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Wind Turbine and Heat Pumps – Balancing wind power fluctuations using flexible demand

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Abstract-- **In order to overcome portfolio imbalance for traders of variable power from wind we have built an 'Imbalance Reduction System' (IRS) and performed a real-world field test with it, in which imbalance is minimized within a real-time electricity market portfolio, consisting of wind power and industrial and residential consumers and producers (Combined Heat and Power for district heating; residential heat pumps; industrial cold store; emergency generators). IRS uses the PowerMatcher concept, a coordination system for supply and demand of electricity in a which multi-agent system is combined with microeconomic principles. IRS appears to offer opportunities for embedding less predictable generators such as wind power more smoothly in the portfolio.**

We describe the context and operation of the Imbalance Reduction System and discuss a number of results from the performed field test. Also we introduce a business model for the balance responsible party, based on the e3-value method.

Index Terms-- Business economics, Cooperative systems, Dispersed storage and generation, Electronic markets, Power control, Distributed control, Power demand and supply, Wind power generation

I. INTRODUCTION

In [1] the European Wind Energy Association, EWEA, refutes the "intermittency" myth, which describes wind power as an intermittent energy source. It is stated that wind power, like many sources of power supply and demand, is a technology of variable output. Variability is a problem only if it results in unreliable predictions.

In this respect electricity supply from wind is subject to a number of disadvantages in a liberalized market setting. It cannot aim at peak production at peak prices. Also it is subject to the risk of over- and underproduction, causing imbalance in an energy portfolio. Especially in current power exchange markets, such as the Dutch APX (Amsterdam Power Exchange) or the Scandinavian Nord-Pool, this results in a poor market position.

EWEA rightly concludes that wind power has to be considered relative to the overall demand variability and the variability and intermittency of other power generators: "The variability of the wind energy resource is important to consider only in the context of the power system, rather than in the context of an individual wind farm or turbine".

On the Dutch market electricity producers and traders have to forecast their production and consumption on a daily basis and communicate this to the transmission system operator (TSO), TenneT. The total demand and supply must be in balance on the market as a whole. The TSO compensates deviations that occur real-time by contracting regulating power. The costs for this balancing operation are put on those parties in the market that deviate from their forecast program. Similar to the conclusions of EWEA for the power system as a whole, an energy program responsible party having a large share of wind power, should consider the imbalance in the context of his portfolio as a whole, and not look solely at the imbalance of its wind power. If the portfolio consists of only wind power, it should be enhanced with other electricity producers and consumers that can be influenced in their behavior.

This paper presents a field test in which wind power is supplemented with other producers and consumers in one portfolio. In this portfolio deviations in wind power from the predicted power are tuned by influencing the other devices in order to reduce the total imbalance in the portfolio. The means of control is the PowerMatcher [2], [3], [4]. The field test shows that agent-based electronic markets in a commercial cluster are able to reduce a substantial part of cluster imbalance. They reduce the cost for the market parties as well as the need for regulating power. Massive implementation of this concept will reduce the financial risk of producers and traders with a large share of wind power or any other variable resource, and make the grid and the electricity markets more stable as compared to the non-controlled wind park feed-in.

II. 2. BALANCING RESPONSIBILITY AND WIND POWER

In countries with a deregulated energy market like the United Kingdom, The Netherlands and the Scandinavian countries, the bigger market parties (those that make use of the transport services of the independent system operators) are obliged to make daily plans for production, transport and consumption of electricity. These so-called programs have to be handed in at the TSO, the operator of the high-voltage electricity network. In the Netherlands these programs have to be handed in before 12:00 hours and plan the 24-hours period starting at the next midnight with a resolution of 15 minutes.

The TSO uses all programs to ensure the stability of the electricity network. For the sake of grid stability it is important that every Balancing Responsible Party (BRP) sticks to her own program. To enforce this, each party that has a deviation from his program is charged for it. These charges are referred to as imbalance costs.

In order to retain the power balance additional generation/consumption capacity has to be bought by the TSO in the short time ahead balancing and regulation markets. The system operator, based on the individual program deviations, charges the cost of the overall imbalance among program responsible parties causing the imbalance. This is effectuated some days after production/consumption based on metering 15-minute data. Thus, deviations on energy programs at program realization time are settled by the imbalance pricing system. There are two imbalance prices, for shortage and surplus separate. The imbalance price for shortage is linked to the regulation price for positive power, whereas the imbalance price for surplus is linked to the regulation price for negative power. Another important

The PowerMatcher development and the field test performed are part of the EU project "CRISP – Distributed Intelligence in Critical Infrastructures for Sustainable Power" [10], under the 5th framework programme

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aspect of the pricing is the different kind of contributions to system balance that program responsible parties can have. Two kinds are identified: passive contribution and negative contribution. A passive contribution is an imbalance with an opposite sign to system imbalance and a negative contribution is an imbalance with the same sign as the system imbalance. These differences can only be identified if during one settlement period there is dispatch of regulation and reserve power in one direction. Then, passive contributions are awarded the regulation price minus an incentive component whereas negative contributions pay the regulation price plus the incentive component. In case of bi-directional dispatch during a settlement period passive or negative contributions can not be identified, in which case imbalance price for surplus is directly linked to the dispatch price for negative regulation and reserve power whereas imbalance price for shortage is linked to the dispatch price for positive regulation and reserve power. A comprehensive description of the Dutch balance market is given in [5].

Due to their uncertainty in power prediction on a 24 hour term, the production of electricity by less predictable energy resources like wind and PV (Photovoltaic) leads to additional imbalance on the day-ahead market for the programs of a trading party: the day-ahead (12-36 hours) predicted amounts may deviate more from the actual realizations than other electricity suppliers and demanders. As a rule of thumb, for every 3 kWh of wind power there is 1 kWh imbalance [6]. This deviation leads to extra costs for the producer. Production and consumption figures are settled a number of days after actual delivery using metering data as collected by a certified metering company. Thus a time gap exists. Mostly, there are no real-time production or consumption data available to adapt to changes in the program as submitted the day before nor is the effect of improved accuracy of shorter time-ahead predictions taken into account.

III. The Imbalance Reduction System IRS

A. *Field test configuration*

The field test, carried out with communicating energy devices located in different parts of The Netherlands, aims at automatically reducing the imbalance in the program of a commercial trader with wind power, by enhancing its program by additional, flexible, installations. Figure 1 shows the actual field-test configuration.

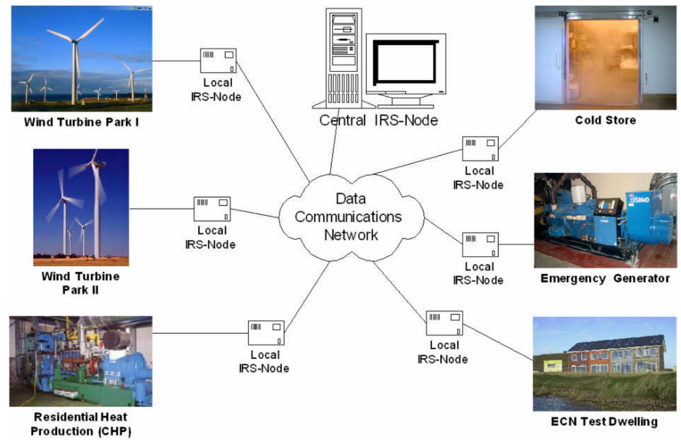

Figure 1. Field test configuration for the imbalance reduction system

On the supply side, the experiment includes two wind turbine parks, an emergency generator, and Combined Heat and Power (CHP) installations connected to a heat distribution network in a residential area. The demand side in the portfolio consists of controllable cooling loads in a meat-processing factory and a cluster of houses utilizing electric heat pumps. All control systems and one of the dwellings are actually connected in the field test, except for the final control of the installations, which is done only in the dwelling. A simulation of installations, derived from models of the individual installation's processes, makes it possible to compare the agent-mediated control from the electronic power market with conventional control The capacity of the heat pump in the dwelling is negligible in comparison with the other installations. Therefore another 100 dwellings are simulated during the field test, each with its own individual behavior. Using a wind prediction model and installation models of the different nodes in the field test, a day-ahead profile of the enhanced program is constructed [6].

The IRS field experiment is positioned in the Dutch imbalance market, so the imbalance market mechanism of the Dutch TSO as described above is followed. For each balancing period of 15 minutes the day-ahead programs are compensated in real-time for over/under-realization by adapting the control strategy of the flexible installations, using agent algorithms operating on an electronic market via an ICT network. As electricity consumption and production profiles depend on the time of year, four seasons over 2005-2006 are covered.

B. *PowerMatcher™ imbalance reduction*

The control mechanism used in the IRS field test is based on the PowerMatcher concept. The PowerMatcher is a market–based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over–all match between electricity production and consumption. In the PowerMatcher method each device is represented by a control agent, which tries to operate the process associated with the device in an economically optimal way, while staying within its process boundaries. The electricity consumed or produced by the device is bought, respectively sold, by the device agent on an electronic exchange market. The PowerMatcher concept can be used in a real market setting, but may also be applied as an agent based coordination system.

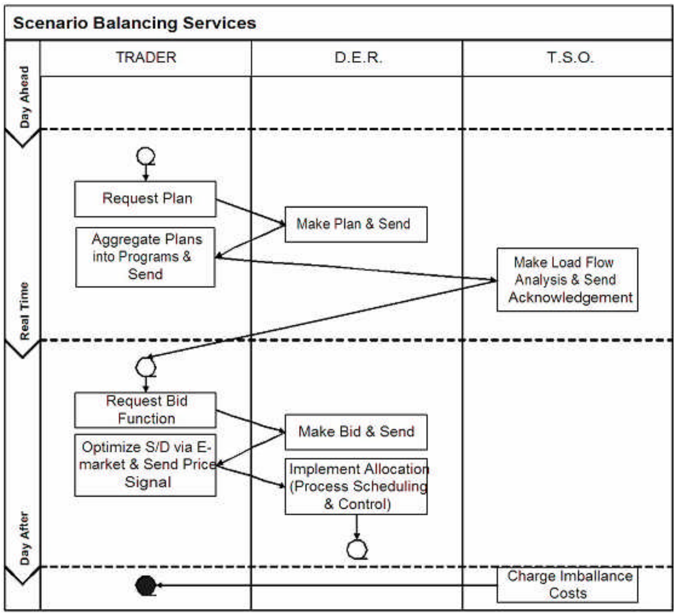

Fig 2. *IRS market schedule*

The imbalance reduction system works as sketched in figure 2. Every day, at 12:00 hours, the installations hand in a program of expected demand or supply. The wind farms offer their predicted power based on a prediction model developed by ECN [6]. In real-time, every period of 15 minutes each installation makes a bid on the electronic exchange market. The wind farms bid their real-time expected power. All other installations bid according to their flexibility in demand and supply. The total real-time demand / supply is matched against the program that has been handed in the previous day. Thus, if the wind farms produce a shortage in power compared to their program, the flexibility of other installations is used in order to produce more than their program (or to consume less). Hence the IRS market aims at reducing the total imbalance of the field test configuration. A comprehensive description is given in [7].

IV. Field Test Results

A. Imbalance reduction

Figure 3 shows the imbalance from the wind power (red) versus the resulting imbalance from the whole portfolio in the field test (blue).

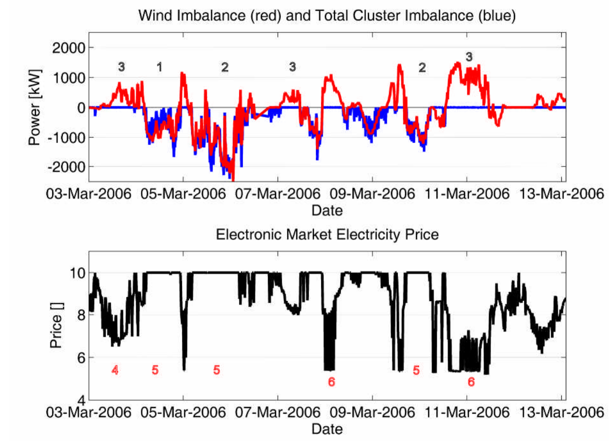

Fig 3. Imbalance reduction (above) and price fluctuations

The blue line lies on the x-axis nearly 50% of the total period, meaning that a power balance has been established. The following phenomena are visible:

1. Underproduction of the wind turbine can only be partially compensated for. The portfolio imbalance (blue) is less than the wind power imbalance (red), but is not reduced to zero.
2. During some periods of underproduction the wind power shortage cannot be compensated for at all.
3. Some periods with large wind deviation can be compensated for completely in the cluster. The portfolio imbalance is zero.

The same figure 3 also shows the development of the prices (black) according to the IRS market. An artificial price bandwidth of 5 €ct (minimum) and 10 €ct (maximum) is used. High prices show shortage of electricity in the portfolio (to be expected in case of underproduction of the wind turbine). Low prices show surplus.

4. Prices are fluctuating between minimum and maximum in periods that the portfolio is in balance. It demonstrates that the principle of market-based coordination works.
5. A period with maximum prices (10 €ct), results from the fact that the cluster of installations is unable to compensate completely for underproduction. A shortage remains.
6. Low prices (near 5 €ct) tend to occur in periods of large overproduction. Prices keep closer to 7-8 €ct for periods with smaller overproduction. In this case a gradual decrease of prices can be seen, indicating a gradual exhaustion of buffers in the portfolio.

The fact that underproduction of wind power cannot be compensated for in the portfolio is due to the cluster composition. The CHP installations in the cluster have a large capacity and thus could be expected to be able to compensate for underproduction of wind power. However, the CHP installations are scheduled to always be on in wintertime, so they can be turned off to avoid overproduction in the portfolio, but they do not provide extra capacity for compensation of underproduction. The production capacity of the emergency generator is too small to have more than a minor influence.

Since the residential dwelling and the cold store have been simulated a hundredfold, and the CHP installations can be switched off, the portfolio does have the capacity for compensation of overproduction.

B. Local autonomy

Agents operating on the IRS market lead to different control strategies than conventional schemes, but by no means they lead to inferior control. Figures 4 and 5 show the result of operating the heat pump for space heating and tap water heating in the residential dwelling. They show the difference in strategy between conventional control of the tap water temperature in figure 4, having the shape of a saw-tooth, and the PowerMatcher control in figure 5, shaped on the market outcome: if the market price goes up, the heat pump is switched off, and hence the tap water temperature goes down. While in the conventional control strategy the tap water temperature recovers after each usage dip to a level of 50°C, the PowerMatcher strategy uses the flexibility in the temperature band between 40°C and 55°C.

The experiments performed show that local autonomy is feasible and agent systems are a good paradigm to guarantee this autonomy. Due to their local intelligence agent systems also have the advantage that the amount of communication towards a central supervisory system is drastically reduced.

Technical disturbances several times led to failure of the system, leading to unacceptably low temperatures in the dwelling. As a lesson in a follow-up project a backup control has been implemented: whenever the market fails, conventional backup control takes over [8].

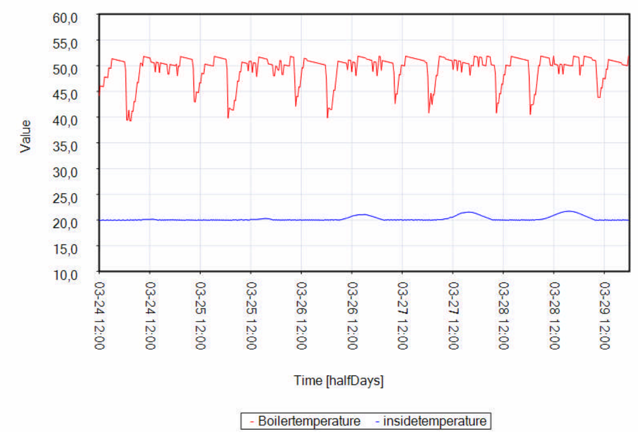

Figure 4. Conventional control: tap water temperature and room temperature

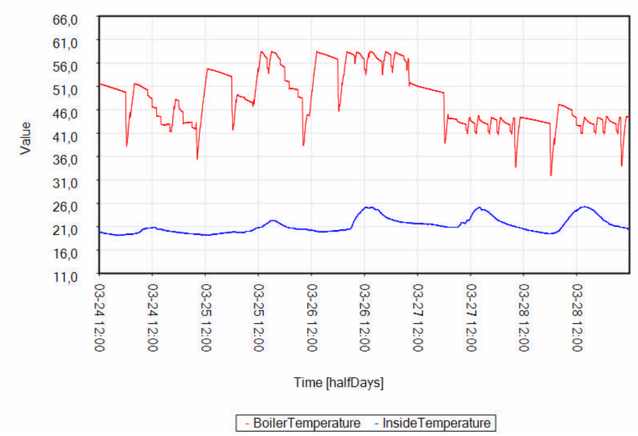

Figure 5. IRS control: tap water temperature and room temperature

C. Communication speed an other timing aspects

Communication speed is not essential for an IRS market. Communication through ADSL and UMTS did not lead to any performance or congestion problems. Programs, bids and allocations are communicated through short messages. Failure in the system, such as communication loss and malfunction of components, can disturb the market. It requires robust algorithms at the central node, although not every failure can be counteracted if no information is available about the reason of failure. For the experimental cluster market rounds of 15 minutes did not pose any problem. Even higher frequency markets (up to several minutes) are feasible.

D. ICT Components

The IRS field test has been built using off-the-shelf computing and communication hardware. They have been used to interconnect and interface the cluster of power generation and consumption installations in a network using secure Internet-technology in an isolated branch of the public Internet, a virtual private network (VPN). On these computers, tools have been installed for data-collection (OPC-Server), database storage (SQL-Server) and safe execution of novel control algorithms.

On-site connection to existing energy management systems has been made according to the design layout. OPC-Server proved to be a good mechanism to access local installation data, without detailed knowledge about the installation control software.

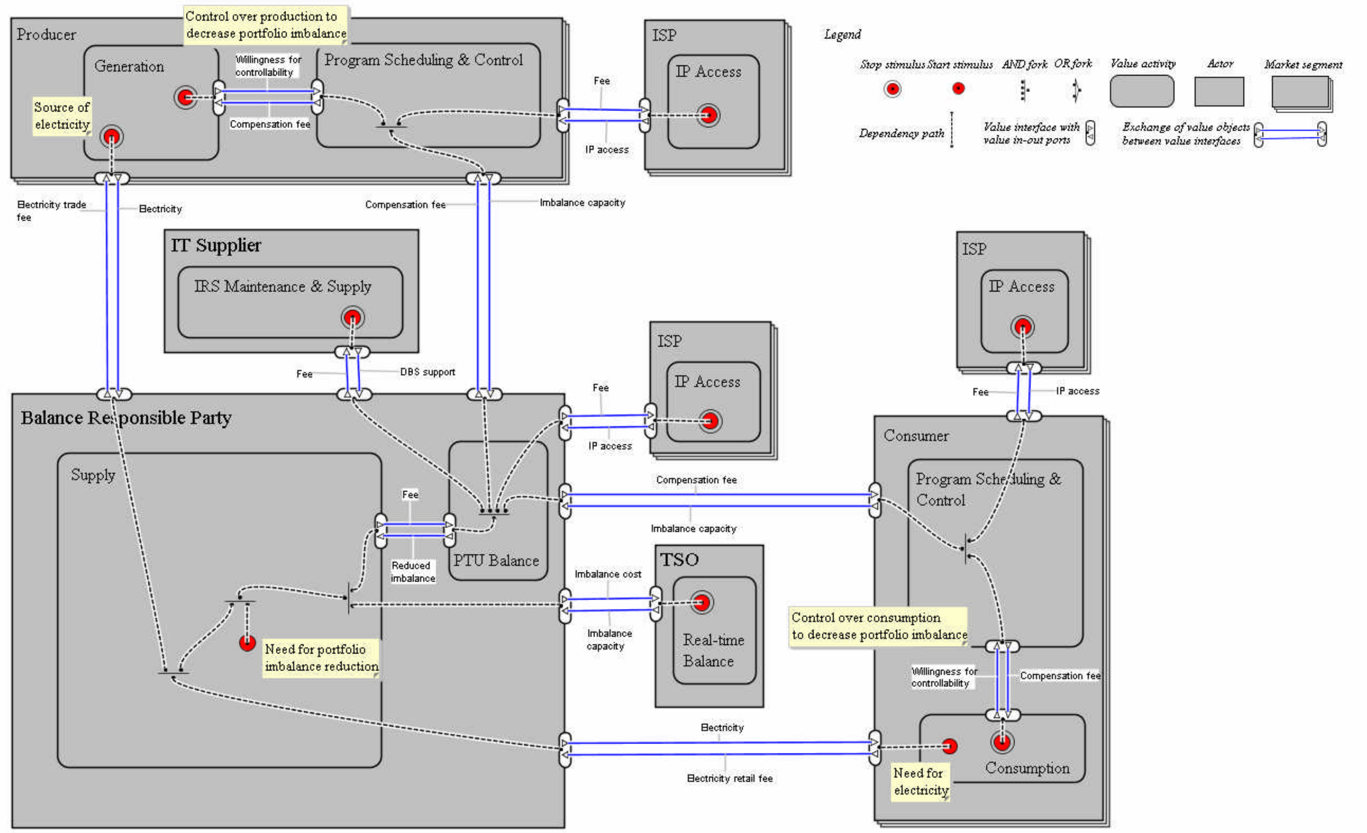

Figure 6. Initial Value-based Business Model of the Intermittent Imbalance Scenario

V. Business Modeling

Since the introduced IRS-service has to operate in a competitive world, it is important to reason over its commercial and technological feasibility. In order to do so, as a first step we consider the construction of a business model from a profitability/economic value point of view. To generate such a business model we employ the e3-value method [9]. The benefit of the tool is that the drawn business model shows the essentials of business activities in terms of actors performing value-adding activities, creating and exchanging value objects. Constellations of stakeholders of business cases can be too complex, necessary investment and maintenance costs as well as revenues are hard to articulate and distribute among the participants. The value-based modeling approach supports the identification of ownerships on these financials thus allows us to reason over the financial feasibility of IRS for each stakeholder.

Figure 6 shows our initial value-based business model of the scenario. It is based on the configuration and settings of the field test portfolio described above and in [7]. The construction phase of the model involves the identification of the main stakeholders (depicted by rectangles), of their executed value activities (depicted by rounded rectangles) and of the exchanged value objects (parallel lines via value ports) that support the execution of such activities.

The articulation of the stakeholders follows the condition that the scenario treats electricity as a commodity; thus the physical distribution is out of the scope of this analysis. Besides the “traditional” stakeholders, such as the Balance Responsible Party (BRP) or producers other important stakeholders (e.g. IT supplier) are identified due to the fact that the successful implementation and maintenance of IRS on the market relies on IT.

The same situation appears during the identification of the executed value activities. Besides the traditional, domain-given activities (such as “Supply” and “Production”) the reduction of imbalance calls for additional, IT-based activities (such as “PTU[1] balance” and “IP access provision”). The assignment of the identified value activities follows the setting of the field test and the interests of the participating stakeholders.

The detailed explanation of the model happens by tracking through the complex scenario path. It starts from the start stimulus that stands for an appearing need. It triggers for different value exchanges between actors and value activities to execute. The scenario path traces through these and ends in the stop stimulus, representing that the initial need is satisfied.

The description starts from the appearing demand for electricity. This need is attached to the consumers of the portfolio. According to the settings of the field test this demand is satisfied by the produced electricity of the portfolio, implying that end stimulus occurs assigned to the producers. In case of deviations from the forecasted e-program of the BRP (from the actual performance), the TSO provides extra balancing capacity (“Imbalance capacity”) and as a consequence, BRP pays

[1] PTU stands for “Program Time Unit’, which is equal to 15 minutes in The Netherlands.

penalty (“Imbalance fee”) to cover the costs of TSO. Up to this point, the scenario description reflects on the situation and thus would stop here if no extra balancing power would be employed.

However, the high penalty costs with respect to imbalance triggers for the need of portfolio balancing. This need appears assigned to the BRP. It introduces a newly performed activity, “PTU balance”. This activity provides “Reduced imbalance” for the supply and thus generates extra profit by paying less to TSO. To perform this activity, IT-support, IP access and successful cooperation coming from the consumers and producers (execution of “Program scheduling and control” activity) of the portfolio are needed, thus “PTU balance” triggers for more offsets within the scenario path.

By performing the “Program scheduling and control” activity, now producers and consumers provide the necessary “Imbalance capacity” in order to reduce deviations. In return, they receive “Compensation fee”. Consumers and producers should also possess IP access. The offsets of the scenario path towards the ISPs indicate this requirement of the IT-service.

The constructed business model supports the reasoning over the financial feasibility of the business case. It clearly articulates ownerships and thus responsibilities over different activities and provided/received value objects. The depicted value exchanges offer the first step towards the financial analysis. All the exchanges are coupled in- and outgoing value objects and they support value activities. Value objects follow the principle of reciprocity: if a value object is provided, a value object is expected in return. Each value exchange is constructed as such that they involve money flow. This concept allows the construction of profitability sheets. These sheets show the net value flow, for each actor and value activity involved, based on these in- outgoing value objects.

This analysis, however, only provides a rough financial overview. Since it is based on in- and outgoing value objects, it does not take into account additional money out-flows, such as necessary IT-investments or operational costs. In addition, the valuation of some objects (e.g. valuation of “Compensation fee”) is influenced by producer- or consumer-specific performance indicators of their executed activities. The notion of value activity holds an integrated view on these additional financials and performance measurements. As a second step towards, a more detailed analysis of value activities is needed in order to provide a better insight. It is currently performed as a part of an ongoing research.

VI. Conclusions and Future Research

The field experiment shows that agent-based electronic markets as applied in the Imbalance Reduction System can be a large step towards solving an important electricity market barrier (imbalance by imperfect prediction) for Wind Power. By making use of large buffering capacity in a number of installations large parts of the wind power fluctuations can be eliminated. This reduces costs for the market parties as well as the need for regulating power. As a next step elaboration of the business model is needed: how to make the IRS concept profitable for all market actors. Also an embedding of IRS in the regulating power market may add value to the cost-profit.

The PowerMatcher can be used for other barriers than Wind (and Solar) as well. In fact the flexibility of the PowerMatcher enables applications in a number of areas in which energy balancing can be profitable, from controlling of virtual power plants to energy management in local networks with a large share of local generation.

VII. Acknowledgment

A large number of people contributed to the implementation of the field test. From Eneco, Cor Duyvenvoorde provided us with access to the installations. Fred Kuijper, Sjaak Kaandorp, René van de Schilden, Paul Seignette and Roel van Rossum contributed to establishing to ICT-network nodes and connections to the process control systems. Discussions with Hans Akkermans, Josco Kester, Gerrit Jan Schaeffer and Per Carlsson about the agent algorithms are gratefully acknowledged. Roelof Schuitema and Niels Sijpheer provided us with the installation models and managed part of the experimental facilities at ECN. Arno Brand provided us with the Wind Prediction software system to IRS.

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IX. Biographies

Cor Warmer was born in Utrecht, on March 8, 1955. He graduated as a mathematical statistician from the Universiteit van Amsterdam in 1981. He joined ECN in 1981 as a mathematics and statistics consultant in a scientific mainframe environment. He was later involved in a large number of projects for data and object modeling. His current research includes process optimization of large energy consuming systems and optimization of power demand and supply flows in the distribution network using market based agent algorithms.

Maarten Hommelberg was born in Tilburg, on

October 9, 1978. He graduated in the field of building services on the University of Technology in Eindhoven in 2005. The graduation subject was titled "Software agents for a building management system". His first and current employer is ECN. He is currently working on optimizing power demand and supply flows in the distribution network using market based agent algorithms.

René Kamphuis was born in 1952. He graduated from Nijmegen University in 1976 in Chemistry. After that he got a Ph. D. from Groningen University in Chemical Physics.

His employment experience at ECN started with a position at the computing center. From there he went to a number of software engineering positions. Since he is with the unit Renewable Energy in the Built Environment. He has been involved in a number of projects concerning the application of agent technology for comfort management in buildings and dynamic distributed applications in the electricity network.

Koen Kok (1969, male) received Bachelor degrees in Electrical Engineering (1992) and Computer Engineering (1992). After a short working period at the University of Groningen, he started to study Computer Science at the same university and received his MSc in Computer Science in 1998.

From 1998 to date, he is working as Researcher and Project Co-ordinator at ECN. He is working in the interdisciplinary field between electrical engineering, systems control and ICT. His current research focus is on intelligent distributed control mechanisms for electricity grids with a high penetration of distributed generation.