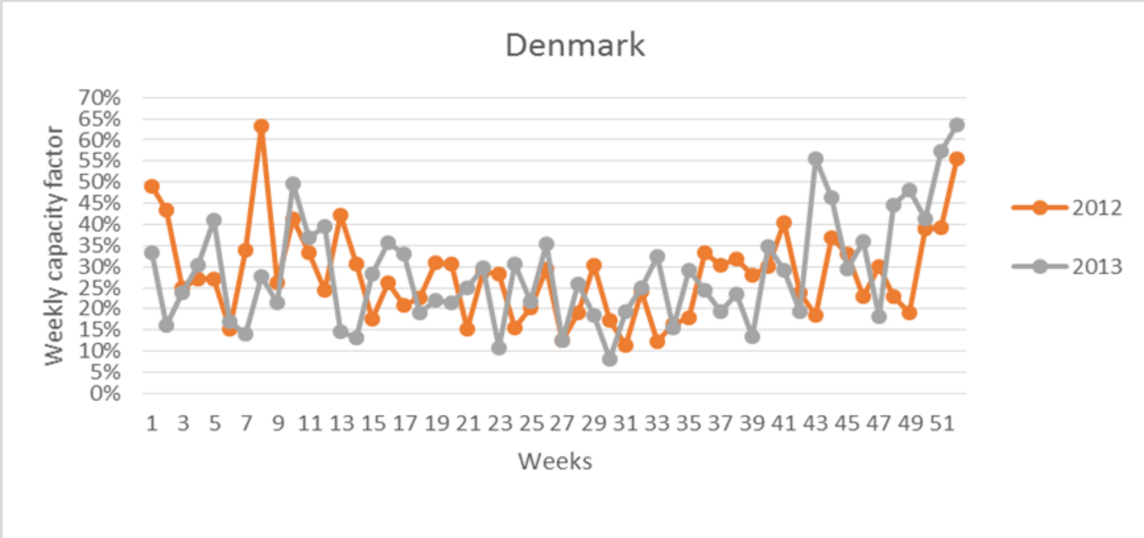

Germany 2013
Daily capacity factor
Days

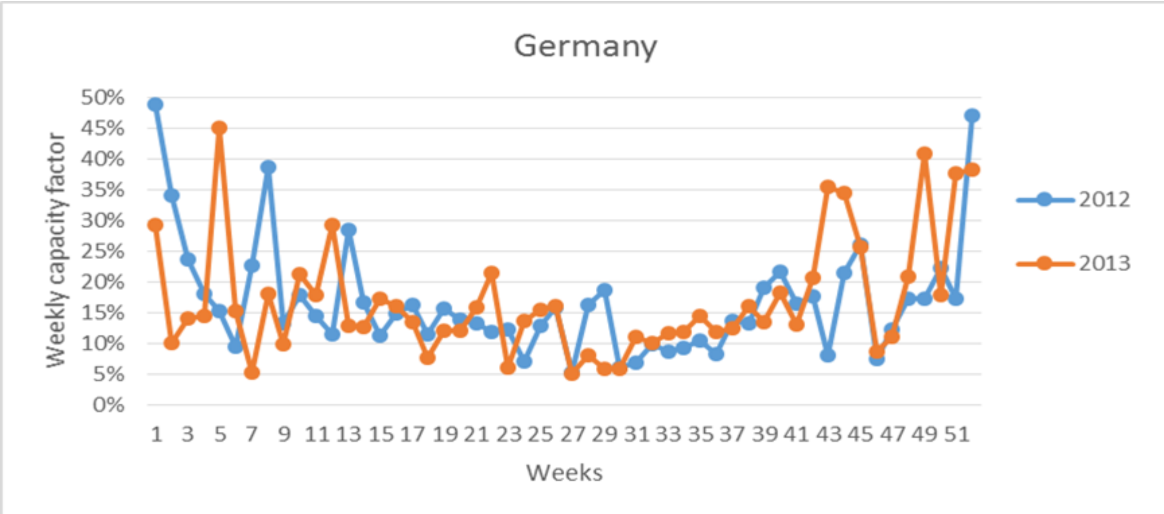

Ireland 2013
Daily capacity factor
Days

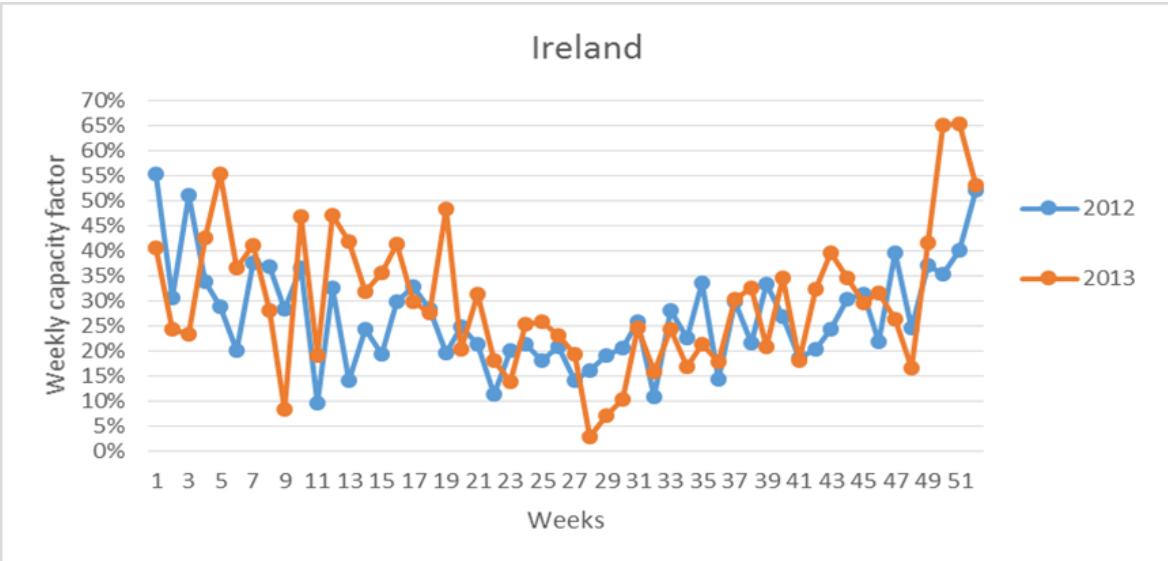

France 2013
Daily capacity factor
Days

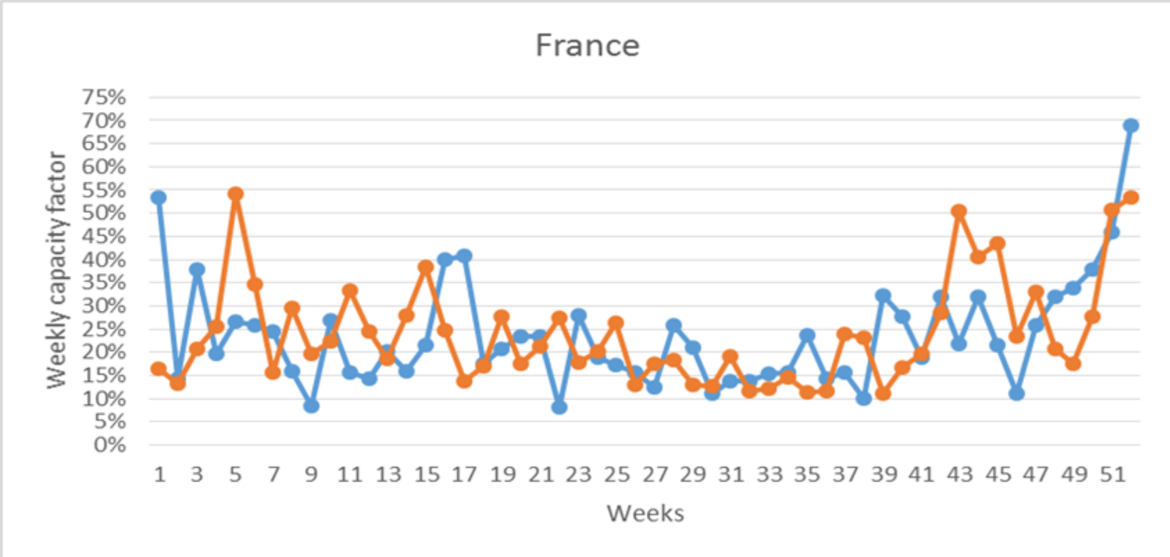

Spain 2013
Daily capacity factor
Days

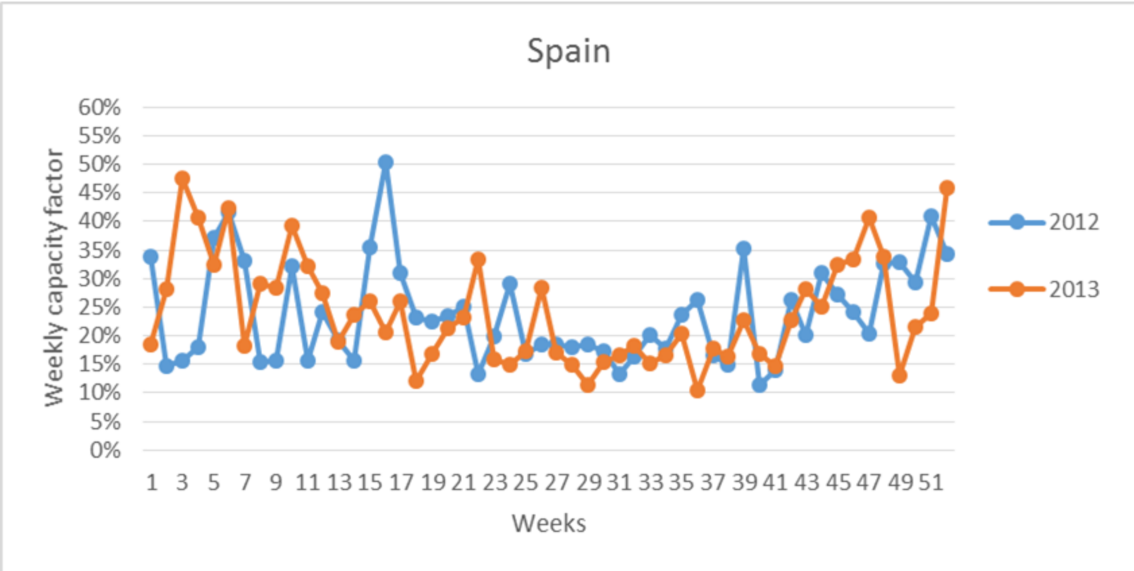
B3: Weekly time series of wind power production (% of maximum power output) for the period 2011-2013



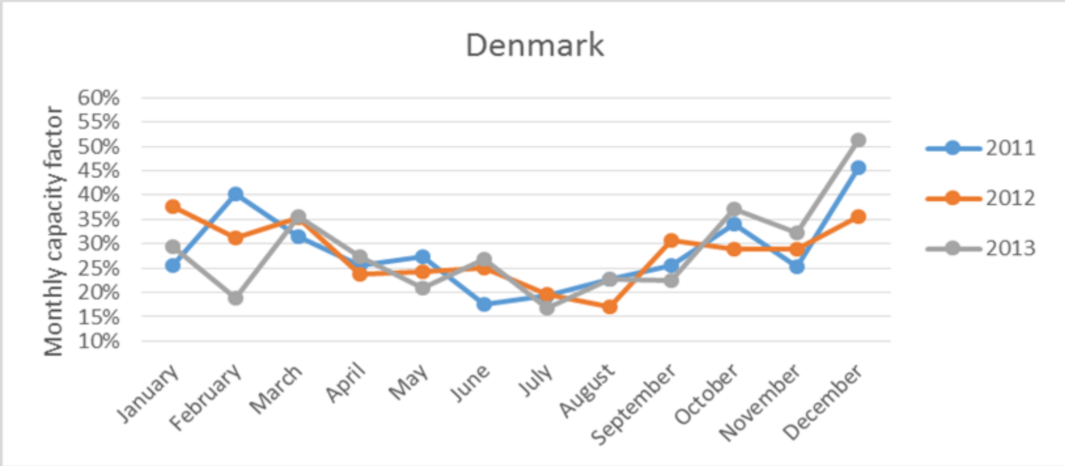


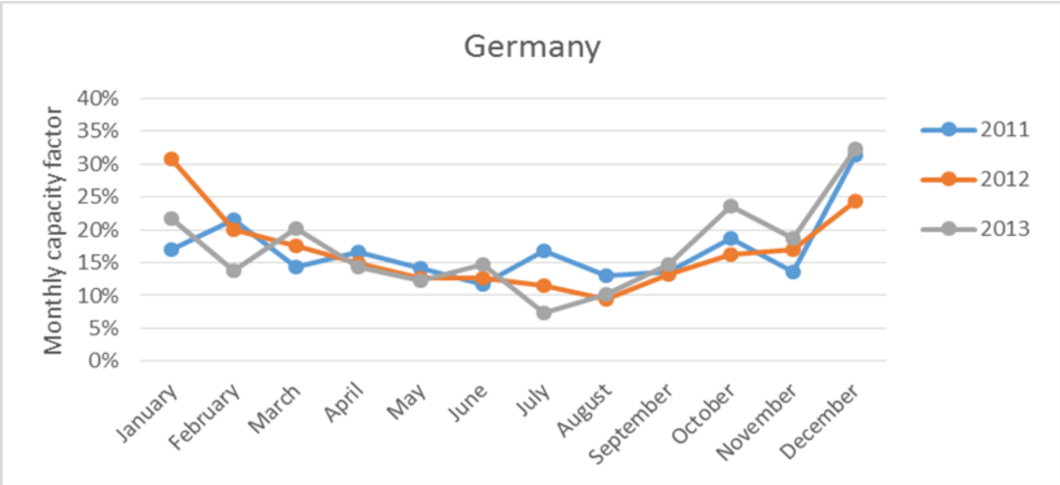


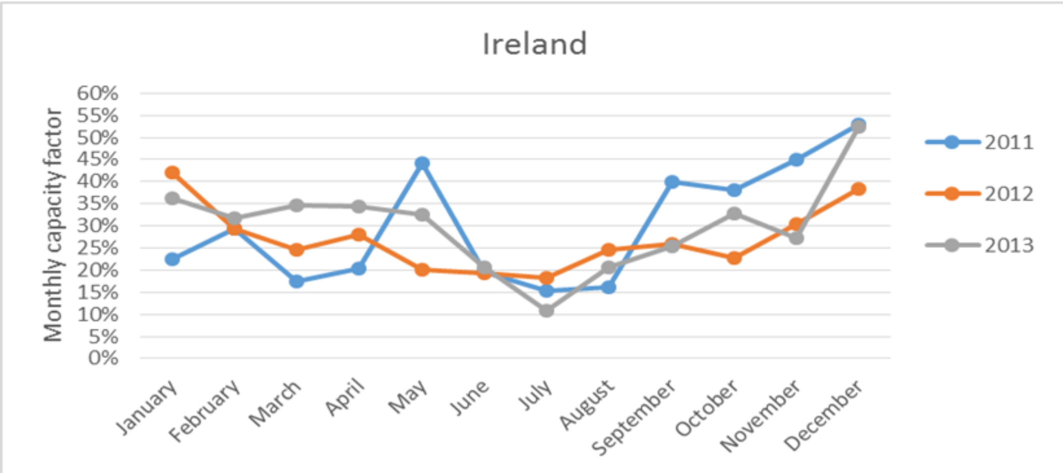

France
Weekly capacity factor
75%
70%
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51
Weeks

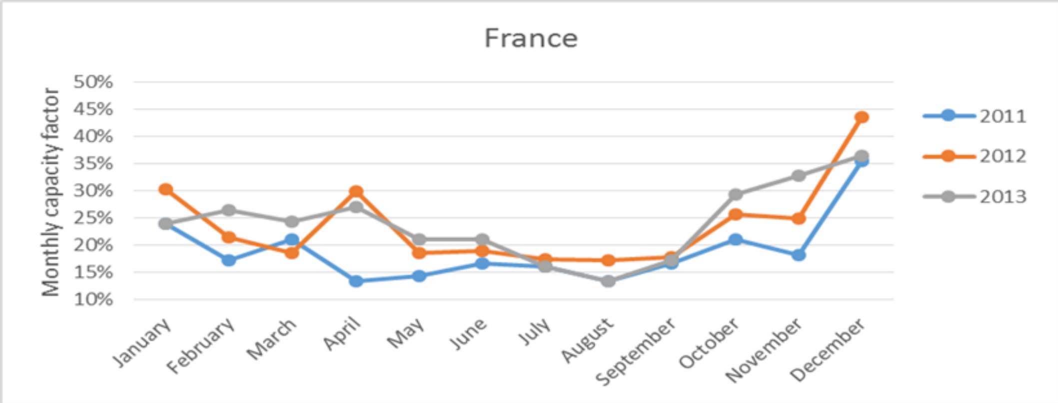

Spain
Weekly capacity factor
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51
Weeks
2012
2013

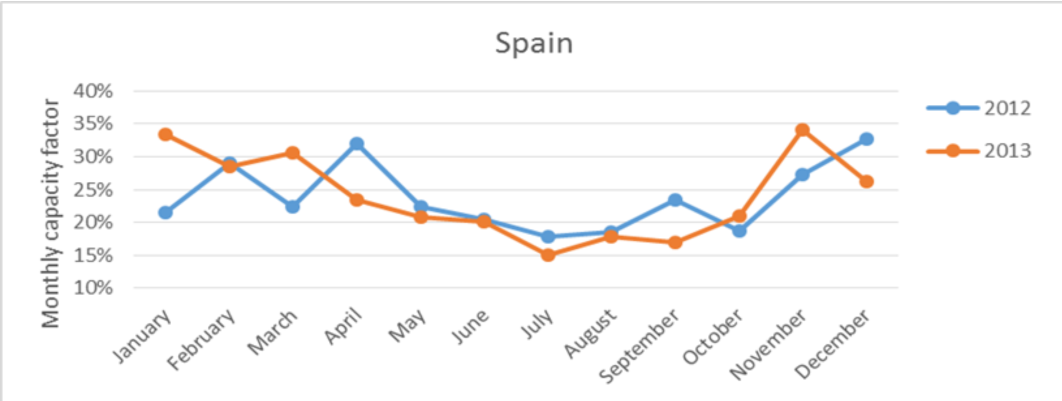
B4: Monthly time series of wind power production (% of maximum power output) for the period 2011-2013











B5: The correlation coefficient as a function of the distance

Table 33. Distance (in km) required for the correlation coefficient to drop by 50% at different starting points (in km) on different time scales.

Starting point (km)	hourly	daily	weekly	monthly
500	425	493	736	1385
750	383	467	764	1559
1000	309	405	748	1667
1250	213	321	705	1732
1500	103	221	641	1766

Table 34. The reduction of the correlation coefficient (in %) for a distance of 500 km at different starting points on different time scales.

Starting point (km)	hourly	daily	weekly	monthly
500	56%	50%	38%	26%
750	62%	53%	36%	23%
1000	75%	60%	36%	21%
1250	107%	73%	38%	19%