Long-term trends in the wind supply in the Netherlands

Alexander Bakker(1), Jan Coelingh(2) and Bart van den Hurk(1)
(1) Royal Netherlands Meteorological Institute/KNMI, PO Box 201, NL-3730 AE, De Bilt, Netherlands
(2) ECOFYS Netherlands, P.O. Box 8408, 3503 RK Utrecht, Netherlands
Contact: (1) bakker@knmi.nl(1) / (2) J.Coelingh@ecofys.com

Summary

Different measures for wind energy potential show very different long-term variations and trends. This seriously complicates the estimation of future long-term wind supply. Therefore, it is necessary to better understand these discrepancies. know the main causes of the reported decline. For this purpose different types of indices for the Netherlands are analysed and the influential production based index Windex-CBS is compared to different wind speed observation indices and to an index based on geostrophic wind speed.

High mutual correlations (monthly and annual) between the indices indicate that they do efficiently account for natural variability. Yet, the trends of the different indices do substantially differ from each other. The decrease of Windex-CBS is twice as large (200%) as the decrease of the wind speed based index. The trend of the difference between both indices is highly significant. This suggests that the Windex-CBS is contaminated by non-climatic or methodological factors. W-obs does not suffer from such factors and is therefore the preferred measure of wind supply.

About 80% of the decrease in W-land is explained by natural long-term variations in the wind climate. Long-term variability substantially increases the climatic uncertainty of future long-term yields. Geo-indices are potentially very useful for the quantification of the long-term variability as they do efficiently explain the natural variability of wind supply and because of the possibility to construct long time series.

1 Introduction

In Northwest Europe, wind supply is commonly expressed by means of a windiness index. A windiness index *W* is a measure of monthly/annual potential electricity production relative to its long-term average. National or regional indices are used to evaluate the performance of wind turbines and farms, to assess the natural variability and trends and to estimate future wind energy yields. Yet, different types of indices show very different trends and variabililty.

This study aims to evaluate the differences between five windiness indices for the wind energy potential in the Netherlands. Subsequently, it is shown how this information can be used to estimate near-future multi-year energy yields.

2 Windiness indices

2.1 Windex-CBS/Windex-WSH (production based)

Windex-CBS is the most influential measure for Dutch wind energy potential. In 2009, Statistics Netherlands (Centraal Bureau voor Statistiek/CBS) has taken over the systematic recording of wind supply in the Netherlands from Wind Service Holland (WSH). Despite small differences between both production indices, it was reasonably justified to simply extend the already reported Windex-WSH time series by Windex-CBS from 2008 onwards [1].

Windex-WSH was recorded from 1988 up to 2008. Before 1996, Windex-WSH was derived from wind speed observations by a meteorological consultancy (Figure 1). Since we want to clarify differences between production based indices and wind speed based indices, we applied our analysis also to the period 1996-2010.

WSH and CBS chose 1996-2005 as reference period on the basis of the availability of enough production data. This means that the long-term (1996-2005) average Windex-WSH equals 100% by definition. The same reference period is used for the alternative indices as defined in this chapter.

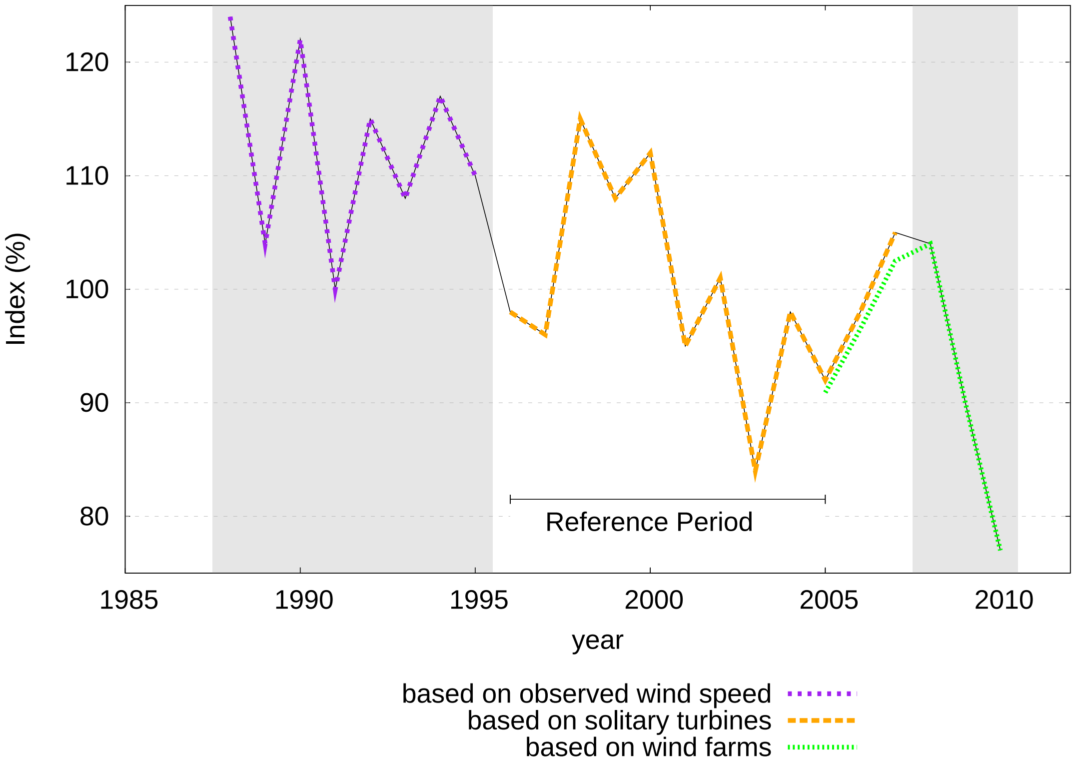

Figure 1. Annual Windex-WSH and Windex-CBS. Thin continuous line is the combined windiness index. The short dashed line is Windex-WSH based on wind speed observations (1988-1995), the long dashed line Windex-WSH based on the energy productions of many freestanding turbines (1996-2008) and the dotted line Windex-CBS based on energy productions of many wind farms (2004-2010).

2.2 Windex-obs (wind speed observations based)

Windex-obs uses the concept of potential wind U_p. U_p represents wind as it would have been measured over open grass land (surface roughness z_s=0.03m) at height h_p=10 meters. It is derived from observed wind and corrected for time and wind direction dependent deviations in local surface roughness by application of gustiness analysis [2]. As a consequence, time series of U_p are free of trends due to changes in local surface roughness or nearby inconsistencies (say within 200-500m).

Seven measurement sites situated in a relevant part of the Netherlands have been selected for the construction of Windex-obs (Figure 2, red dots). For each site, hourly U_p (1988-2010) is translated to a monthly windiness index. Windex-obs is the arithmetic mean of the seven site-indices. First, the potential wind is extrapolated to wind U_t at hub-height (h_t=90m) assuming neutral conditions:

$$U_t = U_p \left(\frac{\log(h_t / z_s)}{\log(h_p / z_s)} \right) \qquad (1)$$

Subsequently, a representative power curve (of the Nordex N-90 turbine) is applied to transform U_t to hourly energy production yields, Figure 3). Finally, the estimated hourly yields are aggregated to monthly and annual values and indexed by dividing by the long term average (1996-2005).

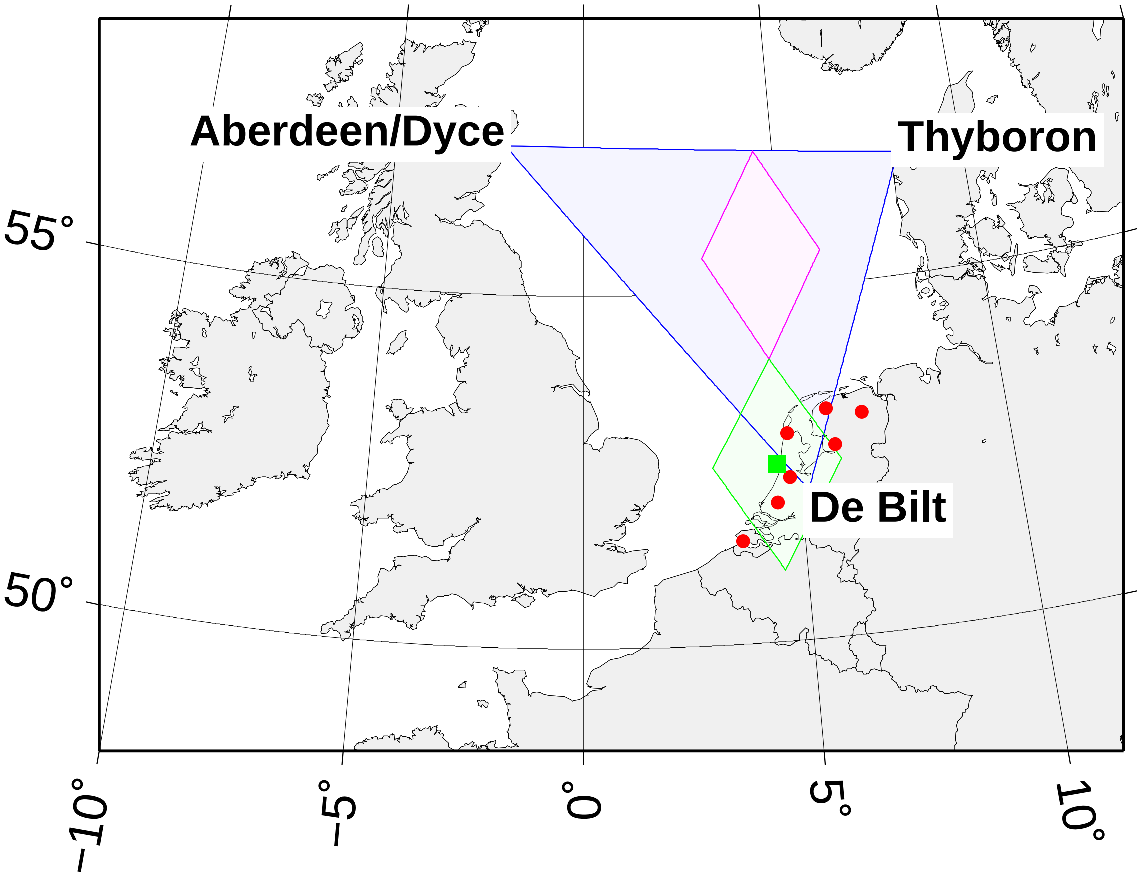

Figure 2. Measurement sites for wind speed and areas for which geostrophic wind speed has been derived. Windex-obs and U10-obs are derived from potential wind at red dots. The gridpoint on which U10-ERA is based, is indicated by the green square. ERA-Interim geowind is derived for the transparent diamonds-shaped areas (G-ERA is based on the green area) and ECA&D geowind for the large triangle-shaped area.

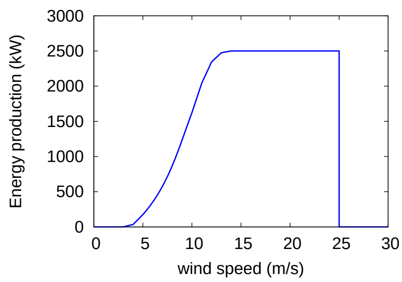

Figure 3. Power-curve wind turbine Nordex N-90

Windex-obs appears hardly sensitive to the assumptions made and to inconsistencies within the applied data [3]. The atmosphere above the Netherlands tends for instance to modest stability and not to neutral conditions. This slight incorrectness, however, will hardly affect Windex-obs if this incorrectness is on average constant in time. Changes in the measurement chain of wind speed hardly affect the results [4] and Windex-obs is also insensitive for the applied hub-height.

Observed changes in Windex-obs are therefore a combined result of stability and roughness changes and changes in the large-scale atmospheric circulation.

2.3 U10-obs

This index is like Windex-obs based on the potential wind as derived from the seven measurement sites. Yet, the wind speed has not been transformed to U_t and energy yields before aggregating.

2.4 U10-ERA

U10-ERA is very similar to U10-obs, but rather than observations, six hourly wind speed is retrieved from the ERA-Interim reanalysis archive are used [5]. A reanalysis is a meteorological data assimilation of observed weather applying a single consistent Numerical Weather Prediction model. Within the reanalysis also the land use is free of changes and so the surface roughness is constant.

2.5 G-ERA

G-ERA is very similar to U10-ERA, but geostrophic wind speed (geowind) is used rather than wind speed at 10m level. Geowind is a theoretical wind, balancing atmospheric pressure gradients and the Coriolis effect and is consequently independent of surface friction. At monthly and annual timescales, geowind and windiness indices correlate very well [6,7]. Therefore, it is an attractive measure to study the influence of changes in large scale circulation. The geowind at a certain grid point is derived from the pressure gradients between four surrounding grid points [3].

3 Differences in variability

The different indices show very high mutual annual and monthly correlations (R>0.97, Figure 4). This implies that all indices represent well the (timing of) the natural variability.

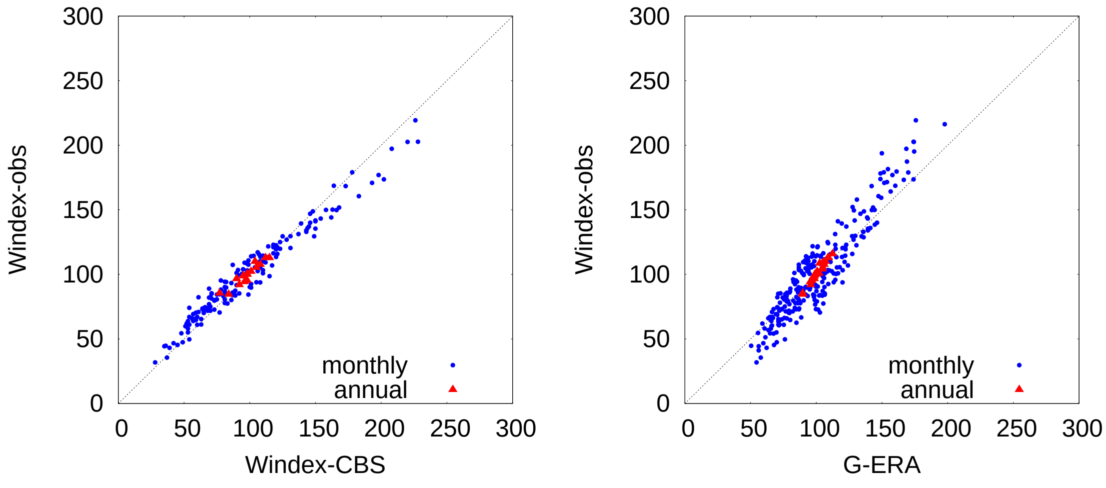

Figure 4. Scatterplots of monthly (blue) and annual (red) values for different pairs of indices

Yet, the standard deviation of Windex-CBS and Windex-obs is about twice as large as the other indices (Table 1). This discrepancy originates from the fact that Windex-CBS and Windex-obs really represent wind energy potential rather than wind speed [3]. The energy generation of the applied wind turbines is most sensitive for small variations in U_t if U_t is relatively low (3-7 m/s, see Figure 3). In the Netherlands, wind turbines commonly operate at such wind speeds. As a result, the relative variability of the production is larger than the variability of the wind speed and geostrophic wind. In the case that the turbines operate at much higher wind speeds (say between 5 and 15 m/s), the relative variability will be smaller than of the wind speed.

	1988-2010	1989-2010	1996-2010
Windex-CBS	8.5	8.5	8.9
Windex-obs	8	7.9	8.6
U10-obs	4.4	4.4	4.8
U10-ERA	**X**	4.4	4.8
G-ERA	**X**	5.6	6.1

Table 1. Annual standard deviation after detrending [% of long-term average (1996-2005)]

4 Differences in trends

In correspondence to the variability, the indices U10-obs, U10-ERA and G-ERA also show very well comparable trends of about -0.3%/yr (table 2). This implies that the influence of possible changes in atmospheric stability or in meso-scale surface roughness is very limited; substantial changes in stability would have led to a trend difference between G-ERA (free atmosphere wind) and U10-ERA (surface wind); and serious changes in meso-scale roughness would have led to a trend difference between U10-ERA (constant surface roughness) and U10-obs (sensitive to changes in meso-scale roughness). It appears that about 80% of the decrease in U10-obs originates from the decrease in G-ERA, i.e. from changes in large-scale atmospheric circulation.

	1988-2010	1989-2010	1996-2010
Windex-CBS	-1.17	-1.07	-1.08
Windex-obs	-0.59	-0.46	-0.47
U10-obs	-0.34	-0.28	-0.29
U10-ERA	**X**	-0.31	-0.27
G-ERA	**X**	-0.28	-0.28

Table 2. Trend with respect to long term average (1996-2005) [%/yr]

As with the variability, the decrease of Windex-obs is larger than the decrease of U10-obs. This is logical since the decrease appeared to originate largely from the natural variability in the large-scale circulation.

The decrease in Windex-CBS is about twice as large as in Windex-obs (figure 5). This discrepancy very likely originates from methodological or non-climatological factors [3]. The construction of Windex-CBS/WSH, for instance, was two times substantially changed (in 1996 and 2009). Despite all the efforts to properly concatenate the different types, those changes are very plausible causes for an artificial contribution to the observed trend. Also aging of the turbines was not explicitly taken into account, which could have led to an overestimation of the observed decrease. Yet, those and other hypotheses cannot be checked as the necessary data lack.

On the other hand, inconsistencies in the observed wind speed data (within the measurement chain, within the surroundings etc.) on Windex-obs have been extensively investigated [3] and their effect appeared limited. Therefore, we think Windex-obs is the preferred measure for monthly and annual wind energy potential.

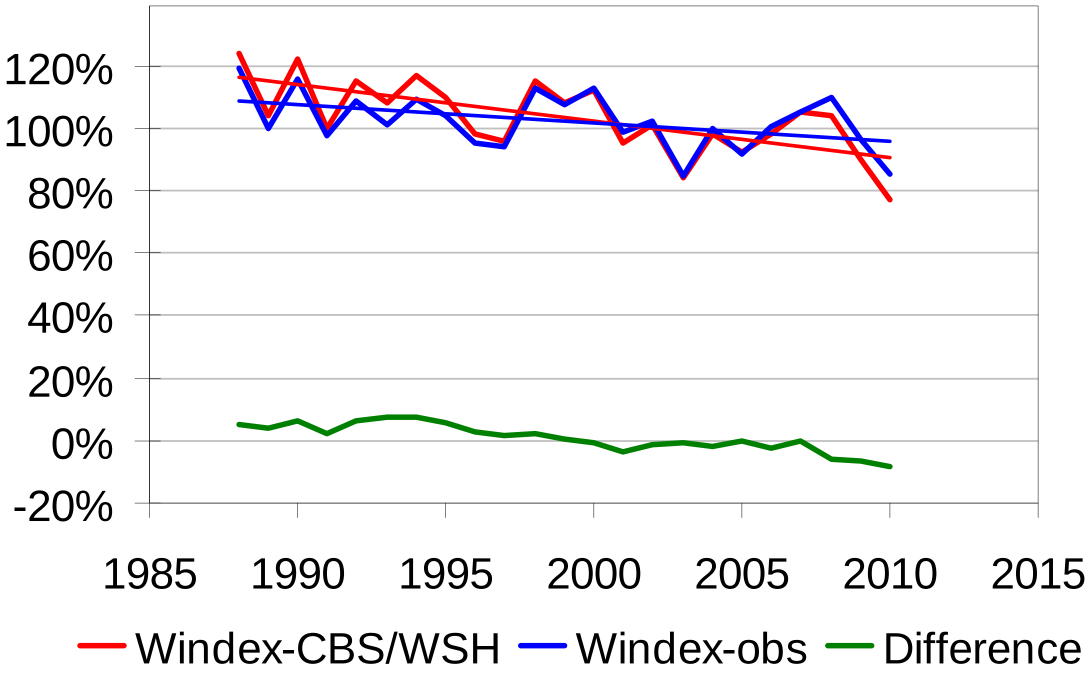

Figure 5 Windex-CBS and Windex-obs and their mutual difference with time

5 Perspectives

Windex-obs seems to be most representative for long-term variability of the wind energy potential in the Netherlands. The index is subject to a decrease of about 0.5 % per year, which is largely explained by natural long-term variability. The remaining question is how future long-term wind supply predictions could benefit from this information.

5.1 Long-term variability in wind climate

Geostrophic wind speed is a measure of large-scale atmospheric circulation that well explains the variability and a large part of the decline of the wind energy potential in and around the Netherlands. The calm-down of wind conditions from the last decades is generally attributed to natural multi-year variations (without clear periodicity) [6,8], also known as long-term persistence or the Hurst phenomenon [9]. In wind climate, the Hurst phenomenon could be interpreted as the tendency to cluster calm or stormy wind years in a relatively short period. Yet, such calm or windy episodes are hard to predict. Therefore, the existence of long-term persistence substantially increases the uncertainty of the estimated future long-term wind supply [6].

5.2 Quantification of the climatic uncertainty

Long-term persistence (LTP) is quantified by the Hurst exponent (*H*). *H* commonly ranges from 0.5 which yields no LTP (i.e. complete independence between successive years) up to 1.0 [10]. In case of known *H* and standard deviation σ_W of a windiness index *W*, the standard deviation of the *k*-year aggregated mean value $W^{(k)}$ is:

$$\mathrm{StD}\left(W^{(k)}\right) = \frac{\sigma_W}{k^{1-H}} \qquad (2)$$

which for *H*=0.5 reduces to the classical statistics law

$$\mathrm{StD}\left(W^{(k)}\right) = \frac{\sigma_W}{\sqrt{k}} \qquad (3)$$

Close to our area of interest Bakker and Van den Hurk found H_G of about 0.6 - 0.65 for geowind [6]. Assuming H_W=0.65, the climatic uncertainty of 10-year (*k*=10) aggregated wind energy yield can be estimated as follows. First, we estimate the one-year standard deviation StD($W^{(1)}$)=9.0% without detrending because the trend originates from natural variability rather than from structural changes. Second, we can use equation 2 to estimate the uncertainty of the estimated population mean E(*W*) (*n*=22) and the natural variability of $W^{(10)}$. Third, we use the quadratic sum of both components. So, we obtain a combined uncertainty of 5.0%. This is in contrast to 3.4% as combined uncertainty would have been estimated in the absence of LTP.

For newly planned wind farms that cope with a wide range of uncertainties about future energy yields, this will hardly affect the overall uncertainty of the future 10-year aggregated energy yield. When wind farms finally get operational, the many non-climatic uncertainties rapidly reduce and the climatic uncertainty and natural variability become more dominant.

5.3 Sensitivity of estimate to *H* and time series length

The exercise of the previous section is highly sensitive to the Hurst exponent and the length *n* of the windiness index time series (Figure 6). For known *H*, the influence of the time series length *n* on the overall uncertainty is limited as *n* is more than 1.5 or 2 times the prediction horizon *k*. This means that the overall climatic uncertainty largely depends on the natural variability (i.e. the unpredictability of the annual wind conditions) if the observed time series is sufficient long (*n*/*k*>1.5).

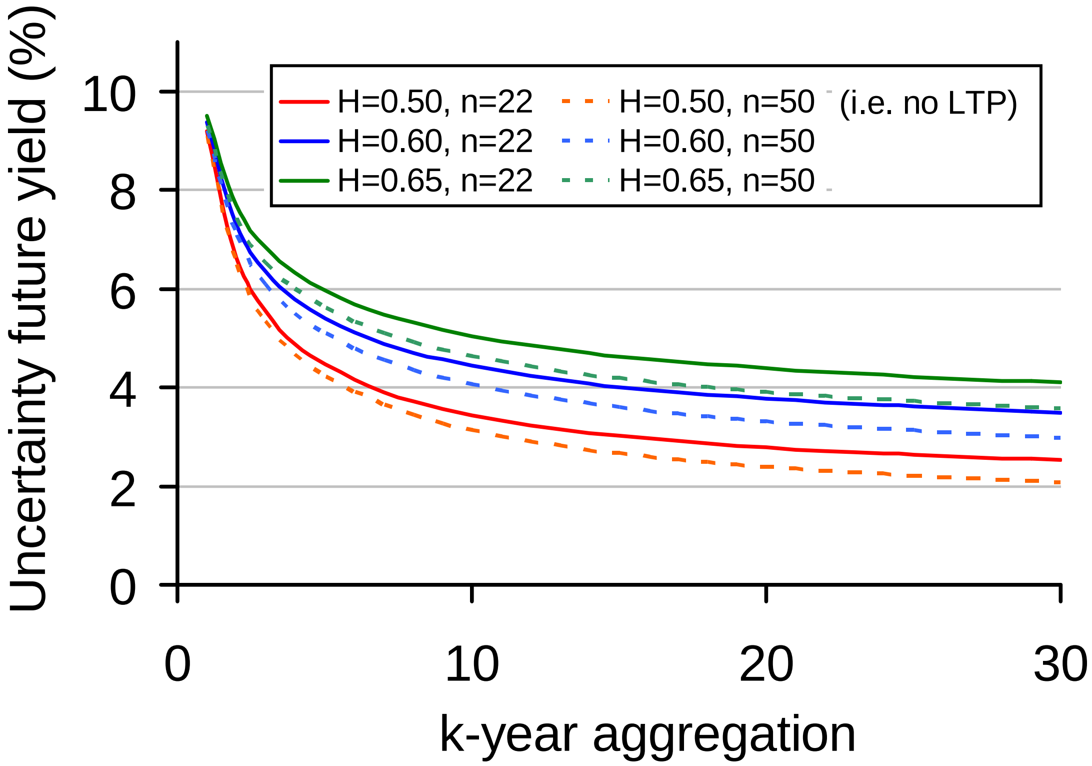

Figure 6. Climatic uncertainty of future yields for different Hurst exponent *H*, time series length *n* and prediction period *k*

Yet, the estimated uncertainty is very sensitive to the estimated *H* and accurate estimates of *H* do require long time series (*n*>100) [6,11].

5.4 Estimation of Hurst exponent and long-term variability

The scarcity of long (*n*>100) homogeneous wind speed records are scarce or even non-existent. Therefore, variations in wind climate are often investigated on the basis of proxies derived from observed pressure data [8]. Bakker and Van den Hurk [6] applied geowind derived from daily sea level pressure extracted from the European Climate Assessment (ECA) dataset [12].

In this study, we tested the potential of geowind derived from observations to study natural long-term variability in wind supply. However, the ECA database did not contain suitable data to assess wind conditions in the Netherlands and west of the Netherlands in the North Sea. The annual geowind within the closest investigated area and the ERA-Interim geowind in the centre of this area (Figure 2, blue triangle and pink diamond) have a mutual correlation of 0.95 for the period 1989-2007. This implies that the geowind derived from station data for large areas (mutual station distance between of about 500-800 km) is a good proxy for natural variability in wind supply too.

So, if appropriate sea level pressure data could be obtained this method may be applied to estimate the uncertainty of near future wind supply. And such data series do exist. Cornes [13] for instance, has recently homogenised daily pressure series spanning 1670-2007 for Paris and 1692-2007 for London. Also for Germany, daily pressure series are available from at least 1850 (ECA&D/ http://eca.knmi.nl/dailydata/datadictionary.php).

6 Conclusions

Windiness indices based on wind speed observations are preferred over production based indices if the effect of local inconsistencies can be properly minimised. This is efficiently done by applying the concept of potential wind.

Sufficient estimates of wind at hub height and potential energy yields from potential wind are important for accurate estimations of the relative variability. Small systematic errors are tolerated if these systematic errors are on average constant with time.

The observed decrease in wind energy potential of about 0.5 % per year between 1988 and 2010 originates largely from natural variability within the large-scale circulation. This large-scale circulation is subject to significant (non-periodic) long-term variations. The existence of this long-term variability substantially increases the climatic uncertainty of future long-term energy yields. The influence of climatic uncertainty on the overall uncertainty of newly planned wind farms is limited. Climatic variability is however relevant for long-term yield predictions for operational wind farms where many other uncertainties rapidly reduce with operation time.

Estimates of this uncertainty would require long records (*n*>100 years). Those records lack for our study area and a more pragmatic approach is necessary to quantify the effect of long-term variability. Long proxy records could be constructed from observed pressure data if such data would be easily available. Uncertainty estimates of future long-term energy yields would seriously benefit from such long records.

7 References

1. Segers R. Windex op basis van productiedata van het CBS afgeleid uit registratie van CertiQ. *Technical Report*; Statistics Netherlands/CBS: The Hague, the Netherlands, 2009 (in Dutch)
2. Verkaik J. Evaluarion of Two Gustiness Models for Exposure Correction Calculations. *Journal of Applied Meteorology* 2000; 39(9):1613-1626.
3. Bakker AMR, Van den Hurk BJJM, Coelingh JP. Decomposition of the windiness index in the Netherlands for the assessment of future long-term wind supply. *Wind Energy* (in review)

4. Wever N. Quantifying trends in surface roughness and the effect on surface wind speed observations. *Journal of Geophysical Research* 2012 (in review)
5. Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P et al. The era-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* 2011; 137(656): 553-597.
6. Bakker AMR, and Van den Hurk BJJM. Estimation of persistence and trends in geostrophic wind speed for the assessment of wind energy yields in northwest Europe. *Climate Dynamics* 2012; Doi:10.1007/s00382-011-1248-1. (accepted)
7. Albers A, Long term variation of wind potential: how long is long enough? *German Wind Energy Conference* 2004, Wilhelmshaven, Germany
8. Alexandersson H, Schmith T, Iden K, Tuomenvirta H. Long-term variations of the storm climate over NW Europe. *The Global Atmosphere and Ocean System* 1998; 6:97-120.
9. Koutsoyiannis D. Nonstationarity versus scaling in hydrology. *Journal of Hydrology* 2006; 324(1-4):239-254.
10. Koutsoyiannis D. Climate change, the Hurst phenomenon, and hydrological statistics/Changement climatique, phénomène de Hurst et statistiques hydrologiques. *Hydrological Sciences Journal* 2003; 48(1): 3-24.
11. Tyralis H, Koutsoyiannis D. Simultaneous estimation of the parameters of the Hurst-Kolmogorov stochastic process. *Stochastic Environmental Research and Risk Assessment* 2010; :1–13.
12. Klok EJ, Klein Tank AMG. Updated and extended European dataset of daily climate observations. *International Journal of Climatology* 2008; 29(8):1182–1191.
13. Cornes R. Early Meteorological Data from London and Paris: Extending the North Atlantic Oscillation Series. *PhD Thesis* 2010, Climate Research Unit, School of Environmental Sciences. University of East Anglia.