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Flexible conventional power plants in smart grids – quo vadis?

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Abstract: In the ongoing discussions about the future energy system, smart grids are seen as a promising solution to match renewable energy production and energy consumption by using sophisticated information and communication technologies. However, flexible conventional power plants which play an essential role in stabilising the current energy system especially in terms of compensating the intermittent generation by renewables are not considered in these discussions. The aim of this paper is to propose approaches on how to properly integrate flexible conventional power plants into the future energy system by structurally combining virtual and conventional power plants in order to create reliable virtual power plants. It is shown that by extending the information exchange an almost constant power output can be provided by the reliable virtual power plant independently of the actual weather situation. Additionally, this structural adaptation is not only used to improve the control performance in terms of power output but also allows a decoupling of energy trading mechanisms by introducing compensation control power as a new service within the energy market explicitly dealing with the intermittent generation by renewables.

1. Introduction

Analogously to the electrification of railways, smart grids aim at improving the energy system by adding new technologies, i.e. information and communication technologies (ICT), to an existing infrastructure. The main goal of smart grid applications lies in balancing the power production and consumption in a decentralised way by means of demand side management strategies shifting the energy consumption to time periods in which the grid is fed by renewable energy sources [1].

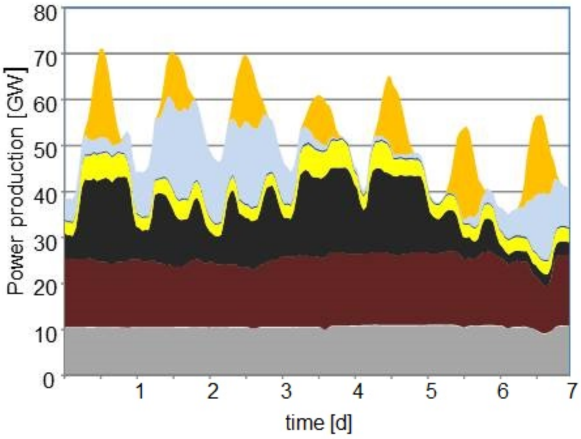

Figure 1: Power production of one week in April, 2014; relevant colours: black indicates hard-coal fired power plants, orange shows PV production and light blue indicates power produced by wind (sources: [2], [15], internal STEAG calculations)

Figure 1 indicates the share of the respective power producing sectors to the power production of one selected week in April 2014. The figure shows that, due to the low specific fuel costs, nuclear and lignite-fired power plants (grey and brown) act as base-load operating power plants whereas, due to the high fuel prices, almost exclusively must-run gas-fired power plants are in operation. Consequently, mid-load operated hard-coal fired power plants have to provide fast load changes including services (primary, secondary or tertiary control) to compensate fluctuations in the grid caused by intermittent renewable energy supply (PV a wind) [11]. Hence, from the perspective of renewables demand side management tasks are currently realised in an aggregated way by the load variations of these flexible power plants.

In particular, conventional power plants increasingly need to deal with prediction errors regarding the intermittent production by renewables of some gigawatts even on short notice [2] instead of purely focussing on reserve control power for compensating unexpected outages of large producers or consumers as initially intended.

However, despite the essential role of flexible and reliable conventional power plants in the current energy system, these power plants do not play any role in the current smart grid considerations. Taking the changing role of these power plants into account with the emerging focus on compensating intermittent generation, two questions arise:

- Are the current control and communication structures well suited to deal with the current and even evolving requirements of the renewable-driven energy system or are there structural adaptations which enable flexible conventional power plants to meet these requirements in an even more efficient way?

- Is the current energy market well suited to deal with the compensation of intermittent power generation or do adapted control structures allow for appropriately adapting the related energy trading mechanisms?

The focus of this paper lies in proposing concepts for suitably integrating flexible conventional power plants into smart grids by structurally combining renewable and flexible conventional power plants resulting in *reliable virtual power plants.*

The strategy uses the fact that in the current operation of conventional power plants sophisticated ICT solutions can hardly be found and services like reserve power and load changes either rely on purely analogue measurements (i.e. frequency of the grid) or very simple communication infrastructures. Consequently, by considering a conventional power plant as a structurally coupled counterpart to a virtual power plant (VPP) consisting of distributed renewable energy sources (RES) [3][13] and by using additionally available data such as weather forecasts as well as relevant aggregated data provided by the VPP an efficient compensation of the intermittent generation can be obtained. Suitable concepts are given by model-based control strategies, e.g. feed-forward disturbance rejection [4][10] or model predictive control (MPC) [6][7].

As a second effect this strategy enables adaptions of the energy trading mechanisms. Instead of the necessity of using day-ahead transactions, intraday auctions as well as control power to counteract the prediction errors in the RES production, *compensation control power* can be introduced as a new service provided by flexible conventional power plants purely focussing on compensating the intermittent generation by renewables.

The paper is organised as follows. In Section 2 the current role of flexible conventional power plants used in mid-load operation is described and state-of-the-art flexibility measures are introduced. Section 3 proposes concepts to combine flexible conventional power plants and virtual power plants showing potential benefits of establishing conventional power plants in future smart grids. Based on these concepts a new trading model introducing compensation control power as a new service is described in Section 4.

2. Flexible power plants

2.1. Current role in the energy system

Due to the lack of sufficient storage capabilities in the current energy system the power production and power consumption need to be balanced at any time. Therefore, the stability of the grid currently relies on the capability of flexible conventional power plants to provide fast load changes and control services (primary, secondary or tertiary control) in order to compensate unexpected outages of power plants or deviations in the power consumption. Additionally, the requirements on the flexibility of these plants have been recently significantly increased due to the necessity of counteracting the volatile energy production by renewable sources [11].

Beside this load change flexibility which is inevitable for preserving the stability of the grid, measures such as optimised start-up as well as reduction of minimum load likewise play an important role in the current system but more with the focus on running conventional power plants in a cost efficient way. All of these measures are briefly described in the following section.

2.2. Flexibility measures

2.2.1. Fast load changes and control power

To counteract unpredictable events such as outages of power plants or prediction errors regarding the energy consumption and to counteract the volatile energy production of intermittent sources, fast load changes and control services need to be provided by reliable and flexible energy producing units.

The measures to improve load gradients as well as pre-qualifying the power plant for providing control power very often simply adapt the control algorithms in the unit control system and use intrinsic storage capabilities, e.g., throttling of turbine valves or control of the extraction steam flow [8][12].

Severe modifications of processes can be generally avoided. Hence, as the current control algorithms of conventional power plants are rather designed to guarantee stability than focussing on the transient behaviour in terms of fast load responses the potential and the chances for the success of these optimisation measures are generally promising.

2.2.2. Optimised start-up and reduced minimum load

Both optimised start-up and reduced minimum load have the same goal, namely, to reduce costs which would occur due to starting the plant [9]. On the one hand the optimisation of the start-up procedure aims at reducing the oil consumption during the start-up process and making the process reproducible in terms of timing until synchronisation in order to avoid unnecessary waiting times.

On the other hand, reduced minimum load aims at completely avoiding the costs for start-up by bridging limited time intervals in which the plant would have been normally shut down due to low energy prices. Hence, if the minimum load is decreased the loss due to operating the plant in these time intervals is decreased as well.

2.3. Communication infrastructure

In the current operation of a conventional power plant, ICT only plays a secondary role especially when it comes to external data exchange. Services like reserve power and load changes either rely on purely analogue measurements (i.e. frequency of the grid) or very simple communication infrastructures which very often still require manual operations, i.e. load requirements provided by the load dispatcher are not directly forwarded to the unit control system but to the operator which has to manually set the necessary actions.

3. Compensation of intermittent generation

3.1. Current mechanism

The current mechanism to compensate intermittent generation provided by RES (PV and wind) uses a mix of two measures:

- Control power for compensating sudden prediction errors (primary, secondary, tertiary control).
- Rescheduling measures which are based on day-ahead and intraday transactions on the energy spot market due to refined forecast information [14].

Figure 2 shows the current situation in terms of primary control. The goal of the control loop is to keep the frequency f of the grid in a surrounding of the respective set-point f_{SET}, i.e. 50 Hz in the European grid. Based on the deviation between the desired frequency and the actual frequency of the grid, the controller provides the set-point $P_{SET,FCPP}$ adopted by the unit control of the respective controllable and flexible conventional power plants (FCPP) which together with the uncontrollable conventional power plants P_{UPP} and the energy produced by VPPs P_{VPP} and the remaining RES P_{RES} gives the complete power output P_{OUT} of the system. G(s), $G_v(s)$, $G_r(s)$, $G_g(s)$ and C(s) denote the respective transfer functions [4] of the FCPP, the VPP, the RES, the grid and the controller.

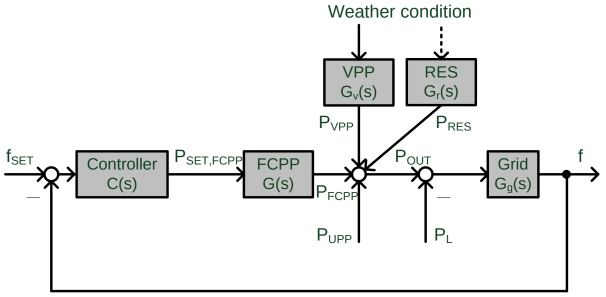

Figure 2: Primary control

As long as the power output P_{OUT} of all producing units coincides with the overall power consumption P_L the frequency does not vary and maintains the respective set-point f_{SET}. However, unexpected outages of conventional power plants or large consumers, and, increasingly important, deviations in the prediction of the power production provided by renewables affect the frequency and force the primary controller to establish a new operating point by adapting the power output of the FCPPs. As the primary controller is a static controller due to stability reasons, a steady-state error needs to be accepted. In order to drive the frequency to the desired set-point f_{SET} the secondary controller (PI controller) does not only take the frequency into account but also the exchange energy between concerned areas.

3.2. New approach

3.2.1. Motivation

The approach proposed in this paper aims at structurally combining unreliable renewable energy sources (PV and wind) aggregated within a virtual power plant (VPP) and reliable and flexible conventional power plants in order to improve and simplify the compensation of intermittent generation. Currently, the power generation of the renewables and the FCPP is indirectly coupled by means of the frequency of the grid (see Figure 2) which is a clear indicator whether or not the power production and power consumption are balanced. However, considering renewables a direct coupling is possible using a more involved information exchange between the VPP and the FCPP.

The underlying idea is that due to the increased energy production by renewables the control services should be split into:

1. Rescheduling and conventional control power (primary, secondary, tertiary control) for dealing with unpredictable outages of energy producing units or large consumers, or deviations in the predicted energy consumption.
2. Compensation control power for exclusively dealing with intermittent generation by VPPs which uses additionally available ICT-based information within the control loop.

In the following three approaches are described considering the second item. All of these approaches consider the FCPP and the VPP as a single energy producing unit which, henceforth, is denoted as *reliable virtual power plant (RVPP)* illustrating the idea that the varying production of the VPP is immediately compensated by the FCPP. Hence, the power output of the overall RVPP remains constant independently of the actual weather conditions and, therefore grid-related services (primary, secondary and tertiary control) as well as the necessity of rescheduling measures for the respective power plants can be reduced.

The adapted primary control loop is depicted in Figure 3 where the VPP and the FCPP are now represented by a single block.

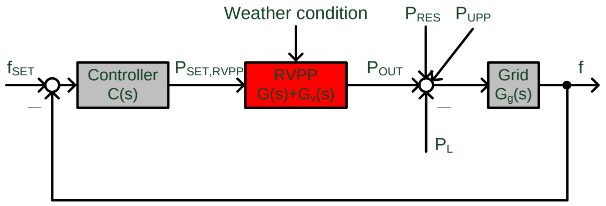

Figure 3: Adapted primary control loop

3.2.2. Indirect power coupling

A simple control structure for realising the RVPP is shown in Figure 4. Here, instead of the frequency the power output provided by the FCPP and the VPP is fed back and compared to the external set-point $P_{SET,RVPP}$.

The structure indicates that the variations of the power output coming from the renewable sources can be seen as a disturbance of the control loop. Consequently, the controller needs to be designed to provide suitable disturbance attenuation properties. This can be implemented by, e.g., suitably tuning a standard PI controller [5].

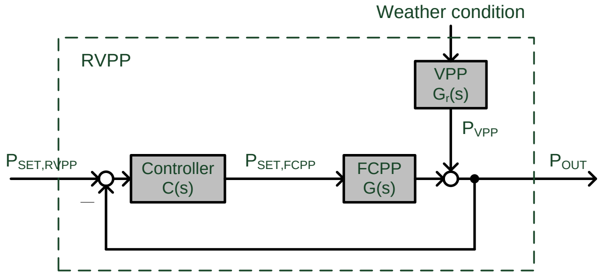

Figure 4: Simple closed-loop control

3.2.3. Direct power coupling using model-based feed-forward disturbance rejection

As the dynamics G(s) of the FCPP are generally known there are more involved control structures which can take G(s) into account in order to more efficiently compensate the effect of the disturbance caused by the VPP by means of additional feed-forward control [4][10].

This is depicted in Figure 5. Here, an additional path has been added which adapts the input signal of the FCPP $P_{SET,FCPP}$ to the current power output P_{REN} of the VPP. The feed-forward structure uses the inverse model of the FCPP and an additional filter F(s) which is generally necessary to get a proper realisation of the inverse transfer function of the FCPP and to face input constraints [4].

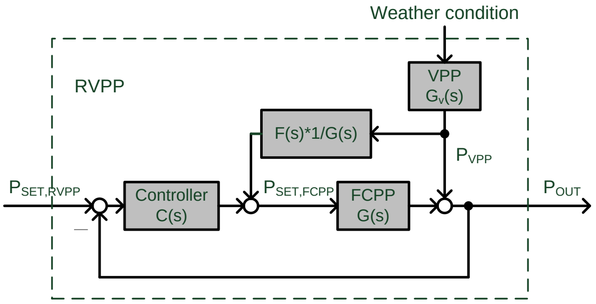

Figure 5: Model-based control using feed-forward disturbance rejection

3.2.4. Direct power coupling using model-predictive control

An even more involved structure is presented in Figure 6 using model-predictive control [6] where the controller, based on equidistantly updated input data, solves an optimisation problem to produce an optimal output $P_{SET,FCPP}$ with respect to predefined cost functions.

Beside the evaluation of the deviation between the current status of the system P_{OUT} and the requested set-point P_{SET} the input data can be chosen arbitrarily depending on the control goal. Hence, in the scenario considered in this paper, suitable information is given e.g. by weather forecasts and the current weather conditions affecting the VPP as well as the power output of the VPP.

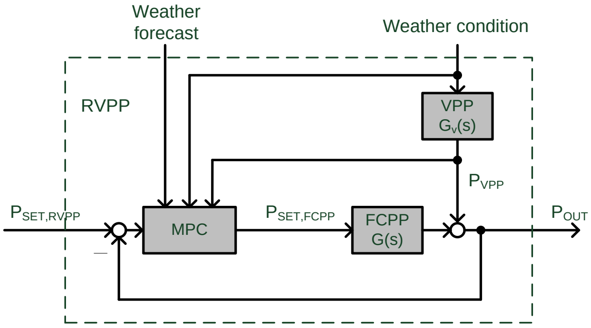

Figure 6: Model-predictive control

3.2.5. Simulations

The following simulations compare the simple closed-loop control (indirect power coupling) and the model-based control strategy using feed-forward disturbance rejection (direct power coupling) to illustrate that additional information and a suitable integration of this information can significantly improve the performance of the closed-loop system. In this example, the set-point $P_{SET,RVPP}$ to be followed by the RVPP is given by 450 MW, where initially

$$P_{FCPP} = 400\ MW$$
$$P_{VPP} = 50\ MW$$

holds. The FCPP is described by the third-order transfer function

$$\mathrm{G}(s) = \frac{1}{(1+60s)(1+60s)(1+60s)}.$$

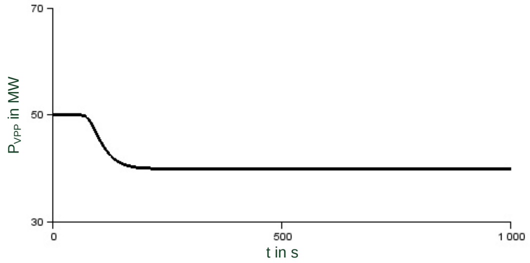

Figure 7: Decreasing power production by the VPP

The resulting RVPP is subject to a decreasing power production of the VPP by assuming that after 60 s the wind conditions change and the power output is quickly reduced to 40 MW (see Figure 7). By means of the PI controller

$$C(s) = K_P E(s) + \frac{K_I}{s} E(s)$$
$$E(s) = P_{SET,RVPP}(\mathrm{s}) - P_{OUT}(\mathrm{s})$$

with the controller parameters K_P=2.5 and K_I=0.01 the trajectory of the resulting power output of the RVPP with indirect power coupling is depicted in Figure 8.

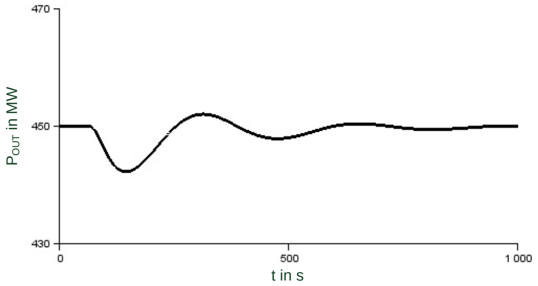

Figure 8: Power output of the RVPP using the simple closed-loop control

Stationary, the power output P_{OUT} matches the set-point but the transient behaviour shows large oscillations due to the change in P_{VPP} and the slow dynamics of the FCPP.
This behaviour can be improved by model-based control using feed-forward disturbance rejection as considered next. With the third-order filter

$$\mathrm{F}(s) = \frac{1}{(1+5s)(1+5s)(1+5s)}$$

the resulting power output is illustrated in Figure 9 which clearly shows a significant reduction of the oscillations during the transient phase.

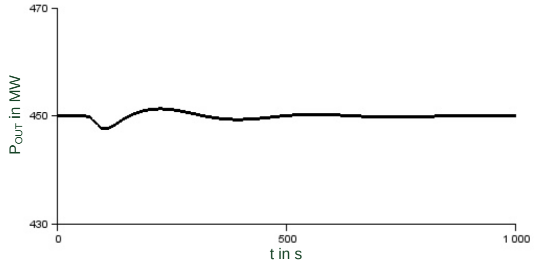

Figure 9: Power output of the RVPP using model-based control with feed-forward disturbance rejection

A drawback of this structure is given by the fact that depending on the system dynamics large input signals might result as shown in Figure 10. This causes problems if the input of the system is subject to constraints which occurs in almost all practical applications.

To avoid this issue the filter F(s) can be adapted accordingly which, however, degrades the control performance. Alternatively, flexibility measures using the intrinsic storage capabilities of FCPPs as briefly described in Section 2.2.1 can be applied to circumvent this problem (see Figure 11) or forecast information can be used to be able to start the required control actions already in advance.

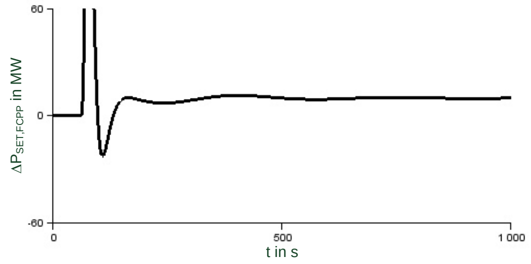

Figure 10: Plant input signal using model-based control with feed-forward disturbance rejection

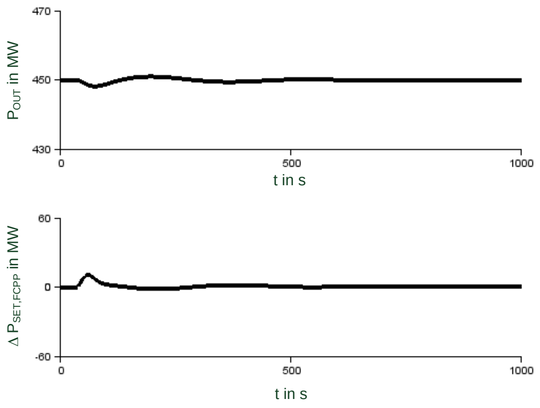

Figure 11: Potential power output and plant input signal when using throttling of turbine valves and control of the extraction steam flow in a coordinated way as additional measures

4. Compensation control power

In the current energy market the compensation of prediction errors in terms of energy production by RES (PV and wind) is mainly based on short-term transactions, i.e. day-ahead or intraday auctions based on refined weather forecasts, and on control services [2][14].

By considering a splitting of the control power market (see Figure 12) into

- the conventional provision of primary, secondary and tertiary control served by FCPPs including rescheduling measures which explicitly deal with outages and fluctuating energy consumption as well as RES which are not served by RVPPs, and
- a new compensation control power service provided by RVPPs which exclusively deals with intermittent generation by PV and wind,

transactions on the energy market required for compensating the weather-related prediction errors can be reduced. Moreover, new incentives for flexibility measures for conventional power plants can be set.

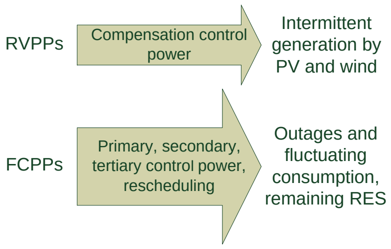

Figure 12: Decoupling of the control power market

However, the realisation of the RVPPs requires a distinct allocation of FCPPs (a single unit or a pool of FCPPs) to the respective VPPs where load specific requirements and even geographical aspects need to be taken into account. In the future, especially load specific requirements become increasingly challenging due to the increasing installation of PV and wind sources making a suitable clustering even more challenging.

5. Conclusion

In this paper concepts considering a structural combination of flexible conventional power plants and virtual power plants have been proposed which aim at efficiently compensating the volatile power production by PV and wind. The simulation results illustrate that the resulting reliable virtual power plant is capable of providing an almost constant power output by means of an involved information exchange between the conventional and virtual power plant. Consequently, grid-related control services and rescheduling measures including the relevant transactions on the energy market which are necessary to compensate the intermittent power production by PV and wind can be reduced.

References

[1] P. Palensky and D. Dietrich: "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads." IEEE Transactions on Industrial Informatics, vol. 7, no. 3, pp. 381-388, 2011. DOI: 10.1109/TII.2011.2158841.

[2] EEX Transparency platform available on http://www.transparency.eex.com/de/.

[3] K. E. Bakari and W. L. Kling: "Virtual power plants: An answer to increasing distributed generation." Proceedings of IEEE Innovative Smart Grid Technologies Conference, pp. 1-6, Gothenburg, Sweden, 2010.

[4] J. Lunze. Regelungstechnik 1: Systemtheoretische Grundlagen, Analyse und Entwurf Einschleifiger Regelungen, Springer, 6. Edition, 2007.

[5] K. J. Åström and T. Hägglund. PID Controllers: Theory, Design, and Tuning. ISA, 1995.

[6] A. Bemporad and M. Morari: “Robust model predictive control: A survey.” In Lecture Notes in Control and Information Sciences, A. Garulli, A. Tesi and A. Vicino, eds., vol. 245, Springer, pp. 207-226, 1999.

[7] E. F. Camacho and C. Bordons. Model Predictive Control. Advanced Textbooks in Control and Signal Processing. Springer, 2nd Edition, 2007.

[8] M. Kurth, H. Lens, J. Marquard, A. Dengel, W. Schweißthal and C. Kolligs: “Vergleich und Einsatz von Speichertechnologien aus Sicht eines Kraftwerksbetreibers.“ In VGB PowerTech Journal, vol. 12, pp. 68-75, 2011.

[9] H. Lens: “Mid-Load Operation of Large Coal-Fired Power Plants.” Proceedings of PowerGEN Europe, Cologne, Germany, 2013.

[10] K. J. Åström and R. M. Murray. Feedback Systems: An Introduction for Scientists and Engineers. Princeton University Press, 2008.

[11] U. Tomschi, B. Weidmann and S. Eckstein: “Anforderungen an die konventionellen Kraftwerke und deren Möglichkeiten.“ Proceedings of 10. GMA/ETG-Fachtagung Netzregelung und Systemführung, Munich, Germany, 2011.

[12] M. Kurth and G. Kallina: “Möglichkeiten zur Verbesserungen des Regelverhaltens von Dampfkraftwerksblöcken.” Proceedings of 9. GMA/ETG-Fachtagung Netzregelung und Systemführung, pp. 68-73, Munich, Germany, 2008.

[13] P. Asmus: “Microgrids, Virtual Power Plants and Our Distributed Energy Future.“ In The Electricity Journal, vol. 23, pp. 72–82, 2010.

[14] EPEXSPOTINTRADAY Market data available on http://www.epexspot.com/en/market-data/intraday.

[15] DESTATIS available on https://www.destatis.de.