Renewable Energy and Mathematical Economics for the Environment

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1 Overview

This proposal request is for seed money to grow a thriving exchange between students and faculty in the ORFE department at Princeton and Mathematics and Statistics/Economics departments at Humboldt, which would then be leveraged into a larger and long-term collaboration with external funding from the US and German Science Foundation and industrial partners. This research and training component concerns mathematical and statistical analysis of issues related to the transition of energy production in Europe and the US from fossil-fuel based to increasing reliance on renewable technologies.

Energy production has seen dramatic and unpredictable swings in just the past handful of years, with more such technological, political and natural surprises likely to come. For instance, dwindling oil reserves have been replenished by numerous discoveries; technological improvement has aided in extraction from deeper wells and tar sands and fracking has rapidly cut natural gas prices; a drop in silicon prices has made solar panels cheaper. Carbon emissions targets and the potential adoption of electric cars loom as game changers for the energy market.

Analyzing the interaction between the three dimensions of exhaustibility, cost and emissions of different fuels types, as well as their inherent uncertainty is a key concern for consumers, producers, market regulators, and policy makers. By viewing the fuel sources though the tools of modern dynamic game theory, one can capture the three dimensions of the “trilemma”. The participants are extremely heterogeneous in terms of energy producing capabilities, reserves, emissions and costs. They interact and compete through energy markets.

Models of optimal exploitation of natural resources, efficient use of renewable energies and implementation of cleaner technologies give rise to an array of mathematical and statistical challenges. Within framework of the Humboldt-Princeton partnership we intend to develop (i) new game-theoretic models to determine socially optimal strategies for the exploitation of exhaustible resources and use of renewable energies, (ii) new equilibrium models for pricing and efficient allocation of emissions credits under the European Union Emission Trading Scheme, and (iii) novel statistical methods for calibration of equilibrium models for emission credits, weather and energy derivatives.

The team from both universities represents broad expertise in stochastic modeling, statistics and mathematical finance and economics. The members have long experience working on energy, environmental and climate problems. There has been prior collaboration between the ORFE department and Mathematics & Economics departments at Humboldt over the past decade, with a number of collaborations and publications. Since 2007, we have held a series of biennial Humboldt-Princeton Conferences (alternately in each location) where the latest developments on Statistics, Mathematical Finance and Economics are presented. The fourth conference was at Princeton in November 2013. We are applying for support from the Princeton-Humboldt Partnership to move this collaboration to the next level, from which we can apply for funding for a closer graduate training partnership across the sciences and engineering, funded from external sources.

2 Project & Objectives

The proposed project *Renewable Energy and Mathematical Economics for the Environment* will encourage the development of a structured doctoral program by:

- sponsoring cutting-edge and cross-disciplinary research projects in the emerging field of mathematical environmental economics;

- integrating young researchers from Humboldt into the research network of Princeton faculty members and vice versa;
- sponsoring summer school to expose students to the latest developments in optimization, probability, game theory and statistics related to environmental economics;
- sponsoring conference series to allow students and young researchers to network and to share their latest research with their peers;
- sponsoring research visits of students young researchers at HU or PU including the possibility of participating in the many events organized by our CRC and (I)RTGs;
- offering co-supervised Ph.D. projects.

2.1 Student and Faculty Exchange

We intend to exchange faculty members and students alike. Humboldt and Princeton Faculty members will travel to the respective partner institution to deliver mini-courses, share their research and expertise with students at all levels and initiate new research projects. Specifically, we apply for funding for

- two Humboldt researchers (Horst, Lòpez Cabrera) to spend three months at PU to lecture and to collaborate with Carmona, Fan and Sircar on models of emissions markets, resource exploitation and statistical analysis of weather risk;
- two Princeton researchers (Carmona, Sircar) to spend three months in Berlin to give lectures and to collaborate with Horst, H addle and Lòpez Cabrera on game theoretic models of energy production and their empirical analysis and calibration.

Student exchange is one of our top priorities. We therefore apply for funding for up to 12 students to spend one month at the respective partner institution. We will make every effort to award half of the travel awards to female researchers. One travel stipend would be reserved for the Hilda Geiringer Postdoc, a position awarded by the SFB 649 to female researchers in recognition to the first woman to hold the title of Privatdozent in applied mathematics in Berlin. Possible candidates for the exchange problem include Julio Backhoff (HU Mathematics), Tatiana Gonzalez (BMS), Paulwin Graewe (HU Mathematics), Dorte Kreher (HU Mathematics), Franziska Schulz (HU, Economics); and Yidong Dong (ORFE, Princeton), Dan Lacker (ORFE, Princeton) and Patrick Chan (Applied Math, Princeton).

2.2 Summer Schools and Workshops

Summer Schools, Conferences and Workshops are key to the training of young researchers. Within the framework of the HU-PU strategic partnership, we intend to organize the follows events:

- Summer School on *Energy Finance* (2016). This summer school will be held in Berlin and sponsored by the SFB 649 with further support from the BMS. We apply for travel support for up to 10 Princeton students (all levels) to attend the school and for support of one additional external lecturer.

- In collaboration with ETH Zürich, our RTG 1845: ”Stochastic analysis with applications in biology, finance and physics” organizes an annual summer school in probability that would be of interest to the students of Carmona, Fan and Sircar. We hence apply for a total of 4 travel stipends for Princeton students to attend the 2015 and 2016 RTG summer schools.

- A Humboldt-Princeton Conference *Mathematics & Statistics of Renewable Energy*, to be held in Princeton in the Fall of 2015. We apply for 8 travel stipends for Humboldt PhD students to attend the conference.

- A joint conference with NUS (National University of Singapore) on *Financial Sustainability* to be held in Princeton in 2016. We apply for travel stipends for 10 Humboldt researchers.

3 Promotion of Global Aspirations and Longer Term Funding

Our team brings together scholars from a variety of disciplines, facilitating interactions between academia and practice with the aim of enhancing knowledge transfer and identifying new directions of research in mathematical environmental economics. Support for young academics is a priority for this partnership. Our overall goals are specific support for young academics and especially for women in academia, a focus on international and interdisciplinary work as well as the integration of international doctoral candidates. The aim in all this is to achieve and maintain the highest quality of education and supervision for doctoral candidates. Furthermore, we hope to encourage and promote social networking amongst our doctoral candidates, thus creating closer links among themselves and with their home university.

An important step in pursuing this aim is the foundation - in the long run - of a structured doctoral program in Mathematical Environmental Economics or, more generally, Sustainability. The latter could comprise not only the areas of energy markets, sustainable exploitation of natural resources, sustainable energy production and the (economic and financial) risks associated with it, but also topics related to financial markets such as systemic risk, financial contagion, and financial market imperfections and sustainable economic growth. On the broader topic of sustainability, we plan to reach out to our colleagues at the National University of Singapore (NUS). Its Risk Management Institute and Center for Quantitative Finance hosts some of the leading experts world-wide on quantitative finance in general and systemic risk in particular. At this point we should also mention that U. Horst (HU) and S. Kou (NUS) are organizing the First Berlin-Singapore Workshop on Quantitative Finance and Financial Sustainability in Berlin this year and that our partners from NUS have already expressed their interest in organizing future conferences in collaboration with PU.

If funded, we will use the seed to raise funding for a joint graduate exchange. In our opinion, there are two options. The first is to apply for an International Research (Graduate) Training Group (IRTG) through the German Science Foundation (DFG) and the US National Science Foundation (NSF), and possibly in collaboration with NUS. The Princeton PIs have been successful in obtaining a 5-year \$2.2*m* Research Training Grant (RTG) from NSF for funding US graduate students, and that is ending in Spring 2014. This experience will be useful for establish in international RTG with Humboldt.

The second is to raise industry funds. In fact, our initiative of establishing a doctoral program in the above mentioned area fits very well with the ongoing "Berlin-Potsdam-Labs 2030" initiative of the "Verein Berliner Kaufleute und Industrieller (VBKI)" to raise sizable private funding to promote high-level research in selected fields such as mathematics in the Berlin-Potsdam area. The initiative is lead by Jurgen Kluge, the former Head of McKinsey Germany. The VBKI has recently approached the DFG Research Center Matheon to help them identifying priority research areas in mathematics that could be of potential interest for industry partners. Among these areas is visualization, scientific computing for drug design, insurance mathematics, and energy risk.

There is no doubt that the support of our research plans through the Humboldt-Princeton partnership and the possibility of an institutionalized cooperation with PU would greatly appeal to private donors. Companies we could approach include Vattenfall, the Berlin-based energy provider; Allianz (who have offices in New York, Berlin and Singapore); Munich Re, which has an office in Princeton; and NRG, an energy company in Princeton whose CEO and founder David Crane is a Princeton alumnus and friend of the ORFE department.

These are all options we shall pursue during the first year of this project and during the PI's visits to each other. At the university level, we would participate in an effort to establish a dual graduate research program in Engineering & Sciences between Princeton and Humboldt, analogous to the longstanding one between the two institutions in the Humanities.

4 Detailed Research Agenda

Our research will focus on novel mathematical and statistical methods for applied problem related to energy and the environment. We describe the projects and areas of natural collaboration, which will be between the PIs and the graduate students at both institutions.

4.1 Emissions Market

Emission trading schemes, also known as cap and trade systems, have been designed to reduce pollution by introducing appropriate market mechanisms. In such systems, a central authority sets a limit (cap) on the total amount of pollutant that can be emitted within a pre-determined period. To ensure that this target is complied with, a certain number of credits are allocated to appropriate installations, and a penalty is applied as a charge per unit of pollutant emitted outside the limits of a given period. Firms (often energy providers) may reduce their own pollution or purchase emission credits from a third party, in order to avoid accruing potential penalties. The transfer of allowances by trading is considered to be the core principle leading to the minimization of the costs caused by regulation: companies that can easily reduce emissions will do so, while those for which it is harder buy credits.

Following up on previous research by René Carmona (PU) and his co-authors on emission trading schemes, we intend to develop tools to help policy makers and regulators understand the pros and the cons of the emissions markets. Our primary focus will be on models of equilibrium pricing and hedging of emission credits, i.e. on models where emission credits are priced based on supply and demand. Such pricing schemes have so far only been developed for risk neutral firms. Risk neutrality greatly simplifies the mathematical analysis but it is unsatisfactory from an economic perspective.

Patrick Cheridito (PU), Ulrich Horst (HU) and their collaborators have recently established a mathematical framework for equilibrium pricing of financial securities under rather general assumptions on the preferences and characteristics of market participants. Analyzing the market for emission credits calls for a generalization of their methods in order to allow for an interplay between financial markets (emission rights) and goods markets (electricity, oil, coal,). We intend to establish such generalizations and to analyze optimal production, abatement and investment decisions and hedging schemes for emissions markes beyond the benchmark case of risk neutrality. A particular focus will be on the impact of firms' expectations about weather conditions (effecting the amount of energy produced by renewables) or the development of new technologies for electricity storage on the pricing of emission credits.

4.2 Power Markets and Weather Risk

We will also deal with the modeling and forecasting of power markets like the EEX and its dependencies with weather variables. For example, energy consumption is highly sensitive to weather conditions and thus the stochastic demand can be replicated by temperature indices. Power prices are plagued by high volatility, positive skewness, volatility clustering and large spikes. Furthermore, evidence of the substantial impact of exogenous fundamental drivers, and their nonlinear response functions, is well established. The challenge is to develop multivariate statistical tools (e.g. non-semiparametric conditional quantile models for unbalanced data) to capture the relationship between weather factors and energy prices. The interactions between different markets will be studied in a multivariate setting as well as their covariance structure. As an application we will analyze risk bounds using derivatives. Forecasting tail probabilities and Value at Risk (VaR) however, despite their popularity for stock markets, remains under research and deploys concrete questions in energy trading.

Amongst energy, electricity stands out due to its non-storability. Supply and demand have to be balanced out at every point in time. Since electricity is mainly traded in a day-ahead market, short-term adjustments in supply due to forecasting errors can lead to enormous financial losses. Our aim is to quantify the weather related risk in electricity demand and to apply nonparametric conditional quantile models to forecast electricity demand and to obtain estimates of the uncertainty and dispersion of future demand taking weather conditions into account. This research involves Lòpez Cabrera, Härdle, Fan and Sircar. The outcome of this project as well as the previously described project will give a solid base for the price formation of renewables (e.g. wind power) which are strongly weather dependent, as well as CO2 emissions.

4.3 Contracting under Limited Liability

Industrial and financial firms are subject to large risks: the former are prone to accidents and the latter are exposed to sharp drops in the value of their assets. Preventing these risks requires managerial effort. Systematic analyses of industrial accidents point to the role of human deficiencies and inadequate levels of care. A striking illustration is offered by the explosion at the BP Texas refinery in March 2005: after investigating the case, the Barker Panel concluded that "BP executive and corporate refining management have not provided effective process safety leadership." Similarly, large losses incurred by banks and insurance companies during the recent financial crisis were in part due to insufficient risk control.

The design of incentives to mitigate risk under asymmetric information and limited liability has developed into an active and competitive research area of modern mathematical economics over the last decade. Dynamic contracting probelms and dynamic equilibrium pricing problems share a common mathematical basis. Extending previous research by Humboldt and Princeton mathematicians (Backhoff, Horst, Sircar) on problems of optimal risk sharing under asymmetric information we intend to analyze the stability of optimal contracts and risk mitigation schemes with respect to the characteristics of the market participants and model parameters. Several Princeton researchers (especially Y. Sannikov) have developed new control-theoretic methods for characterizing optimal contracts under asymmetric information but limited themselves to risk neutral players. From a practical perspective it is of upmost importance to understand if and when their main results are valid under risk aversion and how stable the results are with respect to changes in the model parameters (large losses or accidents are rare events hence the frequency of their arrival is difficult to estimate). The former is the topic of the ongoing dissertation project of J. Backhoff (a BMS student working under the supervision of Horst).

4.4 Commodities, Energy & Exhaustible Resources

Commodities and energy markets have gained increased importance both in terms of regulatory concerns such as a way to control emissions, and as a growing arena for investment to diversify from at or declining traditional assets. Understanding the increased "financialization" of commodities markets leads to feedback models, the solution of which poses interesting challenges in nonlinear PDE. Discerning the relative interplay between growing demand due to industrialization and demand due to financial speculation is a delicate inverse problem that requires sophisticated numerical schemes.

Many of these markets are oligopolies, or governed by a few energy providers, and this leads to problems in dynamic game theory that require analysis of BSDEs (Backward Stochastic Differential Equations) or systems of PDE (Partial Differential Equations). The resulting game effects build new links between stochastic control and competitive equilibrium. These models pose new challenges in the theory of coupled systems of nonlinear PDEs, while giving insight into how to promote the switch from traditional exhaustible energy source to sustainable alternatives, given the ongoing technological advances. Extending these frameworks to large player limits and other equilibrium solution concepts connects to the emerging area of mean-field games.

These areas provide fertile ground for collaboration between Carmona and Sircar at PU, and Horst at HU, and especially their graduate students. The development of respective analytical and computational tools is crucial in helping energy policy makers trust and rely on quantitative methods in decision making and regulatory functions.