Impact of German Wind Generation Forecasts on Net Transfer Capacities

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***Abstract*—Because of its localization and its variability, wind generation can rapidly change the pattern of physical electrical flows between AC interconnected countries and adds more uncertainty in power system operation. Therefore, the increasing installed wind generation capacities may hamper the commercial net transfer capacities made available between countries.**

Through a statistical analysis using generalized additive models (GAM) on data from March 2008 to June 2010, this paper looks at the impact of the day-ahead hourly forecasts of German wind generation on the day-ahead net transfer capacities (NTCs) from Germany to France.

Results are five-fold. First, the analysis shows that wind generation forecasts have a significant impact on the NTC, by explaining around 14% of the deviance. Second, this effect is negative: more the wind blows, less NTC are available. Third, German wind generation areas have different impacts. The paper shows that 50Hz and Amprion have the greatest influence. Fourth, the German consumption forecast impacts the NTC, but to a lower extent than wind generation forecasts, while the French consumption exhibits no significant effect. Last, the modeling is still incomplete and several improvements are proposed.

NOMENCLATURE

f_i	Spline function i in the estimated model
$\hat{f}_i$	Estimated function of f_i obtained by projection on a spline basis
t	Hour of operation. For the sake of simplicity, this index is omitted throughout this paper
$C^{DE}(t)$	Day-ahead consumption forecast in Germany for delivery at hour t [MW]
$C^{FR}(t)$	Day-ahead consumption forecast in France for delivery at hour t [MW]
DE	Deviance explained by the estimated model
$D(t)$	An integer comprised between 1 (i.e., the 1st of January) and 365 to qualify the day number of hour t
LRI	Likelihood ratio index of the estimated model
$NTC^{DE \to FR}(t)$	Net Transfer Capacity (NTC) made available in day-ahead by the Transmission System Operators (TSOs) for the exchanges from Germany to France for delivery at hour t [MW]
$W^{DE}(t)$	Day-ahead wind generation forecast in Germany for delivery at hour t [MW]
$W^{z}(t)$	Day-ahead wind generation forecast in the German area z, i.e., 50Hz, Amprion, EnBW or Transpower, for delivery at hour t [MW]
α	Intercept of the estimated model [MW]
$\epsilon(t)$	Residual error of the estimated model for delivery at hour t [MW]
$\mathcal{D}$	Deviance of the estimated model
$\mathcal{D}_0$	Deviance of a model with only one constant
$\mathcal{L}$	Likelihood of the estimated model
$\mathcal{L}_0$	Likelihood of a model with only one constant

I. INTRODUCTION

Regularly, the European Transmission System Operators (TSOs) calculate the commercial capacities that will be made available to exchange electrical energy between market areas through various mechanisms, such as the day-ahead electricity spot market. These commercial capacities, called Net Transfer Capacities (NTCs), thus play a crucial role in European electricity markets [1].

In order to determinate the NTCs, TSOs model the various elements of the electrical system such as generation, network topology and consumption, which implies a huge amount of data and relatively complex load-flow modeling [2]. In particular, as the integration of wind generation increases with time, its potential impact on NTC calculations is emphasized as well. To schematically illustrate this potential impact, Fig. 1 represents a change in flows because of wind generation. In this example, a 1,000-MW wind generation increase in North of Germany is compensated by a 1,000-MW fossil-fuel generation reduction in South. This change in the generation dispatch induces a variation of the physical flows in the electrical network. If such power flows exhibit a round shape, they are called loop flows and their evaluation is essential for TSOs in order to properly assess NTCs. Therefore, this simple example, which illustrates actual power system operation events identified by some European TSOs [3] and

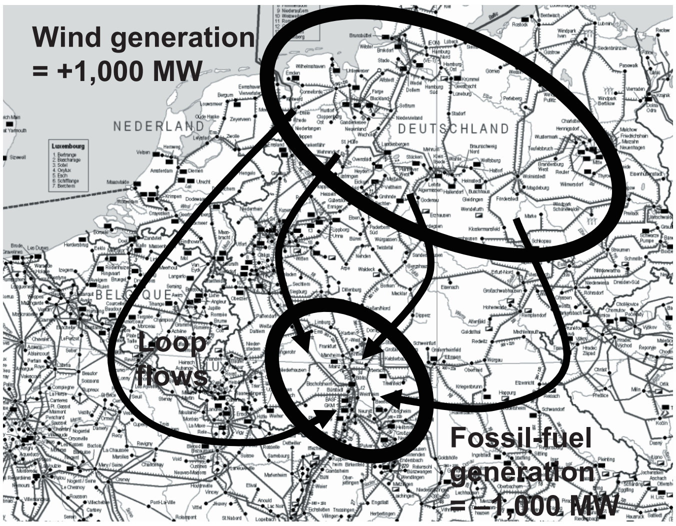

Fig. 1. Illustration of the potential impact of a change in the generation dispatch due to wind generation. Map from [5]

theoretical cases described using a bottom-up model [4], shows that wind generation has to be taken into account by TSOs in NTC calculations. Furthermore, since wind generation is by nature uncertain, TSOs may have to take extra margin while estimating NTCs, which may lead to NTC reductions. Therefore, wind generation forecasts are strongly likely to impact NTCs.

The objective of the present paper is to evaluate the effect of German day-ahead wind generation forecasts on the net transfer capacity from Germany to France through a top-down approach. Section II describes the data considered in this paper. Then, section III introduces the method selected, i.e., a Generalized Additive Model (GAM). Last, section IV presents the method implementation and the results.

II. Data description

The data available for this study span from the 18th of March 2008 to the 26th of June 2010, and represent 18,249 hourly observations.

A. Net transfer capacities

The hourly net transfer capacities are calculated by the European TSOs two days ahead before being sent to the day-ahead electricity market operators. This paper is focused on the NTC from Germany to France, because this NTC exhibits a strong variability and hence is likely to be impacted by wind generation. The time series $NTC^{DE\rightarrow FR}$ was downloaded from the data platform entsoe.net [6] and is plotted in Fig. 2.

$NTC^{DE\rightarrow FR}$ shows a clear seasonality between Summer and Winter. The lower values during Winter demonstrate that the increase of physical power flows during this season hampers the benefits from the increase of the line thermal limits. Regarding thermal limits, convection depends on wind [7]. Therefore, with an increased usage of dynamic line ratings in the future, wind would be likely to increase NTCs.

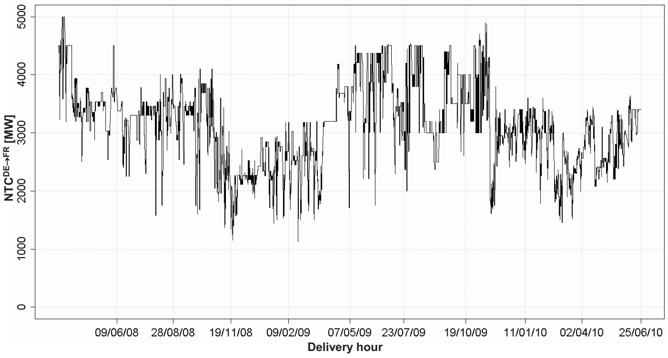

Fig. 2. Day-ahead net transfer capacity $NTC^{DE\rightarrow FR}$ as a function of time

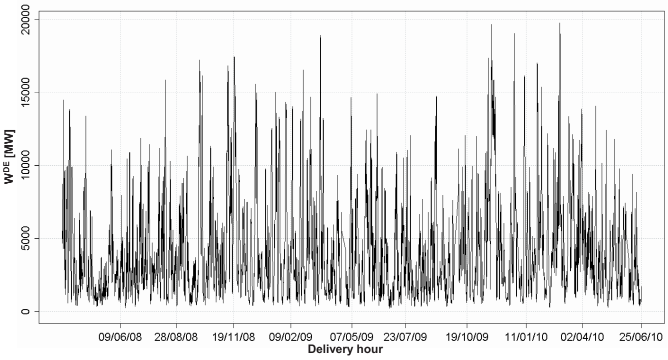

Fig. 3. Day-ahead wind generation forecast W^{DE} as a function of time

Last, the stepwise shape in the series demonstrates that this variable depends on human decisions, and not from a purely natural phenomenon. On other European interfaces, the stepwise effect is even neater, with a discretization granularity at 100 MW on some interfaces [6].

B. Wind generation

German day-ahead wind generation forecasts were downloaded from TSOs' websites [8]–[11] and the geographical localization of each German TSO is given in Fig. 4. Because TSOs calculate the NTC two days ahead [12], using the two-day-ahead wind generation forecast would have been more consistent. However, this value was not available at the time of the study. As the day-ahead wind generation forecasts are available for every 15 minutes, the hourly averages have been taken after testing other transformations, such as the maximum forecast over the hour.

Fig. 3 shows the series of the aggregated German wind forecast W^{DE}, which is basically the sum of W^{50Hz}, $W^{Amprion}$, W^{EnBW} and $W^{Transpower}$. Strong wind generation forecasts are thus observed, with values up to 19.8 GW.

C. Demand

The French and German day-ahead demand forecasts, C^{FR} and C^{DE}, were also downloaded from the data platform entsoe.net [6]. They have been included in the model since they are easily available and they are likely to have an

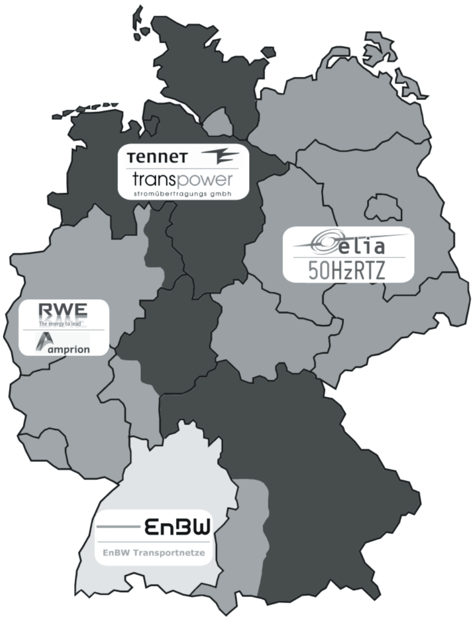

Fig. 4. Geographical localization of German TSOs [13]

impact on the NTC, as explained in section I. The day-ahead demand forecasts are not plotted here as they do not bring any particular insight.

III. Methodology

This work aims at describing the potential links between variables. Therefore, no predictive modeling has been performed. Amongst the various methods available to assess such potential links between wind generation forecasts and $NTC^{DE \to FR}$, three methods were implemented in this study. After trying two linear models, a semi-parametric modeling was finally chosen because of its better fit to catch non-linear effects of the dataset.

The first method tested is a logistic regression [14], which aims at calculating the NTC's ownership probability to one of the defined categories ($NTC^{DE \to FR}$ low, medium or high) as a function of the German wind generation forecast W^{DE}. This quite simple method can only give simple qualitative results, such as a high wind generation forecast has a high probability to lead to a low NTC.

The second method uses a segmentation technique [15] to fit a piecewise linear regression model in which all the parameters are estimated at once. The particular segmentation technique [15] exhibits four advantages: (a) it detects segments with specific trends; (b) it automatically chooses the length and the position of the segments; (c) the algorithm is simple and does not require any dynamic programming; and (d) it leads to short computation times (a few minutes) for the dataset considered here. On the down side, an empirical parameter is needed to find the appropriate number of segments. Furthermore, this model was unfortunately costly in parameters for the considered dataset. In fact, this method led in this case to 35 segments and thus around 100 parameters, as each segment includes a constant, a slope and the temporal indication of the start of the segment.

The third method implemented is a Generalized Additive Model (GAM) [16]. The GAM technique chosen here is explained in [17] and is available in the R-package mgcv [18]. The first advantage of a GAM is to remove the assumption of linear effects. In fact, the links between the NTC and the explanatory variables are modeled here by spline functions, which are piece-wise polynomial functions with regularity constraints at the knots [17]. Furthermore, a GAM is additive, so it allows to easily interpret the effects of each explanatory variable and it avoids performing specific statistical analysis to select beforehand the explanatory variables. As a third advantage, this particular technique does not need any empirical parameters to find the appropriate knots and to estimate the regularity of the functions. Moreover, though GAM techniques were initially developed for non-temporal data, they prove their interest for time series, for example in the analysis of the French consumption [19]. Regarding the number of parameters, the estimated degree of freedom (edf), which equals the trace of the smoothing matrix [18], is around eight for each explanatory variable considered here. Therefore, the model has a reasonable number of parameters in this case. Last, computation time is not an issue for this dataset, as models are estimated here in a few minutes. Because of all these advantages over the two other methods tested, this model was selected as the most appropriate for this study. Therefore, the rest of this paper is focused on the implementation and the results from this GAM.

IV. Results

A. Model estimation

The model estimated in this paper is written as in (1), where α is a constant, D is a day variable introduced in order to take into account the temporal effect, f_n are spline functions and $\epsilon \sim \mathcal{N}(0, \sigma^2)$.

$$\begin{aligned} NTC^{DE \to FR} &= \alpha + f_{11}(W^{50Hz}) + f_{12}(W^{Amprion}) \\ &\quad + f_{13}(W^{EnBW}) + f_{14}(W^{Transpower}) \\ &\quad + f_2(C^{DE}) + f_3(C^{FR}) + f_4(D) + \epsilon \end{aligned} \quad (1)$$

Fig. 5 shows the estimated functions $\hat{f}_i$ obtained by projections on a spline basis with the R-package mgcv [18]. Results are four-fold. First, from our modeling and under the dataset considered, the German wind generation forecasts mostly exhibit a negative effect on the NTC from Germany to France.

Second, the estimated functions obtained for each TSO show different interactions. On the one hand, the wind generation forecasts of 50Hz (W^{50Hz}) and Amprion ($W^{Amprion}$) exhibit a clear negative effect on $NTC^{DE \to FR}$. For 50Hz, this effect can be explained by an important installed wind generation capacity, with observed peaks at 8.3 GW. For Amprion, this negative influence may be due to its geographical proximity with the French and Dutch boundaries (see Fig. 4),

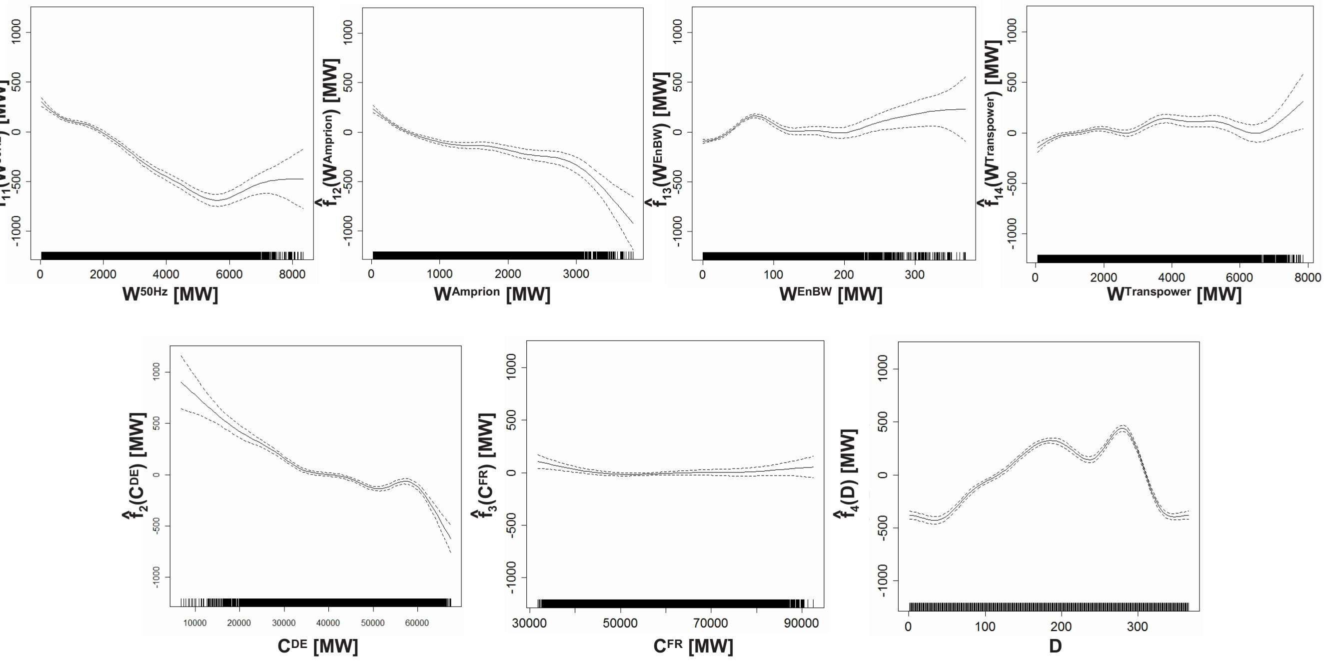

Fig. 5. Estimated functions $\hat{f}_i$ for model (1)

which may favor loop flows. On the other hand, though being close to the French border, the EnBW zone has a small amount of installed wind generation capacity that leads to a negligible impact of W^{EnBW} on $NTC^{DE\rightarrow FR}$. Regarding Transpower, the effect is also negligible, whereas the maximum wind generation forecast equals 7.8 GW.

Third, the estimate function $\hat{f}_3$ related to the French consumption forecast C^{FR} is mainly flat. Furthermore, though being statistically significative, probably because of the shape of $\hat{f}_3$ for low C^{FR}, the approximate p-value [18] related to C^{FR} is less significative than those for the other explanatory variables. The limited impact of C^{FR} on $NTC^{DE\rightarrow FR}$ seems logical, since German TSOs are in charge of computing the NTC from Germany to France and thus may not have a good vision of the French consumption. However, this conclusion is likely to change by the adoption in November 2010 of a coordinated NTC calculation by French and German TSOs alongside the Central-West Europe (CWE) market coupling initiative [20], which includes a larger geographical area than the one considered in the dataset. From the German point of view, the German wind generation forecast C^{DE} clearly impacts negatively the net transfer capacity $NTC^{DE\rightarrow FR}$.

Last, the day number D plays also a role in estimating $NTC^{DE\rightarrow FR}$. From a physical point of view, the day number takes into account the changes in the maximal operating line intensities. However, this variable is also likely to serve as a proxy to other explanatory variables. Hence, the inclusion of new explanatory variables may improve the model.

Regarding residuals, they first do not show any particular auto-correlation from a PACF analysis, which validates the time independency hypothesis. Second, Fig. 6 provides the

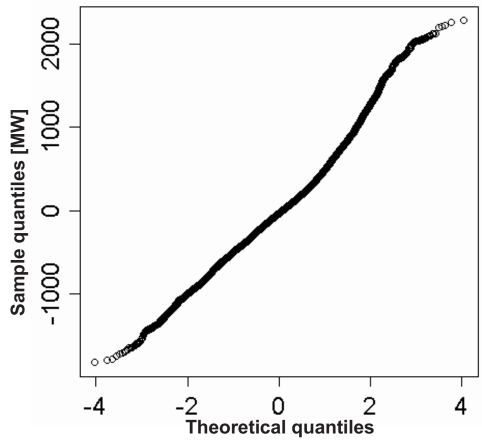

Fig. 6. QQ-plot of residuals from model (1)

QQ-plot associated to the residuals of the estimated model. The horizontal axis is related to a normal distribution, while the vertical axis exhibits the sample quantiles. As the QQ-plot is close to a line, the assumption relative to a normal distribution of the residuals is relatively good. However, regarding model accuracy, the residuals are up to 2,200 MW, with a standard deviation at 540 MW, which is large in comparison to the observed $NTC^{DE\rightarrow FR}$ (see Fig. 2).

B. Model completeness

In order to check the completeness of model (1), the deviance explained (DE), as defined in (2), has been calculated, where $\mathcal{D}$ is the deviance of the estimated model with explanatory variables and $\mathcal{D}_0$ is the deviance of a model

TABLE I
CONTRIBUTIONS OF EXPLANATORY VARIABLES TO THE DEVIANCE EXPLAINED IN MODEL (1)

Explanatory variables	Contributions to the DE
D	5.3%
W^{50Hz}	3.4%
C^{DE}	2.2%
W^{EnBW}	1.1%
$W^{Amprion}$	1.0%
$W^{Transpower}$	0.3%
C^{FR}	0.1%

with only one constant [18]. The deviance explained (DE) thus quantifies the completeness of an estimated model. A hypothetical DE equaling 100% would indicate that all the information necessary to explain the NTC variations would be in the estimated model. The DE is thus similar to the Likelihood Ratio Index (LRI) defined in (3), sometimes called pseudo-R^2 [21]. The difference between these two metrics lies in the usage of the log-likelihood for the LRI and the deviance for the DE. Note that the amplitudes of variations because of a given explanatory variable are given by the related estimated function $\hat{f}_i$, as shown in Fig. 5. Model (1) estimated here exhibits a deviance explained of 40.6%, which shows that this modeling clearly brings information, but is still incomplete.

$$DE = 1 - \frac{\mathcal{D}}{\mathcal{D}_0} \tag{2}$$

$$LRI = 1 - \frac{\ln \mathcal{L}}{\ln \mathcal{L}_0} \tag{3}$$

It is also important to evaluate the contribution of each explanatory variable to the model. Therefore, for each explanatory variable, the DE without the related estimated function $\hat{f}_i$ has been estimated, keeping the other estimated functions as in the full model (1). The DE of this reduced model is then subtracted to the DE of the full model. This difference gives what is called here the contribution to the deviance explained. The results are given in Table I and are classified by order of contribution. First, the limited effect of Transpower is confirmed. Second, by estimating the DE of the model with no wind generation forecast, it appears that wind generation forecasts contribute at 13.8% to the deviance explained. As deviance is not additive, this contribution to the DE does not equal the sum of all the wind forecast contributions in Table I. Therefore, in a statistical modeling, wind generation forecasts have to be taken into account, though they are not sufficient to explain properly the NTC variations. Third, it appears that the wind generation forecasts bring much more information to the model than consumption forecasts. Especially, the negligible contribution of C^{FR} is confirmed, and the contribution of C^{DE} is limited at around 2%. However, taking into account the regional demands instead of the national ones and considering correlation between C^{DE} and D are likely to improve the model.

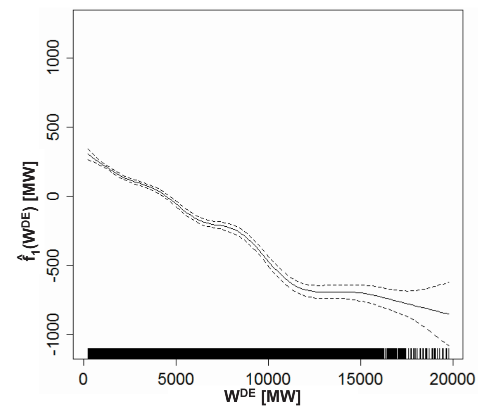

Fig. 7. Estimated function $\hat{f}_1$ associated to the German wind generation forecast W^{DE} in model (4)

C. Impact of the aggregated German wind generation forecast

In order to assess a simpler model, a second GAM has been estimated as described in (4), where α, f_2 and f_4 have been re-estimated and exhibit similar shape as for model (1). Fig. 7, which represents the function $\hat{f}_1$, clearly shows again the negative link between German wind generation forecast and the NTC from Germany to France. This new model, though being more simple has a deviance explained of 38%, instead of 40.6% for model (1), with a contribution of W^{DE} to the DE of 14.3%.

$$\begin{aligned} NTC^{DE\rightarrow FR} &= \alpha + f_1(W^{DE}) \\ &\quad + f_2(C^{DE}) + f_4(D) + \epsilon \end{aligned} \tag{4}$$

V. CONCLUSION

The main contribution of this paper is to propose a top-down approach to assess the impact of wind generation and consumption forecasts on the commercial transfer capacities (NTCs). Data used includes around 18,000 hourly observations from March 2008 to June 2010. Amongst the three implemented models, i.e., a logistic regression, a segmentation technique and a generalized additive model (GAM), only the latter is presented in this paper because of its fit for this particular problem. However, all the three models show the same negative relation between day-ahead wind generation forecast and the day-ahead NTC from Germany to France.

Results are five-fold. First, the analysis shows that wind generation forecasts have a significant impact on the NTC, by explaining around 14% of the deviance. Second, this effect is negative: more the wind blows, less NTC are available. Third, German wind generation areas have different impacts. The paper shows that 50Hz and Amprion have the greatest influence. Fourth, the German consumption forecast impacts the NTC, but to a lower extent than wind generation forecasts, while the French consumption exhibits no significant effect. Last, the modeling suffers from various limits and needs future improvements. In particular, the current model explains only very partly NTC variations.

Beyond these conclusions, this work opens perspectives for future work. First, the modeling can be improved, especially by considering the explanatory variables as non-independent from each other. For instance, the German demand C^{DE} is correlated to the day D, and the German regional wind generations are likely to be correlated to each other. Another way of improving the modeling would be to include additional variables such as: (a) two-day-ahead wind generation forecasts; (b) line maintenance operations, which are difficult to code properly as a line maintenance can have very different impacts; (c) the generating units that are online close to the border; (d) the gradient of the expected regional equilibrium between generation and consumption; (e) the ratio of wind generation over the consumption; or (f) generation and consumption data related to other neighboring countries, such as Poland, Czech Republic or the Netherlands. Other methods, such as the quantile regression seem promising and should be investigated as well. Last, using a longer data timeline is likely to improve the model estimation, though the NTC calculation techniques may have changed over the last decade.

Second, the same methodology could be applied to other frontiers, especially those close to Belgium or the Netherlands, which are subject to loop flows.

Third, as this method relies on historical data, it cannot help predict the future impact of an increased wind generation integration. The quantification of the long-term link between NTCs and wind generation forecasts should be studied by using bottom-up models. However, the present paper showed that long-term economic studies, such as [1], may have to include an analysis of their sensitivity to a potential dependency between NTCs and wind generation.

Last, similar modeling has to be performed regularly to confirm these conclusions, as power system conditions change over time (e.g., with a greater integration of wind generation in the European portfolio), as well as the TSOs' operation rules, for example with the adoption of a coordinated NTC calculation.

To conclude, this paper results in two recommendations to policy makers. First, since German TSOs clearly include wind generation forecasts into their NTC calculation and because understanding NTC calculation is essential for stakeholders to better anticipate the future electricity markets, TSOs should publish their NTC calculation methodologies. Second, regarding data, the research community would benefit from the timeline extension of data made available by the ENTSO-E, which is currently set to two years.

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