Reporting on the research track on "Pricing and optimization of intraday/day-ahead electricity and futures contracts", Mathematics for Energy Systems program, Isaac Newton Institute

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. Highlights and collaborations:

a. Michael Coulon, Rüdiger Kiesel, Florentina Paraschiv, Peter Tancov: We bring a significant contribution to the literature concerning pricing intraday (ID) electricity by analyzing historical data on trading books in the continuous ID trading. We show the importance of taking into account demand/supply variables to price electricity. We explore simulation models for the evolution of updated weather forecasts with focus on wind and photovoltaic.
b. Fred Espen Benth, Giulia di Nunno, Florentina Paraschiv: We explore and shape the volatility of intraday prices by a new approach in the literature applying stochastic volatility models with time change.
c. John Moriarty, Florentina Paraschiv, Jan Palczewsk: This research aims at moving towards automatic intraday trading: We propose new approaches for optimal bidding behavior in intraday markets taking into account updated information on demand/supply variables, in particular updated forecasting errors in wind and photovoltaic infeed.
d. Fred Espen Benth and Almut Veraart: Advances in random field modeling: this research group explores extensions of the theoretical frame of standard random field models towards a more general representation by allowing for stochastic volatility in the noise term.
e. Fred Espen Benth, Florentina Paraschiv, Michael Schuerle, Almut Veraart: Data mining approach for identifying fields of electricity prices with a spatio-temporal structure suitable for random field modeling with stochastic volatility in the noise term and significant patterns in the risk premia and volatility term structure.
f. Fred Espen Benth, Giulia di Nunno, Florentina Paraschiv, Barbara Rüdiger-Mastandrea: This research plan proposes a data mining approach to explore the dynamics of correlation structures on the spatio-temporal dimensions in electricity random fields. The main goal is to advance the research on random field models by exploring *fields of copula functions.*

. How the programme advanced research in the field

1. Identification of patterns in intraday prices, move towards trading strategies and automatic trading

In recent years the expansion of renewable energy sources has been forged ahead massively across the globe. As electricity generation from renewable energy sources cannot be predicted reliably in the long-term, there will be an increasing demand for electricity trading in short-term electricity markets. Energy firms face thus the challenge of moving towards automatic trading, which requires the identification of trading strategies based on local demand/supply patterns as well as cross-border energy flows.

i. We bring a significant contribution to the literature concerning pricing intraday electricity by analyzing historical data on the bidding behavior in the continuous trading. We show the importance of taking into account demand/supply variables to price electricity

➔ Florentina Paraschiv and Rüdiger Kiesel

1. First, we explore a comprehensive and unique data set of intraday transaction prices and linked demand/supply fundamental variables. Intradaily updated forecasts of renewable power generation (solar, wind) constitute the heart of our data collection. These are the same real-time renewable forecasts as available to traders on the intraday market. This is the most extensive data set used in the literature to study the intraday electricity market.
2. Second, we propose the first fundamental model for 15-minute intraday prices that incorporates the slope of the merit order curve. This is a substantial improvement over Kiesel and Paraschiv (2017) since electricity prices react asymmetrically to renewable forecast changes depending on the merit-order-curve slope.
3. Third, we include lagged prices of neighboring 15-minute contracts in our fundamental model in the spirit of a cross-sectional analysis.

ii. We explore and shape the volatility of intraday prices by a new approach in the literature applying stochastic volatility models with time change

➔ Fred Espen Benth, Giulia di Nunno, Florentina Paraschiv

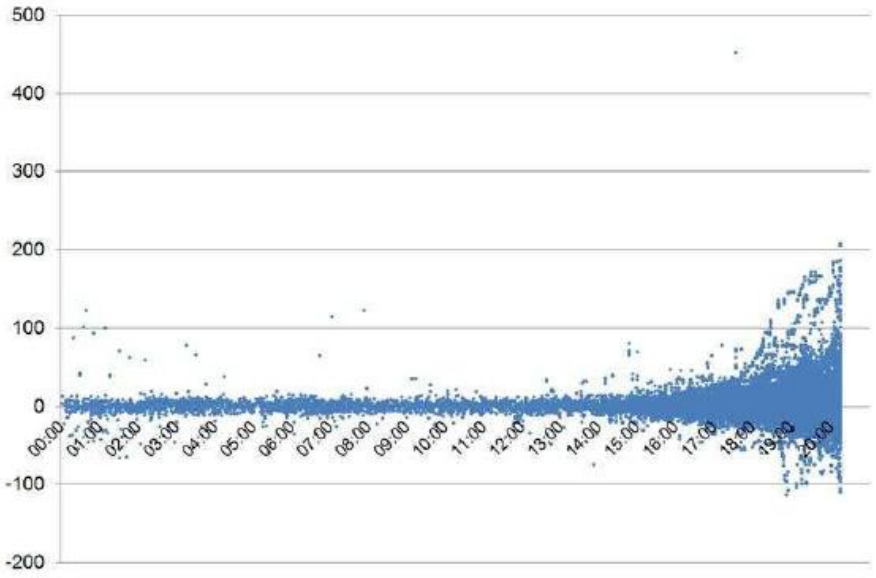

Figure 1: Differences between ID prices and day-ahead prices aggregated over 6 years

iii. Move towards automatic ID trading: We propose new approaches for the identification of optimal bidding behavior in intraday markets taking into account updated information on demand/supply variables

➔ John Moriarty, Florentina Paraschiv, Jan Palczewski

In the intraday market, electricity suppliers have the chance to balance out gaps in the demand/supply not covered in the day-ahead market, imbalances mainly caused by the volatile wind and photovoltaic production. The volumes of trades in this case include both demand and supply-side bids. The continuous bidding in the intraday market ends with 30 minutes before the beginning of delivery period. Prior to gate closure, as explained above, at each time of the bid updated forecasts of wind and photovoltaic are available online, and the supplier's position may be adjusted continuously by trading. Since both the updated renewables forecasts and the intraday prices are dynamic, there are associated opportunity costs that make trades in the intraday market suboptimal. It is therefore highly relevant to assess these opportunity costs with respect to both optimal timing and quantity of the bid given the magnitude of forecasting errors in renewables.

Original thinking and scientific renewal: To our knowledge, this will be the first study in the literature in which updated real-time ex-ante forecasting errors of wind and photovoltaic will be used as input to optimize the bidding behavior in the intraday market. The novelty of this study consists also in the dynamic nature of the optimization problem, leveraging cutting-edge techniques from mathematical finance

(Pham (2009)). This requires the novel joint simulation of the trajectories of forecast errors and electricity prices. The main challenge for optimization is that the model has highly multidimensional and complex dynamics, including feedback effects (where trading affects prices). We will therefore exploit the very latest developments in Least Squares Monte Carlo optimization, which have boosted its accuracy, lowered numerical complexity, and allowed feedback. These developments include control randomisation and regress-later approximation (Balata and Palczewski (2017)).

2. Advances in random field modeling reflected in energy data

Electricity intraday, day-ahead and forward prices have been impacted by several structural changes over time mainly determined by the continuously increase in renewable energies that had an effect on both price expectation and volatility. At the same time, the academic literature sheds light on typical seasonal patterns in electricity prices with respect to the time to delivery (maturity) dimension. An example in this sense is the evolution of intraday electricity prices over time (temporal dimension) and over the delivery time (maturity) dimension, as shown in Figure 2. We observe an increased volatility due to an increasing need to balance out renewable energy in the intraday markets over time, while the volatility shows a clear seasonal pattern within a day. Thus, a realistic stochastic model should explore electricity prices on two dimensions simultaneously allowing for spatio-temporal dynamics. Random field modeling is a useful tool in this respect and has been applied previously to forward electricity prices.

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

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

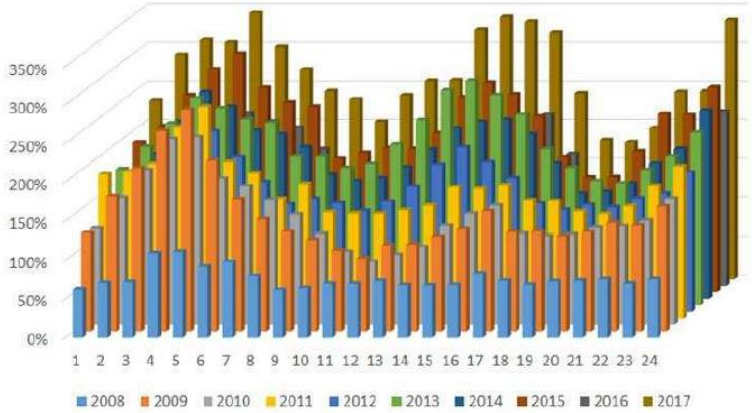

Figure 2: Evolution of volatility of intraday hourly products in different years (source Michael Schuerle)

Random-field models for forward prices in power markets have been explored statistically and mathematically by Andresen et al. (2010). There the authors model electricity forwards returns for different times to maturity using a multivariate normal inverse Gaussian (NIG) distribution to capture the idiosyncratic risk and heavy tails behavior and conclude the superiority of this approach versus Gaussian-based multifactor models in terms of goodness of fit. Their analysis seems to be based on the assumption that forward prices follow an exponential spatio-temporal stochastic process. When modeling forward prices evolving along time to maturity rather than time at maturity, one must be careful with how the time to maturity affects a price change. Indeed, in this so-called Musiela parametrization context of forward prices an additional drift term must be added to the dynamics to preserve arbitrage-freeness of the model. This feature is reflected in the spatio-temporal random field model applied to electricity price forward curves in Benth and Paraschiv (2017). Using functional data analysis, the authors shed light on the statistical properties of risk premia, of the noise, volatility term structure and of the spatio-temporal noise correlation structures. After explaining the Samuelson effect in the volatility term structure, the residuals are modeled by an infinite dimensional NIG Lévy process, which allows for a natural formulation of a covariance functional.

In the research track on pricing and optimization of intraday/day-ahead electricity and futures contracts, we had several groups working on advances in random field modeling and their applications to intraday/forward electricity prices:

- ➔ Almut Veraart and Fred Espen Benth: work on an extension of the theoretical frame of standard random field models towards a more general representation by allowing for stochastic volatility in the noise term. This is highly relevant, given that empirical evidence shows stochastic volatility in electricity prices.
- ➔ Fred Espen Benth, Florentina Paraschiv and Michael Schuerle: Data mining approach for identifying fields of electricity prices with a spatio-temporal structure suitable for random field modeling with stochastic volatility in the noise term and significant patterns in the risk premia and volatility term structure.
- ➔ Fred Espen Benth, Giulia di Nunno, Florentina Paraschiv, Barbara Rüdiger Mastandrea: A data mining approach to explore the dynamics of correlation structures on the spatio-temporal dimensions in electricity random fields. The main goal is to advance the research in random *field models by exploring fields of copula functions.*

. Did the programme successfully bring different communities together, and are there research results or specific outputs that highlight this

The INI MES program research track on Pricing and Optimization brought together researchers from three fields of research and expertise:

- mathematical finance and statistics (Fred Espen Benth, Rüdiger Kiesel, Giulia di Nunno, Barbara Rüdiger-Mastandrea, Peter Tankov, Almut Veraart, Florian Ziel)
- economics and finance (Florentina Paraschiv)
- operations research (Michael Schuerle, Michael Coulon)

The interdisciplinary approach consisted also in bringing together researchers with various methodological approaches to analyzing the energy markets: purely theoretical versus data-driven/empirical approaches.

8 various research sub-groups have been created during the kick-off meeting. In all brainstorming sessions, preliminary discussions about the economics of energy markets and energy systems, as detailed below, were essential to contour the research abstracts:

--> Input from economists and engineers

- Technical characteristics of energy trading

- Price formation in intraday and day-ahead markets

- Description statistics and visual inspection of data on price evolution, trading activity, volatility features

- Identifications of patterns in energy data

- Identification of "fields" of data structures in the electricity markets suitable for random field modeling (e.g. spatio-temporal structures like electricity price forward curves, historical data of intraday trading in intraday markets for different delivery periods)

--> Input from mathematicians and statisticians:

- The patterns identified in electricity prices were explored on several dimensions (temporal or spatial/delivery time)

- Recall expertise in mathematics and statistics to find suitable functions that shape various features (volatility, expectations, risk premia) of electricity prices (intraday, day-ahead, futures)

- Move towards *functional data analysis*: help generalizing existing patterns with great relevance for pricing, hedging

- The identification of price patterns shaped by suitable mathematical functions help forming trading strategies which can be integrated in the optimization of bidding behavior in intraday and day-ahead markets

- The resulting interdisciplinary research ideas are highly relevant to move toward *automation of electricity trading*

--> **Additional interdisciplinary research ideas: experts in energy systems need the input from statisticians to assess risk**. Typically, classical risk indicators focus on the consequences of accidents in the energy sector, but do not evaluate their probabilities of occurrence or the risk averseness. These are serious drawbacks, as in risk-based decision-making it is important to account for risk preferences. To overcome this drawback, in this study, Value-at-Risk (VaR), Expected Shortfall (ES) and the Spectral Risk Measures (SRM), which are commonly used in the financial realm, are applied within an energy security perspective.

. What plans and direction have you identified for future investigations

The research track on pricing and optimization of energy markets comprised an interdisciplinary research team. The research topics described above will be further investigated in meetings at the Imperial College London, Norwegian University of Science and Technology, University of Duisburg-Essen, University of Oslo, or University of St. Gallen. The meetings will be financed from existing research projects of the participants to the research tracks at their home universities to help the MES emerging research advance. Emerging research will be presented in upcoming workshops and conferences that will allow for future investigations.

- CMStatistics 2019, (Florentina Paraschiv and Michael Schuerle presenting research that advanced during the MES INI programme)

- 26th Annual Meeting of the German Finance Association (DGF) that will include a special stream dedicated to energy research, organized by Rüdiger Kiesel, participant in the program and in this track
- Almut Veraart and Fred Espen Benth will organize workshops in mathematical finance that will open the stage for presentations of future research that emerged in the MES INI program

. Are there notable impacts outside academia, or to other areas of academia beyond mathematics

- ➔ Impact outside academia: The planned research on intraday pricing and optimization of the bidding behavior will be mainly happening at NTNU Trondheim and the University of Duisburg-Essen and it is tied to a **collaboration to energy firms** (e.g. Skagerak, BKK and Tronderenergi, in Norway or RWE in Germany).
- ➔ Impact to other areas of academia beyond mathematics: the interdisciplinary research emerging from the brainstorming sessions in the MES program will be disseminated in relevant conferences in the area *economics and finance of energy markets* as well as *operations research*. The real world problems identified in energy markets are approached by a new spectrum of methods, complementary to those typically employed by economists/engineers.

. Plans for publications:

The paper proposed below, which advanced during the MES INI program, will be included in the proposal to the theme issue on the Mathematics of Energy Systems, Philosophical Transactions of the Royal Society A.

A tentative title: "A Fundamental Model for Continuous Intraday Electricity Trading of 15-Minute Contracts"
- The name and affiliation of the lead author: Marcel Kremer, PhD candidate University of Duisburg-Essen, Chair for Energy Trading and Finance
- Names of co-authors from the INI MES programme:

- ➔ Florentina Paraschiv
- ➔ Ruediger Kiesel

The following two research papers that advanced during the MES INI program are currently under review in academic journals:

- Escobar, D., Paraschiv, F. & Schürle, M. (2019). Recovering the shape of distortion functions in power markets, working paper, to be submitted to the **Journal of Banking and Finance.**

- Paraschiv, F., Reese, S.M., Ringkjøb Skjelstad, M. (2019). Portfolio Stress Testing Applied to Commodity Futures. Under review in **Computational Management Science**.

Generally speaking, emerging research from this research track is suitable for publications in *applied mathematics* journals, **energy journals** (that accept interdisciplinary research), or *quantitative finance journals*.

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- Escobar, D., Paraschiv, F. & Schürle, M. (2019). Recovering the shape of distortion functions in power markets, work in progress.
- Paraschiv, F., Reese, S.M., Ringkjøb Skjelstad, M. (2019). Portfolio Stress Testing Applied to Commodity Futures. Under review in Computational Management Science.
- Kremer, M., Kiesel, R., Paraschiv, F. (2019): The impact of renewable energies for continuous intraday electricity trading, Philosophical Transactions of the Royal Society A (submitted)
- Spada, M., Paraschiv, F., Burgherr, P. (2018). A comparison of risk measures for accidents in the energy sector and their implications on decision-making strategies. Energy, 154, 277-288
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- Pham, H. (2009). Continuous-time Stochastic Control and Optimization with Financial Applications. Springer.