NTNU
Business School

Institute for Operations Research and Computational Finance
University of St.Gallen

Isaac Newton Institute
The Mathematics of Energy Systems

Econometrics of Intraday Electricity Prices

Florentina Paraschiv

Norwegian University of Science and Technology
University of St. Gallen, Switzerland

Cambridge, 1st May 2019

Agenda

- **Intraday modeling: knowledge needs for industry firms**
- Intraday prices, stylized facts
- Threshold model for intraday pricing
- INI MES, Pricing Track: emerging research topics
- Conclusion

Knowledge needs for industry firms

Energy firms need to learn about what **trading strategies** they should use in the ID market as bottlenecks open to adjacent areas with different price levels. Major challenge: balance out renewable energy sources

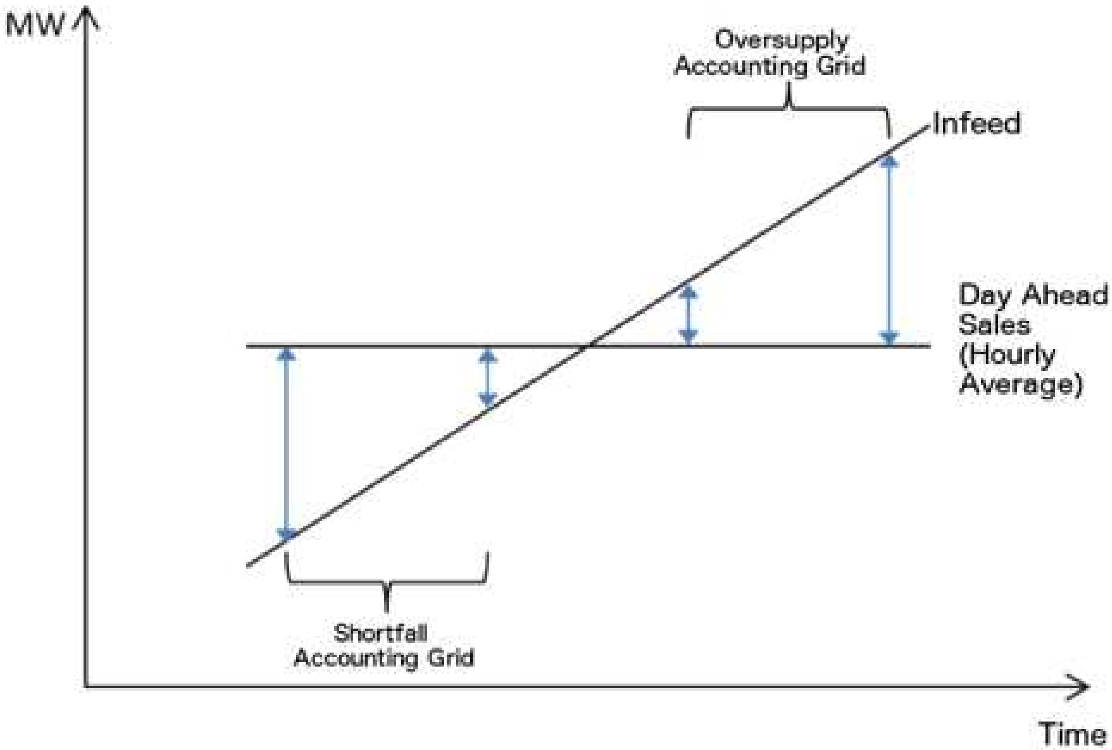
- Need for **accurate forecasts of intraday prices and volumes**. Two classes of approaches:
  - Link ID prices to demand/supply fundamentals
  - Employ purely stochastic models
- Move towards **automatic intraday trading:**
  - Trading in ID markets done manually (Norway) which is costly
  - Identify trading strategies based on a rigorous identification of local demand/supply patterns as well as cross-border dynamics
- **High-value trading:**
  - Optimal ID timing and volume in the continuous bidding process
  - Adaptive bidding strategy that is able to react optimally to new information as it becomes available

Agenda

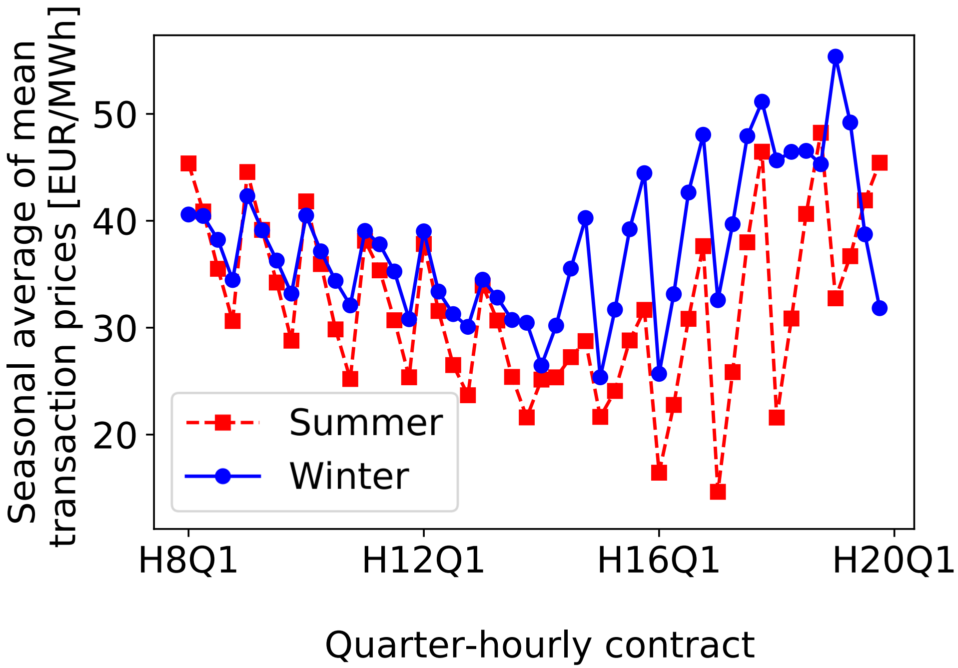
- Intraday modeling: knowledge needs for industry firms
- **Intraday prices, stylized facts**
- Threshold model for intraday pricing
- INI MES, Pricing Track: emerging research topics
- Conclusion

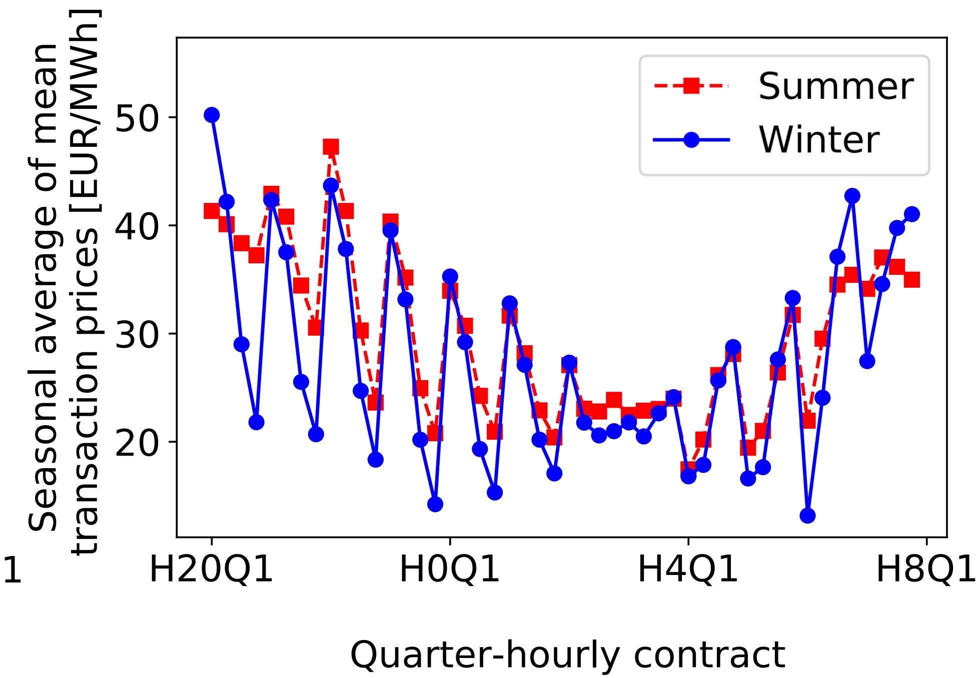
Motivation for Trading IntraDay Market

- Correction or optimisation of DayAhead position
  - renewable energy producer – changes of forecasts
  - power plant outages
  - optimisation of power plant usage (generator)
  - optimisation of demand (consumer)
- Balancing quarter-hour ramps with quarter-hour contracts
- Proprietary trading



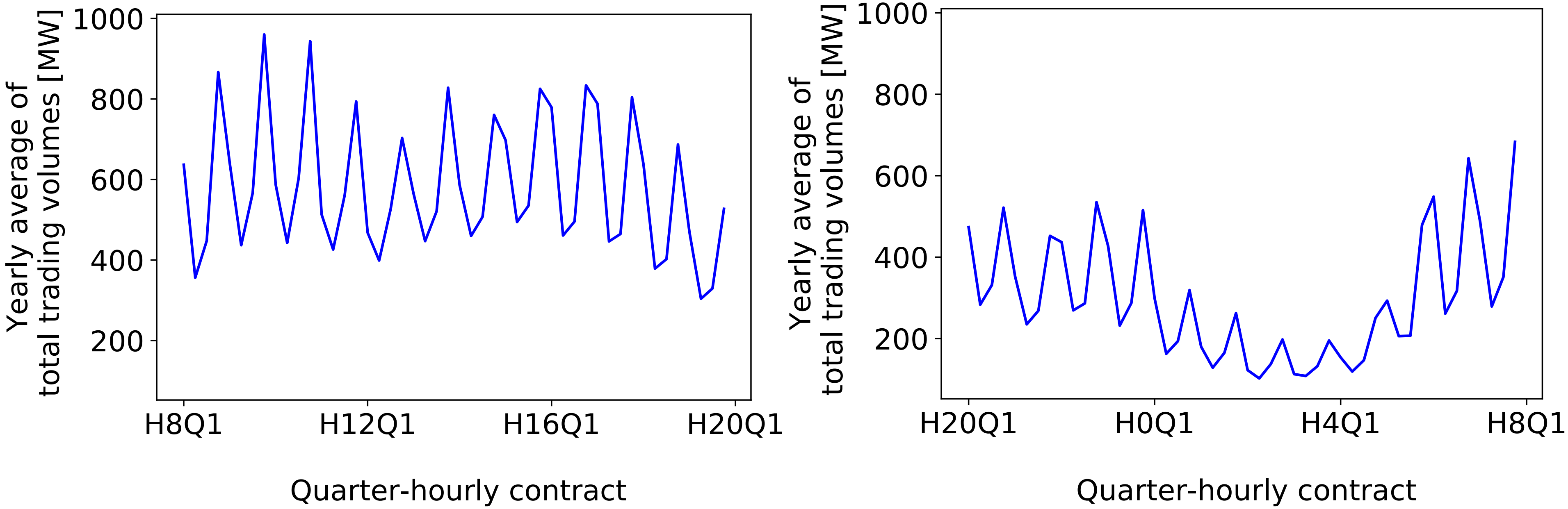
Seasonality pattern of intraday quarter hourly products





- Average over ID prices observed between: January 1 – December 31 2015
- Peak: Sawtooth-like shape due to sun ramping up and down profile
- Off-peak: Sawtooth-like shape linked to the design of conventional power plants (ramping up/down) or market convention (?)

Seasonality pattern of intraday volumes



- U-shaped: largest volumes of trades 1st and last quarter of each hour (buy/sell pressure)

Pattern in trading volume

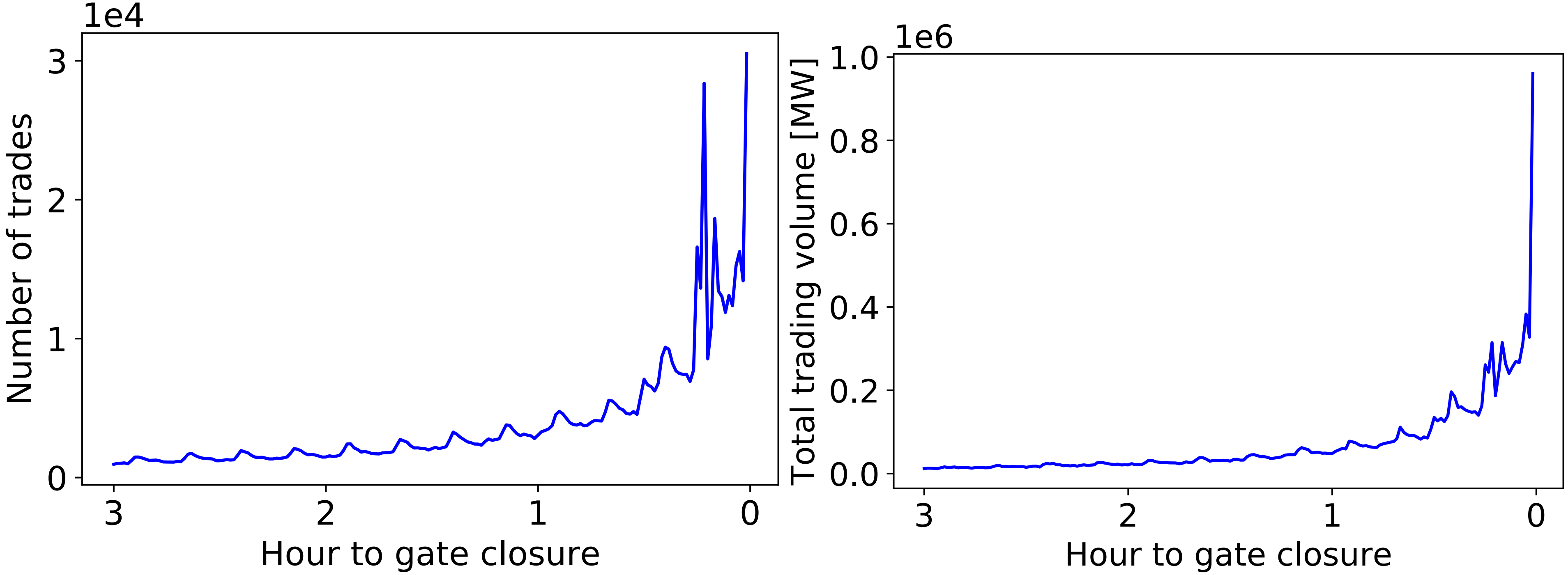


Figure 1: Time evolution of the number of trades (left) and total trading volume (right) through the trading session towards gate closure

- 3 to 4 hours before gate closure: the total trading volume increases from 12 GW to 48 GW
- 30 minute before gate closure: 135 GW
- 15 to 13 minutes before: vast number of transactions executed, but low trading volume
- 1 minute before gate closure: volume peaks at 960 GW

Increased uncertainty in weather forecasts closer to delivery

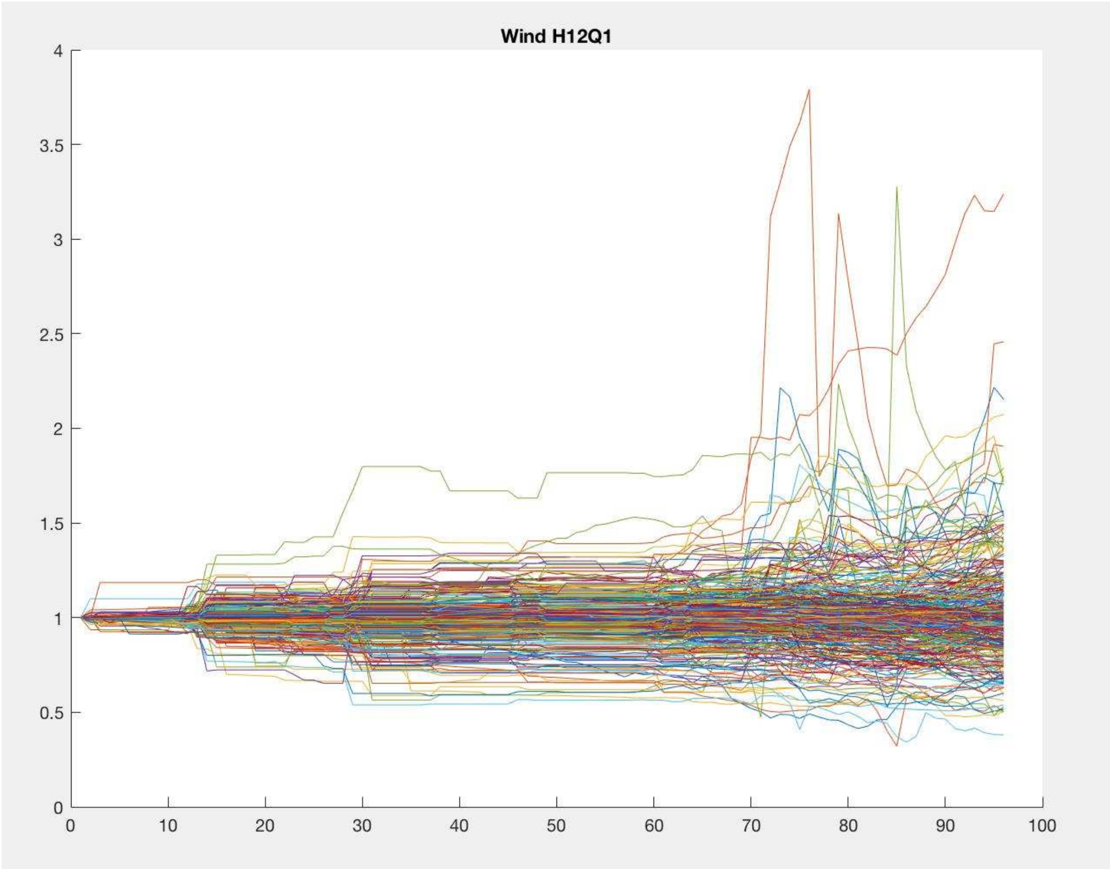


Figure 2: Data source: RWE. Calculations Wei Li (NTNU)

- We observe that the closer it comes to delivery, the uncertainty of weather forecasts around the realized values increases

Agenda

- Intraday modeling: knowledge needs for industry firms
- Intraday prices, stylized facts
- **Threshold model for intraday pricing**
- INI MES, Pricing Track: emerging research topics
- Conclusion

References

- *Kiesel, Ruediger; Paraschiv, Florentina. (2017)* Econometric analysis of 15-minute intraday electricity prices. Energy Economics. vol. 64.
- *Kremer, Marcel; Kiesel, Ruediger; Paraschiv, Florentina. (2019)* A fundamental model for continuous intraday electricity trading of 15-minute contracts, working paper.

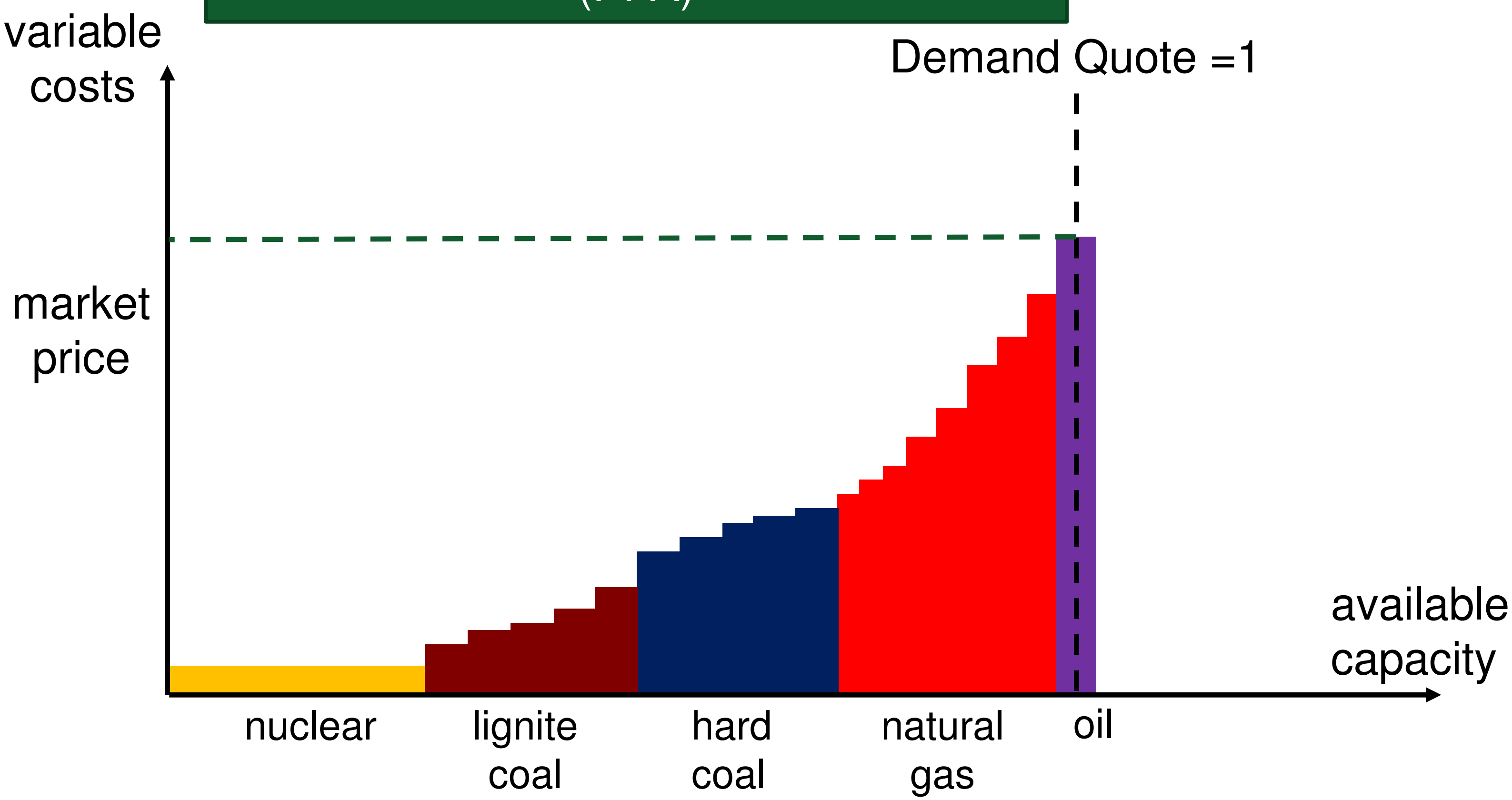
Modelling assumptions

- **Assumption 1**: market participants adjust their *prices in the ID continuous bidding* to *forecasting errors of wind and photovoltaic* as these become available from weather data providers (in 15 minute frequency).
- **Assumption 2**: the speed of adjustment of ID price to updated forecasting errors depends on the "gap" between the expected demand and the day-ahead planned power plant availability.
- Model choice: threshold model with threshold variable Demand Quote

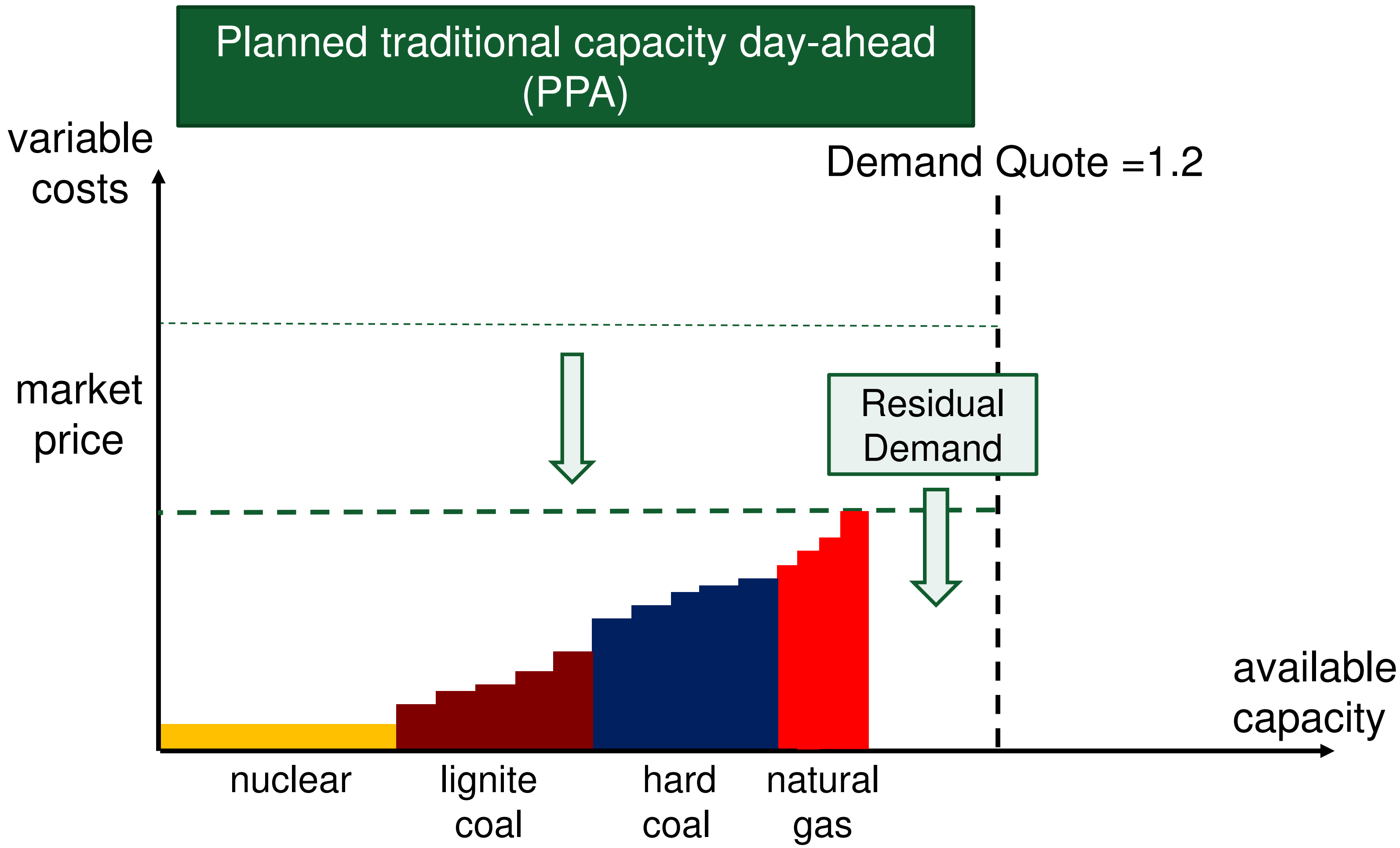
$$DemandQuote_t = DemandForecast_t / PPA_{d,t} \tag{1}$$

- The $DemandForecast_t$ is the demand forecasted (day-ahead) for a certain hour of one day. $PPA_{d,t}$ is the (traditional) power plant availability planned day-ahead for that hour of the day (coal, gas, oil).

Planned traditional capacity day-ahead (PPA)

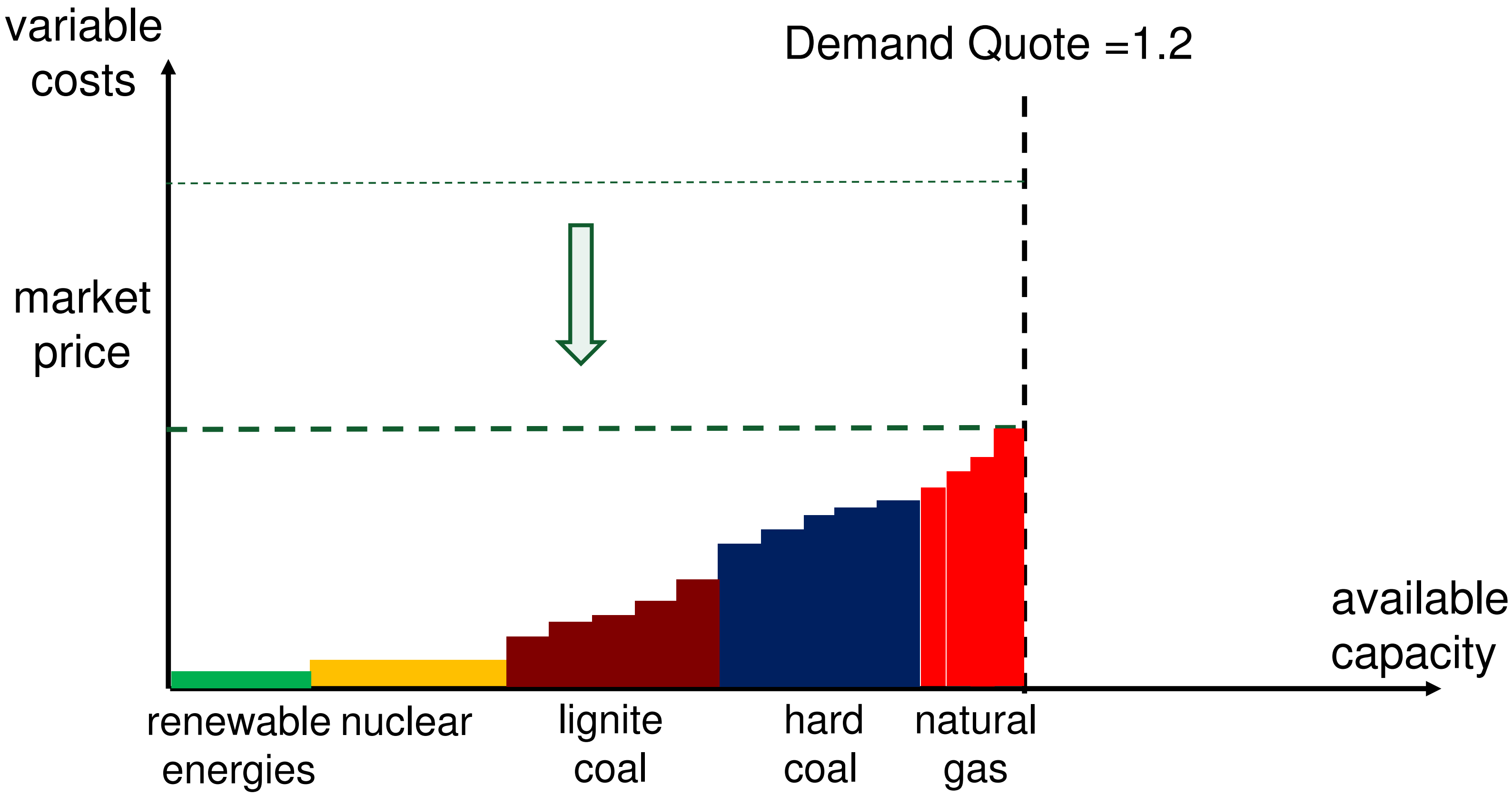


The traditional planned capacity for the day-ahead covers fully the expected demand for electricity. There is no (very low) market expectation of renewables.



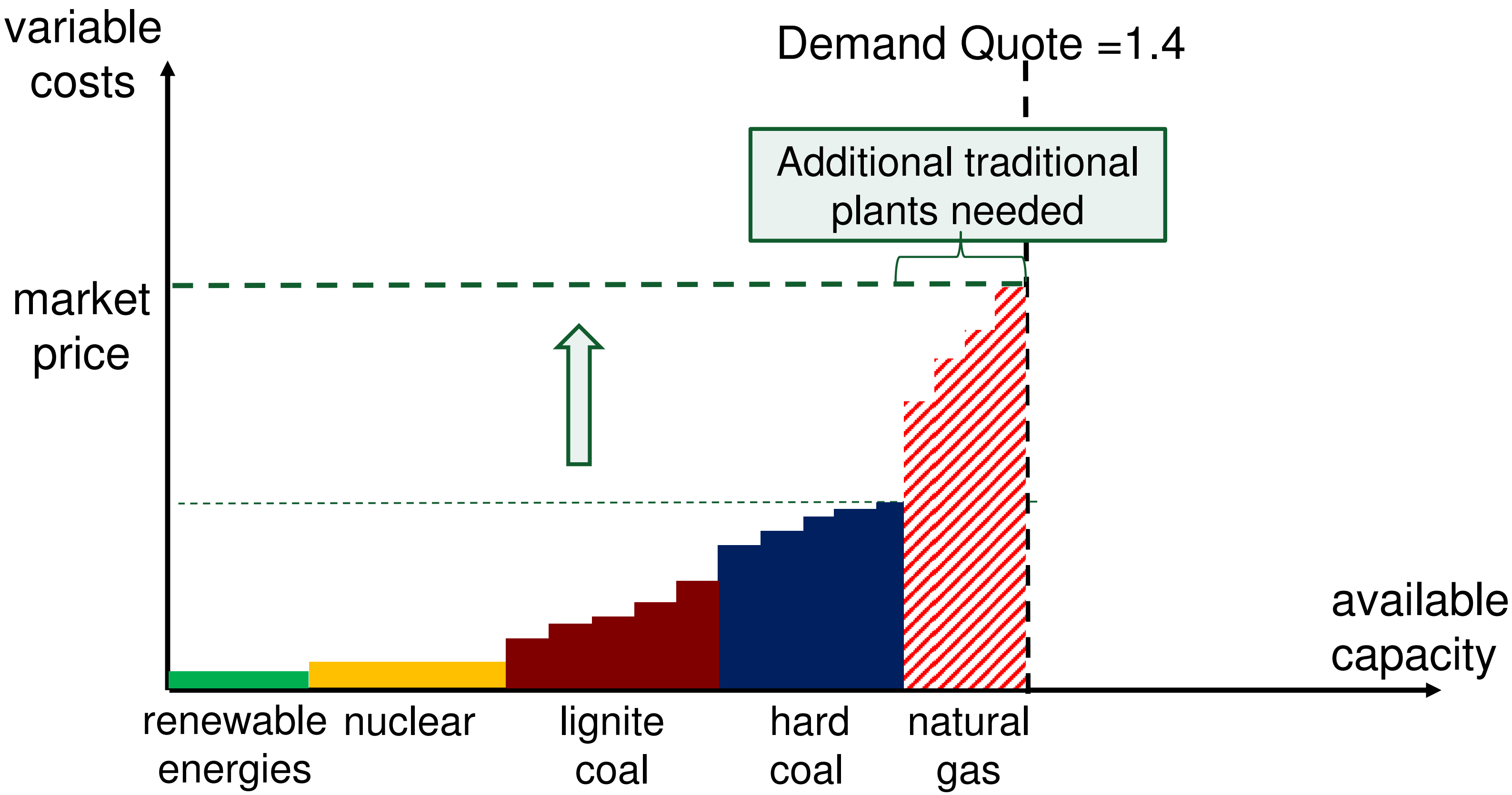
The traditional planned capacity for the day-ahead does not fully cover the expected demand, since market participants expect (up to 20%) renewables infeed in the market. The price is expected to decrease.

Planned capacity day-ahead and expected infeed from renewables



The renewables infeed decreases residual demand and supresses intraday prices.

Planned capacity day-ahead and expected infeed from renewables



If the renewables infeed does not supplement the excess demand, bidding for additional traditional capacity intraday can become costly: upwards pressure on the intraday prices.

Model for the continuous trades for quarter-hourly products

- Data: January 1 to December 31, 2015, 15-minute contracts traded on the German continuous intraday power market at EPEX SPOT
- We investigate ID prices change when new information on wind and PV for a certain delivery period of interest becomes available intra-day
- We look at the trade-off between autoregressive terms and fundamental factors impacting the intra-day price formation process

Model specification

$$\begin{aligned}(\Delta P_t^{ID})^h &= c^h + \alpha_1^h \Delta P_{t-1}^{ID} \mathbf{1}_t^h + \alpha_2^h \Delta P_{t-2}^{ID} \mathbf{1}_t^h + \alpha_3^h \Delta P_{t-3}^{ID} \mathbf{1}_t^h \\ &+ k_w^{hn} (\Delta Wind_t^{ID}) \mathbf{1}_t^h \mathbf{1}_t^n + k_w^{hp} (\Delta Wind_t^{ID}) \mathbf{1}_t^h \mathbf{1}_t^p \\ &+ k_{PV}^{hn} (\Delta PV_t^{ID}) \mathbf{1}_t^h \mathbf{1}_t^n + k_{PV}^{hp} (\Delta PV_t^{ID}) \mathbf{1}_t^h \mathbf{1}_t^p \\ &+ \gamma^h DemandQuote_t^{Dahd} \mathbf{1}_t^h + \epsilon^h Volume_t^{ID} \mathbf{1}_t^h + \beta_h \sqrt{\Delta t}\end{aligned}$$

$$\begin{aligned}(\Delta P_t^{ID})^l &= c^l + \alpha_1^l \Delta P_{t-1}^{ID} \mathbf{1}_t^l + \alpha_2^l \Delta P_{t-2}^{ID} \mathbf{1}_t^l + \alpha_3^l \Delta P_{t-3}^{ID} \mathbf{1}_t^l \\ &+ k_w^{ln} (\Delta Wind_t^{ID}) \mathbf{1}_t^l \mathbf{1}_t^n + k_w^{lp} (\Delta Wind_t^{ID}) \mathbf{1}_t^l \mathbf{1}_t^p \\ &+ k_{PV}^{ln} (\Delta PV_t^{ID}) \mathbf{1}_t^l \mathbf{1}_t^n + k_{PV}^{lp} (\Delta PV_t^{ID}) \mathbf{1}_t^l \mathbf{1}_t^p \\ &+ \gamma^l DemandQuote_t^{Dahd} \mathbf{1}_t^l + \epsilon^l Volume_t^{ID} \mathbf{1}_t^l + \beta_l \sqrt{\Delta t} \qquad (2)\end{aligned}$$

Model specification

- We find that the first 3 lags of price changes should be selected in the autoregressive part of the model
- Changes in the wind $\Delta Wind_t^{ID}$ and in PV ΔPV_t^{ID} are real time updated forecasts, available at the time when the bids are placed
- $Volume_t^{ID}$ is the volume of trade at the time when the price change is observed
- As the bids for a certain quarter of an hour do not occur at equal time intervals, we include the control variable $\sqrt{\Delta t}$ in our list of explanatory variables

Hour 12, global OLS without threshold

OLS estimation of the model including fundamental variables
Dependent variable Delta Price

	H12Q1		H12Q2		H12Q3		H12Q4	
	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.
Co	-0.558	(0.672)	-0.674	(0.977)	-0.111	(0.765)	-0.032	(0.799)
DeltaPrice1	-0.175**	(0.086)	-0.167*	(0.043)	-0.207*	(0.038)	-0.140*	(0.020)
DeltaPrice2	-0.071**	(0.032)	-0.040	(0.023)	-0.077**	(0.036)	-0.079*	(0.020)
DeltaPrice3	-0.102	(0.060)	-0.018	(0.017)	-0.039	(0.021)	-0.020	(0.013)
DemandQuote	0.109	(0.499)	0.408	(0.755)	0.156	(0.578)	0.088	(0.635)
Volume	0.053*	(0.019)	0.012	(0.009)	-0.012	(0.009)	-0.013**	(0.006)
SqrTimeStep	0.423	(1.570)	1.868	(1.365)	1.010	(1.348)	1.683	(1.853)
DeltaWindIntrP	-0.001*	(0.000)	-0.001	(0.001)	-0.001*	(0.000)	-0.001*	(0.000)
DeltaWindIntrN	-0.001*	(0.000)	-0.001	(0.001)	-0.001	(0.001)	-0.002**	(0.001)
DeltaPVIntraP	-0.002**	(0.001)	-0.002**	(0.001)	-0.002**	(0.001)	-0.004*	(0.001)
DeltaPVIntraN	0.000	(0.001)	-0.001	(0.001)	-0.002**	(0.001)	-0.002**	(0.001)
Rsquared	7.296%		4.705%		7.011%		8.411%	
No. Obs.	6859		5449		6558		7931	

OLS estimation of the autoregressive model excluding fundamental variables
Dependent variable Delta Price

	H12Q1		H12Q2		H12Q3		H12Q4	
	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.
Co	0.006	(0.077)	0.004	(0.099)	0.005	(0.092)	0.003	(0.066)
DeltaPrice1	-0.172*	(0.012)	-0.167*	(0.014)	-0.206*	(0.012)	-0.137*	(0.011)
DeltaPrice2	-0.065*	(0.012)	-0.041*	(0.014)	-0.077*	(0.013)	-0.078*	(0.011)
DeltaPrice3	-0.099*	(0.012)	-0.018	(0.014)	-0.041*	(0.012)	-0.019	(0.011)
Rsquared	3.715%		2.733%		4.219%		2.187%	
No. Obs.	6859		5449		6558		7931	

Interpretation of results

- Fundamentals become more important during peak hours
- The role of wind and PV forecasting errors increases with the market expectation for an increased expected share from renewables (formed day-ahead)
- R^2 increases when including fundamentals
- Threshold effects only in Demand Quote

Hour 12, Quarters 1–4, First Sample Split

Regime 1								
	H12Q1		**H12Q2**		**H12Q3**		**H12Q4**	
Threshold value	<= 1.245∗		<= 1.245∗		<= 1.146∗		<= 1.197∗	
	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.
Co	-0.669	(1.982)	-0.693	(3.302)	0.421	(2.418)	0.365	(3.418)
DeltaPrice1	-0.202	(0.118)	-0.126*	(0.043)	-0.191**	(0.075)	-0.108*	(0.031)
DeltaPrice2	-0.065	(0.043)	-0.042**	(0.021)	-0.142	(0.085)	-0.082**	(0.040)
DeltaPrice3	-0.099	(0.078)	-0.010	(0.018)	-0.023	(0.078)	-0.030	(0.017)
DemandQuote	0.163	(1.685)	0.518	(2.798)	0.036	(2.104)	-0.378	(3.069)
Volume	0.070**	(0.028)	0.022	(0.012)	-0.007	(0.029)	0.003	(0.016)
SqrTimeStep	-1.363	(2.119)	-0.205	(1.886)	-9.905	(5.560)	0.880	(2.436)
DeltaWindIntrP	0.000	(0.001)	0.000	(0.001)	0.005*	(0.002)	-0.001	(0.001)
DeltaWindIntrN	-0.001	(0.001)	-0.001	(0.001)	-0.006*	(0.001)	0.002	(0.002)
DeltaPVIntraP	-0.003*	(0.001)	-0.003*	(0.001)	-0.007**	(0.003)	-0.002	(0.002)
DeltaPVIntraN	0.001	(0.001)	-0.001	(0.001)	-0.002	(0.002)	-0.003*	(0.001)
Rsquared	9.155%		3.806%		27.371%		7.764%	
No. Obs.	3911		3052		487		2438	

Regime 2								
	H12Q1		**H12Q2**		**H12Q3**		**H12Q4**	
Threshold value	> 1.245∗		> 0.757∗		> 1.146∗		> 1.197∗	
	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.	Coeff	Std. err.
Co	0.125	(1.349)	-1.036	(1.809)	-0.037	(0.928)	0.405	(0.944)
DeltaPrice1	-0.094**	(0.040)	-0.256*	(0.060)	-0.208*	(0.040)	-0.155*	(0.022)
DeltaPrice2	-0.108	(0.040)	-0.046	(0.053)	-0.072	(0.038)	-0.075	(0.020)
DeltaPrice3	-0.099**	(0.043)	-0.035	(0.035)	-0.039	(0.022)	-0.011	(0.018)
DemandQuote	-0.216	(0.965)	0.630	(1.304)	0.065	(0.693)	-0.163	(0.692)
Volume	0.018**	(0.008)	-0.006	(0.013)	-0.012	(0.010)	-0.021*	(0.006)
SqrTimeStep	1.140	(1.439)	3.942**	(1.758)	2.263	(1.191)	-0.097	(1.700)
DeltaWindIntrP	-0.002*	(0.000)	-0.002**	(0.001)	-0.001*	(0.000)	-0.001	(0.001)
DeltaWindIntrN	-0.001*	(0.000)	-0.002**	(0.001)	-0.001	(0.001)	-0.002**	(0.001)
DeltaPVIntraP	0.000	(0.001)	-0.001	(0.001)	-0.002**	(0.001)	-0.002**	(0.001)
DeltaPVIntraN	-0.001	(0.001)	-0.002**	(0.001)	-0.001	(0.001)	-0.004*	(0.001)
Rsquared	8.868%		10.760%		6.590%		11.624%	
No. Obs.	2948		2397		6071		5493	

Threshold Effects

- Demand Quote can be identified as threshold
- Hour 12: Wind/ PV forecasting errors only significant in high demand quote regime
- High demand regime: the coefficient of volume of trades is significant and has a positive sign for the first quarter but it turns into negative in quarter 4:
  - Sun ramping down effects: market participants need to increase the conventional output *buy pressure increases prices*
  - Sun ramping up effect: *sell pressure decreases prices*

Agenda

- Intraday modeling: knowledge needs for industry firms
- Intraday prices, stylized facts
- Threshold model for intraday pricing
- **INI MES, Pricing Track: emerging research topics**
- Conclusion

INI MES Research Track on Pricing: "Shaping" the volatility by fundamental-free stochastic models

–> *Research group:* Fred Espen Benth, Florentina Paraschiv

$$\sigma_t = \sigma_c + \sigma_0 \exp^{-\alpha(t-t_0)} + \sigma_1 \exp^{-\beta(t_1-t)} + \gamma\sigma_t W_t$$

–> *Research group:* Giulia di Nunno, Florentina Paraschiv, Michael Schuerle: stochastic volatility models with time change

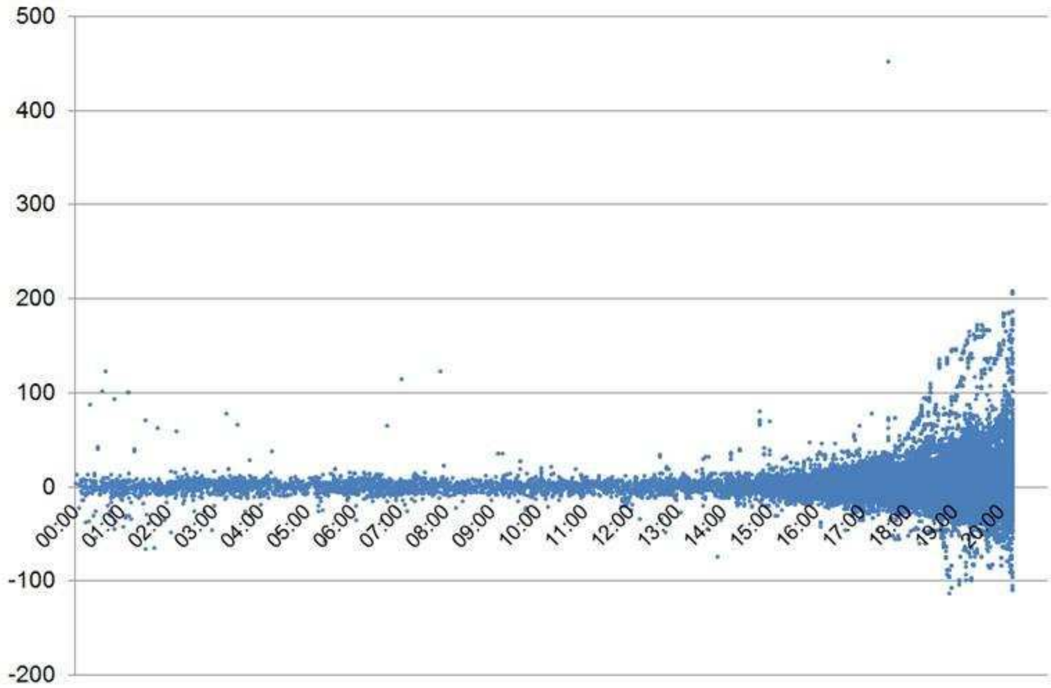


Figure 3: Differences between ID prices and day-ahead prices aggregated over 6 years

INI MES Research Track on Pricing: Intraday prices as a random field?

–> *Research group:* Fred Espen Benth, Giulia di Nunno, Florentina Paraschiv, Barbara Ruediger-Mastandrea

$$df_t(x) = (\partial_x f_t(x) + \theta(x) f_t(x))\, dt + dW_t(x)\,,$$

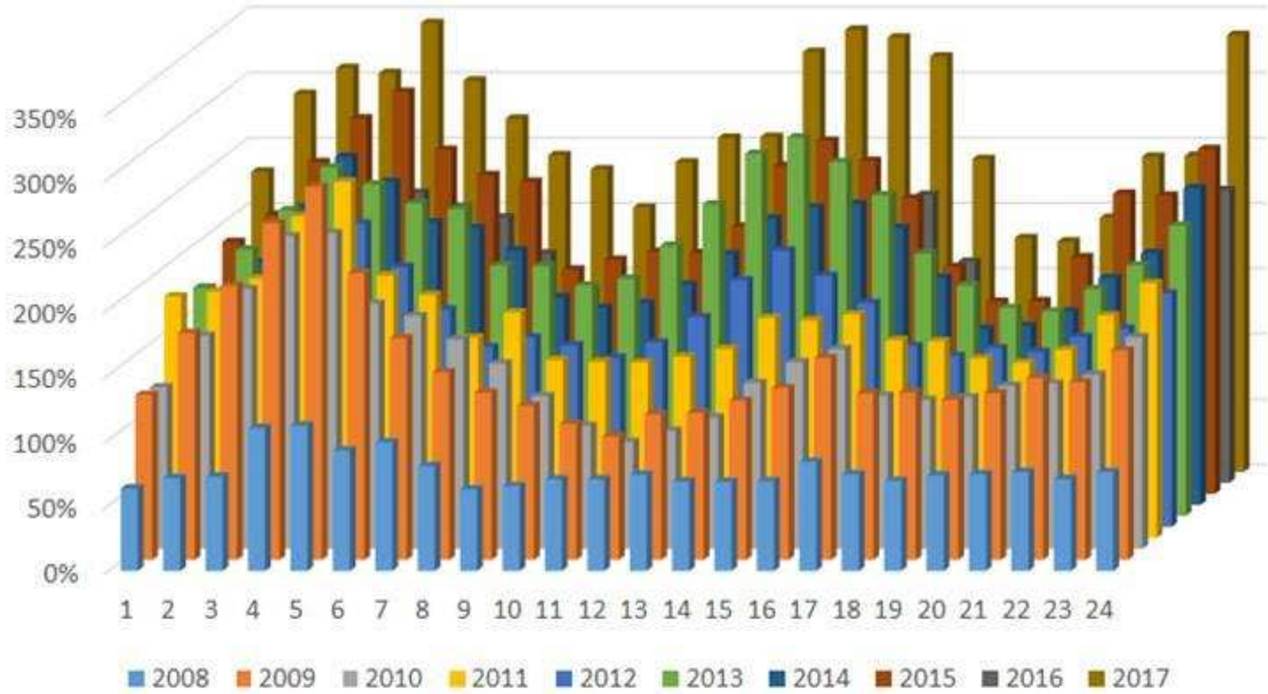
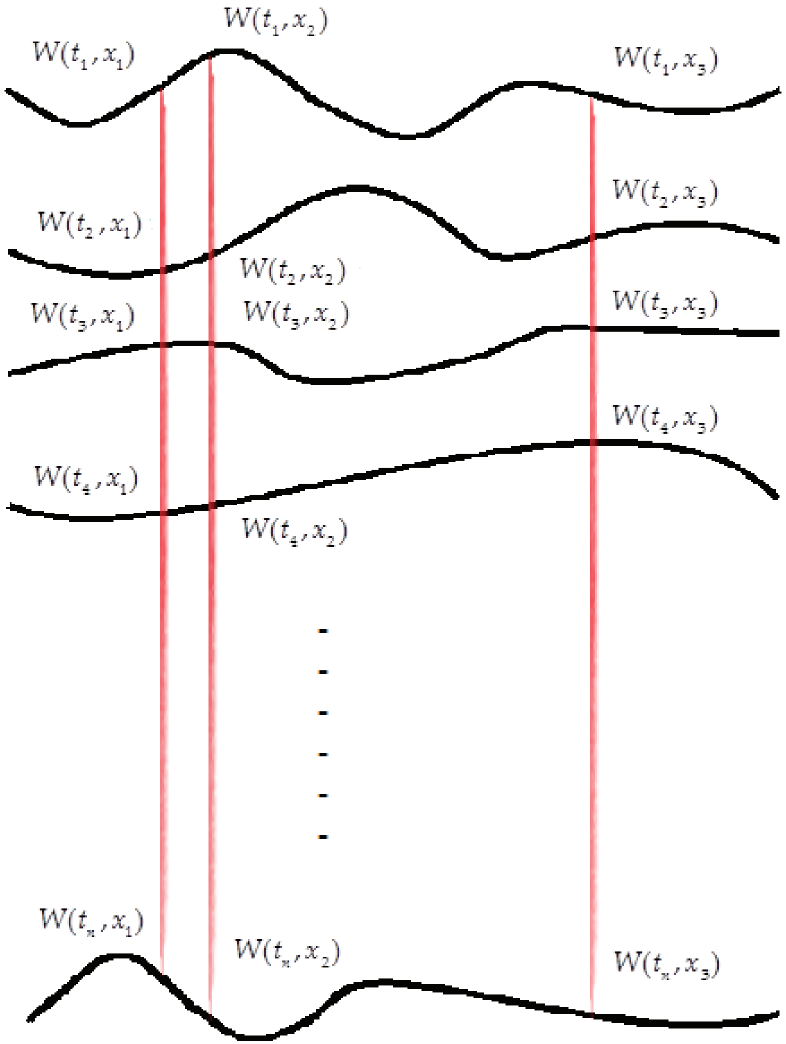


Figure 4: Evolution of volatility of intraday hourly products in different years (source Michael Schuerle)

Excursus on random fields



- Viewed in isolation, each point on the string follows a Brownian motion.
- Even though each point on the string moves randomly, the string does not break apart, so $W(t,x_1)$ and $W(t,x_2)$ are not independent.
- However, $W(t,x_1)$ does contain some variation independent of $W(t,x_2)$.

If $W(t,x)$ is distinguished by the spatial correlation structure of its increments:

$$c(x_i,x_j) = cor[dW(t,x_i), dW(t,x_j)]$$

$W(t,x)$ is a RANDOM FIELD

Price Forward Curves for Electricity as Random Field

- We furthermore assume that the deasonalized forward price curve, denoted by $f(t,x)$, has the dynamics:

$$df(t,x) = (\partial_x f(t,x) + \theta(x) f(t,x))\; dt + dW(t,x)$$

- We fitted the model to data: $dW(t,x)$ is **coloured noise**, with **heavy tails** (leptokurtic distribution) but no clear evidence for conditional volatility

$$W(t+\Delta t, x) - W(t,x) \approx \widetilde{\sigma}(x)(L(t+\Delta t, x) - L(t,x))$$

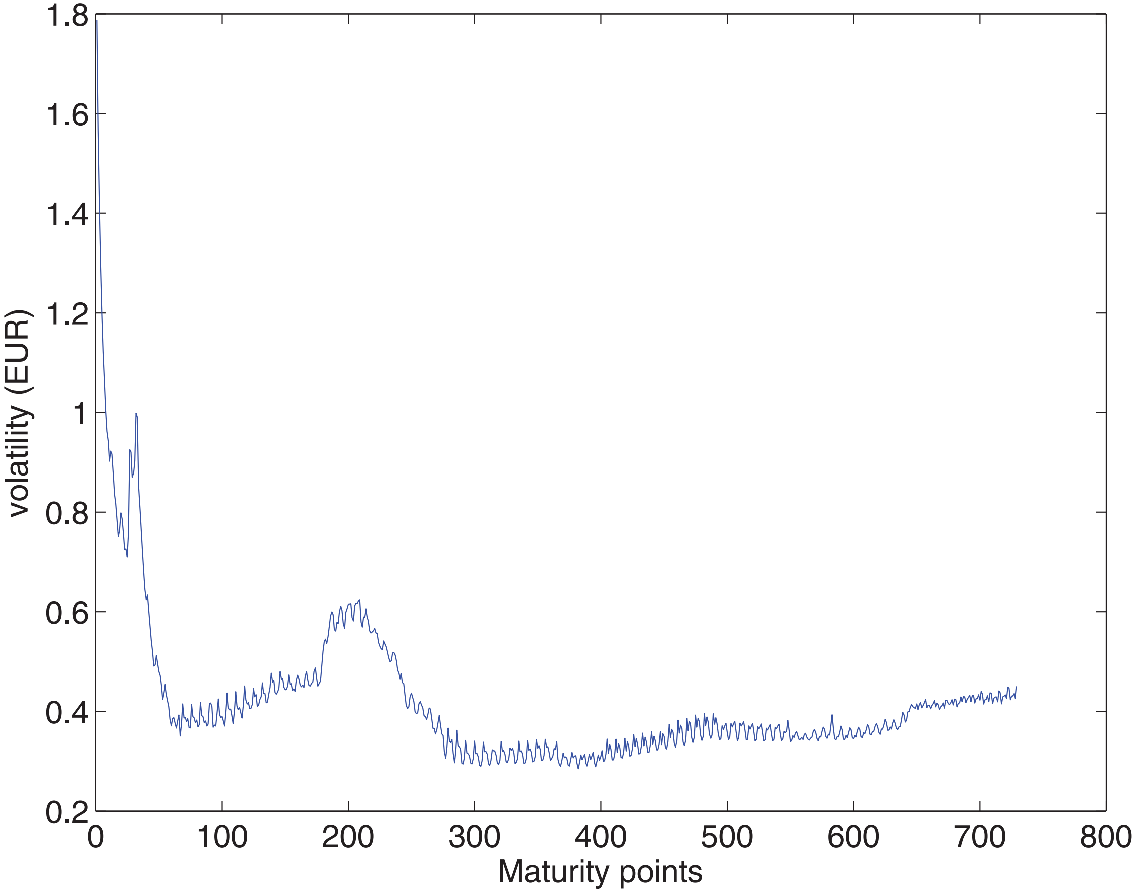
$$\mathbb{E}[L(t,x)L(t,y)] = q(x,y)$$

- $q(x,y) = \exp(-\gamma|x-y|)$ for a constant $\gamma > 0$.
- $t \mapsto (L_t, g)_2$ is a Normal-Inverse-Gaussian (NIG) Lévy process on the real line.
- Source: *Benth, Fred Espen; Paraschiv, Florentina. (2017) A space-time random field model for electricity forward prices.* ***Journal of Banking & Finance. vol. 95.***

INI MES Research track on pricing: Functional data perspective on forward curves (electricity, weather forecast)

–> *Research group:* Fred Espen Benth, Florentina Paraschiv, Michael Schuerle, Almut Veraart
–> In statistics literature this is a trendy topic, very suitable to energy term structures

$$\widetilde{\sigma}(x) = a \exp(-\zeta x) + b$$



Agenda

- Intraday modeling: knowledge needs for industry firms
- Intraday prices, stylized facts
- Threshold model for intraday pricing
- INI MES, Pricing Track: emerging research topics
- **Conclusion**

Conclusion

- An important step towards *automatic trading* is a careful selection of pricing models:
  - *Fundamentals matter*: asymmetric adjustment of intraday prices to updated information on weather
  - The intensity of this link depends on the market expectation of renewables infeed day-ahead (demand minus power plant availability)
  - The location of the threshold can be used by market participants to adjust their bids accordingly – move toward *high value trading, identify trading strategies*
- Maths helps shaping stylized facts: – move toward *functional data analysis* to "shape" volatility term structure, risk premia, noise distribution
- INI MES, Pricing Track: emerging research topics showed the need for *interdisciplinarity* for identifying realistic modeling approaches

References on intraday modeling

- K. Hubicka, G. Marcjasz, R. Weron (2019) A note on averaging day-ahead electricity price forecasts across calibration windows, IEEE Transactions on Sustainable Energy 10(1), 321–323.
- B. Uniejewski, G. Marcjasz, R. Weron (2019) Understanding intraday electricity markets: Variable selection and very short-term price forecasting using LASSO, International Journal of Forecasting.
- Ch. Kath, F. Ziel (2018) The value of forecasts: Quantifying the economic gains of accurate quarter-hourly electricity price forecasts, Energy Economics 76, 411–423.
- Kiesel, Ruediger; Paraschiv, Florentina. (2017) Econometric analysis of 15-minute intraday electricity prices. Energy Economics. vol. 64.
- Benth, Fred Espen; Paraschiv, Florentina. (2017) A space-time random field model for electricity forward prices. Journal of Banking & Finance. vol. 95.
- Faria, E. T. and S.-E. Fleten. (2011) Bidding hydropower taking the Elbas market into account, Computational Management Science 8(1-2), 75–101.
- Engmark, E., Sandven, H, Klaeboe G, S.-E. Fleten. Stochastic multistage bidding optimisation in an intraday market with limited liquidity, Proceedings, European Energy Market 2018.
- S. O. Ottesen, A. Tomasgard, S.-E. Fleten. Multi market bidding strategies for demand side flexibility aggregators in electricity markets, Energy 149, 120–134.