Proceedings of the 41st Hawaii International Conference on System Sciences - 2008

Agent-based Electricity Balancing with Distributed Energy Resources, A Multiperspective Case Study

Koen Kok[§][‡], Zsófia Derzsi[§], Jaap Gordijn[§],
Maarten Hommelberg[‡], Cor Warmer[‡], René Kamphuis[‡], Hans Akkermans[§]

[§]Free University Amsterdam, Faculty of Exact Sciences - Business Informatics
De Boelelaan 1083a, 1081 HV Amsterdam, The Netherlands
Email: {koenkok, zderzsi}@few.vu.nl; gordijn@cs.vu.nl; hans.akkermans@akmc.nl

[‡]Energy research Centre of the Netherlands (ECN) - Intelligent Energy Grids
P.O. Box 1, 1755 ZG Petten, The Netherlands.
Email: {j.kok, hommelberg, warmer, kamphuis}@ecn.nl

***Abstract*— Distributed generation (DG) of electricity is providing an increasing part of the worldwide electricity supply. At the same time, there is a big potential of demand response resources. When — in a geographical area or in the contract portfolio of an energy trader — the number of these Distributed Energy Resources (DER) increases, clustered control of DER by common ICT (information and communication technology) systems can add value. Due to the fine-grained and distributed nature of DER, the design of such a system needs to meet heavy requirements, e.g. regarding scalability and openness. Further, these systems need to balance multiple stakes in a multi-actor environment. Multiagent systems, especially those based on electronic markets have been identified as key technologies in this respect. This paper presents a multiperspective case study of the design, implementation and performance of such a system for the business case of imbalance reduction in commercial clusters of DER. The benefits of this approach are shown by field experimental results of a real-life DER cluster with an imbalance characteristic dominated by wind electricity production. The approach resulted in substantial imbalance reductions. Further, a thorough analysis of the networked business constellation is given, together with an indication how business modelling techniques can be used to asses the financial feasibility of the business idea.**

I. INTRODUCTION

Distributed generation (DG) of electricity is providing an increasing part of the worldwide electricity supply. DG consists of different sources of electric power connected to the distribution network or to a customer site. This approach is distinct from the traditional central-plant model for electricity generation and delivery. Examples of DG are photovoltaic solar systems, small and medium-scale wind turbine farms, and the combined generation of heat and power (CHP). When the share of DG increases in a geographical area or in the contract portfolio of an energy trader, clustered control of DG by common ICT (information and communication technology) systems can add value [1]. The value drivers originate either in the energy markets —as clustered control of DG increases market power— or in network operations —as active network management increases infrastructure efficiency. Clustering of DG in itself has positive effects, as it partially smoothes the individual stochastic behaviour of most types of DG. Actively utilizing the flexibility in the electricity production of the cluster allows for profile shaping of the aggregated power output. In the latter case the aggregation can be operated as a *virtual power plant* (VPP), i.e. a system that is operated similar to a 'normal' electrical power plant, but consists of a high number of small and medium-sized units interconnected by an ICT-system.

Another development is the increasing utilization of *demand response resources* (DRR): those electricity consuming installations that can alter their operations in (near) real time in respond to signals from the energy markets or electricity network operators. From the viewpoint of controllability, DG and DRR are equivalent: increasing production has the same effect on the supply and demand balance as decreasing consumption, and vice versa. Hence, the treatment of demand response as a resource. Accordingly, DRR-units can be incorporated in virtual power plants as well. Because of the common nature of DG and DRR we use the overarching term *Distributed Energy Resources* (DER) in the remainder of this text.

Due to the fine-grained and distributed nature of DER, the design and implementation of a common ICT system for coordination is not trivial. Specific information system requirements include [2], [3]:

- The information system architecture must be well scalable. The number of components actively involved in the coordination can grow huge quite easily and they may well be spread over a vast area. Centralized control of such a complex system may reach the limits of scalability and communication overhead rapidly.
- The information system architecture must be open: individual DER units can connect and disconnect at will and future types of DER —with own and specific operational characteristics— need to be able to connect without changing the implementation of the system as a whole. Therefore, communication between system parts must be

uniform and stripped from all information specific to the local situation.
- The information system must facilitate a multi-actor interaction and balance the stakes on the global level (i.e. the aggregated behaviour: reaction to energy market situation and/or network operator needs) and on the local level (i.e. DER operational goals).
- In most cases, different system parts are owned or operated by different legal persons, so the coordination mechanism must be suitable to work over boundaries of ownership. Accordingly, the power to take decisions on local issues must stay with each individual local actor.

Different authors identified Multiagent Systems (MAS) as a suitable design paradigm for Distributed Energy Management: [4], [5], [6], [7], [2], of which the latter three propose the use of *electronic equilibrium markets* as the core coordination mechanism.

Electronic markets provide a framework for distributed decision making among different actors in computational multiagent systems based on microeconomics. Microeconomics is a branch of economics that studies how economic agents (i.e. individuals, households, and firms) make decisions to allocate limited resources, typically in markets where goods or services are being bought and sold. One of the goals of microeconomics is to analyze market mechanisms that establish relative prices amongst goods and services and allocation of limited resources amongst many alternative uses [8]. Whereas economists use microeconomic theory to model phenomena observed in the real world, computer scientists use the theory to let distributed software systems behave in a desired way. Market-based computing is becoming a central paradigm in the design of distributed systems that need to act in complex environments. Market mechanisms provide a way to incentivize parties (in this case software agents), that are not under direct control of a central authority, to behave in a certain way [9], [10]. A microeconomic theory commonly used in MAS is that of general equilibrium. In general equilibrium markets, or exchange markets, all agents respond to the same price, that is determined by searching for the price that balances all demand and supply in the system. From a computational point of view, electronic equilibrium markets are distributed search algorithms aimed at finding the best trade-offs in a multidimensional search space defined by the preferences of all agents participating in the market [11], [12]. The market outcome is *Pareto* optimal, a social optimal outcome for which no other outcome exists that makes one agent better-off while making other agents worse-off.

In *Market-based Control*, agents in a MAS are competing for resources on a equilibrium market whilst performing a local control task (e.g. classical feedback control of a physical process) that needs the resource as an input. For this type of MAS, it has been shown by formal proof that the market-based solution is identical to that of a centralized omniscient optimizer [13]. From the viewpoint of scalability and openness of the information architecture, this is an important feature. In the centralized optimization all relevant information (i.e. local state histories, local control characteristics and objectives) need to be known at the central level in order to optimize over all local and global control goals. While in the market-based optimization the same optimal solution is found by communicating uniform market information (i.e. market bids stating volume-price relations), running an electronic equilibrium market and communicating the resulting market price back to the local control agents.

This paper presents a multi-perspective case study of market-based control for coordination of clusters of DER. The rationale behind the business idea roots in energy wholesale markets that use the mechanism of *Balancing Responsibility* to charge for used reserve capacity for frequency regulation. The business idea relies heavily on ICT and implements a *networked business constellation*. We study the case from a technological perspective as well as from a business perspective. We show how market-based control can be used for imbalance reduction in clusters of DER via a *Distributed Balancing Service* (DBS). We show how the DBS is implemented in a field experiment. The experimental results give an indication of the benefits of DBS in terms of reduced imbalance in a real-life DER cluster whose imbalance characteristic is dominated by wind electricity production. Further, we analyze the networked business constellation and indicate how business modelling techniques can be used to asses the financial feasibility of the business idea.

In section II the principles behind market-based control are discussed in somewhat greater depth and the *PowerMatcher*, an implemented market-based control system dedicated for distributed energy management, is introduced briefly. After that, (section III) the business idea explored in the case study is presented together with the value driver behind the idea. Section IV focusses on the technology by describing the field test implementation of DBS. Further, that section describes the main results and insights from the field experiment. After that, in section V, we give the business perspective of the system, presenting a business model that describes the extensive value network enabled by the DBS information system. Finally, in section VI we present the lessons learned and conclusions.

II. MARKET-BASED CONTROL IN ELECTRICITY

A. Market-based Control

The type of market-based control used in this document is *price-based*, where a price is used as the control signal (as opposed to *utility based*, where price is implicit). Whether — in a specific application — the price has a monetary value or is virtual and solely used as a control signal depends on the particular implementation and on the business case behind the application.

In a typical application of market-based coordination, there are several entities producing and/or consuming a certain commodity or good [1]. Each of these entities is represented by a local control agent that communicates with a market agent

---

[1] Or a series of commodities. Here we treat the single-commodity case for simplicity

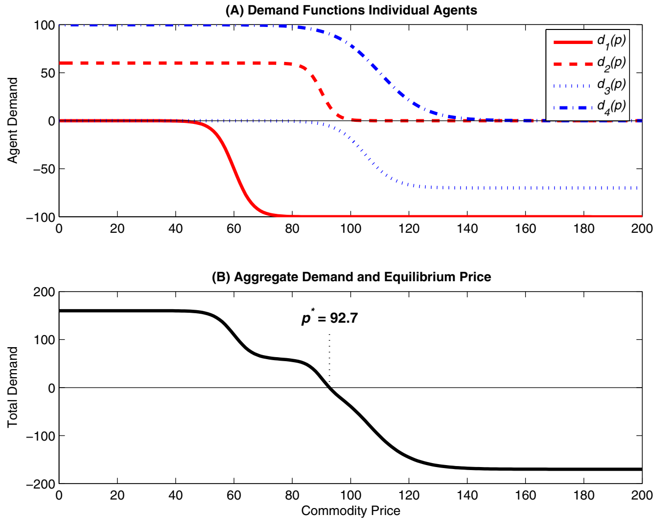

Fig. 1. Example general equilibrium market outcome. (A) Demand functions of the four agents participating in the market. (B) General equilibrium price p^* and locational prices p_{RIGHT} and p_{LEFT}.

(auctioneer). Each market round the control agents create their market bids, dependent on their state history, and send these to the market agent. These bids are ordinary, or *Walrasian*, demand functions $d(p)$, stating the amount of the commodity the agent wishes to consume (or produce) at a price of p. The demand function is negative in case of production. After collecting all bids, the market agent searches for the equilibrium price p^*, i.e. the price that clears the market :

$$\sum_{a=1}^{N} d_a(p^*) = 0 \tag{1}$$

where N is the number of participating agents and $d_a(p)$ the demand function of agent a. The price is broadcast to all agents, who can determine their allocated production or consumption from this price and their own bid.

Figure 1 shows a typical small-scale example of price forming in a (single-commodity) general equilibrium market with four agents. The demand functions of the individual agents are depicted in graph (A). There are two consuming agents, whose demand decreases gradually to zero above a certain market price. Further, there are two producers whose supply, above a certain price, increases gradually to an individual maximum. Note that supply is treated as negative demand. The solid line in (B) shows the aggregate demand function. The equilibrium price p^* is determined by searching for the root of this function, i.e. the point where total demand equals total supply.

B. The PowerMatcher

The study case described below has been implemented using the PowerMatcher, a software toolbox for market-based control of DER (see Figure 2). The PowerMatcher is developed for *Supply and Demand Matching* (SDM) in electricity networks or in trading portfolios with a high share of DER. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the overall match between electricity production and consumption.

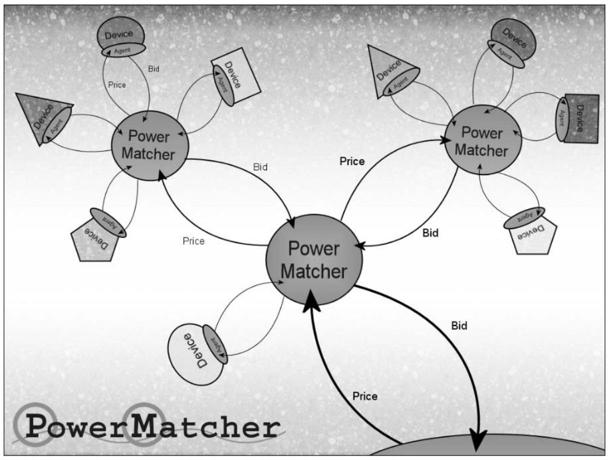

Fig. 2. PowerMatcher software architectural sketch.

From the viewpoint of controllability, devices that produce or consume electricity fall into six main classes, each having a specific agent strategy implemented in the PowerMatcher agent library. An agent strategy is a mapping from the device state history to a demand function shape. We look at three of the six classes in this article, for a full overview of the PowerMatcher we refer to [2]. The first class consists of stochastic-operation devices, such as solar and wind energy systems, where the power exchanged with the grid behaves stochastically. As the power output is not controllable, the standard demand function shape is a flat line at a magnitude of the current production level. The second class is shiftable-operation devices, which must run for a certain amount of time regardless of the exact moment and thus are shiftable in time. An example of such a device is a ventilation system in a utility building that needs to run for 20 minutes each hour. The third class comprises thermal buffer devices. Examples of these devices are heating or cooling processes, whose operation objective is to keep a certain temperature within two limits. Changing standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (see figure 3). Devices in this category can both be electricity consumers (electrical heating, electrical cooling/freezing) and producers (combined generation of heat and power).

Local agents self-interested behaviour causes electricity consumption to shift toward moments of low electricity prices and causes production to shift toward moments of high prices. So, matching of demand and supply emerges on the global-system level.

The electronic market implemented by the PowerMatcher is distributed itself, based on the CoTree algorithm [12]. Subgroups of local control agents connect to an intermediate PowerMatcher agent that aggregates the bids (performing part

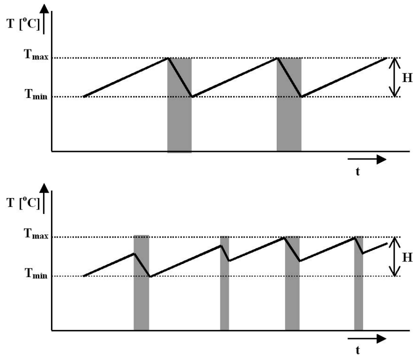

Fig. 3. Operation shifting in a cooling process whilst obeying process state limits.

of the demand-functions summation of market equation (1)) and passes the result on. In this way, each non-leaf node aggregates the information passed by its entire sub-tree. When the (binary) tree-structure overlaying the agent network is well-balanced in its height, this results in a system that is highly scalable with respect to the number of agents.

III. BUSINESS VALUE DRIVER AND BUSINESS IDEA

A. *Balancing Responsibility*

As a result of deregulation of electricity markets, functions of network management and electricity supply have been unbundled and placed under separate legal entities in a number of world regions. The parties active on the electricity wholesale market are free to buy from or sell to players of their choice. System operators carry out tasks of infrastructure operations. Here, we focus on the maintainer and operator of the high-voltage transmission network, referred to as *Transmission System Operator* (TSO). One of its tasks is maintaining the instantaneous demand and supply balance in the network. In several regions (e.g. European countries, South Africa,...), a system of balancing responsibility gives wholesale trading parties incentives to maintain their own portfolio balance. Moreover, this system provides means to charge the costs made by the TSO when maintaining the real-time system balance to the parties responsible of the unbalance. This system of balancing responsibility consists of three instruments:

- **Balancing responsibility:** the obligation of wholesalers to plan their production and consumption and to make this plan available to the TSO. Parties having this responsibility are referred to as *balancing responsible parties* (BRPs).
- **Reserves for frequency response:** the TSO contracts generation capacity for primary, secondary and emergency frequency-response reserve. Production sites of a certain capacity are obliged to make available a predefined portion of their capacity to the TSO, while others are free to offer reserve capacity. This offer is done in the form of a bid. In case of (smaller or bigger) system-wide imbalance, the TSO calls off the reserves available in the order of their bid prices, in order to restore the instantaneous system balance.
- **Settlement of imbalance costs with the balancing responsible parties:** in a later stage, the TSO charges the actual costs for the used reserve and emergency capacity to those BRPs that had deviations from their energy programs. These charges are referred to as imbalance costs.

Among different countries or states where balancing responsibility is being used, the implementation details and terminology may vary. A common key aspect is a *notification* done by the BRPs to the TSO stating their future production or consumption. These notifications consist of one or more *settlement periods* (each typically 15 or 30 minutes long) over which the BPR indicates his expected average power to be exchanged with the network. The notification has to reflect the party's position on the power markets, i.e. the net result of all its trades on the different markets for each settlement period. The notification to the TSO can be done until the *gate closure time*. After this time the BRP is not allowed to trade any power with other market parties. Hence, the TSO gate closure typically coincides with the closure of the day-ahead or intra-day power exchange markets.

In real time, deviations between the planned electricity production and consumption at system-wide level become visible to the TSO through deviations in the voltage frequency (50 or 60 Hz). If the load increases and the generation stays, the frequency will decrease, whereas if the load decreases, the frequency will increase fast. In real time, the TSO monitors the frequency, and maintains the real-time system balance by adjusting generation up and down using the contracted "reserves" for frequency response. In this way, the TSO compensates for those activities of BRPs that deviate from their notification. Afterwards, the TSO compares the real, measured, energy profile of the full portfolio of each BRP, with its notification. For every settlement period, the costs for reserve and emergency capacity made by the TSO are spread over all BRPs that caused imbalance in that particular period.

In the Netherlands, where the field test described below is located, each settlement period is 15 minutes in length and the notification consists of 96 of these periods, spanning a full day. The gate-closure time is at noon the day before, shortly after the day-ahead electricity wholesale market closes.

B. *Portfolio Imbalance: Wind Energy*

As may be clear, the system of balancing responsibility imposes imbalance risks to market parties. Among BRPs, this risk will vary with the predictability of the total portfolio of the BRP. BRPs with low portfolio predictability are faced with higher imbalance risks.

Typically, wind power is one type of DER that suffers from low predictability. This gives higher imbalance costs resulting in a lower market value for electricity produced by wind turbines. In general, any market disadvantage due to high imbalance costs can be reduced by increasing either the predictability or the controllability. Using specialized

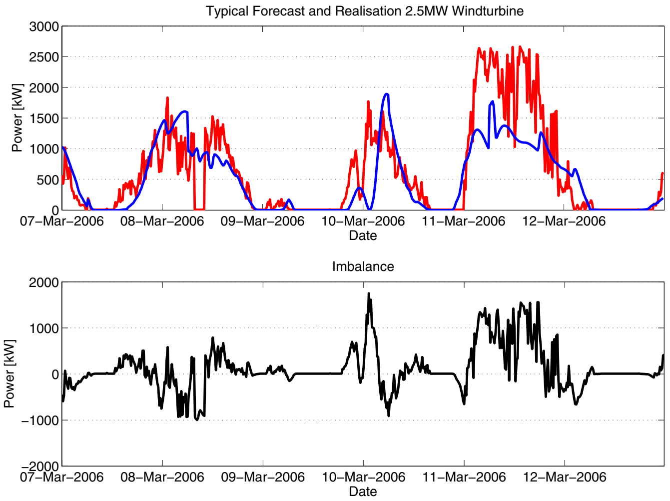

Fig. 4. Typical Wind Electricity Unpredictability. Top: Day-ahead forecast (blue) and actual production (red) of a 2.5 MW wind turbine in Kreileroord, The Netherlands. Bottom: Resulting imbalance (actual minus forecasted).

forecasting techniques as post-processors to high-resolution meteorological models, the day-ahead predictability of wind energy production has been improved substantially in the last few years [14], [15]. However, a substantial error margin remains. Figure 4 shows a typical remaining forecasting error profile of such a system. The figure shows three main sources of wind energy forecasting errors in three consecutive windy periods. In the first windy period in the figure, around March 8th, the forecast is relatively good, but the turbine is out of operation for a certain period of time, presumably for technical reasons. For the next windy period, both the complex shape and wind magnitude of a passing weather system were forecasted fairly well, but the timing wrongly forecasted. Finally, around March 11th, the forecasting system gives a good forecast for both shape and timing of the passing weather system. Unfortunately, the magnitude of the electricity output is seriously underestimated, resulting in a high imbalance level.

C. *Balancing Activities of Commercial Parties*

To manage imbalance risk, market participants undertake balancing activities. These activities can both take place before gate closure and after it, in the settlement period itself:

- **Pre Gate Closure:** typically, balancing activities before Gate Closure occur in the power exchanges. Market parties fine tune their positions to the expected aggregated profile of their portfolio by selling or buying expected surplus or deficit respectively.
- **Post Gate Closure:** after gate closure each BRP is on its own: each trade with other market parties cannot be notified to the TSO and, thus, will contribute to the imbalance position of the BRP. The BRP can only influence the producing and consuming units in its own portfolio to achieve in real-time the desired net physical energy exchange with the network.

D. *Business Idea: Agent-based Balancing in a DER Portfolio*

It may be clear that high predictability and/or high controllability of the total BRP portfolio pays off in the form of lower imbalance costs. The business idea at hand focusses on the controllability side of the coin: the actions a BRP can perform in the post gate closure stage to let its DER portfolio follow the forecasted profile as notified to the TSO. The innovative idea is to use PowerMatcher agent-based coordination for this purpose. This creates a *Distributed Balancing Service* (DBS), an IT-enabled service that coordinates among the DER installations in order to let them react to the total imbalance within the cluster.

In this cases study, we assume that the TSO does not publish imbalance (price) information in real-time[2] and the BRP has no means to estimate the sign and magnitude of the current imbalance. In this case the best strategy of a BRP is minimizing its portfolio imbalance in each settlement period.

IV. FIELD TEST IMPLEMENTATION AND RESULTS

A. *DBS Information System Implementation*

The DBS information system has been implemented in a field test setting in The Netherlands. For the purpose of the field test, five different installations were brought together in the portfolio of a virtual BRP. In reality, the installations represent a small part of the portfolios of two different BRPs, but for the sake of the experiment they were assumed to represent the full portfolio of one single BRP. Figure 5 gives the configuration of the field test. Note that the number of five DER entities is rather small regarding the business rationale behind the field test. The main aim of the field test was to get field experience with market-based control using different types of DER. Due to the small size of the cluster all local agents could be connected to one PowerMatcher node (see Figure 2) that performed the price forming process.

To all DER sites hardware was added to run the local control agents on. These agents interacted with the existing local measurement and control system. Further, the local agents communicated with the electronic market system using a virtual private network running over a standard ADSL internet connection or (in one case) a UMTS wireless data connection.

The implemented scenario script of the Distributed Balancing Service is given below. The script follows the stages of the BRP balancing activities as discussed in subsection III-C. The second stage was the particular focus of the field test, as these coordination activities in near-real time form the innovative part of the new service.

Day before (shortly before Gate Closure = 12:00 hours):

1 BRP sends request for plan to all DER.
2 DER makes the plan and sends it back.

---

[2] This was the case in the market environment of The Netherlands at the time the field test was performed. Only recently, the Dutch TSO started to publish the momentary system-wide imbalance volumes every minute on the internet with a 2 to 3 minute delay. Using this information a BRP could follow an active strategy, e.g. counteract the system imbalance when it is relatively high and, thus, imbalance prices are expected to be high. However, this is not included in the case study.

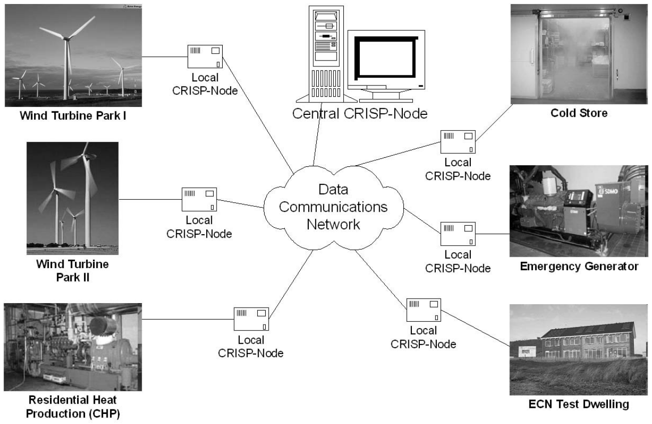

Fig. 5. Configuration of the DBS field test.

3 BRP aggregates plans into a Notification and sends it to TSO.

4 TSO does load flow analysis and does redispatch if necessary [3].

In Near-Real Time (within the 15-minute Settlement Period):

5 BRP requests demand function from DER.

6 DER creates it and sends it back.

7 BRP optimizes supply & demand via e-market, and sends the resulting price signal to all DER.

8 DER implements its allocation following from price (process scheduling and control)

* *Repeat steps 5-8 for each Settlement Period in the Notification*

Day after:

9 TSO collects measured profiles, determines BRP imbalance and charges imbalance costs to BRP.

B. DER Portfolio

Table I gives an overview of the capacities of the individual installations included in the test. In order to give the smaller sized installations a good influential balance compared to the bigger ones, two of the sites were scaled up by an on-line simulation.

TABLE I
PRODUCTION (P) AND CONSUMPTION (C) CAPACITIES OF THE FIELD TEST INSTALLATIONS

Site	P/C	Capacity	Virtual
Wind Turbine	P	2.5 MW	-
CHP	P	6 MW	-
Cold Store	C	15 kW	1.5 MW
Emergency Generator	P	200 kW	-
Heat Pump	C	0.8 kW	80 kW

Short descriptions of the included field test sites:

- **Wind Turbine.** The wind turbine is located in the north-west of The Netherlands. The day-ahead forecast of the turbine's output is made using a dedicated wind energy output forecasting method [15]. Note that the marginal operating costs of a wind turbine are virtually zero, as it does not include fuel expenses. In the current market situation, the average imbalance costs are lower than the price for wind electricity. Thus, it will not be economically attractive to curtail the output power of wind turbines for purposes of imbalance cost reduction. Hence, the turbine is the largest source of imbalance in the cluster. Accordingly, the turbine's control agent always states inflexible — or inelastic — production bids of a magnitude equal to the current power output.
- **CHP.** The combined heat and power production unit is located in the center of The Netherlands. Its produced heat is fed into a heat network of a residential area. The complete CHP plant consists of three separate CHP installations. When running, the power production of each of these equals to 2 MW electrical and 20 MW thermal. The electricity is fed into the electricity network, i.e. delivered to the BRP. The heat is fed into a large heat buffer, from which the heat demand of the residential area is supplied. The control agent's local control objective is to keep the storage level of this buffer within a predefined temperature band. Since the operation of the CHP-system is crucial for the heat supply to a large number of dwellings, participation in a field test system imposed a high operational risk. For this reason, the field test system did not control the physical system itself, but a validated software model of the system. However, the local DBS information system was implemented completely, only the local control signals were fed into the software model instead.
- **Cold Store.** The cold store is a large industrial freezing storage of a meat processing factory. The control agent's local control objective is to keep the storage level of this buffer within a predefined temperature band. The precautionary measures described for the CHP apply here as well: to minimize the operational risk the local control system signals were fed into a validated thermal model of the cold store.
- **Emergency Generator.** The emergency generator is a diesel-fuelled generator located in a multistory car park. In case of an interruption of the electricity supplied from the grid, the generator supplies electricity to the buildings's electrical system. The control agent will switch the generator on when the price level on the clusters's electronic market exceeds the marginal cooperating costs of the generator. These include fuel and maintenance costs as well as an additional cost penalty for every system start.
- **Heat Pump.** Heat pump system for domestic space heating and hot tap water heating. When the device is switched on, it consumes 0.8 kW electrical power and delivers 8 kW to either the space heating radiators or the hot tap water buffer. The control agent's local objective is to keep the temperatures in the living room and in the

---

[3] The flow analysis and the redispatch is outside the scope of this document, but added here for reasons of completeness

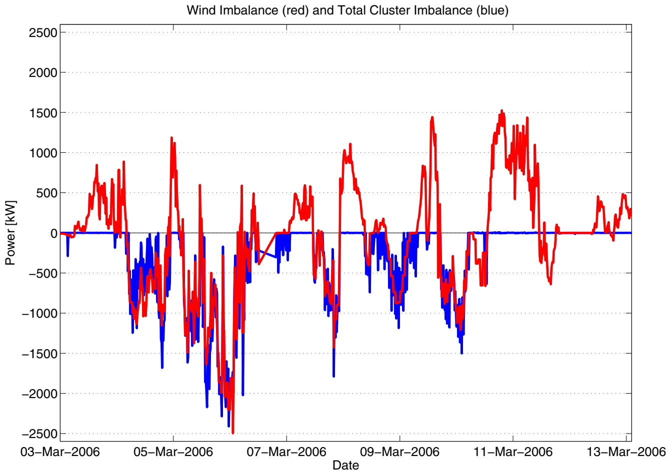

Fig. 6. Wind Imbalance (red) and Total Cluster Imbalance (blue).

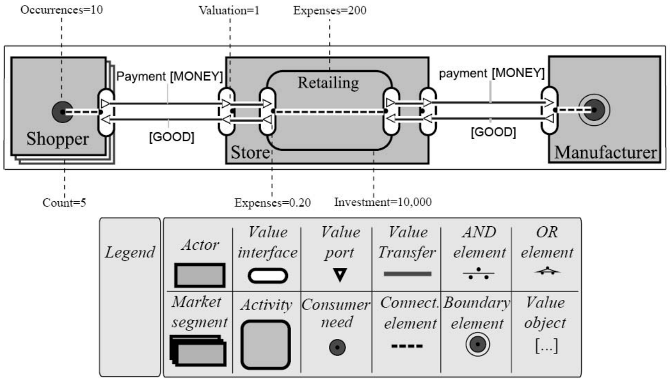

Fig. 7. Educational example

water buffer within a predefined temperature band around their respective setpoints. The heat pump is installed in a research dwelling at ECN, a real house having virtual inhabitants. The heat-demand behaviour is simulated by a computer system that opens and closes hot water taps and showers and adjusts room thermostat settings automatically according to the behavioural pattern of an average Dutch household with 4 persons. This site was included in the cluster in order to gain insight into the software agent's performance on a real-life thermal process.

C. Imbalance Reduction Results

As is the case with almost any research prototype field implementation of comparable size and complexity, the resulting data set is dominated by 'teething troubles'. However, the field test resulted in a number of periods of good data quality, enough to draw well-funded conclusions from.

One of these periods is depicted in Figure 6. This figure shows the imbalance as caused by the wind turbine together with the imbalance of the cluster as a whole. In this figure the wind imbalance serves as the reference case. As the other installations were altering their operations in order to reduce the cluster imbalance, there is no insight in the reference figure of the whole cluster imbalance (i.e. when all installations would be running freely). However, the wind turbine is the main source of imbalance in the cluster, so it gives a good, 'on the save side', estimate, as the total imbalance will likely be higher.

The total imbalance reduction over the 11-day period in the figure is 40%. As is clear from the figure this reduction is mainly achieved by compensating for the *overproduction* of the wind turbine. Apparently, there is enough flexibility in the cluster to increase consumption and decrease production in these periods. Most of the *underproduction* of the turbine is not compensated at all. Apparently, the flexibility to increase production or to decrease consumption is much lower. Closer analysis of the individual agents' behaviour suggested a reason for this. As the weather was quite cold during this period, the CHP's residential area demanded high volumes of heat. Consequently, the CHP was in a 'must-run' situation with no room to shift production towards the periods of wind underproduction. One of the goals of a current simulation study is to verify this.

V. BUSINESS CASE ANALYSIS

A. *The* e^3-value *methodology for economical feasibility*

To analyze the business-case, we employ the *e^3-value* methodology. To make this paper self-contained, we briefly introduce the *e^3-value* modelling concepts below as well as the *e^3-value* way of reasoning about economic feasibility (see for a more detailed explanation [16]). The *e^3-value* methodology provides modelling constructs for representing and analyzing a network of enterprizes, exchanging things of economic value with each other. The methodology is ontologically well founded and has been expressed as UML classes, Prolog code, RDF/S, and a Java-based graphical *e^3-value* ontology editor and an analysis tool, which is available for download (see http://www.e3value.com/) [16]. In the following text, we use an educational example (see Figure 7) to explain the ontological constructs.

An *actor* is perceived by his/her environment as an economically independent entity. The Store and Manufacturer are examples of actors. Actors exchange *value objects*. A value object is a service, a good, money, or even an experience, which is of economic value for at least one of the actors. An actor uses a *value port* to provide or request value objects to or from other actors. Actors have one or more *value interfaces*, grouping value ports, and showing economic reciprocity. So, in the example, Goods can only be obtained for Money and vice versa. A *value transfer* is used to connect two value ports with each other. In the example, a transfer of Good or Payment are both examples of value transfers. A *value transaction* groups value transfers that all should happen, or none at all. A *market segment* composes actors into segments of actors that assign economic value to objects equally. The Shopper is a market segment, consisting of a number of individual shoppers. An actor performs one or more *value activities*.

These are assumed to yield a profit. In the example, the value activity of the Store is Retailing. A *dependency path* is used to reason about the number of value transfers as well as their economic value. A path consists of *consumer needs*, *connections*, *dependency elements* and *dependency boundaries*. A consumer need is satisfied by exchanging value objects (via one or more interfaces). A connection relates a consumer need to a value interface, or relates various value interfaces internally, of a same actor. A path can take complex forms, using AND/OR dependency elements taken from Use Case Map scenarios [17]. A dependency boundary represents that we do not consider any more value transfers for the path. In the example, by following the path we can see that, to satisfy the need of the Shopper, the Manufacturer ultimately has to provide Goods.

B. Business Model

Figure 8 shows an e^3-*value* model for the DBS case study. The focus is on the participating enterprizes and what they *transfer* of economic value, and not on the required soft- and hardware components yet.

There are different market segments of 'electricity generators' in the form of 'wind turbines', 'Combined Heat Power generators' (CHPs) and 'emergency generators'. All these generators offer 'electricity' and request 'money' in return. Different types of generators exist because, due the nature of the generator (volume of total electricity power, predictability of this volume), the pricing schemes may be different. Additionally, they offer 'operational flexibility', meaning that a portfolio holder (here the 'supplier') may influence the amount of electricity production, in return for 'money'. There are 'consumers' who buy 'electricity' and pay 'money' in return. Also, they offer 'operational flexibility' so that a portfolio holder can influence their amount of electricity consumption, and they request some 'money' in return for that. Normally, the 'generators' and 'consumers' must also pay a fee to the 'Transmission System Operator' (TSO), if their real-life production/consumption deviates from their forecasted production/consumption (which is always the case). This *balance-responsibility* is in the DBS e^3-*value* model taken over by a 'supplier' of which we have one. The 'generators' and 'consumers' are all in the portfolio of the 'supplier'. The 'supplier' pays a penalty ('money') to the TSO for the amount of imbalance caused. This amount can be reduced by controlling the 'generators' and 'consumers' near real-time. Finally, there is a 'wholesale market operator'. The role of this operator is to sell electricity to the 'supplier' in case of shortage or to buy electricity from the 'supplier' in case of a surplus.

An e^3-*value* model provides a snapshot of value transfers for a certain timeframe; here, for 15 minutes, since it is used as a discrete interval to calculate fees, based on the actual production/consumption. All the modelled *consumer needs* occur within this timeframe.

Now, tracing through the 'A' dependency path, the 'consumer' has a need for a certain amount of kilowatt-hours (kWh) (see Figure 8). The 'wholesale market operator' has also a need for electricity. These needs are satisfied by the 'supplier'. He buys electricity from the 'generators' of his portfolio, and from the 'wholesale market operator' in case of a shortage, as can be seen from the 'B' path. From the 'C' path it can be seen that the 'supply & trade' activity requires 'balancing control', and so control of the operation of 'generators' and/or 'consumers' in terms of operational flexibility. 'Balancing control' operates together with the 'operation control' activity, which is executed by consumers and generators. Since such a control moment is needed once per 15 minutes (timeframe of the model), there will be precisely one occurrence, so one 'operational flexibility' transfer between the 'supplier' and the 'generators'/'consumers'. However, due to the fact that market segments aggregate actors, explosion elements are needed (fork (#2)-(#5)) in order to achieve one occurrence per actor in such a market segment. Despite the efforts of the 'supplier', there will always be some imbalance (because the 'supplier' can control *near* real-time). This is modelled by the *AND* fork (#1).

The e^3-*value* model calculates, as shown, the occurrences for each dependency path element for the 15-minutes timeframe. We assume that investments in generators and in consumption control equipment were done earlier, so we do not consider these. Investments related to ICT were estimated using UML deployment diagrams. If we assign pricing schemes (valuation functions) to the model, assume an amount of electricity power needed, assume a number of generators and consumers, and assume how much required electricity power can be satisfied by the portfolio's participants, we can derive for each 15 minute timeframe net value sheets for each enterprize involved. When e^3-*timeseries* is used, it is possible to concatenate a series of e^3-*value* model snapshots, capturing many sequential timeframes of each 15 minutes. Then, a Discounted Net Present Cash Flow [18] sheet per actor can be derived to judge the financial attractiveness of the DBS, which we do not discuss in detail due to space restrictions. In table II, such a sheet is (as an example) given for the 'CHP generator'.

In [19] we use the DBS case to demonstrate a novel, structured approach to relate business value modelling (using e^3-*value*) to information systems modelling (using UML-deployment diagrams).

VI. DISCUSSION AND CONCLUSION

In this paper we have shown how multiagent systems (MAS) based on general equilibrium theory can be used for electricity balancing in clusters of DER. The case study we describe takes a multiperspective view from information systems, electricity and business.

In the information systems perspective we have argued that common ICT systems for clustered control of DER need to balance multiple stakes in a multi-actor environment. Accordingly, such a system needs to meet heavy requirements regarding scalability and openness. In the field study we have shown that using the advanced ICT technologies of MAS and electronic markets the functional objective of clustered

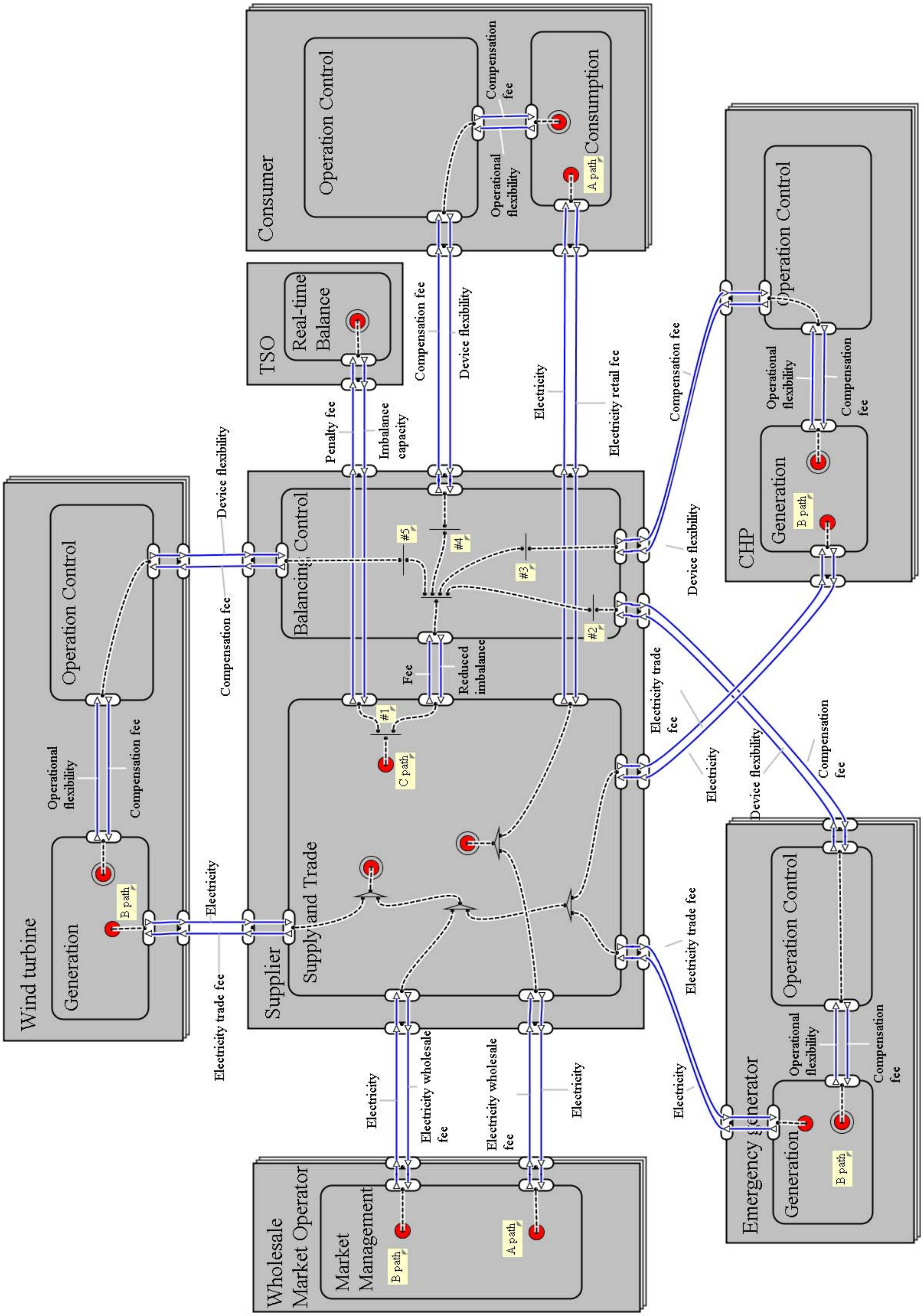

Fig. 8. e^3-*value* model of the Distributed Balance System

TABLE II

NET VALUE FLOW SHEET FOR 'OPERATION CONTROL' ACTIVITY OF ONE CHP

Actor/Activity:	CHP- 'Operation control'					
Timeframe:	period 0					
					Economic Value	**Total**
INVESTMENT					3,870	
Timeframe:	period 1					
Value Interface	**Value Port**	**Value Transfer**	**Occurrences**	**Valuation**	**Economic Value**	**Total**
Device flexibility,MONEY			1		0.735	
	out: Device flexibility	(EXPENSES)	1	0.005	-0.005	
	in: MONEY (Compensation fee)	MONEY	1	0.002	0.74	
Operational flexibility,MONEY			1		-0.666	
	out: MONEY (Compensation fee)	MONEY	1	0.0018	-0.666	
Net Cash Flow:						0.069
Timeframe:	period 103,680 + 1					
...						
Discounted Net Cash Flow:	1,715.12					

operation of DER can be realized. This system uses a simple and uniform data interchange between actors based on market information. Its information system architecture is tree shaped, where each non-leaf node aggregates the information passed by its entire sub-tree. These two features ensure an open and well-scalable system.

As seen from the electricity perspective, the benefits shown in the field experiment are substantial. In the real-life DER portfolio with a wind power dominated imbalance characteristic, the imbalance reduction reached to 40%. This makes the approach a good addition to the current options for dealing with wind power unpredictability, like wind/diesel combinations and balancing by conventional power plants. Topics that need further research include the factors that influence the flexibility level of the aggregate and the system behaviour when the number of attached DER is increased substantially.

In the business perspective, we have shown that this ICT-enabled business case consists of a complex networked value constellation. Modelling techniques to discover all necessary value transfers between different actors are indispensable to reason about the financial feasibility of the business idea.

ACKNOWLEDGMENTS

The authors wish to thank all people at ECN who helped in realizing the distributed balancing field test within the CRISP project.

This work has been partly sponsored by the EU-funded projects CRISP (NNE5-2001-00906) and FENIX (518272), the JACQUARD/NWO funded project VITAL (838.003.407), and the VUA funded project VUBIS.

REFERENCES

[1] International Energy Agency, *Distributed Generation in Liberalised Electricity Markets*. Paris: International Energy Agency, 2002.

[2] K. Kok, C. Warmer, and R. Kamphuis, "PowerMatcher: multiagent control in the electricity infrastructure," in *AAMAS '05: Proceedings of the 4th int. joint conf. on Autonomous Agents and Multiagent Systems*, vol. industry track. New York, NY, USA: ACM Press, 2005, pp. 75–82.

[3] ——, "The PowerMatcher: Multiagent control of electricity demand and supply," *IEEE Intelligent Systems*, vol. 21, no. 2, pp. 89–90, March/April 2006, part of an overview of the 4 best industrial contributions to AAMAS05.

[4] R. Gustavsson, "Agents with power," *Communications of the ACM*, vol. 42, no. 3, pp. 41–47, 1999.

[5] D. Cohen, "Using real–time web technology to manage DE networks," in *Proceedings of Distributed Power 2001*. Intertech, 2001.

[6] F. Ygge and H. Akkermans, "Power load management as a computational market," in *Proceedings of the 1st Int. Conf. on Multi-Agent Systems*, V. Lesser, Ed. MIT Press, 1996. [Online]. Available: citeseer.ist.psu.edu/ygge96power.html

[7] P. Carlsson, "Algorithms for electronic power markets," Ph.D. dissertation, Uppsala University, 2004.

[8] A. Mas-Colell, M. Whinston, and J. R. Green, *Microeconomic Theory*. Oxford University Press, 1995.

[9] R. K. Dash, D. C. Parkes, and N. R. Jennings, "Computational mechanism design: A call to arms," *IEEE Intelligent Systems*, vol. 18, no. 6, pp. 40–47, November/December 2003.

[10] T. W. Sandholm, "Distributed rational decision making," in *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, G. Weiss, Ed. Cambridge, MA, USA: The MIT Press, 1999, pp. 201–258. [Online]. Available: citeseer.ist.psu.edu/sandholm99distributed.html

[11] M. P. Wellman, "A market-oriented programming environment and its application to distributed multicommodity flow problems," *Journal of Artificial Intelligence Research*, vol. 1, pp. 1–23, 1993.

[12] F. Ygge and H. Akkermans, "Resource-oriented multicommodity market algorithms," *Autonomous Agents and Multi-Agent Systems*, vol. 3, no. 1, pp. 53–71, 2000, special Issue Best Papers of ICMAS–98.

[13] H. Akkermans, J. Schreinemakers, and K. Kok, "Microeconomic distributed control: Theory and application of multi-agent electronic markets," in *Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures*, 2004.

[14] B. Ernst, "Wind power forecast for the german and danish networks," in *Wind Power in Power Systems*, T. Ackermann, Ed. John Wiley and Sons Ltd, Januari 2005.

[15] A. Brand and J. Kok, "Forecasting wind power by a quarter of the hour," in *Proceedings of the 2003 European Wind Energy Conference*. Brussels, Belgium: EWEA, 2003.

[16] J. M. A. J. Gordijn, "Value based requirements engineering: Exploring innovative e-commerce ideas," *Requirements Engineering Journal*, vol. 8, no. 2, pp. 114–134, 2003.

[17] R. J. A. Buhr, "Use case maps as architectural entities for complex systems," *IEEE Transactions on Software Engineering*, vol. 24, no. 12, pp. 1131–1155, 1998.

[18] R. Brealey, S. Myers, and F. Allen, *Corporate Finance*. McGraw Hill Higher Education, 2005.

[19] Z. Derzsi, J. Gordijn, K. Kok, H. Akkermans, and Y.-H. Tan, "Assessing feasibility of IT-enabled networked value constellations: A case study in the electricity sector," in *Proceedings of CAISE 2007*, 2007.