Joint Operation for Mitigating the Power Variability in Balance Circles

included Wind and Cogeneration Units using Heat Storage Tank

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Abstract— **The fast growing in wind power penetration into power systems can be challenging and expensive due to the intermittency of wind resources. One possible solution to overcome the problems is integrating wind generation with large scale storage. In this paper joint operation of wind power unit and cogeneration power plant with heat storage is studied on the EEX spot market. Based on heat demand, wind power prediction, and spot price forecasting optimal operational schedule is determined one day ahead, where the objective function is the gross profit. In the prediction models classical time series methods are applied while optimal operational schedule is computed by mixed integer linear programming.**

Keywords-wind power; cogeneration; heat storage; day-ahead market; forecasting; optimization

I. INTRODUCTION

The fast growing in wind power penetration into electrical power systems can be challenging and expensive due to the intermittency of wind resources. The difficulties stem from the non-dispatchable nature of wind power and can be broken down into components associated with variability and uncertainty. As a consequence increasing the benefits from the use of wind energy through the improvement of wind power prediction system's performance can be identified as one of the priorities in wind energy research [1]. Several studies concerning the participation of wind energy in electricity markets have been carried out, considering different market mechanisms and various prediction methodologies [2].

In market driven electricity trading the balance circle is a group of producers, marketers, and consumers where a balancing mechanism is used to match supply and demand in all time periods. In [3] a balance circle owner is considered where the owner purchases electricity from a wind energy producer. The aim of investigations was to analyze how the variability of wind energy generation influences the imbalance cost with different wind power capacities. Over a given wind capacity the imbalance charges increase in such a way that consumes the revenue of wind production. The wind power prediction can yield a considerable savings in imbalance charges.

A number of solutions have been proposed to mitigate the wind power variability. There are solutions combining wind generation with large scale electric energy storage systems (e.g. [4], [5], [6], and [7]) such as pumped hydro storage [8], advanced battery banks, flywheels [9], and compressed air energy storage systems ([10], [11] and [12]). These energy storage systems may be used to manage energy imbalances, to time shift wind energy into high demand periods, and increase overall capacity factor.

In [12] the optimal jointly operation of a wind farm and a compressed air unit was studied in a day-ahead market. The wind farm operator has the option to use the compressed air unit into hours with high market prices, to manage energy imbalances, and for energy arbitrage by purchasing electricity from the market. Two-stage stochastic optimization was applied where the optimization problem is formulated as mixed integer linear programming task.

In this paper optimal joint operation of wind farm and cogeneration power plant with heat storage tank in a balance circle is studied on the EEX spot market. Based on heat demand, wind power prediction, and spot price forecasting optimal operational schedule is determined one day ahead, where the objective function is the gross profit of the balance circle. To get insight of the benefit for mitigating the wind farm operational challenges using joint operation, we also compute the profit for standalone wind farm. In the prediction models classical time series methods are applied while optimal operational schedule is computed by mixed integer linear programming.

II. MODELL DESCRIPTION

In our study we assumed that the sell of electricity are settled on European Electricity Exchange (EEX) spot price. The power contracts are made for delivery the following day. In our study we follow the method in [13], where the authors investigated the role of advanced wind power forecasting tools in Dutch spot market.

To form balance circle we selected a district heating system of Hungary included a cogeneration unit with gas turbine which is connected to heat recovery boiler generating steam. The steam generated in heat recovery boiler is then used to run a steam turbine, which is in turn is connected to a generator which converts the mechanical energy to electrical energy. When the steam has passed through the turbine one part of the steam flows into the water medium of the district heating system. Another part of the steam is condensed and led back into the heat recovery boiler transferring its heat energy into the environment, and the process is repeated.

That cogeneration unit and heat water boiler was supplemented with a heat storage tank. This configuration is in a joint operation with wind farm in the same balance circle. The simplified heat flow diagram of the balance circle with main nominal parameters of the generating units is shown in Fig. 1.

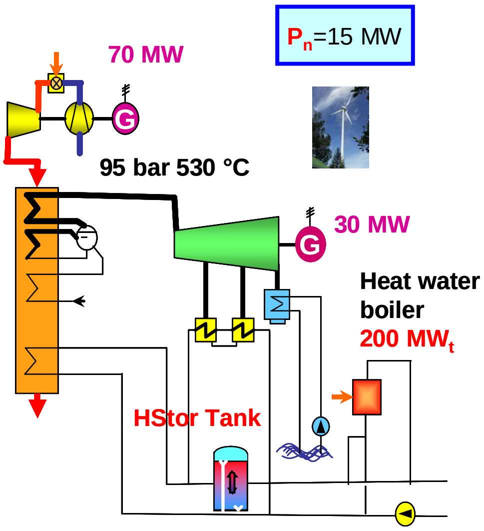


Figure 1. Balance circle included cogeneration power plant, heat storage tank, and wind power plant

In this configuration the electricity production is basically determined by the heat demand of the district heating system. The optimal power schedule of the cogeneration unit based on the gross profit depends on the heat demand and spot price.

Nowadays thermal storage tanks could be useful components in district heating systems. The main purpose of storage is to balance heat and electric power in general and during peak periods. The advantageous of storage is many such as reduced partial load operation, increased electricity generation. Using the heat storage tank there is an opportunity to shift efficient electricity production in the high spot price periods. Different strategies for using heat storage in order to improve cogeneration efficiency are presented in [14].

The main aim of our paper is to study the optimal joint operation of the wind farm and the cogeneration power plant above in a common balance circle supplemented with a heat storage tank. Using the heat storage capacity of the tank the upward and downward regulation can be governed subject to some constraints where the constraints depend on the limit of heat storage capacity, the ramping rate of the tank and the cogeneration unit. Based on wind power prediction, heat demand and spot price forecasting optimal operational schedule is determined one day ahead, where the objective function is the gross profit of the balance circle.

A. *Standalone Wind Farm Operation*

In that case the calculation is very simple. Wind energy w_t sold on the EEX spot market on the price s_t that means gross profit of $\sum_{t\in T} s_t \cdot w_t$, where t the hourly index, T is the daily time period.

B. *Cogeneration Power Plant with Heat Storage Tank*

Heat storage tank may be used to shift high thermal efficient cogeneration electricity into high spot price periods under constraint of supplying heat demand. The sketch of the model is

$$\max \sum_{t\in T} \left(p_t^{spot} \cdot P_t^{COM} - p_t^F \cdot F_t^{COM} - \{ST/SD\cos ts\} \right) \left\langle D_t^{sch} \right\rangle$$

where

p_t^{spot} spot price (Euro/MWh),

p_t^F fuel price (Euro/GJ),

P_t^{COM} performance of the combined cycle unit (MW),

F_t^{COM} fuel consumption of cogeneration power plant (GJ/h),

D_t heat demand (MW),

D_t^{sch} scheduled heat supply using storage (MW).

$\{ST/SDcosts\}$ start/shut down costs,

subject to

$$P_{\min} \le P_t^{COM} \le P_{\max} ,$$

$$-P_{ramp}^{down} \le P_{t-1}^{COM} - P_t^{COM} \le P_{ramp}^{up} ,$$

$$-D_{ramp}^{down} \le D_{t-1}^{sch} - D_t^{sch} \le D_{ramp}^{sch}$$

$$\sum_{t\in T} D_t = \sum_t D_t^{sch} ,$$

C. *Cogeneration Power Plant with Heat Storage Tank and Wind Power Plant*

In the balance circle a wind farm is included with zero variable costs. That means when the wind farm and the combined cycle unit produce electricity together, production costs will be lower. This effect can change the optimal heat supply schedule in order to shift high thermal efficient cogeneration electricity into high spot price periods under constraint of supplying heat demand.

The objective function is changed as

$$\max \sum_{t\in T} \left(p_t^{spot} \cdot P_t^{BAL} - p_t^F \cdot F_t^{COM} - \{ST/SDcosts\} \right) \left\langle D_t^{sch} \right\rangle ,$$

where

$P_t^{BAL} = P_t^{COM} + P_t^{Wind}$ balance circle output (MW),

P_t^{Wind} electric power of the wind power plant (MW).

The constraints are the same as without the wind farm.

The task above can be formulated as mixed integer programming problem where the solutions were obtained using *Gurobi* 5.1 solver.

III. NUMERICAL EXAMPLES

In this section we describe numerical examples calculated with the models. The main parameters of the generating units are depicted in Fig. 1. The maximum heat output of the cogeneration unit is $70MW_{heat}$. The maximum electric power of combined cycle unit is 100MW, which depends on the ambient temperature but that was not considered in the calculations. The minimum electric power of the unit is 10 MW. There is a ramping rate of heat charge in/out, where 40MW/h was considered. The sum of the scheduled hourly heat supply should be equals to the daily heat demand.

Data used in our computations based on historical data available at E.ON Energy Supply Company for the year of 2009. These data are the hourly heat demands and ambient temperatures for a big city in the eastern part of Hungary, and the hourly EEX spot prices. The wind farm with nominal capacity of 15MW is a fictitious unit which was devised based on a real-world wind unit, and wind speed data which operates in the western part of Hungary.

The power contracts are made for delivery the following day. Consequently, in the optimization task predicted data should be used for the heat demand, wind power, and spot price. Starting from the hourly heat demands considering the hourly wind power and spot prices we solved three different optimization tasks for the balance circle, optimization without heat storage tank, optimization with heat storage tank, and optimization with heat storage tank including the wind power plant in a common balance circle.

In winter seasons (January, February, November, December) the combined cycle unit operates on full load, consequently, there is no possibility to gain profit using our storage device.

There is a possibility to make profit using the tank in the spring/fall seasons (March, April, September, October and in the summer months (June, July, August), where is only hot tap water supply. In Table I. the financial results are shown for a week of April where the profit differences can be seen between with and without heat storage versions not included wind generation. Using the tank the optimal heat supply schedule shifted the efficient cogeneration electricity production in the high spot price periods. In Table the daily average of spot prices are also depicted.

TABLE I. FINANCIAL COMPARISONS BETWEEN WITH AND WITHOUT HEAT STORAGE VERSIONS

	EUR/day			EUR/MWh
	Revenue	COSTS	GrPROFIT	SpotPrice
Mond	-281.4	-4 897.1	4 615.7	23.00
Thue	-3 744.5	-6 380.3	2 635.8	36.24
Wedn	-8 044.0	-11 708.3	3 664.3	31.55
Thurs	-3 275.4	-5 840.6	2 565.2	33.65
Friday	-4 227.4	-6 818.6	2 591.2	32.70
Satur	3 425.9	298.3	3 127.6	23.54
Sunday	6 855.1	3 441.8	3 413.4	18.47
WEEKLY	-9 291.7	-31 904.8	22 613.1	28.45

In Fig. 2 the optimal heat supply schedule on Friday can be seen with ramping constraints. The hourly heat supply without heat storage is also depicted.

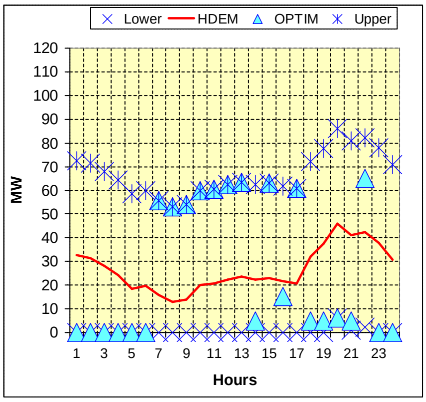


Figure 2. Optimal heat supply schedule with and without heat storage

In Fig. 3 the optimal hourly electric power is shown, where we can see the cogeneration as well as the condensing electric production.

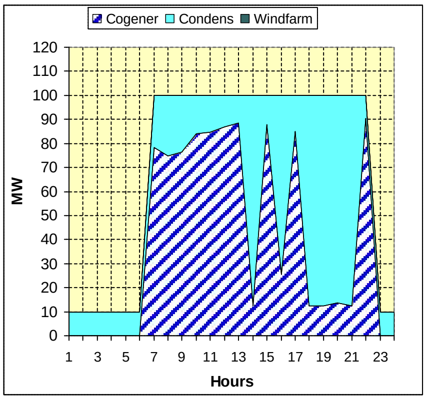


Figure 3. Optimal schedule of cogeneration unit with heat storage

In Fig. 4 the hourly EEX spot prices is shown. The prices between 1-6 are very below 30 Euro/MWh. Late afternoon the prices are much higher than 30 Euro's, but late night decreases to 30 Euro's.

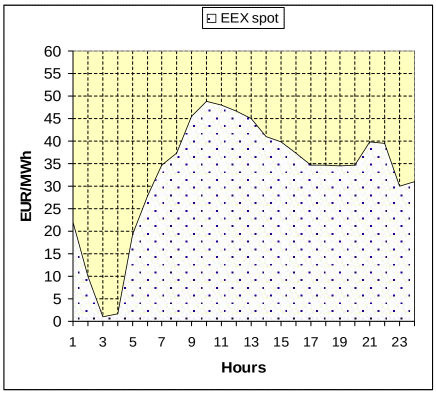


Figure 4. Hourly EEX spot prices

Included wind power plant in the balance circle the optimal hourly heat demand schedule basically changed (see Fig. 5).

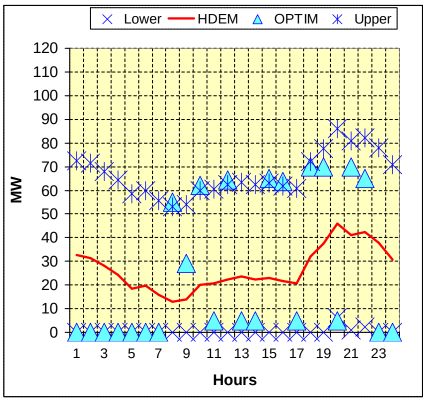


Figure 5. Optimal heat supply schedule included wind farm

As an effect of wind generation the optimal cogeneration pattern drastically changed as we can see in Fig. 6.

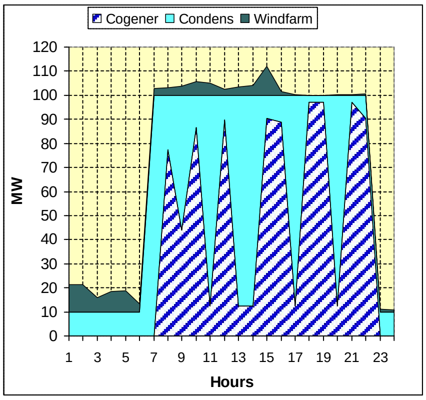


Figure 6. Optimal schedule of cogeneration unit included wind farm

Financial comparisons are shown in Table II, where we can also see the profits for the standalone operation of the wind power plant. The baseline version is the combined cycle unit with heat storage tank. It is compared to the combined cycle unit with heat storage including the wind power plant. The increase of gross profit in comparison with standalone operation is 5.0%.

TABLE II. FINANCIAL COMPARISONS BETWEEN WITHOUT AND WITH WIND POWER PLANT

	EUR/day			EUR/day		EUR/MWh
	Revenue	COSTS	GrPROFIT	Only WIND	Bal.circle	SpotPrice
Mond	-425.5	-463.9	38.4	231.4	269.8	23.0
Thue	0.0	0.0	0.0	665.6	665.6	36.2
Wedn	0.0	0.0	0.0	262.4	262.4	31.5
Thurs	0.0	0.0	0.0	2 950.0	2 950.0	33.6
Friday	-120.0	-160.4	40.4	2 651.8	2 692.2	32.7
Satur	-138.8	-267.3	128.5	221.2	349.7	23.5
Sunday	-29.1	-178.2	149.1	181.8	330.9	18.5
WEEKLY	-713.5	-1 069.9	356.4	7 164.2	7 520.6	28.4

IV. APPLIED FORECASTING METHODS

In our optimization models hourly heat demands, wind power, and EEX spot prices should be forecasted.

Let $\{y_1, y_2, \ldots, y_t, \ldots, y_T\}$ denote the observation made at equidistant time intervals where y_t can be regarded as an observation at time t. Our objective is to model the series $\{y_t\}$ and to use that model to forecast beyond the last observation y_T.

A. *Linear regression and time series models*

In the time series of electric industry there is a strong correlation between the actual value and the values at the previous observations. Observation at time t can be written as $y_t = \phi_0 + \phi_1 y_{t-1} + \phi_2 y_{t-2} + \ldots + \phi_p y_{t-p} + \varepsilon_t$, where ε_t is a zero mean white noise sequence with unknown σ variance. A generalization of this model (e.g [15]) is the mixed autoregressive and moving average process with one exogenous variable (ARMAX) that can be given as

$$y_t - \phi_1 y_{t-1} - \phi_2 y_{t-2} - \ldots + -\phi_p y_{t-p} =$$
$$= \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_{t-2} + \ldots + \theta_q \varepsilon_{t-q} + \vartheta u_t$$

where ε_t white noise process, p is the order of the autoregressive, q is the order the moving average term, ϕ_1, ϕ_2, …, ϕ_p, θ_1, θ_2, …, θ_q and ϑ are the model parameters.

B. *Nonlinear regression with a single variable*

A nonlinear regression with one independent variable is $y = f(x) + \varepsilon$. There are a lot of possibilities to choose function f . Nonlinear regression models even with a single variable lead not only to difficulties in the parameter estimation but also to undesirable statistical properties of their estimators [16]. One of the most versatile models fitting sigmoidal responses having a lower asymptote of zero and a finite upper asymptote is the logistic model $y = \alpha / [1 + \exp(\beta - \gamma x)]$, where α , β , and γ are the model parameters.

V. FORECASTING FOR DECISION VARIABLES OF THE OPTIMIZATION MODELS

There are three quantities which influence the value of objective function of our optimization task, namely, the hourly heat demand, the wind unit generation, and the EEX spot price. In the real world applications we should predict these variables for the next day to define the optimization task. In this section retrospective predictions are exhibited for the variables above on the 17th of April in the year of 2009.

A. *Predictions of the hourly heat demand*

One of the main decision variables in our optimization model is the hourly heat demand. Daily seasonal ARMAX model was applied with six hourly average air temperatures as explanatory variable. In Fig. 7 the forecasts of heat demand can be seen with the historical data.

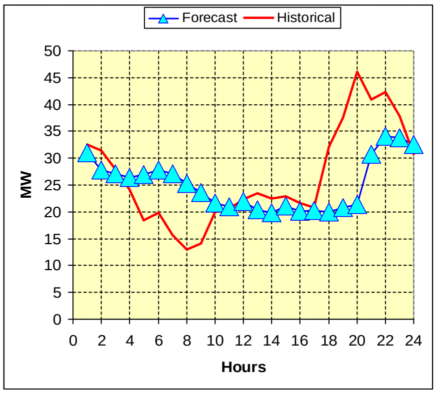


Figure 7. Forecasted and actual heat demand

Figure 8 shows the predicted and actual values of the ambient temperature.

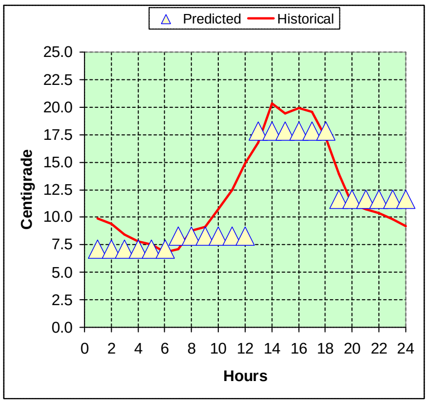


Figure 8. Predicted and actual air temperatures

B. *Predictions of the wind power output*

For the forecast of wind power plant output logistic function was applied with three parameters. The independent variable is the predicted wind speed. In Fig. 9 the predicted and actual wind power are shown.

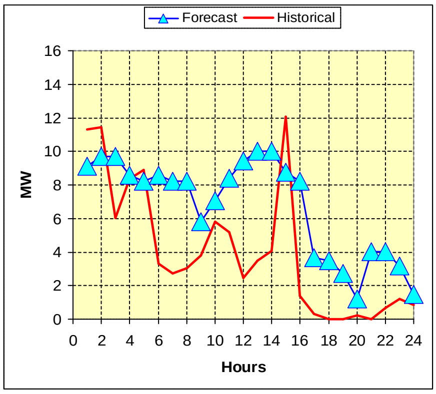


Figure 9. Predicted and actual wind power

Using the simple wind forecasting model above the explanatory variable of wind speed basically determined the accuracy of wind output prediction. Wind speed forecasts on the region of wind unit were performed by the Hungarian Meteorological Service using ALADIN model.

The ARPEGE/ALADIN modeling family is developed in an international cooperation originally initiated by Météo-France together with the European Centre for Medium Range Weather Forecasts (ECMWF). The two institutions were in the initial phase of developing ARPEGE/IFS (IFS: Integrated Forecasting System) spectral global model with major emphasis on the data assimilation ingredients. The main objective of the ALADIN project was to develop an NWP tool which is capable to dynamically adapt (to high resolution) the global model's results and to create a limited area modeling system taking into account all the advantages and constraints of the ARPEGE code system. The ALADIN is a spectral mesoscale, limited area NWP model [17].

Figure 10 shows the predicted wind speed and measured wind speed at the hub of the wind turbine.

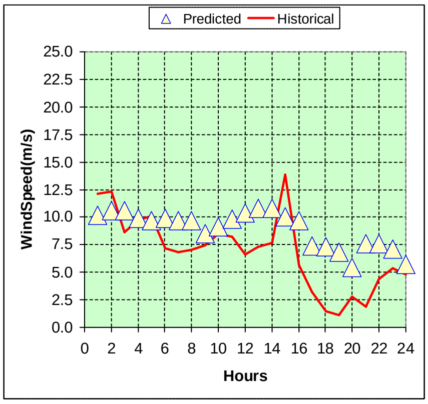


Figure 10. Predicted and measured wind speed

C. *Forecasting of the hourly EEX spot prices*

The gross profit from selling the electricity production is determined by the price on the spot market. For modeling weekly seasonal time series was used.

In Fig. 11 the hourly spot price forecasts can be seen with the historical data.

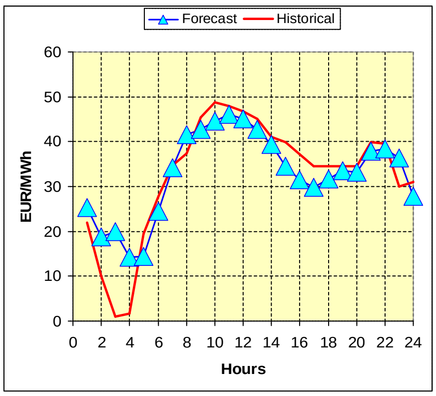


Figure 11. Forecasted and historical hourly spot prices

VI. CONCLUSIONS

The intermittency of wind poses a challenge for wind power integration into electric power systems. Integrating large scale electric storage systems is one option to mitigate the variability of wind power. At the same time heat storage tanks are tried and tested components in district heating systems. The advantage of storage is to reduce partial load operation with increase the efficiency of electricity generation and to shift electricity production in the high price periods. In this paper optimal joint operation of wind power plant and cogeneration power plant in a balance circle is studied in the day-ahead power market, included combined-cycle unit with district heat extraction and heat storage tank. Using the heat storage capacity of the tank the upward and downward regulation can be governed subject to some constraints where the constraints depend on the limit of heat storage capacity and the ramping rate of cogeneration unit.

Based on wind power prediction, heat demand and spot price forecasting optimal operational schedule is determined one day ahead, where the objective function is the gross profit of the balance circle. It was found that the joint operation is capable of assisting the operational decision making process and exhibit a surplus profit in comparison with standalone operation of wind power plant. Our model can be used to do a detailed assessment at the case of heat storage investments. The forecasting and optimization methods applied in our study may be used to develop an interactive procedure for using in the intra-day market.

REFERENCES

[1] G G. Giebel, L. Landberg, G. Karionotakis, R. Brownsword, "State-of-the-Art on Methods and Software Tools for Short-Term Prediction of Wind Energy Production," in Proc. 2003 European Wind Energy Conf., Madrid, pp. 315-320.

[2] T. Ackerman, G. Ancell, L.D. Borup, P.B. Eriksen, B. Ernst, F. Groome, M. Lange, C. Möhrlen, A.G. Orths, J. O'Sullivan, and M. de la Torre, "Where the Wind Blows," IEEE power&energy magazine, vol. 7, no. 6., pp. 65-75, November/December 2009.

[3] L. Varga, "Imbalance Cost Optimization in Balance Circle including Wind Generation using Wind Power Forecasting and Uncertainty Evaluation," in: Proceedings of 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Québec City, Canada, 2010, pp. 789-794.

[4] M. Robinson, "Role of balancing markets in wind integration," in: IEEE PES Power Systems Conference and Expositions, October 2006, pp. 232-233.

[5] J.F DeCarolis, and D.W Keith, "The economic of large scale wind power in a carbon constrained world," Energy Policy, vol. 34, no. 4, pp. 295-410.

[6] R. Walawalkar, J. Apt, and R. Mancini, "Economics of electric energy storage for energy arbitrage and regulation in New York, " Energy Policy, vol. 35, no. 4, pp. 2558-2568, 2007.

[7] J. Barton and D. Infeld, "Energy storage and its use with intermittent renewable energy," IEEE Transactions on Energy Conversion, vol. 19, no. 2, pp. 441-448, June 2004.

[8] J J. Garcia-Gonzalez, R. de la Muela, L. Santos, and A. Gonzalez, "Stochastic joint optimization of wind generation and pumped-storage units in an electricity market," IEEE Transactions on Power Systems, vol. 23, no. 2, pp. 460-468, May 2008.

[9] C. Sourkounis, and F. Richter, "Storage System Management in Wind Parks with high Wind induced Power Fluctuations," in: Proceedings of International Conference on Deregulated Market Issues in South Eastern Europe (DEMSEE), Nicosia, Cyprus, September, 2008, (Paper no. 162).

[10] P. Denholm, and R. Sioshasi, "The value of compressed air energy storage with wind in transmission constrained electric power systems," Energy Policy, vol. 37, no. 8, pp. 3149-3158, 2009.

[11] J.B. Greenblatt, S. Succar, D.C. Denkenberger, R.H. Willams, and R.H. Socolow, "Baseload wind energy: modeling the competition between gasturbines and compressed air energy storage for supplemental generation," Energy Policy, vol. 35, no. 3, pp. 1474-1492, 2007.

[12] G. Doluweera, and W. Rosehart, "Optimal Joint Operation of Wind Generation and Compressed Air Energy Storage Systems Under Resource and Price Uncertainty," in: Proceedings of 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Québec City, Canada, 2010.

[13] P. Pinson, C. Chevallier, and G. Karionotakis, "Optimizing Benefits from Wind Power Participation in Electricity Markets using Advanced Tools for Wind Power Forecasting and Uncertainty Assesment," in Proc. 2004 European Wind Energy Conf., London, pp. 315-320.

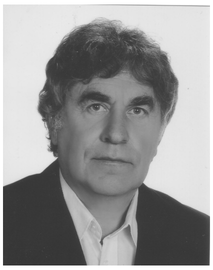
[14] B. Rolfsman, "Combined Heat and Power Plants and District Heating in a De-Regulated Electricity Market," Applied Energy vol. 78, pp. 37-52, 2004.

[15] P.J. Brockwell, R.A. Davis, Time Series: Theory and Methods, Second Edition, New York: Springer, 1990.

[16] D.A. Ratkowsky, Handbook of Nonlinear Regression Models, New York and Basel, Marcel Dekker Inc., 1990.

[17] A. Horányi, S. Kertész, L. Kullman, G. Radnóti, "The ARPEGE/ALADIN mesoscale numerical modeling system and its application at the Hungarian Meteorological Service," Időjárás, vol. 110, pp. 203-228, 2006.

VII. BIOGRAPHIES



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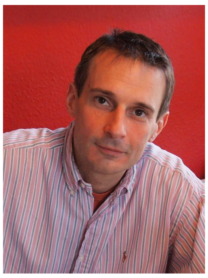
He is a member of the Society of Hungarian Operations Research, and Institute of Electrical and Electronic Engineers (IEEE).



Gergely Mádi-Nagy received his M.Sc. and Ph.D. degrees in applied mathematics from the Eötvös University, Hungary, in 1997 and 2002, respectively. Currently he is an assistant professor at the Department of Operations Research at the Eötvös University and an expert at the IP Systems Ltd. (a consultancy and IT solution provider company specialized for energy markets). His research activities include mixed integer and stochastic optimization, unit commitment, congestion management, risk management, procurement management, customer classification, auctions, in natural gas and electricity markets.

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