

Hanemann, Philipp; Bruckner, Thomas

Research Report

Retrieval Probabilities of Secondary Control Reserve within Systems with a High Share of Renewable Energies

Beiträge des Instituts für Infrastruktur und Ressourcenmanagement, No. 01/2016

Provided in Cooperation with:

Institute for Infrastructure and Resources Management, University of Leipzig

Suggested Citation: Hanemann, Philipp; Bruckner, Thomas (2016) : Retrieval Probabilities of Secondary Control Reserve within Systems with a High Share of Renewable Energies, Beiträge des Instituts für Infrastruktur und Ressourcenmanagement, No. 01/2016, Universität Leipzig, Institut für Infrastruktur und Ressourcenmanagement (IIRM), Leipzig

This Version is available at:

<https://hdl.handle.net/10419/148280>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Retrieval Probabilities of Secondary Control Reserve within Systems with a High Share of Renewable Energies

Philipp Hanemann und Thomas Bruckner ^{A,B}

01/2016



Beiträge des Instituts für Infrastruktur und Ressourcenmanagement
Contributions of the Institute for Infrastructure and Resources Management

Herausgeber:

Prof. Dr. Thomas Bruckner, Prof. Dr. Erik Gawel, Prof. Dr. Robert Holländer und Prof. Dr. Daniela Thrän

Philipp Hanemann und Thomas Bruckner ^{A,B}

Retrieval Probabilities of Secondary Control Reserve within Systems with a High Share of Renewable Energies

Zur Einordnung des Beitrags:

Der Beitrag analysiert Abrufe von Sekundärregelleistung entsprechend unterschiedlicher Zeitscheiben, welche als empirische Wahrscheinlichkeiten interpretiert werden. Er entstand im Rahmen eines Dissertationsvorhabens.

^A Universität Leipzig, Institut für Infrastruktur und Ressourcenmanagement

^B Fraunhofer-Zentrum für Internationales Management und Wissensökonomie IMW

Beiträge des Instituts für Infrastruktur und Ressourcenmanagement, Universität Leipzig

Herausgegeben von Prof. Dr. Thomas Bruckner, Prof. Dr. Erik Gawel, Prof. Dr. Robert Holländer und
Prof. Dr. Daniela Thrän

Nr. 01/2016

ISSN 2364-4346

<http://www.econstor.eu/escollectionhome/10419/107939>

© Institut für Infrastruktur und Ressourcenmanagement, Universität Leipzig, 2016

Die Schriftenreihe „Beiträge des Instituts für Infrastruktur und Ressourcenmanagement“ erscheint mehrmals im Jahr und stellt in unregelmäßigen Abständen den Forschungsstand unterschiedlicher Themengebiete des Instituts vor. Sie vereint Diskussionsbeiträge, Projekt(teil-)berichte sowie herausragende Abschlussarbeiten. Die Beiträge geben dabei die Meinung der Autoren wieder, nicht notwendigerweise auch die der Herausgeber.

Retrieval Probabilities of Secondary Control Reserve within Systems with a High Share of Renewable Energies

Philipp Hanemann, Thomas Bruckner

Abstract—In this paper, empirically determined retrieval probabilities for control power are investigated. Since there is a continuous need for balancing unscheduled deviations of supply and demand, control power is of very high importance for the stability of the power system. Systems that are characterized by a high share of intermittent energy feed-in are especially effected. Since the market conditions have an influence on bidding behavior, those who are participants in the balancing market have an interest in gaining information about the activation of control power. Though the magnitudes have been changing over the last years, there are clear time dependent patterns.

Index Terms—Control power, retrieval probabilities, frequency control, power system economics

I. INTRODUCTION

THE security of supply requires balance between power input and output at every point in time. This is supported by schedules of supply and demand. Because of inevitable deviations in consumption and production, the balance differs more or less continuously from the required power equilibrium. This is represented by a frequency of 50 Hz in the European grid. Therefore, the transmission system operators (TSOs) reserve positive and negative energy capacities that can be activated if needed. Entso-E differentiates these balancing reserves according to their activation time in primary, secondary, and tertiary control. Primary or containment reserve (PR) will be activated within the whole balancing area if absolute frequency deviations exceed 200 mHz. Frequency restoration then will be given by secondary reserve (SR). Finally, SR is replaced by tertiary reserve (TR) [1]. In case of under supply, positive control power is deployed vice versa negative control power.

The most important factors that cause imbalances are power plant outages, forecasting errors of the demand and feed-in of wind and solar energy. Since renewable energy resources such as wind and photovoltaic are volatile by nature, balancing becomes an increasingly important topic in systems with a rising share of intermittent renewables. The market design is also of importance because it effects

the reservation and the activation. While market issues and reservation issues are already discussed in the scientific literature research concerning the activation of control power is still very incomplete. Therefore, to shed some light on this topic will be the task of the actual work.

In the next section, basics on frequency control are provided including the classification, dimensioning and market issues. Also revealed is the importance of detailed knowledge about activation properties.

In section III the method for determining probabilities of empirical activation is introduced. Section IV deals with the empirical results.

II. CONTROL POWER BASICS

A. Dimensioning

Dimensioning of control power can be carried out by deterministic and probabilistic approaches. The total amount of PR within the European balancing area is determined to 3000 MW [2], [3]. This amount is distributed to each country according to its maximum load share.

The dimension used for secondary reserve differs across the control areas. Proposed by the UCTE convention scheme [1] is a minimum amount of

$$P_{SR} = \pm \sqrt{a \cdot P_{max} + b^2} - b$$

where P_{max} is the maximum anticipated load and $a = 10$ MW and $b = 150$ MW are empirically found parameters. In contrast, the probabilistic approach, also known as Graf-Haubrich-procedure, includes additional influence factors beyond just consumption. This seems to be reasonable regarding an increasing share of renewable energies which imposes additional flexibility constraints on the power system. Within this approach, the amount of balancing reserve is based on an accepted deficit level or level of security respectively. It accounts for the number of hours per year where the balancing reserves should be on average sufficient for occurring imbalances. Initially, this was set to 99.90 % [4]. It has been increased to 99.95 % [5]

The probabilistic approach is carried out as follows: at first influence factors that are responsible for imbalances must be identified. Then, their respective empirically found probability density functions concerning the absolute imbalances between

P. Hanemann is a PHD student at the Vattenfall Europe Chair for Energy Management and Sustainability, University of Leipzig e-mail: philipp.hanemann@uni-leipzig.de.

T. Bruckner is director of the Institute for Infrastructure and Ressource Management, University of Leipzig an head of Sustainability Management and Infrastructure Economics Division at Fraunhofer Center for International Management and Knowledge Economy, Leipzig, Germany.

planned and actual schedules are convoluted to an overall probability density function. Its respective confidence intervals, which are given by the deficit level determine the absolute amount of balancing reserve. If only SR reserve influencing factors are included, the respective amount is calculated. The amount of TR is calculated indirectly. At first, a total amount of balancing reserve is calculated, including all control power influencing factors. Subsequently, the previously determined amount of SR is subtracted. Research regarding Germany has been done by [4]–[7]. Research regarding the European system has been undertaken by [8] and [9].

Generally speaking, it is the absolute deviation from planned schedules that leads to the need for control power. Taking this into account, it becomes obvious that schedule leaps also increase the need for balancing power. Figure 1 depicts this schematically. *Schedule* refers to the required power and *real-time* to the actual delivered power due to physical feasibility. In consequence, the total needed *balancing* energy as difference between schedule and real-time increases with the steepness and height of the schedule ramps.

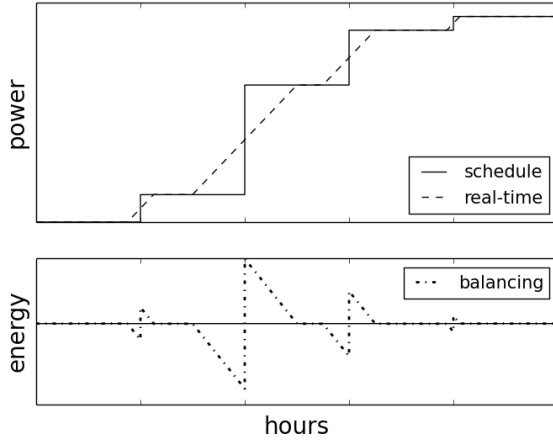


Fig. 1. Impact of ramps on employed control power

B. Retrieval

Because only net imbalances are relevant, it is also possible that some factors oppose each other and thus cancel each other out, which occurs more often in larger systems. To exploit this potential, the four German TSOs merged their balancing services stepwise to the grid control cooperation (GCC) until April 2010. By that, the reserved amount as well as the activation of control power could be reduced [10]–[12] either by one aggregated Merit-Order-List or by energy netting. This has been modeled by [13], [14]. For further reductions the GCC has been expanded to the international grid control cooperation (IGCC) which allows foreign TSOs to participate. Furthermore, the collaboration ensures a cost efficient activation of SR and TR by combined merit-order-lists.

C. Market Design

Suppliers remuneration for SR and TR corresponds to the technical procedure. That includes a payment for reservation of power as well as for delivering energy. In contrast, PR is remunerated only for the reservation. All services are compensated via a pay-as-bid auction. At first, the required capacity is auctioned to the suppliers with the lowest capacity bids (scoring rule). Subsequently, for activation the successful bids are sorted in ascending order by their energy bids (settlement rule) with the exception of PR. Issues that exhibit inefficiencies regarding the market design are discussed in [15]. Using time series analysis, inefficiencies relating to strategic under- and oversupply positions targeting arbitrage opportunities between spot and balancing markets are given in [16]. Pricing reserves analytically is shown in [17], [18]. Approaches to model the market fundamentally have been undertaken by [19]–[21]. [20] also addresses the retrieval deterministically based on empirical data.

Supplier with low (reserve) energy prices are retrieved more often than these with higher prices. This is depicted schematically in Figure 2, which illustrates an activation merit-order consisting of five suppliers. The three time intervals, t_1 , t_2 and t_3 correspond to different activation amounts of control power x . Supplier one is fully activated at t_1 , t_3 , and partly in t_2 , whereas supplier 3 is activated only once in t_1 . Therefore, the probability of retrieval for supplier three is lower than for supplier 1.

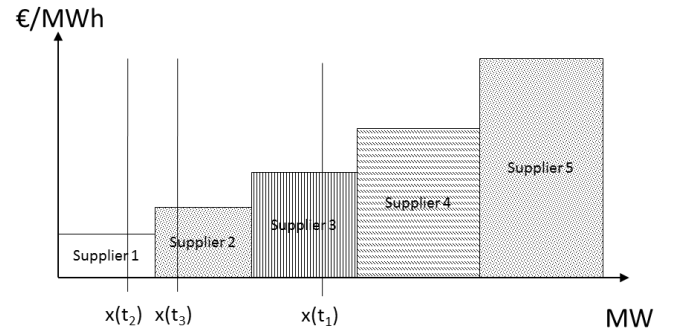


Fig. 2. Merit-order of energy bids and three exemplary control power demands

Providing control power influences power plant operation and profit. Hence, suppliers do have incentives to anticipate retrieval probabilities and to incorporate them into their bidding behavior. The actual market design doesn't evaluate capacity and energy bids simultaneously, and [22] shows analytically how this leads to inefficiencies. Therefore, it is the purpose of this paper to determine such probabilities for the first time. The paper focuses on the case of SR within the GCC. TR will not be considered since due to system design, the previous activation of SR is a necessary condition. Furthermore, TR activation also doesn't solely depend on objective technical conditions.

System participants benefit from our results in different ways:

- 1) Suppliers of balancing reserve get an understanding of the magnitude of their expected retrieval probability. This can be used to optimize their bidding strategies when taking the combination of reservation and energy bids into account.
- 2) The information might be used to increase security of supply and reduction of system costs. The data reveals those time intervals where more or less energy is needed.

III. METHODOLOGY

Assuming that the activation of control power follows independent stochastic processes, historical retrievals can be interpreted as probabilities. The analyzed SR data for the GCC, which is published by the German TSOs [23] covers the time span of July 2011 until December 2013. The data values represent the average retrieval within quarters of an hour. Subsequently, extreme values are underestimated. Nevertheless, due to the inertia within the power system it is a reasonable approximation.

The data will be classified regarding specific time slices. In the following, cumulated frequencies of occurrence are determined per MW and sorted in an increasing order. The empirical probability P that the random variable retrieval X is less than a specified value x is given by the following formula:

$$P(X \leq x) = 1 - P(x \leq X) = 1 - \frac{H(x)}{n} = 1 - \frac{1}{n} \sum_{i: a_i \leq x} h(a_i)$$

where	
$P(X < x)$	retrieval probability
$P(x \leq X)$	cumulated relative frequency
X	random variable retrieval of SR
$H(x)$	cumulated absolute frequency
n	sample size
$h(a_i)$	frequency of the realization a_i
a_i	one specific realization of X , $a_i \in [0, x_{total}]$
x_{total}	total auctioned SR reserve

A specific point $(X, P(X < x))$ on the graph refers to the retrieved amount and the expected frequency. $P(X < x) = 1$ then means that the expected frequency of the amount X is 100 %. On the other hand a value of 0 would mean that such an amount is never expected to occur within the contemplated period.

IV. RESULTS

At first, the time slices are evaluated according to the actual auction design. Subsequently, months and single hours of working and non-working days are considered as well as national holidays. Since there is not sufficient information on the single factors that influence the retrieval of control power, this paper does not attempt to explain the subsequently mentioned patterns.

Although stochastic independence is assumed, the balancing control influencing factors rely heavily on changing parameters such as weather. For this reason, only significant results are commented on.

Specific data points that were used can be obtained through

the author. Using them will allow that the curves can be approximately reproduced by interpolation without knowing the whole data set. The data includes the values for 50, 100, 300, 500, 700, 1,000 and 1,500 MW.

A. Time sliced according to actual market design

Figure 3 illustrates the retrieval probabilities for the different time slices according to the actual market design. It can be seen that the retrieval probability is disproportionately digressive compared with the amount. Furthermore, there is a dependency on the time slice. The retrieval probabilities differ significantly between the two weekly auctioned time domains HT and NT. HT resembles peak-time and includes all hours regarding working days from 8 am until 8 pm. NT accounts for all the residual hours per week. This includes the entire weekend and national German holidays. Hence, the probability of retrieval is highly dependent on the suppliers position within the retrieval merit-order. Given that there are more than 2,000 MW auctioned at the moment in Germany, the retrieval probability for suppliers at this position is practically zero. In total a lot more negative reserve was used than positive. This is valid for peak-time as well as off-peak time. In 2011, the frequency as well as the amount of negative reserve were the highest. The highest retrieval probabilities occurred in 2012. In total the frequency decreased over time.

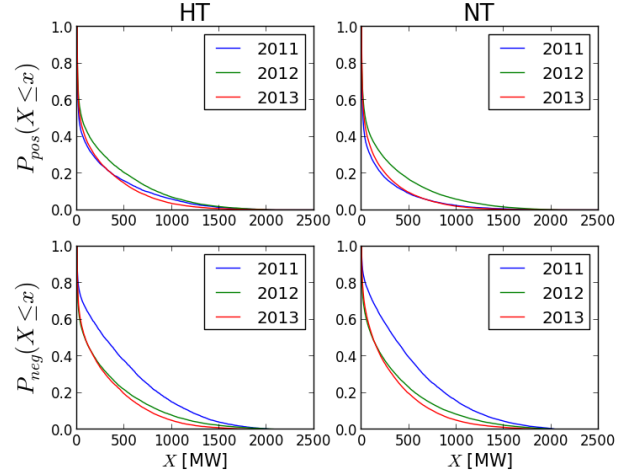


Fig. 3. Retrieval probabilities according to market design Jul 2011 - Dec 2013

The following image plots are used to describe the retrieval probabilities of further time slices. Due to space restrictions and better readability, the used scale is only presented in Figure 4. Red means very high retrieval probability up to one, whereas blue is connected with a low probability up to zero. The transition from red to blue describes a decrease of retrieval probability. As seen in Figure 3 and quantified by the data, the retrieval at 1500 MW is often very low at just one percent. Therefore, the following graphs are only plotted up to this amount.

B. Time slices of single months

Figure 5 and Figure 6 show the average retrieval probabilities regarding single months. Particularly in March 2012 it can

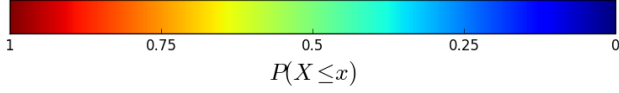


Fig. 4. Image plot sample

be seen that the two reserves appear to act in a complementary manner, which is reasonable since that is their purpose of use, and because imbalances continuously exist. Otherwise, no unambiguous pattern is recognizable on a monthly basis.

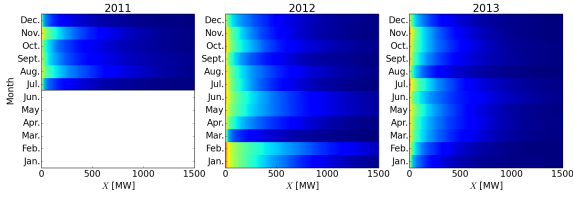


Fig. 5. Retrieval probabilities for positive SR on a monthly basis

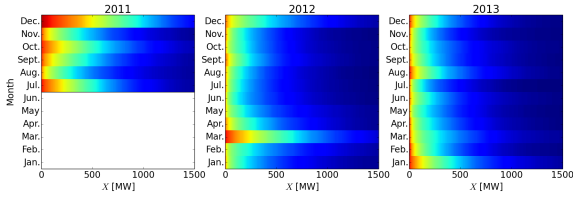


Fig. 6. Retrieval probabilities for negative SR on a monthly basis

C. Time slices of single hours

1) *Positive working day*: Empirical data shows that positive reserve is especially retrieved in the morning hours, with a peak occurring at 6 pm (Figure 7). If one considers the same months, namely Jul - Dec, for all three years one would recognize a similar afternoon peak in 2011, 2012 and 2013. Otherwise, the structure is not significantly effected.

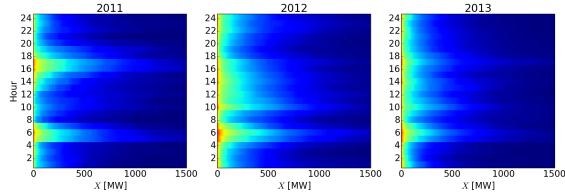


Fig. 7. Retrieval probabilities for positive SR on working days

2) *Positive non-working day*: Compared to the working days, there is no such characteristic peak in the morning. Instead, one occurred in the afternoon between 4-5 pm (Figure 8).

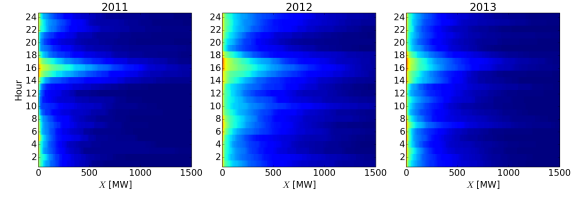


Fig. 8. Retrieval probabilities for positive SR on non-working days

3) *Negative working day*: As stated above, positive and negative control power behave like complements. This is also reflected on an hourly scale. In particular during times when only little amounts of positive reserve were retrieved, the highest amounts of negative reserve were retrieved. However, as already mentioned in section IV-A, the absolute values for negative reserve were much higher than for positive. The highest probabilities of retrieval were connected to the evening hours peaking at 9 pm (Figure 9). Although the pattern remained the same, this has been dramatically reduced in the recent past.

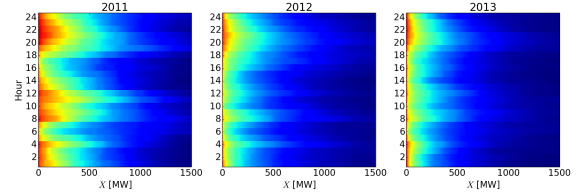


Fig. 9. Retrieval probabilities for negative SR on working days

4) *Negative non-working day*: On non-working days the probability of retrieval was higher than on working days with two particular differences. On the one hand, the pattern in the evening hours was not smooth, peaking at 8 pm (Figure 10). On the other hand, a more distinct probability existed during lunchtime hours.

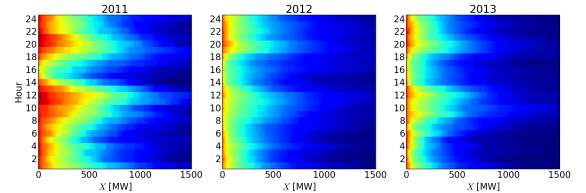


Fig. 10. Retrieval probabilities for negative SR on non-working days

5) *Holidays*: As can be seen in Figure 11, the average amount of retrieved control power is even higher than on non-working days. Negative SR reserve peaks at 9 am and 8 pm. Positive SR peaks at 4 pm.

V. CONCLUSION

The previous work attempted to fill the gap in scientific literature for retrieval probabilities of control power in large power systems effected by a high share of renewable energies in the case of Germany. It was shown that the actual demand for control power is highly dynamic. Furthermore, the retrieval

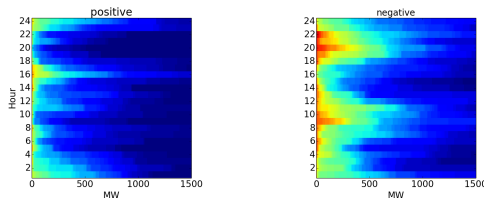


Fig. 11. Retrieval probabilities for SR in 2011-2013 on uniform holidays

probability is disproportionately digressive with the retrieved amount. In the recent past, the probability for retrieval for negative reserve was significantly higher than for positive in the same periods. As given by the system design, positive and negative SR behave like complements. On an hourly resolution patterns emerge with distinct peaks around specific hours. Additionally, there is a difference between working and non-working days. On working days, retrieval of positive SR peaks in the morning, while negative SR peaks in the late evening hours. On non-working days, positive SR peaks in the afternoon. For negative SR there was still a peak in the evening, albeit slightly earlier and a second one around the lunch time hours. This pattern of non-working days is still more exaggerated on public holidays. For further use the results can be approximated with specific data points that can be obtained from the author.

REFERENCES

- [1] "UCTE - Operation Handbook," 2004. [Online]. Available: <https://www.entsoe.eu>
- [2] H. Weber, P. Asal, and E. Grebe, "Characteristic numbers of primary control in the UCTE power system and future requirements," in *ETG-Tage '97, PES Summer Meeting : Berlin, 20. - 24. Juli 1997* / *Vorträge aus der Plenarveranstaltung, den ETG-Fachtagungen, dem Jungingenieur- und Studentenforum am 21. und 22. Juli 1997 in Berlin*. Berlin: VDE-Verlag, 1997, pp. 395–405.
- [3] H. P. Asal, P. Barth, and E. Grebe, "Dynamic System Studies of New Requirements and Strategies for the Primary Control," in *Cigré Sessions 39-106*, 1998.
- [4] Consentec, "Gutachten zur Höhe des Regellenergiebedarfs," 2008. [Online]. Available: <http://www.consentec.de/wp-content/uploads/2011/12/Gutachten-zur-H%C3%B6he-des-Regellenergiebedarfes.pdf>
- [5] —, "Gutachten zur Dimensionierung des Regelleistungsbedarfs unter dem NRV," 2010. [Online]. Available: http://www.consentec.de/wp-content/uploads/2012/01/Gutachten_zur_Hoehe_des_Regellenergiebedarfes_20101.pdf
- [6] I. Ziegenhagen, "Impact of Increasing Wind and PV Penetration Rates on Control Power Capacity Requirements in Germany," Master, University of Leipzig, 2013.
- [7] O. Brückl, "Wahrscheinlichkeitstheoretische Bestimmung des Regel- und Reserveleistungsbedarfs in der Elektrizitätswirtschaft," Dissertation, Technische Universität München, 2006. [Online]. Available: http://d-nb.info/991830261/34?origin=publication_detail
- [8] M. Scherer, M. Zima, and G. Andersson, "An integrated pan-European ancillary services market for frequency control," *Energy Policy*, vol. 62, pp. 292–300, Aug. 2013. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0301421513006733>
- [9] C. Breuer, C. Engelhardt, and A. Moser, "Expectation - based Reserve Capacity Dimensioning in Power Systems with an Increasing Intermittent Feed - in," in *Proceedings of the Conference on European Energy Markets*, Stockholm, Sweden, 2013.
- [10] Bundesnetzagentur, "Monitoringbericht 2010," Bonn, p. 304, 2010. [Online]. Available: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2010/Monitoringbericht2010Energiepdf.pdf?__blob=publicationFile&v=2
- [11] —, "Monitoringbericht 2012," Bonn, p. 308, 2012. [Online]. Available: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2012/Monitoringbericht2012.pdf?__blob=publicationFile
- [12] —, "Monitoringbericht 2013," Bonn, p. 323, 2013. [Online]. Available: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2013/131217/Monitoringbericht2013.pdf?__blob=publicationFile&v=14
- [13] K. Flinkerbusch and M. Heuterkes, "Cost reduction potentials in the German market for balancing power," *Energy Policy*, vol. 38, no. 8, pp. 4712–4718, Aug. 2010.
- [14] K. Flinkerbusch, "Der Markt für Sekundärregelenergie Eine Bewertung des Regellenergieeinsatzes im Rahmen des Netzregelverbundes," *Zeitschrift für Energiewirtschaft*, vol. 35, no. 3, pp. 173–181, May 2011.
- [15] F. Müsgens, A. Ockenfels, and M. Peek, "Balancing Power Markets in Germany: Timing Matters," *Zeitschrift für Energiewirtschaft*, vol. 36, no. 1, pp. 1–7, Oct. 2012.
- [16] S. Just and C. Weber, "Strategic Behavior in the German Balancing Energy Mechanism : Incentives , Evidence , Costs and Solutions," 2012. [Online]. Available: http://www.wiwi.uni-due.de/fileadmin/fileupload/BWL-ENERGIE/Arbeitspapiere/RePEc/pdf/wp1204/_StrategicBehaviorInTheGermanBalancingMechanism.pdf
- [17] —, "Pricing of reserves: Valuing system reserve capacity against spot prices in electricity markets," *Energy Economics*, vol. 30, no. 6, pp. 3198–3221, Nov. 2008. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0140988308000789>
- [18] D. J. Swider, *Handel an Regellenergie- und Spotmärkten: Methoden zur Entscheidungsunterstützung für Netz- und Kraftwerksbetreiber*. Wiesbaden: Deutscher Universitätsverlag, 2006.
- [19] J. Richter, "On the interaction between product markets and markets for production capacity : The case of the electricity industry," 2012. [Online]. Available: http://www.ewi.uni-koeln.de/fileadmin/user_upload/Publikationen/Working_Paper/EWI_WP_11-09_Capacity_Markets.pdf
- [20] S. Jaehnert and G. L. Doorman, "Assessing the benefits of regulating power market integration in Northern Europe," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 70–79, Dec. 2012. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S0142061512002001>
- [21] A. Ortner and C. Graf, "Multi-market unit-commitment and capacity reserve prices in systems with a large share of hydro power: A case study," in *10th International Conference on the European Energy Market (EEM)*, no. May. Stockholm, Sweden: Ieee, May 2013, pp. 1–8. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6607336>
- [22] D. J. Swider, "Efficient Scoring-Rule in Multipart Procurement Auctions for Power Systems Reserve," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 1717–1725, Nov. 2007. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4349129>
- [23] German Transmission System Operators, "www.regelleistung.net" [Online]. Available: www.regelleistung.net

Philipp Hanemann received a Diploma Degree in Industrial Engineering and Management from the Hamburg University of Technology, Hamburg, Germany, in 2010.

Since 2011, he has been with the Institute for Infrastructure and Resources Management at the University of Leipzig. His research focuses on economical influences of electric vehicles and storages on the power system.

Thomas Bruckner received his Diploma Degree and his Ph.D. in theoretical physics from the University of Würzburg in 1992 and 1997, respectively. He was the coordinating lead author for the chapter Energy Systems for the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC). Currently, he is the director of the Institute for Infrastructure and Resources Management at University Leipzig, Leipzig, Germany and head of Sustainability Management and Infrastructure Economics Division at Fraunhofer Center for International Management and Knowledge Economy, Leipzig, Germany. He also holds the Chair for Energy Management and Sustainability. His research interests are on modeling climate change, liberalized electricity markets and decentralized energy systems.