Impact of Generation and Load Patterns on the Central Western European Flow Based Market Coupling

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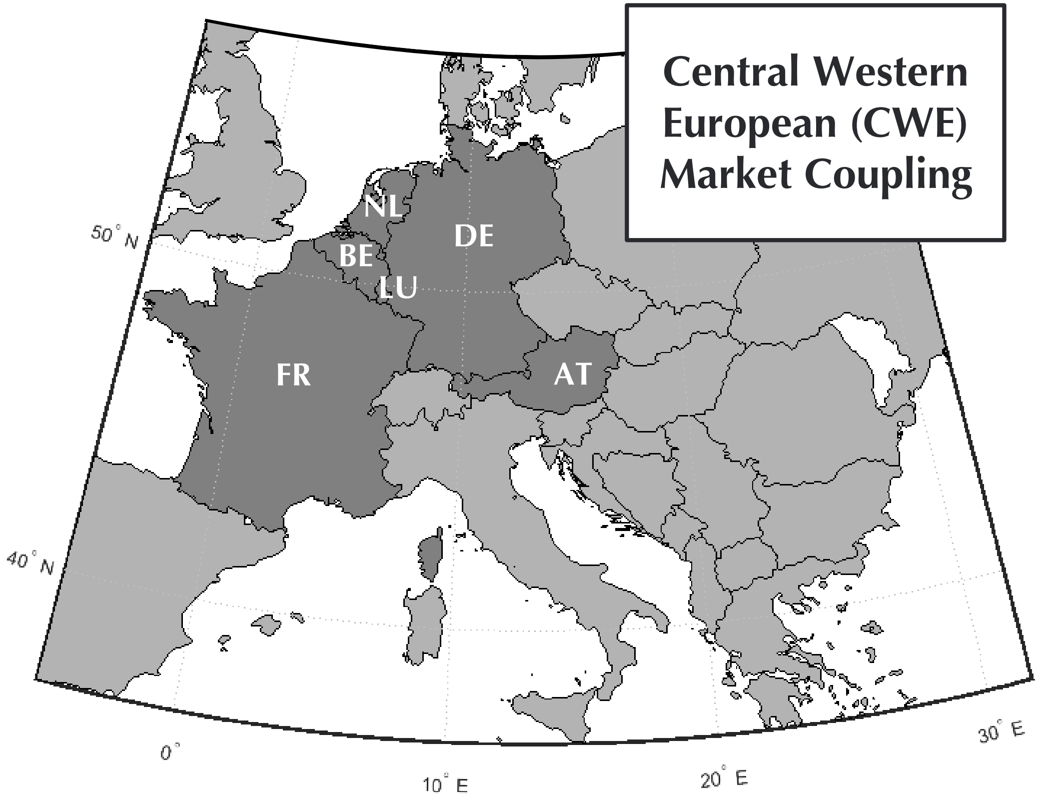
Background

Coupling of National Power Markets in Europe

- Zonal Market Coupling
  - Integration of national electricity markets on the basis of a zonal pricing approach
  - Gradual coupling at a regional level
    - as of 2006 with the first market coupling of the Belgian, Dutch, and French day-ahead markets,
    - later extended to Germany, Luxembourg and Austria
  - Target Model: Single European Electricity Market
- Flow-based Market Coupling
  - Shift from bilateral ATC-based to Load Flow-based Market Coupling in CWE in 2015 (CWE FBMC)
  - Improved representation of the physics of the grid (Kirchhoffs laws), but still zonal approximation
  - Partial integration of capacity calculation and allocation



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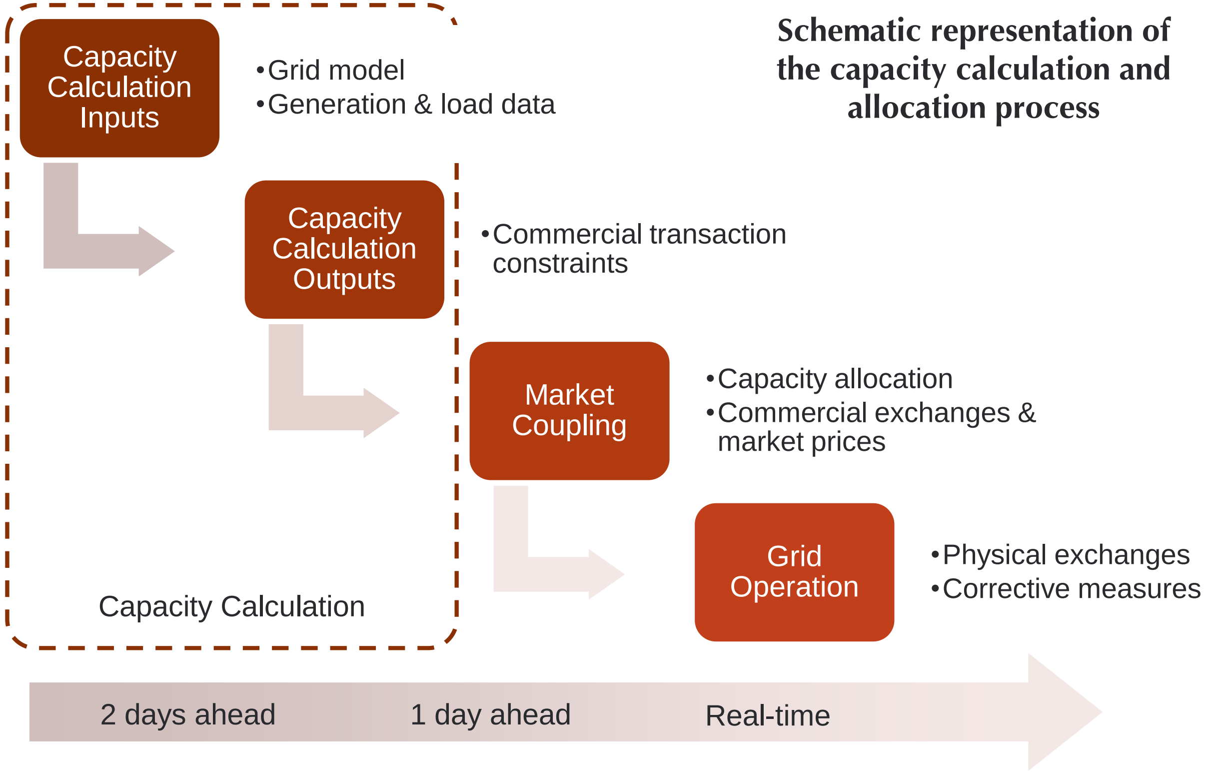
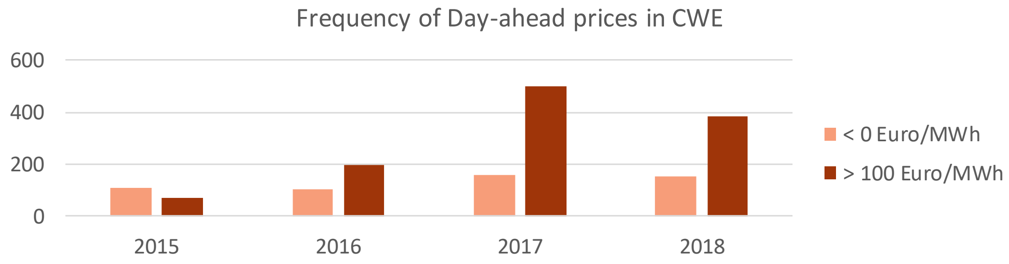
Motivation I

- Capacity Calculation
  - Translation of physical transmission constraints into commercial transaction constraints
    1. Involves several discretionary assumptions, e.g. reliability margins or selection of critical network elements
    2. But is also impacted by fundamental factors, i.e. grid status and generation and load patterns
- What drives commercial transaction constraints and exchanges in CWE?
  - So far, focus on wind power generation as main driver (e.g. Bucksteeg et al., 2015 or Zugno et al., 2013)
  - Wind power might explain low market prices, but not increasing frequency of high prices and corresponding exchanges



Schematic representation of the capacity calculation and allocation process



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Motivation II

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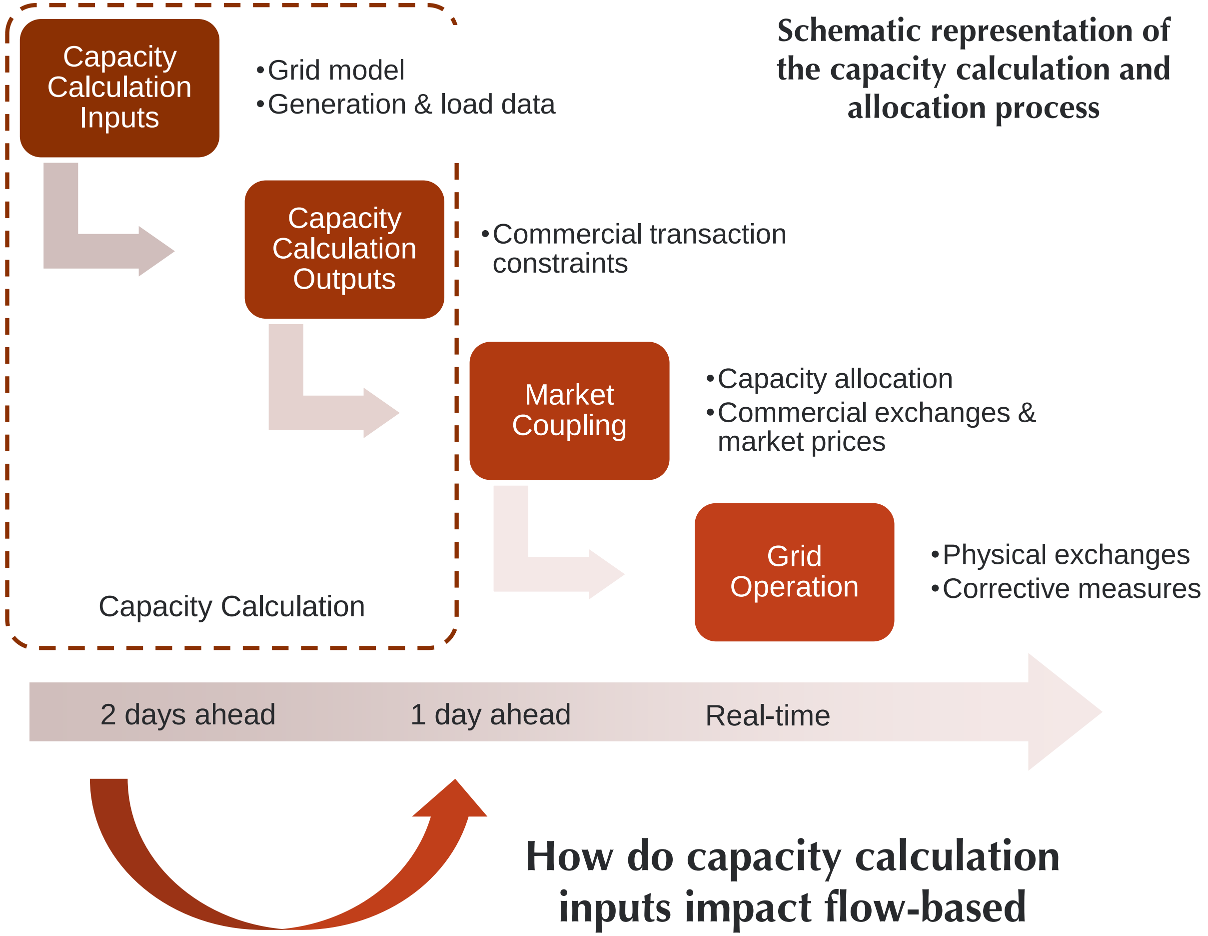
- **Key issue**: commercial cross-border transaction constraints and exchanges are considered to be too low
  - Political discussion focuses on capacity calculation outputs and TSOs discretionary assumptions
  - But what about capacity calculation inputs, i.e. grid model and generation and load data?
- **Main contribution**: shed a light on relationships between inputs and outputs of the capacity calculation and allocation process
  - Focusing on generation and load data
  - Using a statistical model framework



Schematic representation of the capacity calculation and allocation process

How do capacity calculation inputs impact flow-based parameters and market results?

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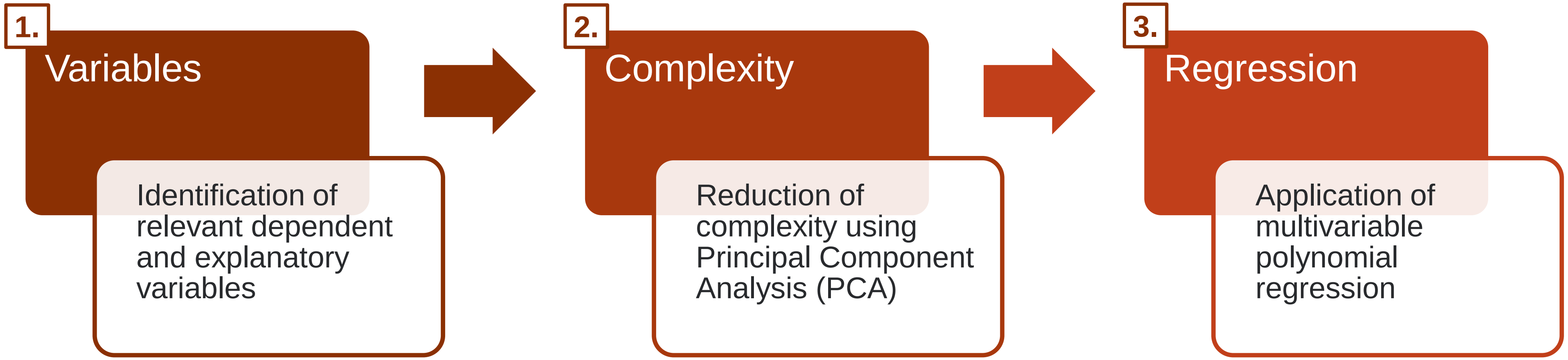
Methodology

General Approach

- Large-scale power systems are characterized by high complexity and nonlinearities
- Approach: Approximation of complex nonlinear relationships using multivariable polynomial regression analysis
- Goal: to identify main explanatory variables, but not to create a "perfect" predictive model
- Three steps:



Methodology

Identification of relevant dependent and explanatory variables

- **Dependent variables**: given by capacity calculation and allocation outputs
- **Explanatory variables**: inductive approach for selection of variables with a focus on key characteristics of considered power systems

Dependent variables	**Description**	**Name**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Capacity calculation outputs	Import and export capabilities (minimum/maximum net positions)	maxNP	X		X	
Market results	Net positions	NP		X		X
Explanatory variables						
Demand and generation situation	Forecast of hourly load (DE, FR, BE, NL)	LOAD			X	X
	Forecast of hourly wind infeed (DE, NL)	WIND			X	X
	Nuclear generation (FR, BE)	NUC			X	X
	Hard coal and lignite generation (DE)	COAL			X	X
	Share of nuclear generation (FR, BE)	NUC/LOAD	X	X		
	Share of wind infeed (DE, NL)	WIND/LOAD	X	X		
Further fundamentals	CO_2-Price (impacting marginal plant)	CO_2			X	X

Methodology

Reduction of complexity and multivariable polynomial regression

- **Principal component analysis** of dependent variables to reduce complexity and identify typical flow patterns for further investigation in the statistical model
  1. Compute centered version of the multivariate time-series: $\tilde{Y}_t = Y_t - \bar{Y}$
  2. Compute covariance matrix and its eigenvectors: $C = \frac{1}{T}\sum_{t=1}^{T} \tilde{Y}_t \tilde{Y}_t^T$
  3. Order eigenvectors according to their eigenvalues in a decreasing manner
  4. Obtain principal components by selecting first n eigenvectors representing most of the variance in the dataset
- **Multivariable polynomial regression**
  – E.g. second order multiple polynomial regression with two variables:
  $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon$
  – Condition number test to detect potential multicollinearity in explanatory variables

Results and Discussion

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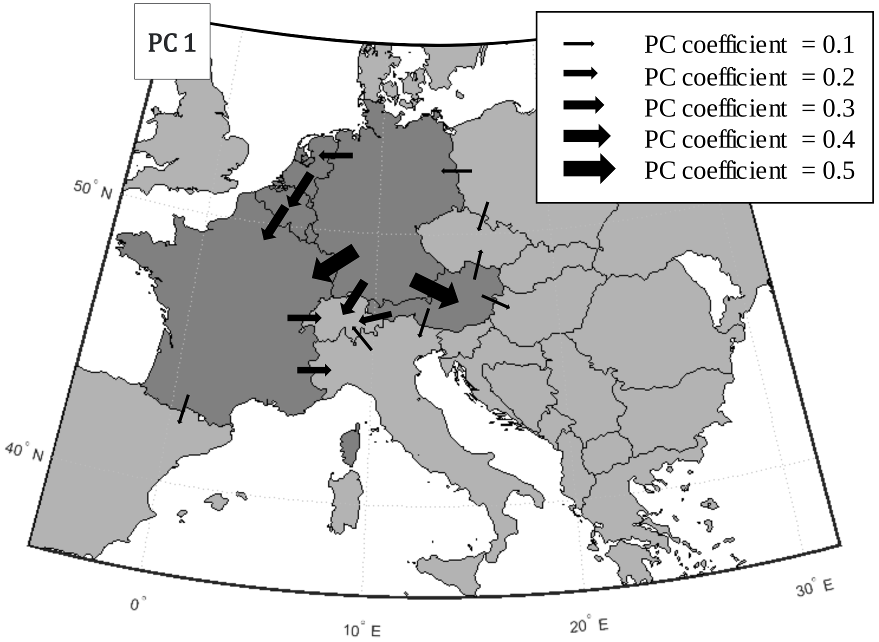
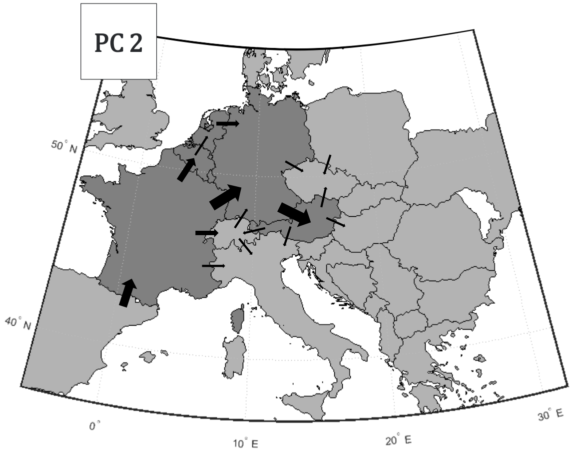
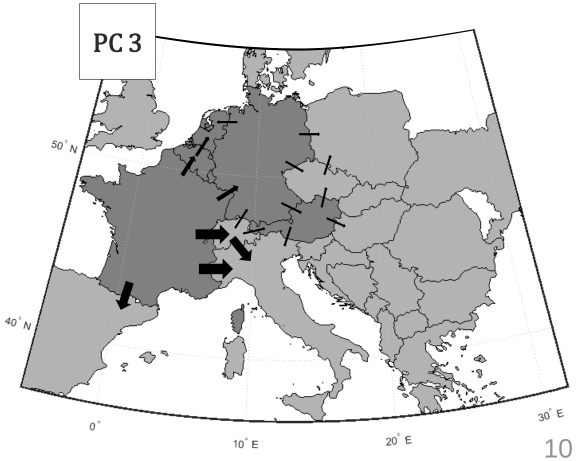
Principal Component Analysis of Commercial Cross-border Flows

- Most of original variance of commercial cross-border flows can be explained by limited number of principal components (PCs)
- First three PCs reveal two typical patterns
  1) Commercial flows directly from Germany to France and Austria and from Germany via the Netherlands and Belgium to France
  2) Flows from France to CWE countries, Switzerland and Italy

Principal component	Individual fraction of variance [%]	Cumulative fraction of variance [%]
1	29.2	29.2
2	17.1	46.3
3	13.7	60.0
4	10.7	70.7
5	8.0	78.8
6	6.1	84.9
7	3.6	88.4
8	3.5	91.9







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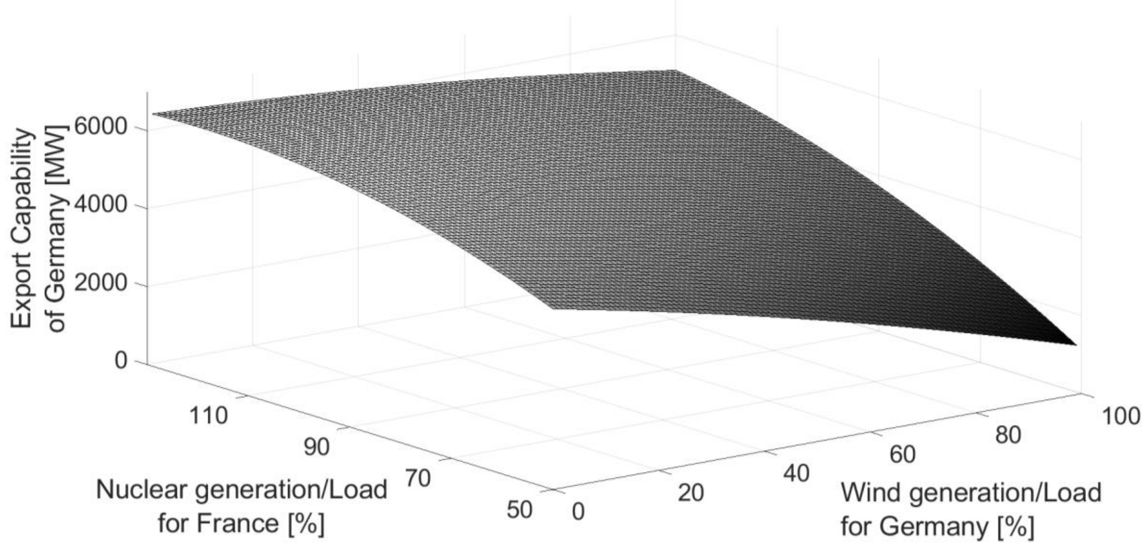
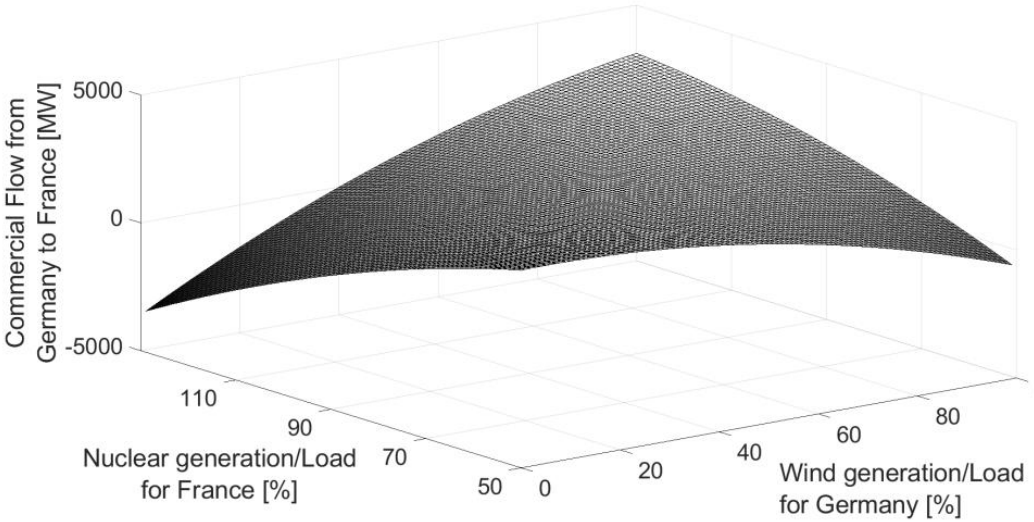
Results and Discussion

- Model 1: Export capability of Germany depends on share of wind infeed in Germany, but also on generation and load situation in France (and Belgium)
  - High wind infeed in Germany lowers export capability
  - Low base load generation in France increases north-south congestion and lowers the export capability





- Model 2: Commercial flow from Germany to France mirrors this effect
  - Export from Germany to France in case of balanced supply situation in CWE countries
  - Reversed flows from France to Germany in case of regional imbalance and north-south congestion in Germany due to high wind infeed

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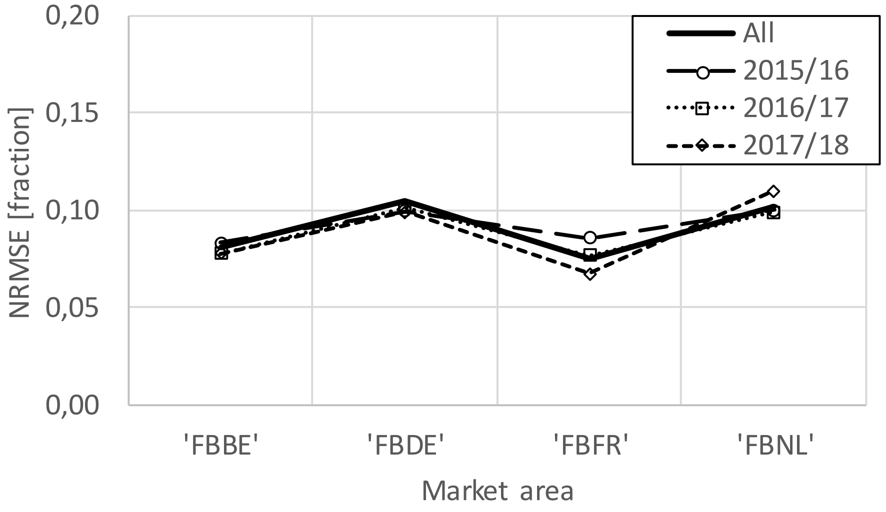
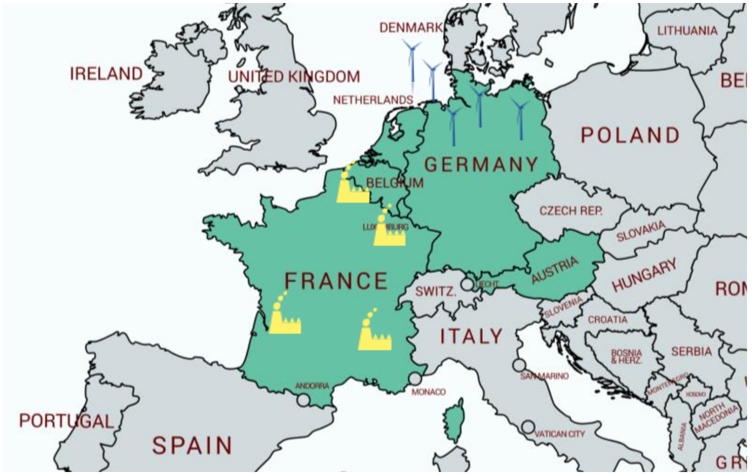
Results and Discussion

- Model 4: Non-stationarity in the data set has a twofold impact on the results
  1. NRMSE is rather stable across the considered years
  2. Structural change in constants and coefficients between 2015/16 and 2017/18*
- Constants: For FR and BE constants turn from positive (export) into negative (import) in 2016/17 and vice versa for DE
- Coefficients for FR net position
  - In 2016/17 nuclear generation in FR and BE become main drivers
  - As of 2016/17 coal generation in DE has a significant and increasingly negative impact
  - Negative impact of DE renewables infeed is decreasing over time
- Coefficients for DE net position reveal increasing impact of conventional generation





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* Period from June to May with in winter period in the center

Conclusion

- **Key issue**: commercial cross-border transaction constraints and exchanges are considered to be too low
- **Main contribution**: shed a light on relationships between inputs and outputs of the capacity calculation and allocation process
- **Results**:
  - Principal Component Analysis of commercial exchanges reveals two typical flow patterns, one with exports from Germany and the other with flows from France to CWE countries, Switzerland and Italy
  - Export capability of Germany depends on share of wind infeed in Germany, but more importantly on generation and load situation in France (and Belgium)
  - Unbalanced generation and load situations in CWE countries are a main driver of low commercial cross-border transaction constraints

➢ Further increase of regional imbalances due to phasing out nuclear and coal will most likely amplify the observed effects

Thank you for your attention!

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Appendix

Results and Discussion

Model 1 (# Observations 26 304)

Variable	BE_Import	BE_Export	DE_Import	DE_Export	FR_Import	FR_Export	NL_Import	NL_Export
Constant	-5 996.69	8 850.23	-5 463.45	-1 160.12	-714.71	11 069.12	-7 474.34	1 011.01
β_1 FR_NUC/LOAD	3 598.77***	-13 258.36***	2 141.55***	9 739.37***	-5 172.72***	-12 287.39***	6 361.61***	3 889.07***
β_2 DE_WIND/LOAD	86.09	6 477.22***	3 001.91***	-5 812.33***	1 704.19	-2 108.32**	2 608.92***	1 742.46***
β_3 BE_NUC/LOAD	-484.22***	5 827.42***	726.43***	9 252.03***	-8 861.18***	257.50	-981.48***	-445.24
β_4 NL_WIND/LOAD	-1 360.76***	-3 111.86***	-159.10	3 726.63**	-2 300.11	7 733.85***	-224.33	-639.68
Rsquare	0.4349	0.5925	0.2759	0.4685	0.3986	0.3096	0.5125	0.5400
CVRsquare	0.4330	0.5916	0.2744	0.4672	0.3973	0.3080	0.5114	0.5390
NRMSE	0.1737	0.1379	0.1209	0.2320	0.1612	0.1527	0.1107	0.1461

*Import and export capabilities: minimum or maximum feasible net position of one market area, while net positions of other market areas are assumed to be zero.

- FR_NUC/LOAD is significant for all import/export capabilities in CWE
- DE_Export mainly driven by generation and load situation in FR and BE and not only dependent on share of wind generation in DE
- No significant impact of share of wind generation in DE on BE_Import and FR_Import

Results and Discussion

Model 2 (# Observations 26 304)

Variable	BE_NP	DE_NP	FR_NP	NL_NP
Constant	-3 911.78	-3 595.76	-50 663.32	9 223.40
β_1 FR_NUC/LOAD	2 181.36***	7 647.52***	100 489.62***	-12 506.35***
β_2 DE_WIND/LOAD	1.08	-21 140.77***	-14 542.18***	6 015.17***
β_3 BE_NUC/LOAD	3 575.15***	11 153.21***	4 984.35***	-6 485.83***
β_4 NL_WIND/LOAD	6 576.73***	17 996.77***	-12 937.36***	5 326.15***
Rsquare	0.6227	0.3014	0.4713	0.3279
CVRsquare	0.6221	0.3003	0.4706	0.3271
NRMSE	0.0933	0.1209	0.1020	0.1213

- FR_NUC/LOAD is main driver of the net position of FR
- Net position of DE mainly driven by share of wind generation in DE and NL, but low Rsquare
- No significant impact of share of wind generation in DE on net position of BE

Results and Discussion

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Model 3 (# Observations 26 304)

Variable	BE_Import	BE_Export	DE_Import	DE_Export	FR_Import	FR_Export	NL_Import	NL_Export
Constant	-3 333.43	13 350.77	-4 648.44	8 786.97	-13 831.18	10 946.75	-5 578.41	4 089.81
β_1 FR_LOAD	-0.08***	0.15***	0.00	0.01	-0.24***	-0.11***	-0.02**	0.03***
β_2 FR_NUC	0.00	-0.21***	0.01	-0.12***	0.51***	0.11***	0.03***	0.12***
β_3 DE_LOAD	0.06***	-0.10***	0.00	-0.01	0.03	-0.07**	0.04***	0.01
β_4 DE_COAL	0.01	0.19***	0.07***	0.12***	-0.29***	-0.32***	-0.08***	-0.04**
β_5 DE_WIND	-0.02***	0.03*	0.06***	0.00	-0.16***	-0.03	0.02**	-0.06***
β_6 DE_PV	0.01	0.10***	-0.01	-0.04**	-0.03	-0.09***	-0.01*	0.04***
β_7 BE_LOAD	0.20**	-0.88***	-0.39***	0.12	-0.20	2.12***	0.06	-0.66***
β_8 BE_NUC	-0.05	0.34***	0.06	-0.44***	0.79***	-1.98***	0.25***	-0.44***
β_9 NL_LOAD	-0.12***	-0.12**	0.00	-0.25***	1.07***	-0.30***	-0.05*	-0.09**
β_{10} NL_WIND	-0.15***	0.12	0.06	-0.23	0.18	-0.67***	-0.20***	-0.21***
β_{11} CO_2	-148.32***	-766.43***	199.22***	203.02***	86.66	-855.27***	216.07***	290.49***
Rsquare	0.2734	0.4651	0.1304	0.3760	0.4277	0.2691	0.4035	0.4412
CVRsquare	0.2684	0.4616	0.1250	0.3723	0.4241	0.2645	0.3997	0.4379
NRMSE	0.1613	0.1232	0.1185	0.2064	0.1318	0.1350	0.1054	0.1285

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Results and Discussion

Model 4 (# Observations 26 304)

Variable	BE_NP	DE_NP	FR_NP	NL_NP
Constant	-1 414.70	16 146.85	10 805.80	4 075.11
β_1 FR_LOAD	-0.05***	0.35***	-1.03***	0.13***
β_2 FR_NUC	0.06***	-0.69***	1.51***	-0.24***
β_3 DE_LOAD	0.12***	0.02	-0.39***	-0.09***
β_4 DE_COAL	-0.15***	0.26***	-0.45***	0.56***
β_5 DE_WIND	-0.05***	0.23***	-0.20***	0.17***
β_6 DE_PV	0.07***	0.06*	-0.10**	-0.04**
β_7 BE_LOAD	-1.01***	-1.63***	2.70***	0.16
β_8 BE_NUC	0.61***	-1.08***	4.35***	-0.18*
β_9 NL_LOAD	0.12***	0.17	1.16***	-0.90***
β_{10} NL_WIND	0.50***	-0.55**	-0.47*	0.69***
β_{11} CO_2	436.97***	-26.56	-3 810.16***	-569.66***
Rsquare	0.7127	0.4796	0.7178	0.5230
CVRsquare	0.7109	0.4767	0.7161	0.5204
NRMSE	0.0814	0.1043	0.0745	0.1022

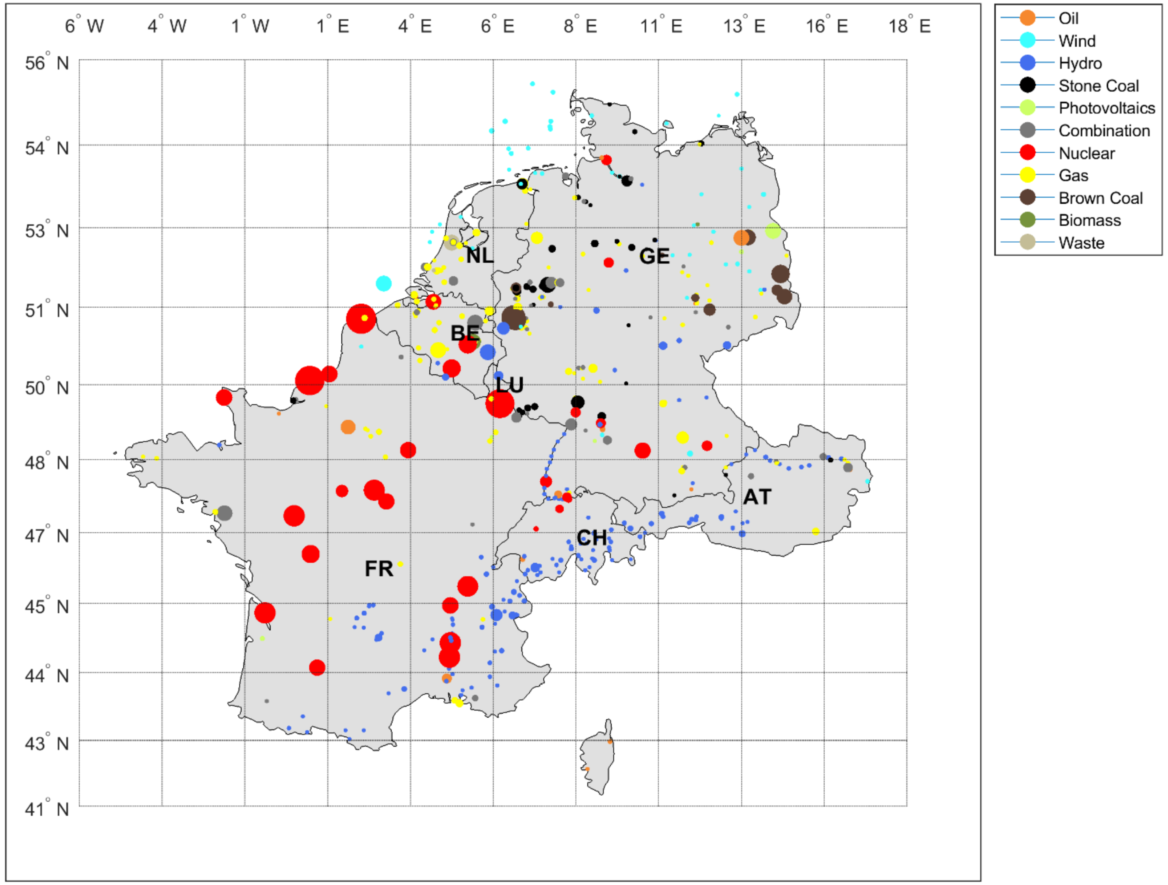
- BE rather importing country (cf. negative constant)
- FR net position mainly driven by generation and load situation in FR and BE
- DE net position rather correlated with generation and load situation in FR and BE, likewise impact of DE wind infeed and coal generation
- NL net position mainly driven by generation and load situation in NL and coal generation in DE
- Increasing CO_2-price leads to more gas plants being in the money reducing BE import as well as FR and NL export, e.g.
  - Shift of marginal plants from NL to BE
  - More spatially balanced generation situation in DE reducing scarcity in Southern Germany

Results and Discussion

Model 4	2015/16				2016/17				2017/18			
Variable	BE_NP	DE_NP	FR_NP	NL_NP	BE_NP	DE_NP	FR_NP	NL_NP	BE_NP	DE_NP	FR_NP	NL_NP
Constant	37.88	-9 604.24	41 156.43	14 769.28	-3 818.88	17 607.90	-28 820.51	3 117.09	643.16	-19 288.76	62 974.03	-8 596.39
β_1 FR_LOAD	-0.11***	0.04	-0.74***	0.00	0.03	0.31***	-0.36***	0.00	-0.21***	-0.15**	-0.66***	0.03
β_2 FR_NUC	0.10***	0.23**	-0.46***	-0.48***	-0.07*	-0.42***	1.47***	-0.36***	0.31***	0.58***	-1.04***	-0.10*
β_3 DE_LOAD	-0.16***	-0.53***	0.04	-0.06	0.14***	0.58***	-0.19	-0.71***	0.13***	0.21**	-0.06	0.07
β_4 DE_COAL	0.03	-0.11	0.14	0.38***	-0.04	0.02	-0.73***	0.77***	-0.05	-0.41***	-0.81***	0.57***
β_5 DE_WIND	0.04*	0.28***	0.06	0.13***	-0.30***	-0.02	-0.42***	0.45***	0.00	-0.14	-0.38***	0.15***
β_6 DE_PV	0.18***	0.33***	-0.33***	0.13***	0.10***	0.08	-0.42***	0.22***	0.15***	0.07	-0.17**	-0.19***
β_7 BE_LOAD	0.05	3.49***	-0.59	-0.41	-1.23***	-1.12	-0.91	3.11***	-0.40	-2.18**	-0.47	0.21
β_8 BE_NUC	0.20	1.60***	-0.72*	0.18	1.66***	0.93	6.07***	-2.77***	-0.58**	-1.37	-5.20***	1.95***
β_9 NL_LOAD	0.59***	0.22	0.93***	-0.40***	-0.17*	-2.25***	1.43***	-0.18	-0.19**	1.89***	1.65***	-0.57***
β_{10} NL_WIND	-0.53***	-2.80***	0.53	0.72**	2.09***	0.43	-0.04	-1.09***	0.96***	-0.59	0.92*	0.38
β_{11} CO_2	-906.80***	-420.46	-2 749.26***	-1 335.51***	1 745.70***	-2 625.52***	2 247.88**	1 519.42***	-320.87***	4 245.67***	-2 899.89***	-62.68
Rsquare	0.7442	0.6045	0.6924	0.5482	0.7283	0.5022	0.7985	0.6185	0.7915	0.5914	0.8377	0.6385
CVRsquare	0.7396	0.5970	0.6866	0.5403	0.7234	0.4938	0.7950	0.6122	0.7875	0.5840	0.8346	0.6326
NRMSE	0.0833	0.0996	0.0857	0.0999	0.0778	0.1017	0.0768	0.0993	0.0775	0.0990	0.0672	0.1100

Regional imbalance of conventional generation

- Heterogeneous generation fleets in CWE countries
- Decreasing levels of conventional generation capacities (in combination with long-term unavailability due to serial defects)
- Increase of renewable generation at the periphery of CWE countries, e.g. wind capacities in Northern Germany
- Increase of regional imbalance regarding generation patterns



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Identification of relevant dependent and explanatory variables

- Dependent variables
  - Given by capacity calculation outputs under the CWE FBMC, i.e. commercial transaction constraints like
    - Import and export capabilities (minimum/maximum net positions)
    - Bilateral exchange capabilities (minimum/maximum bilateral exchanges)
- Explanatory variables
  - Inductive approach for selection of variables with a focus on key characteristics of considered power systems
  - Recent developments help identifying potential key drivers
    - Increase of renewable generation at the periphery of CWE countries
    - Decreasing levels and long-term unavailability of conventional generation
    - Increase of regional imbalances regarding generation patterns

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