Development of a probabilistic methodology for adequacy assessment under uncertainty

– considering spatially correlated uncertainties and flow-based market coupling –

21st Conference of the International Federation of Operational Research Societies

Benjamin Böcker, Julia Bellenbaum, Thomas Kallabis, Christoph Weber
Quebec, 17.07.2017
Challenges in future energy systems

Motivation and methodology overview

Future energy systems are ...

- increasingly supply-dependent by growing shares of renewable energy sources (RES)
- highly uncertain in the amount of RES infeed (almost between 0 and 100% of installed capacity within a year)
- loosing conventional technologies as most important flexibility option

Options to cope with this challenges:

- alternative flexibilities (e.g. storage systems, DSM, power-2-X)
- building or expanding interconnections
Objective: Assessment of security of supply (system adequacy)

Motivation and methodology overview

Security of supply (SoS) increasingly driven by
- following uncertain key factors in the system
  - infeed of RES
  - demand
  - availability of conventional / storage technologies
- available interconnections between regions

Assessment of SoS by using indicators as
- loss of load probability (LOLP)
- expected energy not served (EENS)
Approach: Methodology Overview

Motivation and methodology overview

Stochastic characterization of main uncertainties

Optimal cross-zonal exchange considers interconnections

\[
\text{conventional capacity} + \text{renewable capacity} - \text{demand} = \text{free capacity} \\
\text{Monte-Carlo Simulation}
\]

\[
\min \sum \text{free capacity} \rightarrow \text{remaining free capacity}
\]

Adequacy assessment: LOLP, EENS
<table>
<thead>
<tr>
<th>Agenda</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of a probabilistic methodology for adequacy assessment under uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motivation and methodology overview</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic characterization (Quantile regression and Copula)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probabilistic method for adequacy assessment (Monte-Carlo)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conclusion</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overview

Stochastic characterization (Quantile regression and Copula)

1. Installed capacity / yearly demand, historic data
2. Installed capacity / yearly demand, application data
Quantile regression

- estimation of the marginal conditional (multivariate) distributions
- quantile regression describes uncertainties by parametric estimations of each quantile with respect of their dependencies (e.g. time of the year \(t\), hour of the day \(h\), day of the week \(d\) and region \(r\))

Quantile regressions on functions of \(t\)

\[
\min \sum_{t \in X_i} d_q(t)
\]

\[
d_q(t) = \begin{cases} 
q|e_q(t)| & e_q(t) \geq 0 \\
(1-q)|e_q(t)| & e_q(t) < 0 
\end{cases}
\]

\[e_q(t) = y(t) - f_p(t)\]

\(q\): quantile, \(f_p(t)\): parametrized function

- assuming following double cosine function

\[f_{h,d,r,p}(t) = \alpha_0|h,d,r,p| + \alpha_1|h,d,r,p| \cdot \cos\left(2\pi \cdot t + \beta_1|h,d,r,p|\right) + \alpha_2|h,d,r,p| \cdot \cos\left(4\pi \cdot t + \beta_2|h,d,r,p|\right)\]
Copula

Stochastic characterization (Quantile regression and Copula)

- Copulas describe the dependencies detached from marginal distributions.
- Estimation of copula requires uniformly distributed values, respectively the appropriate quantiles.
- Wide range of copulas is available but only few are suitable for high dimensional problems.
- Gaussian copula is chosen (defined by one parameter).

Gaussian Copula

Source: http://shiny.hydrology.ruhr-uni-bochum.de:3838/
Exemplary Results: PV (Germany)

Stochastic characterization (Quantile regression and Copula)

Gaussian Copula, correlation matrix
Exemplary Results: Wind Onshore (Germany)

Stochastic characterization (Quantile regression and Copula)

Gaussian Copula, correlation matrix
Exemplary Results: Demand (Germany)

Stochastic characterization (Quantile regression and Copula)

- including effects of uncertain supplemented temperature (daily average) on heating
- parametrization shows higher effect in FR than in other countries – more electric heaters
Development of a probabilistic methodology for adequacy assessment under uncertainty

1. Motivation and methodology overview
2. Stochastic characterization (Quantile regression and Copula)
3. Probabilistic method for adequacy assessment (Monte-Carlo)
4. Application
5. Conclusion
For each region, each uncertainty factor and single (or multiple) time step(s):

1. Draw many (~1 million) correlated unif. distr. values (corresponding to quantiles) – using Gaussian copula

2. Use reverse $cdf$ ($cdf^{-1}$) for the direct transformation to normalized (relative) simulation values
Overview

Probabilistic method for adequacy assessment (Monte-Carlo)

3. scale up according to application (e.g. installed capacity or annual demand)
4. calculate **free capacity** for each country
5. identify **critical scenarios** (at least one country with neg. free capacity)
6. perform optimized cross-zonal exchange calculation (FBMC & NTC) for each critical scenario and calculate the **remaining free capacity** as well as **limitations on the transmission lines (resp. critical branches / CB)**
## Optimal cross-zonal exchange (OCZE) calculation

### Problem Formulation

#### Objective function

\[
\min z = \sum_i L_{\text{neg},i}^\text{rem}
\]

#### Main restriction

\[
L_{\text{pos},i}^\text{rem} - L_{\text{neg},i}^\text{rem} + NEX_i^{\text{NFB}} + NEX_i^{\text{FB}} = L_i \quad \text{for } \forall i
\]

#### Restriction non FB

\[
\sum_{c \in \text{NFB}_i^{\text{ex}}} f_c - (1 - \eta_{\text{trans}}) \cdot \sum_{c \in \text{NFB}_i^{\text{im}}} f_c \leq NEX_i^{\text{NFB}} \quad \text{for } \forall i
\]

#### Restriction FB

\[
\sum_k \text{PTDF}_{c,k} \cdot NEX_k^{\text{FB}} \leq K_c \quad \text{for } \forall i
\]

#### Other

\[
L_{\text{neg},i}^\text{rem}, L_{\text{pos},i}^\text{rem}, f_c \geq 0
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_i)</td>
<td>free capacity</td>
</tr>
<tr>
<td>(L_{\text{neg},i}^\text{rem})</td>
<td>remaining negative free capacity</td>
</tr>
<tr>
<td>(NEX_i^{\text{NFB}})</td>
<td>net export – non-flow based (NTC)</td>
</tr>
<tr>
<td>(NEX_i^{\text{FB}})</td>
<td>net export – non-flow based (FB)</td>
</tr>
<tr>
<td>(f_c)</td>
<td>load flow – non-flow based (NTC)</td>
</tr>
<tr>
<td>(K_c)</td>
<td>transfer capacity (NTC), RAM (FB)</td>
</tr>
<tr>
<td>(\text{PTDF}_{c,k})</td>
<td>power-transfer-distribution-factor (FB)</td>
</tr>
<tr>
<td>(\eta_{\text{trans}})</td>
<td>transmission efficiency</td>
</tr>
</tbody>
</table>
Adequacy assessment

Probabilistic method for adequacy assessment (Monte-Carlo)

- free capacity
- number of critical scenarios
- remaining free capacity
- number of remaining critical scenarios
- limitations on the transmission lines (resp. critical branches / CB)

Adequacy indicators such as

- loss of load probability (LOLP) [percent, no unit]
- loss of load expectation (LOLE) [hours / year]
- expected energy not served (EENS) [MWh / year]
- relative EENS per country [percent, no unit]

Relevant limitations on transmission lines and critical branches

- described by marginal impact of transmission restrictions
- on critical time steps
- average over the year
### Agenda

**Development of a probabilistic methodology for adequacy assessment under uncertainty**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivation and methodology overview</td>
<td>1</td>
</tr>
<tr>
<td>Stochastic characterization (Quantile regression and Copula)</td>
<td>2</td>
</tr>
<tr>
<td>Probabilistic method for adequacy assessment (Monte-Carlo)</td>
<td>3</td>
</tr>
<tr>
<td>Application</td>
<td>4</td>
</tr>
<tr>
<td>Conclusion</td>
<td>5</td>
</tr>
</tbody>
</table>
### Scenario Assumptions

**Application**

- **Parametrization (ENTSO-E transparency platform):**
  - Five years of historical time series data (wind on/off, PV, run of river, demand)
  - Conventional technologies (using average availabilities for single typical size, different for winter and summer periods)

- **Application (ENTSO-E Target Methodology for Adequacy Assessment, 2014):**
  - Year 2025 (FBMC state 2016, without Austria)
  - 1’000’000 Monto-Carlo Simulation for each of the 8760 hours

- **Performance (Intel© Xeon 3.5 GHz, parallelization on 4 cores):**
  - Total computation time, ~ one week
  - Fraction of solving OCZE ~90%
  - OCZE/second ~ 170
  - Example: 8760 time steps, 1 million draws
  - LOLP (isolated): 0.001  →  14 hours pure optimization time
  - LOLP (isolated): 0.01  →  140 hours (~6 days) pure optimization time

### Table

<table>
<thead>
<tr>
<th></th>
<th>BE</th>
<th>DE</th>
<th>FR</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual peak load</strong></td>
<td>14.2</td>
<td>79.1</td>
<td>102.1</td>
<td>18.5</td>
</tr>
<tr>
<td><strong>99.9 Quantile</strong></td>
<td>13.6</td>
<td>76.8</td>
<td>94.5</td>
<td>18.0</td>
</tr>
<tr>
<td><strong>Conventional</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear power</td>
<td>5.9</td>
<td>8.1</td>
<td>61.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Hard coal</td>
<td>0.0</td>
<td>26.3</td>
<td>2.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.0</td>
<td>18.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Gas</td>
<td>4.0</td>
<td>21.7</td>
<td>7.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Oil</td>
<td>0.0</td>
<td>2.5</td>
<td>1.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Pump storage</td>
<td>1.3</td>
<td>6.0</td>
<td>17.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>1.2</td>
<td>9.1</td>
<td>6.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Total</td>
<td>12.4</td>
<td>91.8</td>
<td>97.6</td>
<td>20.6</td>
</tr>
<tr>
<td><strong>Renewables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>3.9</td>
<td>47.2</td>
<td>9.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Wind Onshore</td>
<td>2.4</td>
<td>54.0</td>
<td>14.1</td>
<td>5.4</td>
</tr>
<tr>
<td>Wind Offshore</td>
<td>2.3</td>
<td>6.4</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Run of river</td>
<td>0.1</td>
<td>4.2</td>
<td>7.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>1.9</td>
<td>7.5</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>10.6</td>
<td>119.3</td>
<td>33.2</td>
<td>11.9</td>
</tr>
<tr>
<td><strong>Total production</strong></td>
<td>23.0</td>
<td>211.1</td>
<td>130.8</td>
<td>32.5</td>
</tr>
</tbody>
</table>

17.07.2017
## LOLP per country

### Application

<table>
<thead>
<tr>
<th>Country</th>
<th>Mean LOLP</th>
<th>Relative EENS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>isolated</td>
<td>interconnected</td>
</tr>
<tr>
<td></td>
<td>isolated</td>
<td>interconnected</td>
</tr>
<tr>
<td></td>
<td>FB/Cor</td>
<td>FB/Cor</td>
</tr>
<tr>
<td>BE</td>
<td>1.3E-02</td>
<td>2.0E-08</td>
</tr>
<tr>
<td>DE</td>
<td>4.3E-06</td>
<td>1.8E-09</td>
</tr>
<tr>
<td>FR</td>
<td>7.9E-05</td>
<td>1.4E-05</td>
</tr>
<tr>
<td>NL</td>
<td>3.3E-04</td>
<td>1.1E-10</td>
</tr>
<tr>
<td>mean</td>
<td>3.4E-03</td>
<td>3.5E-06</td>
</tr>
</tbody>
</table>

### Maps

- **isolated**: Map showing LOLP per country in isolated mode.
- **interconnected**: Map showing LOLP per country in interconnected mode.
LOLP over time

- isolated case

- effects of planned unavailabilities (conventional technologies)

<table>
<thead>
<tr>
<th></th>
<th>Mean LOLP (isolated)</th>
<th>Mean LOLP (interconnected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FBMC/Correlated (Copula)</td>
<td>FBMC/Correlated (Copula)</td>
</tr>
<tr>
<td></td>
<td>step (ref.)</td>
<td>constant</td>
</tr>
<tr>
<td>BE</td>
<td>1.3E-02</td>
<td>1.6E-02</td>
</tr>
<tr>
<td>DE</td>
<td>4.3E-06</td>
<td>1.2E-04</td>
</tr>
<tr>
<td>FR</td>
<td>7.9E-05</td>
<td>5.4E-04</td>
</tr>
<tr>
<td>NL</td>
<td>3.3E-04</td>
<td>1.1E-03</td>
</tr>
<tr>
<td>mean</td>
<td>3.4E-03</td>
<td>4.4E-03</td>
</tr>
</tbody>
</table>
## Agenda

**Development of a probabilistic methodology for adequacy assessment under uncertainty**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivation and methodology overview</td>
<td>1</td>
</tr>
<tr>
<td>Stochastic characterization (Quantile regression and Copula)</td>
<td>2</td>
</tr>
<tr>
<td>Probabilistic method for adequacy assessment (Monte-Carlo)</td>
<td>3</td>
</tr>
<tr>
<td>Application</td>
<td>4</td>
</tr>
<tr>
<td>Conclusion</td>
<td>5</td>
</tr>
</tbody>
</table>
Summary

- probabilistic methodology for assessing security of supply / system adequacy
  - based of Monte-Carlo simulations
  - facing the rising influence of uncertainties (especially of RES)
  - in a multi-region setting

- characterization of uncertainties due to
  - their marginal conditional distributions (quantile regression)
  - considering spatial interdependencies (Copula).

- taken interconnection into account, over NTC or according the FBMC approach

Conclusion

- Application shows the expected results. Security of supply highly dependent on
  - isolated and interconnected case
  - taking spatial interdependencies into account
  - as well as the schedule of planned unavailabilities
Further improvements by considering

- intertemporal effects
  - RES: depiction of extreme weather periods
  - conventional power plants: outages often stay for several hours till some weeks
  - flexibilities (e.g. storage): limitations of transferable energy

- common failures, e.g. low water and its accompanying effects on lignite generation

- shut down of a huge amount of capacity of a single technology (using heuristics)
  - shut down of nuclear power plants due to security issues (cf. Belgium and France)
  - shut down of lignite/coal due to changes in regulatory / political framework
Many Thanks

Benjamin Böcker
email: benjamin.boecker@uni-due.de
phone: +49 201/183-7306