a) Summary

Title of project:	A competitive agent-based market laboratory for complex energy networks
Name of supervisor(s):	Prof. Dr. Ir. Eric van Heck and Dr. Wolfgang Ketter
Project reference number:	*will be assigned by ERIM*
Keywords (ca. 10):	Agent-Mediated Electronic Marketplaces, Auctions and Exchanges, Decision Support Systems, Intelligent Agents, Machine Learning, Market Forecasting, Multi-agent Systems, Multi-criteria Optimization, Supply-Chain Management, User Preference Modeling
Abstract (max. 250 words):	Sustainable energy systems of the future will need more than efficient, clean, low-cost, renewable energy sources; they will also need efficient price signals that motivate sustainable energy consumption as well as a better real-time alignment of energy demand and supply. At its core, this is a problem of distributing resources among self-interested parties, a problem that markets can solve. Such a market will have considerable complexity and potential for unintended negative consequences. The risks involved in establishing such markets are high without solid research guidance. This project aims to develop results that will provide well-founded guidance on the structure of and the participants in such markets to guide future energy policy. The core research question is:

> *What combinations of market mechanisms and decision support can effectively manage future smart energy grids on behalf of individual, commercial, and public sector stakeholders?*

To answer this question, the PhD student will work on a rich, competitive simulation environment – a laboratory for developing a clear understanding of the emergent phenomena arising from complex interactions of market mechanisms with adaptive, self-interested agents, under the technical and economic constraints of future energy markets.

b) Full Text

1. Supervisory team

1a. Supervisor(s) of the project

Prof. Dr. Ir. Eric van Heck - Professor of Information Management and Markets
Dr. Wolfgang Ketter - Assistant Professor of Information Systems

1b. The expected hours per month that each member of the supervisory team is committed to spend on the project (per member)

Prof. Dr. Ir. Eric van Heck 8 hours/month and Dr. Wolfgang Ketter 16 hours/month

2. Title of the research project

A competitive agent-based market laboratory for complex energy networks

3. Summary of the research problem and research question

We know how to build "smart grid" [1] components that can record energy usage in real time and help consumers better manage their energy usage. However, this is only the technical foundation. Variable energy prices that truly reflect energy scarcity can motivate consumers to shift their loads to minimize cost, and for producers to better dispatch their capacities [15]. This will be critical to the effort to develop a more sustainable energy infrastructure based on increasing proportions of variable-output sources, such as wind and solar power. Unfortunately, serious market breakdowns such as the California energy crisis in 2000 [4] have made policy makers justifiably wary of setting up new retail-level energy markets.

The performance of markets depends on economically motivated behavior of the participants, but proposed retail energy markets are too complex for straightforward game-theoretic analysis. Agent-based simulation environments have been used to study the operation of wholesale power markets [29], but these studies are not able to explore the full range of unanticipated self-interested or destructive behaviors of the participants. Smart grid pilot projects [13], on the other hand, are limited in their ability to test system dynamics for extreme situations. They also lack the competitiveness of open markets, because a single project consortium typically controls and optimizes the interaction of all parts of the pilot regions. Therefore, we are developing an open, *competitive* market simulation platform that will address the need for policy guidance based on robust research results on the structure and operation of retail power markets. These results will help policy makers create institutions that produce the intended incentives for energy producers and consumers. They will also help develop and validate intelligent automation technologies that will allow effective management of retail entities in these institutions.

We call this vision the *Power Trading Agent Competition* (see Figure 1) because it is an example of a Trading Agent Competition[1] applied to electric power markets.

[1] see www.tradingagents.org

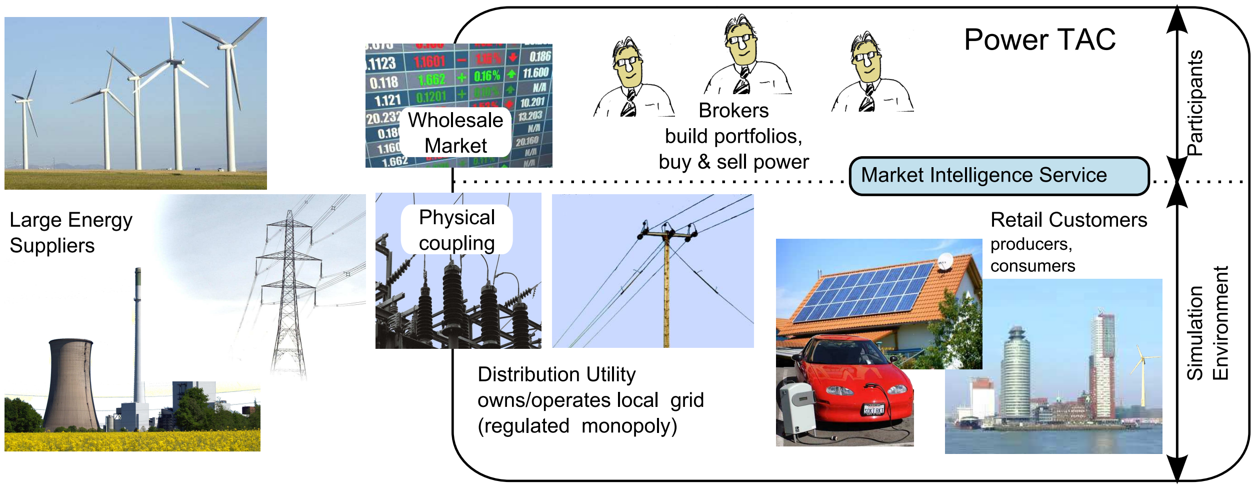

Figure 1: Power TAC Scenario.

Research objective

The challenge is to develop a clear understanding of these complex energy markets without putting producers and consumers at risk [24]. We propose to address this challenge with a program of economic modeling and laboratory experimentation that can test proposed market designs in a competitive simulation environment, similar to the Trading Agent Competition for Supply Chain Management (TAC SCM) [9]. This environment will model a market-based management structure for local and regional energy networks at multiple levels of complexity [17]. It will closely model reality by using real historic data on energy production and consumption, weather, and consumer preferences from the German MeRegio project [13], and the American EPRI/NIST Pacific Northwest project [12], in addition to data from business and horticultural enterprises in the Netherlands. This competition will challenge research teams from around the world to create autonomous agents [35], or agent-assisted support for human decision makers [34], that manage distributed energy producers and consumers effectively and profitably in direct competition with each other. Teams will attempt to exploit the structure of the market, which will be adjusted periodically to defeat counterproductive strategic behaviors. The result will be a body of valuable research data, along with a high degree of confidence that such market structures along with agent-based automation technologies could be safely introduced into the operation of large scale, complex and dynamic energy networks.

The main research question is:

> *What combinations of market mechanisms and decision support can effectively manage future smart energy grids on behalf of individual, commercial, and public sector stakeholders?*

This project includes three important aspects of complexity research. First, the behavior of individual energy producers, consumers, and brokers is studied on the micro level, and aggregated at the macro level in terms of overall market behavior. Second, electrical energy systems and associated markets are large and complex networks that change dynamically over time. Third, this research aims at investigating and increasing the predictability of renewable energy production and consumer behavior in future energy markets.

4. Description of the research project (min. 1000 words)

4.1 Elaboration on the research problem and questions

This project will be part of a larger international multi-disciplinary research program with contributions drawn from Economics, Management Science, Operations Research, Computer Science, Electrical Engineering, and Psychology. The core research questions are about finding ways to manage complex, dynamic smart energy grids using market mechanisms. To answer these questions we will construct a low-risk laboratory environment in the form of a competitive simulation that has demonstrable validity and energy brokers that manage this market.

The main questions of interest to the PhD student are focused on mechanism design of the new energy market, the behaviors of broker agents and the resulting emergent phenomena that can be observed in the simulation. Further, we are interested in modeling the behavior of various types of energy users and how issues like price elasticity can help us to shift energy loads.

The approach we propose draws on our extensive experience with competitive simulations as developers, organizers, and participants in the Supply Chain Management domain [7]. We are aware of two earlier approaches to study power markets using simulations. One is the AMES simulator for studying wholesale power markets described by Sun and Tesfatsion [31]; the other is the work of Conzelmann et al. [10]. Both of these studies use agent-based simulation techniques [32] to study wholesale, not retail markets, and neither of them are competitive simulations in the sense of inviting outside researchers to directly compete in the simulated markets. This is a critical difference, because strategic behavior in complex market situations can take many forms, and no single research group is likely to discover them all. The key advantage of the competitive simulation approach is that a wide range of researchers are invited to apply their creativity to the problem. The result will not be a mathematical proof that no destructive strategies exist, but instead strong evidence that a large number of motivated, experienced researchers have been unable to find one. In addition, the wide range of agent behaviors that will be developed will help to understand how various approaches to solving the broker's decision problems will affect the market and the other brokers [14]. This work will complement an ongoing series of applied research projects such as EU Smarthouse/Smartgrid [20], EU-FENIX [33], EU-INTEGRAL [26], EU-DEEP [11], and CERTS-Olympic Peninsula [12] that were all aimed at developing some forms of agent-based energy management solutions for the integration of distributed energy resources. None of these projects addresses whether the developed concepts are applicable in a competitive environment.

Research Questions

The main research question is split into the following subquestions (the PhD student together with the supervisor team have to decide on which to focus):

Energy sustainability: How can energy markets and brokers contribute to long-term sustainable energy communities? How can individual preferences be aligned and aggregated into a sustainable energy supply chain?

Market Robustness: How well can economic incentives and market structures address the challenges of managing and balancing complex energy markets?

Market Predictions: What combination of observable data and mathematical models will be needed to drive real-time pricing decisions and predict the behavioral responses of energy producers and consumers [25] within a portfolio such that dynamic balance can be maintained?

Customer preferences: How can a broker align energy availability with customer preferences? How will information on source and availability of energy affect consumption behavior, and how will different types of information, or the way this information is conveyed affect consumption behavior?

Participants Behavior: How will future energy markets respond to an increasing proportion of variable, renewable energy sources as opposed to stable base-load sources based on fossil fuels? How will these markets respond to incentives and disincentives designed to promote a transition to renewable energy? What phenomena will emerge from the interaction of energy markets with widespread adoption of adaptive agents for managing energy usage [23, 24]?

Energy Management: How can energy brokers communicate with their members in order to maintain real-time balance between supply and demand of energy? How can price signals be used to effectively maximize utilization of renewable energy sources with respect to non-renewables? How can energy price signals be effectively integrated into technical controls for selected discretionary loads in household and business environments? What combination of market incentives and technical controls will support large numbers of plug-in electric vehicles while minimizing the need for non-renewable energy?

Innovation

Competitions have been an effective way to spur innovation [30, 16, 19, 28]. Research groups from a variety of backgrounds are motivated to solve the same problem using many different approaches. This study will provide clear guidance for policymakers on the capabilities and limitations of open market structures for management of future energy networks, and for organizations that might wish to operate as brokers in these markets. The experimental environment will allow market structures to be evaluated under a variety of real-world conditions. The competitive design will effectively uncover potential hazards of proposed market designs in the face of strategic behaviors on the part of the participating agents. Effects of taxes and incentives can be modeled and tested. Effects of dynamic pricing and technical control systems for household and business consumers and for electric vehicle charging can be evaluated. Complex preference models will be developed to guide tariff designs that are attractive to consumers and brokers, and give brokers sufficient flexibility to balance loads in expectation and in real time. Methods will be developed for charging large numbers of electric vehicles in ways that are technically feasible, economically attractive, and that take advantage of the balancing capacities of vehicle batteries.

Relevance

This program will challenge researchers to develop a clear understanding of the operation of future energy markets and the decision processes of agents that can operate effectively in such markets. It will inject micro-level behaviors of grid components, customers, and energy suppliers. Agents must aggregate these individual behaviors, predicting and influencing supply and demand, and producing macro-level emergent phenomena that must be understood by policy-makers before implementing such markets in the real world. We will combine simulated markets and real-world data to develop solutions that can be applied to help build the self-organizing intelligent energy grid of the future. The results will directly benefit Dutch and European Union industry steering groups and government policy makers. We are in close contact with several Dutch and German industry groups. With this effort we will contribute to the future competitiveness of European businesses and their goal to reduce dependence on imported energy. Further, we will strengthen the Trading Agent Competition (TAC)[2] with a challenging and compelling tournament and promise to attract top tier interdisciplinary researchers, since this topic is of utmost importance to society and our planet as a whole.

4.2 Scientific contribution of the research project.

The proposed research will bring the fields of intelligent agents, machine learning, economics, mathematical programming, and supply chain management to bear in developing techniques to analyze human behavior and to evaluate intelligent decision support systems. The research may also lead to insights in facilitating human decision making in other complex environments.

The scientific contribution of this research project consists of the following items:

- Systematic analysis of design factors for intelligent trading agents in economic environments.
- Systematic research, development and testing of human preference and prediction models for intelligent trading agents in an economic setting.
- Systematic research, development and testing of intelligent trading agents which use the learned human preference, and prediction models to facilitate managerial decision making in an economic setting.
- Other methods that are based on the main research question and the sub-questions listed in Section 4.1.

There are plentiful scientific contributions to the following fields:

- Experimental Economics and Information Systems
- Formal modeling of user preferences
- Development of new machine learning algorithms

[2]see www.tradingagents.org

- Agent architecture and design

4.3 Embeddedness of the proposed project in your ERIM research programme and possible relationships with other current PhD projects

The proposed project fits perfectly within the overall ERIM research program and especially in Logistics & Information Systems (LIS) program. There are possibilities to collaborate with colleagues within ERIM as well, such as Marketing and Psychology. It enhances at the same time collaboration possibilities for current PhD students who work on multi-agent modeling and simulation. The PhD student will have ample opportunities to discuss her findings and gain new insights through the active participation in LARGE (Learning Agents Research Group at Erasmus - www.large.rsm.nl) which was founded and is run by Dr. Wolfgang Ketter, one of the supervisors.

4.4 Research methodology

The research project will go through different phases.

The **research plan** will contain the problem formulation and an analysis of the problem formulation, resulting in a conceptual research model. The following methodologies will be used:

Concept building: This phase exists of a careful analysis of existing retail power markets, including different electronic markets practices and exploratory cases such as auction markets, E-commerce, or the Trading Agent Competition for Supply-Chain Management.

The cases will be analyzed after intensive data collection (literature, web-information, interviews). Data analysis (reliability, validity, utility) will eventually lead to the building of a conceptual intelligent trading agent model.

Concept implementation and testing: The conceptual model will be transferred into a working prototype that will be used in laboratory experiments (with human subjects and computer simulation). The prototype context will be related to a relevant intra-business context (such as procurement advice) and a relevant inter-business context such as markets for smart business networks.

Discovery and followup: Work with large-scale simulations and with human subjects will very likely provide opportunities for discovery and characterization of emergent phenomena that will need to be understood in terms of the applicability and impact on real-world business entities and consumers.

Finally, **reports** of the findings will occur from the beginning to the end of the PhD project. The reports will contain literature reviews, case study research, conceptual model, quantitative studies using experimental research for concept testing.

4.5 Relevant literature, data sources

Relevant literature:

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Possible Data Sources:

- Experimental analysis framework for laboratory experiments with human subjects
- Survey
- MeRegio project (Germany)
- ENECO (Netherlands)
- Midwest ISO data (USA)
- many other sources

4.6 (possible) cooperation with other universities / research groups

This PhD project will cooperate with researchers in the Worldwide Information Systems Community (http://www.isworld.org) and with research groups in the USA, especially with the Carlson School of Management (Dept of Information and Decision Sciences), the Artificial Intelligence Group (Dept of Computer Science) at the University of Minnesota, and the Artificial Intelligence Group (Dept of Computer Science) at the Carnegie Mellon University, and in Germany, especially with the Karlsruhe Institute of Technology. Cooperation will be established with companies that will be interested to validate the potential of intelligent trading agents. Once the PhD candidate finished this PhD project it will be easy to find employment in universities or industries worldwide.

The research team is supported by a Scientific and an Industry Reference Board that will meet at least three times per year with the team to provide them with feedback on the direction and the results of the project. The Scientific and an Industry Reference Board currently consists of Dr. Ad van Wijk (independent entrepreneur; specialized in sustainable energy), and Prof. Dr. Bruce Wollenberg (University of Minnesota and a member of the U.S. National Academy of Engineering; specialized in power systems engineering).

4.7 Planned publications

The research will be published in high quality journals in the fields of Computer Science, such as Journal of Artificial Intelligence Research, AI Magazine, Communications of the ACM and Machine Learning and journals in the field of Information Systems, such as Management Science, MIS Quarterly, Decision Support Systems, and Information Systems Research. Because of the intense interest in the field of this research, ample possibilities will occur to communicate and publish in international conferences. The target for the total period per position will be three to four A publications, presenting the results in at least six international conferences and workshops, and additionally a high quality PhD thesis.

5. Research Plan

5.1 Global & detailed description of the research plan for the first 12 months

The research plan for the first 12 months will contain the following items:

- Literature survey into intelligent trading agents, machine learning, user preference modeling and other relevant theories.
- Starting three exploratory cases, about the context, design and impact of intelligent trading agents on human decision-making.
- Design an experimental analysis framework.
  - Careful analysis of existing retail power markets.
  - Initial analysis of human behavior in retail power markets.
  - Initial model of human preferences in retail power markets.
  - Initial decision recommendation model based on human preferences and prediction models.
- Conceptual research model for the next three years.

5.2 Global description of the research plan after 12 months, which must discuss research planning (data, field work, experiments, interviews,), feasibility and the expected research output

As outlined previously, the risk involved in establishing new retail energy markets is high without solid research guidance. We propose to work within and to extend a rich simulation environment that will help to provide this guidance, by developing a clear understanding of the technical and economic constraints and opportunities that such a market structure will create. In the following we list tasks that the Ph.D. student will undertake to achieve our goals under this proposal. The Ph.D. student has the possibility to focus on one of the particular areas or do a combination of them:

Focus on economic incentives and market structure:

- Design of efficient, robust market mechanisms for organizing the emerging energy network infrastructure, using analytical [21] and empirical [14, 6] game theory analysis.
- Docking and validating [2] the market testbed with real world data.
- Modeling and analyzing three interlocking complex networks: the multi-level distribution grid, the network of business relationships, and the social networks among energy customers and producers.

Focus on decision processes of broker agents:

- Modeling fully autonomous and mixed-initiative agents [3, 8] using machine learning and probabilistic prediction models [18].
- Tactical decisions regarding portfolio development and risk management using rich models of consumer and producer preferences [5].
- Operational decisions regarding supply and demand predictions and load balancing by understanding responses of individuals and businesses to incentives offered by the agent through negotiation [27], and predicting emergent macro-level phenomena [22] using tools of agent-based computational economics [32].

Evaluation

With Power TAC we are building an abstraction of the real world for the particular purposes as outlined. The PhD student with support of the supervisor team will evaluate the Power TAC design through the following three questions:

1. How adequate is Power TAC as a representation of the real world? For instance, we could compare pricing and load balance predictions between Power TAC and the real world from data available from the MeRegio project.
2. How effectively does Power TAC support the research agenda of the participating teams? For instance, are teams effective at modeling preferences or price predictions using Power TAC?
3. How effective is Power TAC for public policy guidance? Do the suggested solutions provide new insights into real world energy policy?

Our complex adaptive simulation will allow for realistic testing of a wide range of technical tools and policy options, such as systems to control discretionary loads based on price signals and user preferences, and differential taxes and subsidies. Broker agents will be judged by economic performance, and simulation scenarios (market rules and policy options) will be judged by a variety of metrics, such as overall consumption, utilization of renewables, quantity of peaking power needed, and end-user energy costs.

6. Required profile of candidate

The candidate must fit in the following profile:

- MSc. or MPhil in Business Administration or Management & Economics, Information Management, Computer Science;
- Excellent study record;
- International orientation and the capacity to speak and write in English fluently;
- Commitment and drive to execute excellent PhD Research.

Since the project is interdisciplinary in nature it offers many opportunities to people coming from different disciplines, such as:

- Computer Science and Artificial Intelligence
- Electrical Engineering and Power Systems
- Economics and Econometrics
- Mathematics/Statistics
- Supply Chain Management
- Business and Information Management

The above areas are focal points, but students from other disciplines have a warm welcome to apply if they a fit and are really interested in the project. General characteristics a student should bring to the project are:

- Understanding of programming and system design.
- Good analytical thinking.
- Strong statistical and preferably econometric skills.