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Balancing Wind Power with Virtual Power Plants of Micro-CHPs

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Abstract—**Higher participation levels of wind power in power systems will increase the need for flexible back-up generation to balance the differences between predicted and realized wind power production. This is often an expensive solution. With distributed energy resources and more ICT at the demand side, novel, and possibly cheaper, ways for imbalance minimization arise. Micro combined heat-and-power (micro-CHP) is a novel domestic-level generation technology, producing heat and power simultaneously. Clusters of micro-CHPs can function as flexible virtual power plants (VPPs). This paper presents the design of an online coordination scheme that can substantially reduce the imbalance volumes and the associated costs for wind power traders by actively controlling a VPP comprising micro-CHP systems. It is shown that the imbalance volume and associated cost can be reduced by 73 % and 38 %, respectively.**

Index Terms--**Imbalance reduction, intelligent control, micro cogeneration, virtual power plants, wind power.**

I. INTRODUCTION

THE integration of stochastic wind power generation in the power system will increase the need for energy balancing. This will lead to different unit commitment and generation dispatch, which influences the costs and revenues of many actors involved [1]. Wind power traders are, for example, faced with the inherent inaccuracies of wind power forecasts [2]. The difference between wind power prediction and realization leads to imbalance volumes and associated costs, which these traders might have to bear. In The Netherlands, as in many other European countries, wind traders are responsible for the imbalance they cause.

At present, energy balancing is principally provided by the supply side of the power system through the flexible operation of thermal power plants, i.e. requiring them to be part-loaded or idling for long periods in anticipation of balancing actions or requests. This flexibility of operation may reduce both asset life and efficiency, leading to increased costs and carbon intensity of electricity generation. A generation company having wind capacity as well as flexible generation in its portfolio could use this other generation to resolve imbalances from wind. This option is disadvantageous in the sense that plants will have to stand idle, thereby not being able to sell electricity at times when this could be profitable. Other options for the trader for resolving its imbalance could be intra-day trading with other market parties (via organized markets or bilaterally), or via imbalance markets (through which, again, flexible plants are dispatched, but these are owned by other traders). With the growing penetration of distributed energy resources and ICT in the power system, novel and possibly less expensive ways for imbalance minimization arise. Distributed energy resources comprise distributed electricity generation, electricity storage options, and load response schemes. Micro cogeneration, or micro combined heat-and-power (micro-CHP), is such a resource. Micro-CHP is a novel domestic-level generation system, producing heat and power simultaneously. Micro-CHP is a promising technology in the near future for countries with moderate climates and well-developed natural gas grids (e.g. the Netherlands, UK, Japan). Applying micro-CHP leads to more efficient energy use, carbon emission reduction and to cost savings of around 10-20 % per household [3]. Households thereby become so-called ‘prosumers’; consumers and producers at the same time. Contrary to most other distributed generation technologies that depend on intermittent primary energy sources, micro-CHP is partially-controllable, meaning that it can be operated within certain operating ranges (see [4] for a taxonomy of types of generator controllability). This partial controllability enables micro-CHP to be utilized in intelligent coordination schemes to enhance the value of the technology. These schemes could involve virtual power plants (VPP), which we define as clusters of distributed generators that are collectively run by a central control entity for a specific objective.

This paper deals with clustered micro-CHP application in VPPs and investigates the potential of these VPPs in providing wind balancing services and imbalance cost

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reduction for wind power traders. This paper takes the Dutch electricity market as starting point: in The Netherlands wind farms are responsible for the imbalance they create. When imbalance costs of wind traders can be reduced the benefits from the cooperation could be shared between wind traders, separate VPP aggregators and even micro-CHP households themselves.

In the existing literature there is not much work done yet on VPPs with micro-CHPs and on VPPs for balancing wind power. On wind balancing with VPPs actually just two publications can be found. The concept of wind balancing with distributed energy resources is discussed in [5], but the balancing process is not quantified. In [6] an imbalance volume reduction of 40 % is reported. A market-based control concept was used, with the local market price in the VPP as control signal. When there is overproduction from the wind plants, the local price drops and induces micro-CHPs to reduce generation output. No associated cost savings where mentioned, however, and also the situations of separate production by the wind plant and the VPP on the one hand and combined production on the other hand were not compared. Looking at the literature, this paper can be considered as novel research.

II. PROPOSED COORDINATION SCHEME

This section describes the envisaged design of the coordination scheme to reduce wind power imbalance with micro-CHP VPPs.

A. System Description

In [7] we defined an aggregator as an actor that actively controls distributed energy resources and/or trades the energy flows to/from households. Here we assume that the aggregator is the actor trading the wind power and the energy to/from households and that he also controls the VPP. In principle the controlling entity could be a different aggregator, but as this choice has no influence on the outcomes of our study, we choose to look at one aggregator. The aggregator can be regarded as a commercial energy company, owning wind generation, retailing electricity and gas to households, and trading on different energy markets. Additionally he also controls the VPP (see Fig. 1). Most energy companies have a broader generation portfolio and customer base, and the wind farm and VPP would then be part of a more complex unit commitment and trading process. To keep things simple, we consider only the wind farm and the VPP here. What we will look at is if the VPP can be more actively deployed to reduce the unfavorable imbalance caused by the wind farm.

It is envisioned that the standard control for micro-CHPs will be heat-led, meaning that the system will operate a certain amount of time each day depending on domestic heat demand. If the heat-led control could be interfered with (‘opened up’) and the produced heat can be stored, a micro-CHP’s operating hours can stay the same in number, but can be shifted in time. Heat storage thereby creates flexibility in operation, while not compromising the heating comfort for the households. The configuration with which the micro-CHPs are assumed to be installed in households was described in [8]. All households in the VPP have installed a heat storage unit to which the produced heat from the micro-CHP is supplied and from which all heat demand is taken. The control objective of the aggregator is to use the VPP to minimize the imbalance costs of both the wind farm and the VPP. Via contractual arrangements with the VPP households, the micro-CHP systems can be actively incorporated in the coordination scheme.

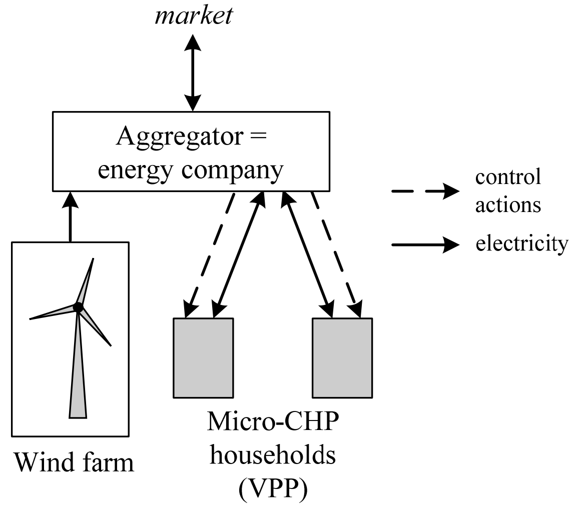

Fig. 1. System overview of the aggregator trading with wind and micro-CHP power and controlling the micro-CHP VPP.

B. The Balancing Market and Program Responsibility

The VPP is considered to operate in the Dutch electricity market. Before explicating the coordination scheme we briefly describe how the Dutch balancing market functions. The Dutch electricity market has a decentralized structure meaning that the transmission system operator (TSO) only has a technical function and supply and demand meet elsewhere than in a mandatory pool, either bilaterally or in voluntary power exchanges [9]. All electricity trading parties should be or fall under a program responsible party (PRP), which submits energy programs (E-programs) to the TSO on a daily basis for the complete following day. The E-programs state the quarterly transactions between electricity sellers and buyers. When the next day the program of PRPs can not be fully met they pay and/or receive imbalance prices over additionally extracted or fed-in electricity, respectively. Extracting more electricity from the system than predicted (i.e. negative imbalance) mostly costs more than the ruling spot market price, and the price received for feeding in more electricity (i.e. positive imbalance) is mostly lower than the ruling spot market price. The TSO operates the balancing market, in which it is a single buyer and in which all large generators have to bid in part of their generation capacity as regulation or reserve power. The total amount of positive and negative imbalance at a certain moment is the sum of the imbalance volumes of all PRPs. The imbalance market functions in such a way that creating imbalance causes economic losses for PRPs and is thereby discouraged.

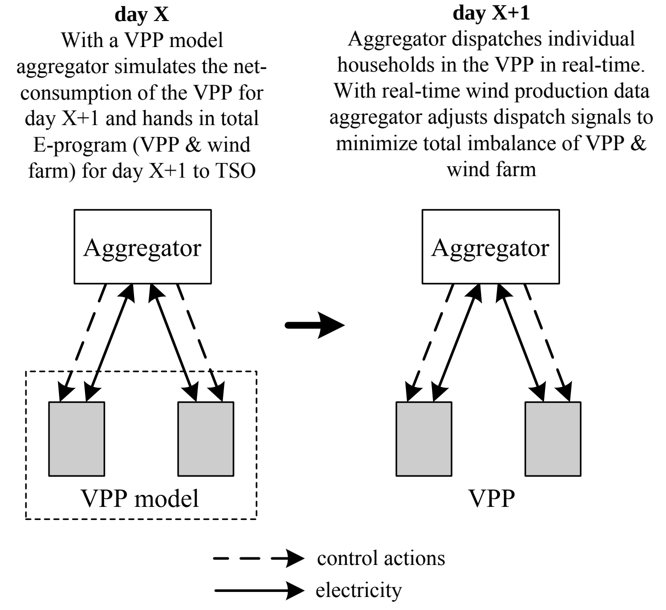

Fig. 2. Different steps in the coordination scheme.

In this work we assume that the aggregator's imbalance can only be resolved via either the imbalance market or internally within the system under study by controlling the VPP. We also assume that the power output of the wind turbines in the farm is uncontrollable (i.e. the blades can not be pitched). The E-program of the aggregator, who we assume is a PRP, can then not be altered. In reality, PRPs could make use of additional options to minimize imbalance. They can also trade intra-day bilaterally or on other markets to try to follow their E-program. In the Netherlands altered E-programs could be handed in to the TSO up to a few hours before the actual moment of delivery. The PRP should then, however, be able to find trading partners that are also willing to alter their E-programs intra-day. Important to note is, that in order to be able to resolve imbalance intra-day, information on the expected imbalance should be available to a PRP. In the case of wind power, this might not be the case or this information may be expensive (i.e. needs advanced forecasting tools). We assume that intra-day forecasts on wind power production are not available to the aggregator and that intra-day trading with other parties is then not an option. The aggregator only has the two previously mentioned options for resolving its imbalance at its disposal. So, we compare the option of being subjected to the imbalance market with the alternative option of controlling the VPP in real-time. It is necessary then, however, to have real-time information on the imbalance situation of the aggregator. Assuming this information is available is fair as real-time power output of the wind farm and the VPP can be measured quite straightforwardly. We acknowledge that a complete study should consider the full range of imbalance resolving options that might be available to the aggregator, and that this work therefore has a certain scope.

C. Steps in the Scheme

Fig. 2 shows the different steps in the proposed coordination scheme. On day X, by using a model of the VPP together with forecasts on the VPP's final energy consumption (heat and electricity), the aggregator simulates the aggregate net-consumption of electricity of the VPP for day X+1. The VPP model is a representation of the actual cluster of households that comprise the VPP. Together with a day-ahead wind power forecast, the aggregator hands in its E-program for day X+1 to the TSO.

On day X+1 the aggregator dispatches the individual micro-CHPs in the households on the basis of the output from the VPP model outcomes of day X. In that real-time dispatch of the VPP, the aggregator ensures that the running micro-CHPs will never run at their maximum or minimum capacity, in that way enabling the running micro-CHPs to up regulate or down regulate a little. With real-time data on wind production and the VPP's net-consumption of electricity the aggregator determines its imbalance volume for each quarter of an hour. On the basis of that information the aggregator then adjusts the real-time dispatch signals for the individual micro-CHPs to minimize the imbalance as much as possible. It is assumed that the micro-CHP systems have a quick response time and can be ramped up and down instantaneously.

III. MODEL DESCRIPTION

This section describes the model of the developed coordination scheme in more detail.

A. Modeling Choices and Assumptions

We assume that each household in the VPP has installed a micro-CHP with similar prime mover technology. As a first option here the Stirling engine is modeled. Households in the VPP differ in terms of energy demand profiles and heat storage volumes, as will be discussed later. For parameter settings regarding the modeled micro-CHP systems, see [8].

In our work, the VPP model with which the aggregator determines the net-consumption of the VPP for the next day (see Fig. 2) is similar to the actual model of the VPP. The only difference is the energy demand profiles that are assigned to the households in both models. These are set differently, thereby causing a small imbalance volume for the VPP.

The communication within the VPP is bi-directional, meaning that information is being sent both from the households to the aggregator and vice versa. Before determining which households to dispatch, the energy levels of the hot water storages in all households are sensed. With this information the aggregator sorts the households and will dispatch the 'coldest' first (i.e. the households with the least thermal energy in their storage). The dispatch signal sent to households comprises information on with which capacity to run the micro-CHP prime mover. This is a form of direct control, as opposed to indirect control via price signals, for example. Control signals can be sent to households via power lines, the internet, GSM or UMTS. With intelligent metering in place, combined with some in-house domotics and sensing

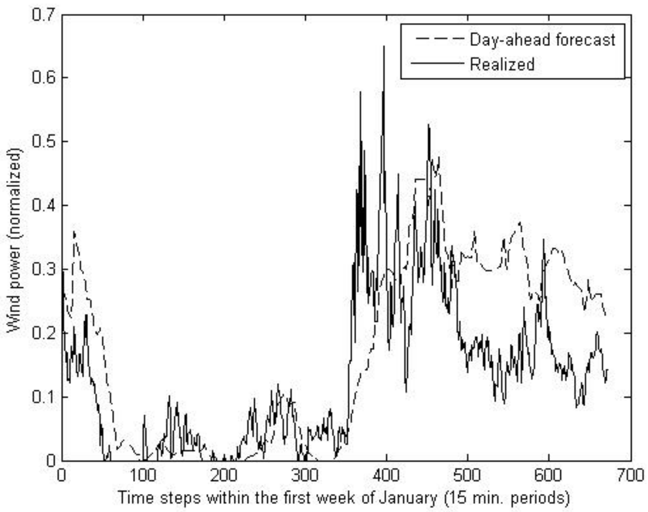

Fig. 3. Normalized day-ahead forecast and realization of power production from a Dutch wind farm.

and actuation equipment, the aggregator can control the micro-CHP systems. After the central dispatch the micro-CHP's operational settings can still be adjusted at the household level due to technological constraints of the micro-CHP system and/or the hot water storage. If the aggregator's dispatch signal causes the storage to overheat, for example, the micro-CHP system will not completely follow the signal and will run at a lower capacity. The actions of the aggregator can then be regarded as a sort of partial-dispatch, because there is a mix of central and decentralized control of the micro-CHP systems in the VPP.

In [10], where a VPP with micro-CHPs is modeled to control aggregate load, the activation sequence of the units is determined based on the thermal demand of the households. To us, this type of sorting seems more difficult to implement, as it is probably more difficult to measure the heat demand of a household than its hot water storage energy content.

The central dispatch of the aggregator is aimed at dispatching a certain amount of micro-CHPs at similar capacity. In the imbalance minimization control we choose, as a first option, to only adjust the output of the already running units and not to start-up new units or shut-down units. Each time step in our model represents a period of 15 minutes, which equal the program time unit of E-programs in The Netherlands.

B. Model Input

In simulating the VPP we have taken a Monte-Carlo approach (see [4] for more information on the applied method). Each household has different electricity and heat demand profiles, a different heat storage volume (between 100 and 200 liters) and different starting conditions for the simulation in terms of heat storage energy level. All data were obtained for the year 2006. In assigning electricity and heat demand profiles we used so-called 'profile fractions' from [11] and average annual domestic electricity and heat demands of 3400 and 12,500 kWh, respectively (taken from [12]). In that way we created one average aggregate profile for domestic electricity demand and one for heat demand. Subsequently, in creating individual domestic electricity demand profiles, for each time period a sample was taken from an exponential distribution, in which the expected value was equal to the average aggregate electricity demand at that time. With an exponential distribution the large demand spikes in households could be simulated. In creating the domestic heat demand profiles, samples were taken from normal distributions, with the expected values equaling the average aggregate heat demand at that time period. Normal distributions were more suitable in simulating the heat demand, as the demand spikes are much smaller than with electricity [13].

For electricity we constructed a time varying price (15 min. resolution), using a merit order of Dutch generation facilities from [14] and load data from [15]. Imbalance prices for extraction and feed-in were obtained from [15]. For remunerating electricity that households feed-back into the system, we assumed net-metering, which means that the prices of imported and exported electricity are equal.

Wind production data from a Dutch on-shore wind farm for the year 2006 were used. As an illustration, in Fig. 3 the normalized day-ahead forecast (obtained with a prediction model) and the actual realized power production from the farm are shown for the first week of January. We simulated a cluster of 200 households with Stirling micro-CHPs, each with a nominal electric capacity of 1 kW_e. The results were then scaled up to represent a VPP of 200,000 households. The nominal capacity of the wind farm was set at 200 MW.

IV. SIMULATION RESULTS

Figs. 4 and 5 graphically depict the degree to which the VPP is capable of reducing the imbalance of the total system consisting of the wind farm and the VPP. The results for two days in January are shown. Fig. 4 shows that by adjusting the micro-CHPs in real-time the handed in E-program can be followed quite well. Fig. 5 shows the reduction in imbalance volume when using the VPP.

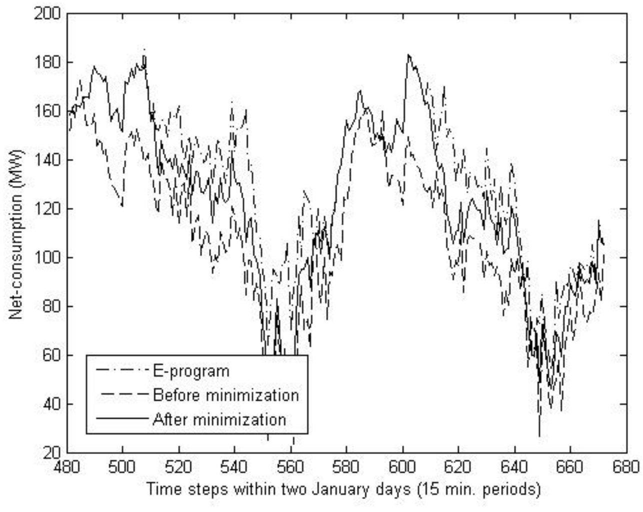

Fig. 4. Aggregated net-consumption of wind farm and VPP in the day-ahead E-program and before and after real-time imbalance minimization.

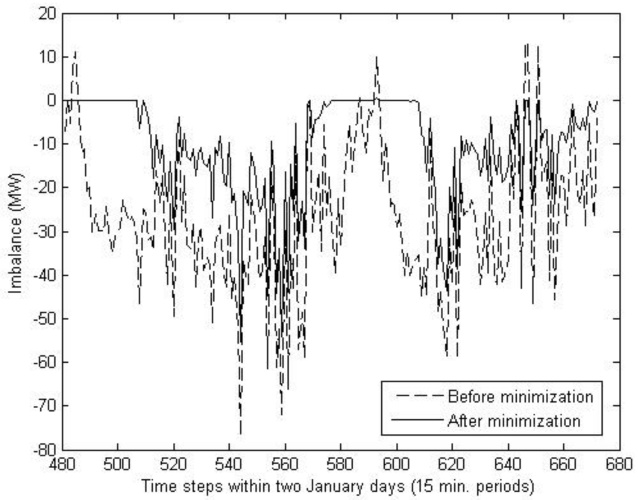

Fig. 5. Imbalance of wind farm and VPP before and after real-time imbalance minimization.

TABLE I
Simulation Outcomes for the month of January for a VPP with 200,000 micro-CHPs of 1 kW_E and a 200 MW wind farm.

Revenues and costs (€/MWh wind sold) and imbalance volumes (MWh)	Before minimization	After minimization
Revenue wind - perfect	38.2	38.2
Imbalance costs wind	16.3	16.3
Net wind revenue	21.9	21.9
Imbalance costs total	16.8	10.4
Imbalance volume total	17316	4666

Table I gives the numerical simulation output for the month of January. Simulating the VPP over the full year was computationally challenging and therefore we took a time period of one month. As the wind farm's power output can not be controlled, the presented 'Before' and 'After' minimization data for the wind farm are similar. In Table I large imbalance volumes and costs can be observed. The imbalance costs were calculated by subtracting the revenues from feeding in more than predicted from the costs of extracting more than predicted. The imbalance costs reduce possible revenues for the wind farm by around 43 %. For the full year, a revenue reduction of 46 % is calculated for the wind farm. The wind farm is responsible for about 90 % of the total imbalance volume of the total system. In January the wind farm submitted E-programs (i.e. expected production) with a total of 35113 MWh. So the imbalance volume is about 49 % of the total submitted volume. By using the VPP the total imbalance volume can be reduced by around 73 %. Associated imbalance costs of the total system can be reduced by around 38 %.

So, by actively using the VPP €224,700 (=(16.8-10.4)*35113) on imbalance costs can be saved for the total system. For the whole year, a saving of about €2 million might be possible (considering that in the summer months there might not be so much flexibility in micro-CHP operation due to the lower domestic heat demand). To make the economic analysis more complete a reference case for the cluster of micro-CHPs was considered as well. As a reference we modeled a cluster of micro-CHPs that were operated under a heat-led strategy (see [4] on the workings of the heat-led control strategy). The costs that the VPP incurs within the cooperation with the wind farm closely match the costs of the heat-led cluster. These costs included electricity costs and revenues, imbalance costs and gas costs (using a gas price of 0.06 €/kWh from [16]). Simulations over longer time periods should provide more thorough insights in the economic performance of the VPP within the coordination scheme and under heat-led control.

When the savings are equally divided by all VPP participants, an annual saving of about €10 per household is arrived at. This will most probably not provide enough incentive for a household to join the coordination scheme on its own initiative. Aggregately, however, these savings could very well provide an incentive to set up the VPP. Energy companies leasing out micro-CHPs, housing corporations installing large numbers of micro-CHPs in their apartments, or other aggregators might find it worthwhile to invest in setting up the coordination scheme, thereby incurring (part of) the economic savings the cooperation entails. Important to note is that the coordination scheme will require investments in ICT and control systems (e.g. central controllers, sensors, actuators) that should be earned back via the operational savings on imbalance costs. We expect that the economic benefit found in this work will lead to acceptable returns on those investments. Part of the required ICT infrastructure might already be in place at the moment one would like to start the VPP. Intelligent metering is being implemented in many countries and there are already many ways for communicating signals to households (e.g. internet, UMTS).

V. Conclusions, Reflection and Future Research

Integrating more wind power in power systems will increase the demand for more flexible generation to balance the differences between predicted and realized wind power production. Clusters of micro-CHP systems can function as flexible generators when organized in VPPs. A prerequisite is then that local control of micro-CHP systems is not too stringent so that external aggregators can control the units. This paper has presented the design of a coordination scheme aimed at reducing the imbalance volumes and associated costs of wind traders. Simulation studies showed that the imbalance volume and associated costs can be reduced by 73 % and 38 %, respectively. These savings could be translated into lower generation costs for wind power and/or better economic incentives for applying micro-CHP systems. The only information that was used in adjusting the VPP in real-time was real-time data on the aggregate net-electricity consumption of the VPP and the wind farm. With this information, the imbalance can be resolved to a large extent. So, even without intra-day information on possible future imbalances, the imbalance can be resolved substantially in real-time. The cost savings per household in the VPP are small, but aggregately substantial economic benefit can be obtained, providing incentives for aggregators to engage in the proposed coordination scheme.

Future research is recommended in the following areas. A sensitivity analysis should be done considering technical parameters as minimal up-time and capacity of the Stirling engine, and heat storage content.

Besides Stirling engines, fuel cells should be modeled. As fuel cells have higher electric and lower thermal efficiencies than Stirling engines, it is expected that they can provide more flexibility and more potential for balancing.

Other dispatching strategies could be researched. As was done in this work, by dispatching the coldest units first, the number of system start-ups in the VPP will probably be quite large. This is not so good for the Stirling engines and might reduce system lifetime. Another option is to keep already running systems in operation as long as possible. The impact on the number of start-ups should then be observed. We also chose to dispatch all units with equal capacity. Another option could be to run the units in 'colder' households with a higher capacity than units in 'warmer' households.

The cost analysis for the VPP should be done more extensively. Gas costs should be included and simulations should be done over longer time periods (e.g. one year). In that way it can be said with more confidence whether the VPP households will not be worse off when joining the coordination scheme. It may be possible, for example, that in the proposed coordination scheme the Stirling prime mover and the auxiliary burner (both constituting the total micro-CHP system) are operated differently than under heat-led control. When the auxiliary burner would operate more in the coordination scheme compared to under heat-led control, this would lead to higher costs as no use is made of the inherent efficiency of the Stirling engine in providing both heat and electricity.

In this paper equal nominal VPP and wind farm capacities were chosen. The proportion between both should be experimented with. For example, can a 100 MW_e VPP balance a 200 MW wind farm much less than a 200 MW_e VPP?

The possibility for imbalance reduction presented in this work could be compared with other alternatives for resolving wind imbalance, as, for example, intra-day trading. These alternatives might require more short-term forecasts of wind power production, however.

To strengthen the business case for investing in a VPP, more control objectives for the VPP could be combined, thereby increasing the savings that could be earned (other objectives could be demand response schemes or ancillary service provision).

Further, in the presented coordination scheme, or in VPPs applied for other control objectives, other or multiple distributed energy resources could be applied. A good example is plug-in electric vehicles.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

[1] B. C. Ummels, "Power system operation with large-scale wind power in liberalised environments (Ph.D. thesis)", Faculty of Electrical Engineering, Mathematics and Computer Science. Delft University of Technology, 2009.

[2] G. Papaefthymiou and P. Pinson, "Modeling of spatial dependence in wind power forecast uncertainty," in *Proc. PMAPS'08, IEEE Conference on Probabilistic Methods Applied to Power Systems*, Puerto Rico, 2008.

[3] M. Pehnt, M. Cames, C. Fischer, B. Praetorius, L. Schneider, K. Schumacher, and J. Vob, *Micro Cogeneration: Towards Decentralized Energy Systems*. Berlin: Springer, 2006.

[4] G. Papaefthymiou, M. Houwing, M. P. C. Weijnen, and L. Van der Sluis, "Distributed Generation vs Bulk Power Transmission," in *Proc. NGInfra-IEEE International Scientific Conference "Building Networks for a Brighter Future"*, Rotterdam, The Netherlands, 2008.

[5] J. K. Kok, C. J. Warmer, and I. G. Kamphuis, "PowerMatcher: Multiagent Control in the Electricity Infrastructure," in *Proc. Fourth International Joint Conference on Autonomous Agents & Multi-Agent Systems, AAMAS'05*, Utrecht, the Netherlands, 2005.

[6] G. J. Schaeffer and H. Akkermans, "CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power - D5.3 Final Summary Report", ENK5-CT-2002-00673, July 10, 2006.

[7] M. Houwing and M. Ilic, "The Value of IT for Virtual Power Plants with Micro Cogeneration Systems," in *Proc. IEEE, International Conference on Systems, Man and Cybernetics*, Singapore, 2008.

[8] M. Houwing, A. Ajah, P. W. Heijnen, I. Bouwmans, and P. M. Herder, "Uncertainties in the Design and Operation of Distributed Energy Resources: The Case of Micro-CHP Systems," *Energy*, vol. 33, issue 10, pp. 1518-1536, October, 2008.

[9] A. C. Correljé and L. J. De Vries, "Hybrid electricity markets: the problem of explaining different patterns of restructuring", in Competitive Electricity Markets, Design, implementation, performance: Elsevier, 2008.

[10] A. D. Peacock and M. Newborough, "Controlling micro-CHP systems to modulate electrical load profiles," *Energy*, vol. 32, issue 7, pp. 1093-1103, 2007.

[11] www.energiened.nl, "Association of Dutch energy producers, retailers and traders".

[12] www.milieucentraal.nl, "Dutch environmental website".

[13] P. C. Van der Laag and G. J. Ruijg, "Micro-Warmtekrachtsystemen voor de Energievoorziening van Nederlandse Huishoudens (in Dutch)", ECN-C-02-006, September, 2002.

[14] L. J. De Vries, "Securing the Public Interest in Electricity Generation Markets; The Myths of the Invisible Hand and the Copper Plate", Faculty of Technology, Policy and Management, Delft University Press. Delft, 2004.

[15] www.tennet.nl, "Website of the Dutch TSO 'TenneT'".

[16] www.cbs.nl, "Dutch Central Bureau of Statistics (CBS)".

VIII. BIOGRAPHIES

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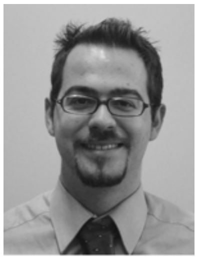

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Marija D. Ilić is currently a Professor at Carnegie Mellon University, Pittsburgh, PA, with a joint appointment in the Electrical and Computer Engineering and Engineering and Public Policy Departments. Professor Ilic also has been appointed honorary chair of Control Of Future Electricity Network Operations at the Department of Technology, Policy and Management at Delft University of Technology. She was an assistant professor at Cornell University, Ithaca, NY, and tenured Associate Professor at the University of Illinois at Urbana-Champaign. She was then a Senior Research Scientist in Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, from 1987 to 2002. She has 30 years of experience in teaching and research in the area of electrical power system modeling and control. Her main interest is in the systems aspects of operations, planning, and economics of the electric power industry. She has co-authored several books in her field of interest. Prof. Ilić is IEEE Fellow and an IEEE Distinguished Lecturer.