Control Power and Variable Renewables: A Glimpse at German Data

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Abstract--**Control power (balancing reserve) is used to restore the supply-demand balance in power systems within seconds to minutes. Variable renewable energy sources (VRE) such as wind and solar power are often thought to increase the reserve requirement significantly. This paper provides a comprehensive overview on balancing systems and presents empirical market data from Germany. We discuss the factors that determine the size of the reserve requirement, showing that VRE are only one of several important drivers. Empirically, despite a doubling of VRE capacity between 2008 and 2012, contracted control power decreased by 20%, and procurement cost fell by 50%. Today, control power adds only 0.3% to household electricity prices. After comparing the German design of control power markets and imbalance settlement to other systems and findings from the theoretical economic literature, we suggest a number of changes to the market design to provide efficient incentives to wind and solar power.**

1. INTRODUCTION

In power systems, the demand-supply balance has to hold at every instant to ensure frequency and voltage stability. Control power[2] is used to physically balancedeviations on short time scales.This paper provides an overview of control power systems and markets, with a focus on the role of variable renewable electricity sources (VRE) such as wind and solar power. We present new empirical data from Germany, where installed VRE capacity exceeds 70% of peak load. Surprisingly, both the reserved capacities for and the costs of control power have decreased since 2008, despite a doubling of installed VRE capacity.

Electricity generation from renewables has been growing rapidly during the last years, driven by technological progress, economies of scale, and deployment subsidies. Renewables are one of the major options to mitigate greenhouse gas emissions and are expected to grow significantly in importance throughout the coming decades (IPCC 2011, IEA 2012, GEA 2012, Luderer et al. 2012). As hydro power potentials are largely exploited in many regions, and biomass needed in other sectors than power generation, much of the growth will come from wind and solar power.

As a consequence of the inherent stochastic nature of wind speeds and solar radiation, VRE are variable and uncertain. Deviates from forecasted schedules as well as variations within the time frame of schedules have to be balanced by the power system. The impact of VRE on control power is sometimes seen as a major and costly challenge for integrating these technologies into power systems and widely discussed in the literature (Grubb 1991, Gross et al. 2006, Denny & O'Malley 2007, Milligan et al. 2009, Holttinen et al. 2011, Katzenstein & Apt 2012, Pérez-Arriga & Battle 2012).

In a broad literature review (Hirth 2012) we found that wind integration studies and other power system modeling exercises often estimate the costs impact of VRE on balancing systems to be positive, but small (below 5 €/MWh_{VRE} even at high penetration rates). However, studies based on market prices sometimes report much higher costs. This study provides a more detailed discussion of control power in the context of rising amounts of wind and solar power. We focus on Germany, for two reasons. Germany is a large system with significant amounts of VRE. At the same time, balancing system data are publicly available.

The paper is organized as follows. Section 2 gives an overview of balancing systems. It clarifies which actors are involved, outlines the technical characteristics of different types of control power in Europe, and explains the way they are used. Section 3 discusses the different factors causing imbalances in power systems and discusses how the amount of reserve capacity is determined, with a focus on the probabilistic approach applied in Germany. Data are presented that show how much tendered capacity has been reduced despite a massive expansion of variable renewables. Section 4 discusses different ways to procure capacity, with a focus on the German control power market where TSOs tender capacity in pay-as-bid auctions. Price data are presented that show a dramatic price drop over the last years as new players have entered the market. Section 5 discusses the other side of the coin: imbalance settlement. Section 6 concludes.

Overall, we find that the impact of VRE on control power is less dramatic than sometimes believed. Nevertheless, we propose a number of market design changes to control power and balancing markets to provide efficient signals to VRE and other actors.

The findings, interpretations, and conclusions expressed herein are those of the authors and do not necessarily reflect the views of Vattenfall or the Potsdam-Institute. Corresponding author: Lion Hirth, Vattenfall GmbH, Chausseestraße 23, 10115 Berlin, lion.hirth@vattenfall.com, +49 30 81824032.

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[2] Control power is sometimes called regulating power (*Regelleistung*), balancing reserve, reserve power, balancing power, regulation, or operating reserve (Short et al. 2011); we follow here European Transmission System Operator terminology (UCTE 2009).

2. Fundamentals of Control Power

This sections explains how balancing systems work, how control power relates to other ancillary services, and gives an overview of the types of control power used in the UCTE and other European synchronous systems.

2.1. *Balancing systems*

We use the term "balancing system" to describe the set of institutions that are used to maintain, and, if necessary, restore the demand-supply balance in large power systems. This includes the procurement, and activation of control power and the allocation of its costs.

Three types of actors play a role in balancing systems: transmission system operators (TSO), balance responsible parties (BRP), and suppliers of control power. Figure 1 gives a high-level overview of their roles and interactions.

BRPs are market entities that have the responsibility of balancing a portfolio of generators and/or loads. Therefore they deliver binding generation and load schedules to the TSOs the day before realization. These schedules can be adjusted until about one hour ahead of delivery. If actual in-feed and consumption deviates from the schedule, system operators balance the system by physically activating control power. BRPs are financially accountable for deviations from their schedules.

TSOs operate the transmission network and are responsible to balance supply and demand in their control area (balancing area). Specifically, they have four obligations: determine the required amount of capacity that has to be reserved as control power (discussed in section 3); acquire the control power capacity and determine the price paid for capacity and energy (section 4); activate the control power in moments of physical imbalance; determine the price of balancing energy, and clear the system financially by charging BRPs according to their imbalance and/or recovering expenses via grid fees (section 5).

Suppliers of control power provide positive or negative reserve capacity to the TSO. They are obliged to deliver energy under pre-specified terms once activated. Typically they receive a capacity (€/MW) and/or energy payment (€/MWh) for this service. Suppliers are traditionally generators, but can also be loads.

We call the institutional setup for acquiring control power the "control power market" and the system to settle BRP's imbalances financially the "balancing power market".

2.2. *Power versus Energy*

Unlike many wholesale markets for electricity, market transactions in the balancing system regularly involve (reserved) capacity and (activated) energy. The required reserved capacities are determined and purchased in advance. Control energy (*Regelarbeit)* can only be activated in the amount of the reserved capacity. Furthermore, it is important to distinguish between positive (upward-regulating) control power and negative (downward-regulating) control power. Positive control power is needed if the system lacks energy and negative control power if there is more production than consumption. Negative control energy is provided by reducing generation or increasing consumption.

2.3. *Control Power, Re-Dispatch, and other Ancillary Services*

Control power is one of a number of ancillary services that TSOs rely on to secure system stability. Short-term deviations in the supply-demand balance, which control power is meant to solve, is not the only threat to stability. If power flows on transmission lines exceed rated capacity, TSOs use counter-trading or re-dispatch to geographically re-located generation and reduce line flows. Local voltage problems require reactive power (voltage support). It is important to keep in mind that

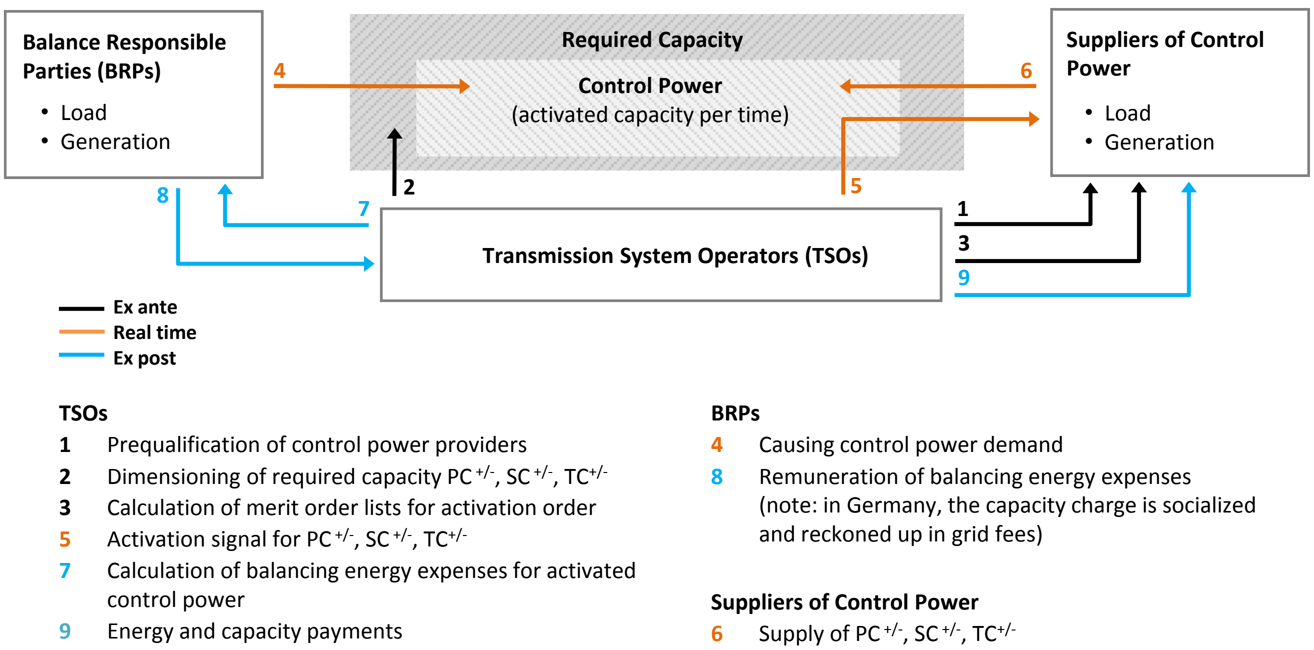

Figure 1. Overview of a balancing system.

control power is not used to change transmission flows.

2.4. *Types of Control Power in Continental Europe*

Depending on the reason for an imbalance, control power is needed in different amounts and at different response times. Consequently, different types of control power have evolved.

In the synchronous power system of continental Europe (the former UCTE) three types of control power are used: primary control, secondary control, and tertiary control (minute reserve) – each positive and negative. They differ in purpose, response time, and the way they are activated (Table 1).

Primary control power ($PC^{+/-}$) has to deliver contracted capacity within 30 seconds after activation. Being a shared resource within the UCTE, it is not activated by TSOs but activated based on the locally measured grid frequency. If the frequency deviates more than 20 mHz from 50 Hz, PC is activated; it is fully activated at 200 mHz deviation. As no generator can start-up fast enough, $PC^{+/-}$ is usually supplied by synchronized generators and hence can be labeled a “spinning reserve”.

Secondary control power ($SC^{+/-}$) has to be available within five minutes after activation. It is activated automatically and centrally by TSOs. Activation depends mainly on the balance of the national control areas (physical net imports minus scheduled net imports), but also takes frequency deviation into account (UCTE 2009, P1). $SC^{+/-}$ can be supplied by some stand-by hydro plants, but is mainly provided by synchronized thermal generators. Hence, to a large extend, it is also a spinning reserve.

Tertiary control power ($TC^{+/-}$) is usually used to replace $SC^{+/-}$. It is either directly activated or in schedules of 15 minutes. In Germany, it has to be available within seven minutes. Activation is a manual decision usually based on current and expected activation of $SC^{+/-}$. Both synchronized and fast-starting stand-by generators supply $TC^{+/-}$.

After a contingency, such as a loss of a large generator, control power is used to stabilize and restore grid frequency. After the generator tripped, consumption exceeds production and the power system is imbalanced. As a consequence, the frequency drops in the entire synchronous network of the UCTE. The speed of the drop depends on the inertia of the power system, mainly the energy stored in rotating masses. The frequency drop activates PC^{+} in the entire UCTE. The activation algorithm is calibrated in such way that enough PC^{+} is activated to compensate for the failed generator. After 30 seconds, PC is fully available, demand equals supply again, and the grid frequency is stabilized. Within five minutes, SC^{+} is activated, mainly in the control area of the failed generator. Now generation exceeds consumption and the frequency rises until it reaches 50 Hz again. Over time SC^{+} is replaced by TC^{+}.

However, control power is not a dedicated contingency reserve, but also used as an operating reserve. For example, forecast errors of VRE are balanced using $SC^{+/-}$ and $TC^{+/-}$, usually without a prior frequency deviations and hence no activation of $PC^{+/-}$. If a control area is out-of-balance, but the UCTE as a whole is balanced, $SC^{+/-}$ will be activated, but not $PC^{+/-}$.

2.5. *Types of Control Power in Other Power Systems*

While the fundamental physical challenges of system balancing are the same in all power systems, the types of control power differ in terminology and technical specifications. For example, in the synchronous system Nordel that covers Norway, Sweden, Finland, and the Eastern part of Denmark, there are four types of control power: primary regulating power, fast active disturbance reserve, fast active forecast reserve, and slow active disturbance reserve. The two “fast” reserves are comparable to $SC^{+/-}$ and the “slow” reserve to $TC^{+/-}$.

As in Nordel, many U.S. systems distinguish control power types by contingency versus operating reserve. As mentioned, in the UCTE $SC^{+/-}$ and $TC^{+/-}$ are used both for contingencies and operational imbalances.

The UK system features a large number of different control power types: primary, high, and firm frequency response (comparable to $PC^{+/-}$); secondary frequency response and frequency control by demand management (comparable to SC^{+}); optional, tendered, and non-tendered fast reserve and different types of short term operating reserve (comparable to $TC^{+/-}$). ENTSO-E (2012a, 34) provides an overview of control power types in other European synchronous systems.

3. DETERMINING THE REQUIRED RESERVE CAPACITY

TSO have to estimate the amount of reserves to be contracted ex ante. The methodologies used for doing this vary across types of control power and across countries. For

Table 1: Types of control power

	Primary Control	**Secondary Control**	**Tertiary Control (Minute Reserve)**
Response Time	30 s (100%), direct (continuously)	5 min (100%), direct (continuously)	7-15 min (100%), director schedule
System	UCTE	Control area	Control area
Control Variable	Frequency deviation from 50 Hz (UCTE system)	Balance of the control area; Frequency deviation	Amount of $SC^{+/-}$ activated
Activation	Based on local frequency measurement	Centralized (TSO); active call through IT	Centralized (TSO); active call through phone / IT
Suppliers (typically)	Synchronized generators, (industrial consumers)	Synchronized generators, stand-by hydro plants, large consumers	Synchronized and fast-starting stand-by generators, large consumers
Reserved Capacity (see section 3)	3000 MW in UCTE (600 MW in Germany)	Decided by TSO (2500 MW in Germany)	Decided by TSO (2500 MW in Germany)

PC$^{+/-}$, European TSOs have agreed to reserve 3000 MW in the UCTE, sufficient to compensate the loss of two large nuclear reactors. This amount is distributed to control areas proportionally to previous year's generation (UCTE 2009, P1). For Germany, this is currently around 600 MW.

The necessary capacities of SC$^{+/-}$ and TC$^{+/-}$are set for each control areas by the respective TSOs. For SC$^{+/-}$, UCTE (2009, P1 B-D5) recommends different methodologies – such as a probabilistic risk management approach or an empiric noise management approach. The latter follows an empirical approximation based on peak load l_{max} (in MW) where C_{SC^+} is reserved positive secondary control capacity and C_{SC^-} is negative capacity.

$$C_{SC^+} = C_{SC^-} = \sqrt{10 \cdot l_{max} + 50^2} - 50 \qquad (1)$$

For TC$^{+/-}$, UCTE (2009) does not provide such methodologies. In Germany, TSOs use a probabilistic approach to determine SC$^{+/-}$and TC$^{+/-}$capacities jointly. We will discuss this in the following two subsections.

3.1. *Variables that Cause System Imbalances*

In general, a number of factors cause imbalances in power systems. One way of categorize them is to differentiate stochastic and deterministic processes (Table 2). Stochastic processes are forecast errors of generation and load. Traditionally, forecast errors of load and unplanned outages of thermal and hydro plants (contingencies) have been the most important factors in this group. Lately, forecast errors of VRE have been added to the list. Deterministic processes are the deviations between the stepwise schedules and continuous physical variables.

Unplanned power plant outages are stochastic processes. They induce an unplanned power shortage in the electricity system and therefore only require positive control power. The probability of an outage is influenced by the characteristics of plants (technology, fuel, age) and the frequency of start- up and shut-down processes. Usually power plant outages last for several hours or days. However, only a part of this time span the outage is relevant for control power. In Germany, BRPs are obliged to replace tripped generators within one hour with scheduled capacities from their portfolio or the market.

Forecast errors of wind and solar production affect the positive as well as the negative control power demand: An overestimation of VRE generations leads to a power shortfall that requires the activation of positive control power. An underestimation has the opposite effect. Wind and solar forecasts are inherently uncertain due to the stochastic nature of the underlying physical processes. While day-ahead forecasts are significant in size, they improve as the prediction horizon shortens. If intra-day markets are liquid, it is only the prediction errors of the latest forecast that requires control power activation.

Load forecast errors and load noise are – like forecast errors of VRE production – stochastic processes which have an impact on the positive and negative control power demand. Load forecast errors are defined as deviation of the scheduled load and the 15-minute average of actual load, whereas load noise is the difference of the actual load in each moment of time and the 15-minute mean of the load.

Besides stochastic processes, the control power demand – and thus the required reserve – is influenced by deterministic processes resulting from the market structure. Schedules for generation and load are usually specified as discrete step functions in 15 minute-intervals. However, loads, VRE, and – to a lesser extend – also dispatchable generators do not change in steps, but smoothly. The deviations of actual load and production from scheduled load and production are called "schedule leaps" (Figure 2). These leaps can have a substantial impact on the control power demand.

While BRPs are obliged to schedule on a quarter-hourly basis, spot market trading on many power exchanges has an hourly granularity. Consequently, many BRPs use hourly schedules, which results in higher deviations (Consentec 2010).

The control area imbalance is the sum of all these imbalances. Usually, individual imbalances cancel out to a large extent. In statistical terms, the control area imbalance follows the joint distribution of the several factors that cause imbalances. We will discuss in turn how to estimate these distributions empirically.

3.2. *Statistical Convolution*

The German TSOs use a probabilistic approach to determine SC$^{+/-}$ and TC$^{+/-}$ capacities, sometimes called the Graf/Haubrich methodology (Consentec 2008, 2010). In contrast to other methods like the empiric noise management approach, the probabilistic approach takes into account the different distribution characteristics of the influencing variables.

Table 2: Control power influencing variables

	Stochastic	**Deterministic**
Thermal and Hydro Generation	Unplanned power plant outages	Schedule leaps of thermal, hydro, and VRE generation, and load
VRE generation	Forecast error for wind and solar production	
Load	Load forecast error, load noise	

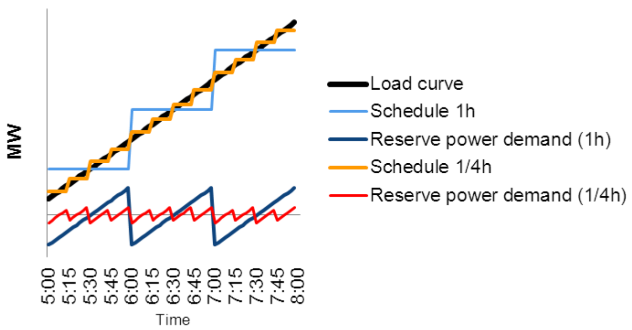

Figure 2. Schedule leaps and activation of control power.

In Germany, the security level was recently increased to 99.95% (Consentec 2010). This corresponds to approximately four hours of the year where the momentary control power demand can exceed the reserved capacities. The German TSOs determine the required capacity for the next quarter based on empirical data of the previous twelve months.

Elsewhere (Ziegenhagen 2013), we have estimated the individual and joint density distributions from empirical data. There we find that one GW of additional wind capacity increases the reserve requirement (SC plus TC) by 30-70 MW.

3.3. TSO Cooperation

The size of a control area determines crucially the shape of the different density functions. A larger control area with a higher number of more diverse loads leads to a more narrow distribution of load forecast errors. Similarly, a geographically larger control area with more and more widely dispersed wind and solar generators leads to a more narrow distribution of VRE forecast errors.

During 2009 and 2010, the German TSOs started cooperating in terms of control power (*Netzregelverbund*). Today, both reserve dimensioning and activation is done jointly. In practice, Germany can be treated almost as one control area (Zolotarev et al. 2009, Zolotarev & Gökeler 2011).

3.4. Control Power Capacities in Germany

In 2012, German TSOs tendered about 600 MW $PC^{+/-}$ and 2000 MW each of $SC^{+/-}$and $TC^{+/-}$(Table 3). This means that total upward and downward regulation capacity was roughly 4600 MW, of which the TSOs can activate 4000 MW, since $PC^{+/-}$ is activated based on the grid frequency.

Figure 4 shows the contracted volumes of secondary and tertiary reserve. Since 2008, total quantities decreased by more than 20%. While downward-regulation quantities remained roughly stable, upward-regulation quantities decreased by about 40%. This was possible even though the level of security was increased from 99.9% to 99.95%. The cooperation of TSOs is probably the most important reason for this decrease.

Table 3: Contracted volumes of control power in Germany (MW).

	$PC^{+/-}$	**SC^{+}**	**SC^{-}**	**TC^{+}**	**TC^{-}**
2008	670	3100	2400	3200	1900
2009	670	2900	2200	2700	2700
2010	640	2400	2100	2300	2400
2011	630	2200	2100	2100	2500
2012	600	2100	2200	1700	2300

Rounded for better readability.

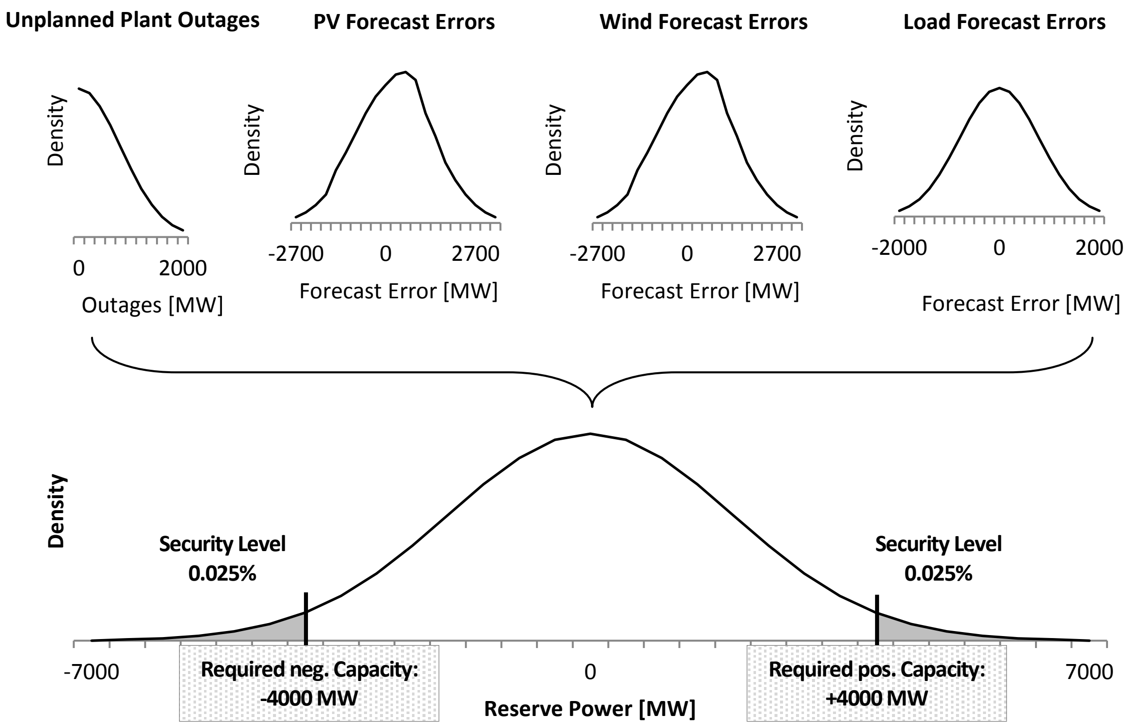

Figure 3. Probabilistic approach for ex-ante determination of requiring capacity of $SC^{+/-}$ and $TC^{+/-}$

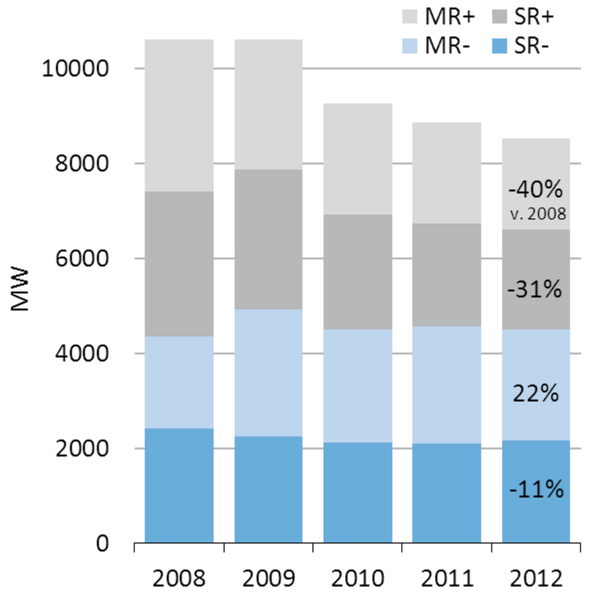

Figure 4. Tendered volumes of secondary and tertiary control power in Germany.

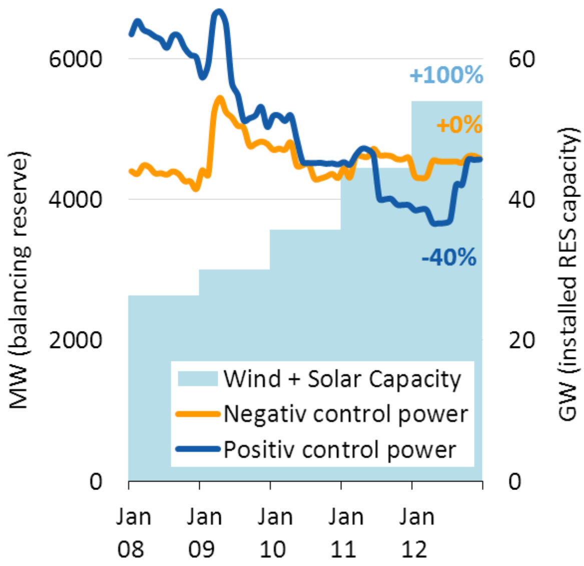

Figure 5. The demand for control power and growth of variable renewables in Germany. Despite the installed capacity of wind and solar power doubling since 2008, the demand for regulating power decreased.

Figure 5 compares these quantities to the installed capacity of variable renewables, wind and solar power. While VRE capacity doubled, control power reserves decreased significantly. The important message of this figure is that there is *not* direct relationship between VRE and reserve requirements. In contrast, other factors can over-compensate the impact on VRE on reserve requirements, and have done so during the last five years in Germany.

In this section we have explained that a number of factors determine the reserve requirement for control power. While wind and solar power increase the reserve requirement, they are not necessarily the dominating factors, even at substantial penetration rates. Specifically, German reserve capacity has been reduced by 20% during the last five years, while installed VRE capacity doubled.

4. Control Power: Market Design and Price Formation

The last section discussed methodologies to estimate the reserve requirement for control power. As a next step, TSOs need to acquire that amount of capacity from generators and loads. The acquisition is mostly organized nationally and follows different concepts in each country. A wide range of institutional setups exist: supply obligation for generators above a certain size with or without compensation, mandatory offers by generators, dedicated tenders schemes, or procuring via power markets. ENTSO-E (2012a) provides a comprehensive overview of market rules in Europe.

4.1. Control Power Market Design in Germany

Since late 2007, the four German TSOs tender control power as pay-as-bid auctions on their common platform www.regelleistung.net. Bidders have to prove that they can deliver control power according to the UCTE requirements (Table 1) before bidding ("prequalification"). $PC^{+/-}$ is traded as symmetric (positive and negative) capacity for the entire auction period (base). SC is auctioned separately as positive and negative power for peak and off-peak periods. TC is auctioned as positive and negative power in blocks of four hours. Hence, there are four SC products and twelve TC products.

All auctions are pay-as-bid auctions: in contrast to uniform (marginal) pricing as on spot markets, bidders receive the price they bid. Bids are accepted based on their capacity price only; activation is done according to the energy price.

The auction design is determined by the energy regulator Bundesnetzagentur. Table 4 summarizes current auction design. In June 2011, auction rules were significantly altered in order to promote market entry of new actors. Apparently, that was successful: the number of prequalified suppliers has strongly increased.

4.2. Price Development and Market Size in Germany

Table 4: Control power market design in Germany.

	$PC^{+/-}$	$SC^{+/-}$	$TC^{+/-}$
Auction Period	week	week	day
Number of Products	1 (base, symmetric)	4 (positive/ negative; peak/off-peak)	12 (positive/ negative; blocks of four hours)
Capacity Payment	yes	yes	yes
Energy Payment	no	yes	yes
Minimum Bid	1 MW	5 MW	5 MW
Number of Actors	15	16	35

The average capacity price for control power in Germany during 2012 was between 1 €/MW per hour and 16 €/MWh (Table 5).[3] PC was the most expensive type of control power and TC^{+} the cheapest. Note that while the SC and TC products are prices for one direction (up or down), the PC price is for regulation in both directions (symmetric).Maybe surprisingly, negative control power was on averagethree to four times more expensive than positive control. Overall, the market size was € 420 million, of which two thirds was SC.

Table 5: Average capacity price (€/MW per hour) and market size (M€ per year, capacity payment only) in 2012.

	PC$^{+/-}$	SC^{+}	SC^{-}	TC^{+}	TC^{-}
Price (€/MWh)	16	3	12	1	3
Amount (MW)	600	2100	2200	1700	2300
Market size (M€)	90	50	220	10	60

Figure 6 shows price development since a common tender scheme was established in 2007 as monthly averages. The four SC products are aggregated as well as the 12 TC products to make the three types comparable. The first observation is that prices are very volatile. Moreover, there is a decreasing price trend in all types. The price level of SC is comparable to TC, which is plausible since they are close substitutes in terms of technical requirements of provision. TC is much cheaper.

Figure 7 shows the price development of the four SC products individually. While during 2008 and 2009 SC^{+} was more expensive than SC^{-}, the opposite is true since then. A similar pattern can be observed in TC markets (not shown). Overall, price volatility is extreme.

The opportunity costs for generators to bid into control power markets are determined on the one hand by increased wear and tear due to ramps when being activated. On the other hand, it is the foregone profit from sales on the spot market. A generator that is in the money and generating electricity at its rated capacity can provide negative (downward-regulating) control power without losing profits – the only cost related to negative control power provision is increases maintenance costs. However, if that generator is to provide positive control, it has to operate below its rated capacity. Reduced electricity sales and part-load efficiency losses increase its opportunity costs. Hence, the opportunity costs of control power provision depend on the status the providing generator would be otherwise, the spread between wholesale price and variable costs, and ramping costs.

There are several hypotheses to explain the features of the price development. Overall, a reduction of control power demand and market entry of new players put a pressure on prices that might explain the overall price decrease. The price increase of negative control versus positive control can be explained by overcapacity on spot markets that reduce the opportunity costs of providing positive control power capacity. The price spike during spring 2011 is related to the phase-out of seven nuclear reactors after the Fukushima accident. The price spike of TC prices in spring 2009 is connected to a shift of control power demand from SC to TC.

Figure 8 shows the price development as a yearly average. Compared to 2008, PC prices fell by 20%, SC by 30%, and TC prices by 60%. In conjuncture with decreasing tendered quantities, this caused the market size to contract 30-60% (Figure 9). The aggregated costs of control power provision fell by 50%.

In terms of costs, regulating power is by far the most important ancillary service in Germany (Bundesnetzagentur 2011, Figure 10). However, relative to the market for electrical energy, control power is marginal in cost terms (Figure 11). With a market size of € 420 million per year it is about 2% the size of the German wholesale market for electrical energy (€ 25 billion). Including all taxes and levies, private households are paying about 280 €/MWh for electricity. Of that, the costs of control power are about 0.3%.

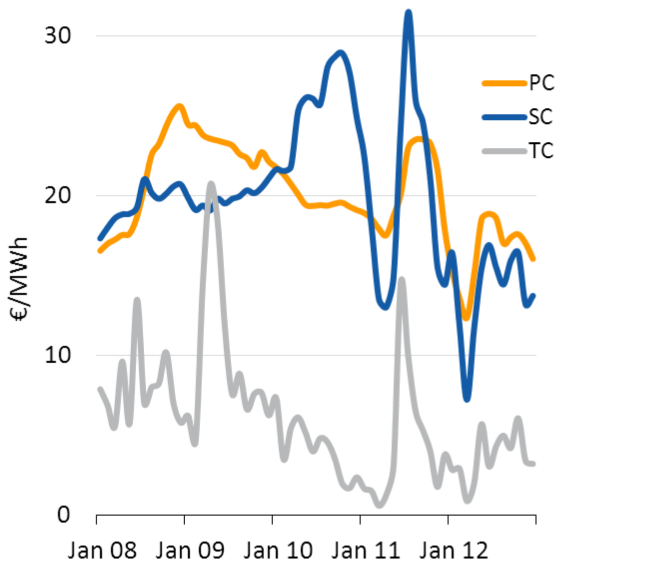

Figure 6. Capacity prices since 2008. The four SC products and the 12 TC products are aggregated to symmetrical base products for comparability

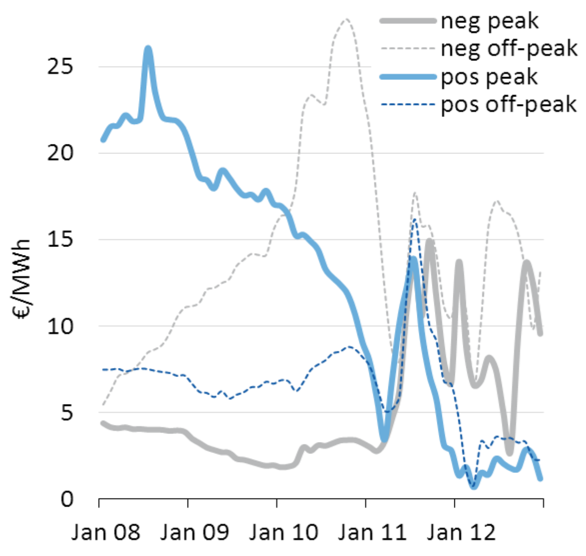

Figure 7. Capacity prices for different SC products.

[3] TSOs report prices usually in €/MW per day, €/MW per week, or €/MW per month. Market actors sometimes use €/kW per year. We report all capacity prices as €/MWh per hour (€/MWh). Note that despite having the same unit, these capacity prices have nothing to do with energy prices.

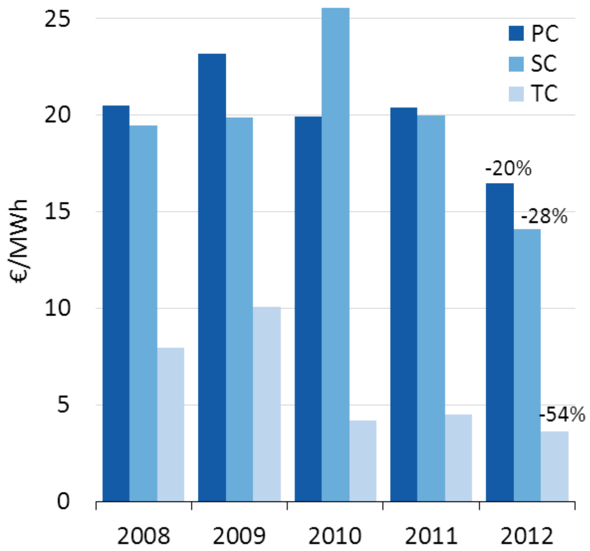

Figure 8. Control power prices as yearly averages. Products are aggregated to symmetric base, as in Figure 6. Relative changes compared to 2008.

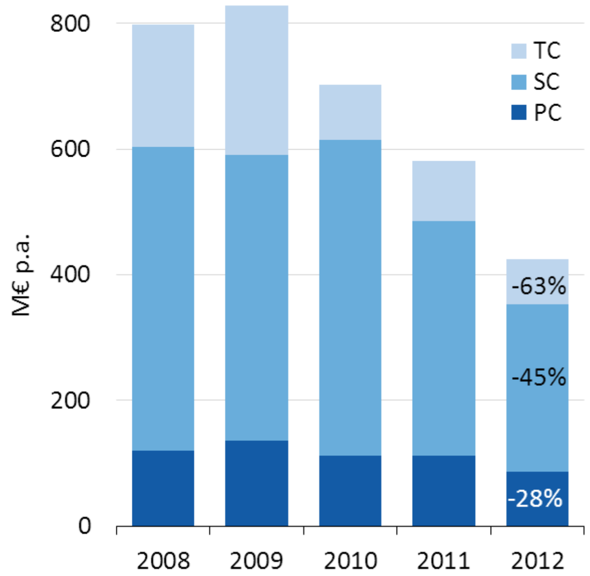

Figure 9. The market size of control power. The overall market size has contracted by 50% since 2008, with tertiary control decreasing most.

4.3. *Incentives and Barriers for Wind and Solar to Supply Control Power*

In principle, wind and solar power are well suited to provide negative control power when they generate electricity: unlike thermal plants, they can be ramped down very quickly without significant increase in maintenance costs. In contrast, they are not well suited to provide upward regulation. Given their low marginal costs, operating below generation possibilities would occasion higher opportunity costs in terms of foregone profits on the spot market than for thermal plants.

However, the ability of VRE to provide negative control power is limited to times when the primary resource is available. Because this is difficulty to project over a week, the current German market design is not well suited to attract VRE as bidders. Consequently, wind and solar power currently do not seem to participate on the market.[4] Daily auctions of products with finer granularity would allow VRE generators to enter this market. Just (2010) shows that independently of VRE, shorter auction periods increase economic efficiency.

Under the German feed-in-tariff, subsidized generators are not allowed to participate in control power markets. However, in early 2012 an optional feed-in-premium was introduced which allows generators to participate. So far, about 40% of VRE capacity has switched to the premium and would be legally able to enter control power markets.

Summing up this section, we find two important results. Firstly, the prices for control power in Germany and the overall costs of control power provision decreased continuously since 2009. The costs for reserve capacity decreased by half. Moreover, control power is a very small component of the total costs of power supply: about 2% of the wholesale energy market or 0.3% of retail consumer prices. Secondly, wind and solar power are well suited to provide negative control power at low cost during times they generate electricity. However, current market design in Germany is not well suited to attract wind and solar power generators as suppliers. While market design reforms were successful to attract entry of new players, product definitions and auction period continue to constitute an entry barrier for VRE.

[4] List of prequalified bidders, retrieved January 27, 2013, www.regelleistung.net/ip/action/static/provider.

5. Imbalance Settlement: Imbalance Prices and Cost Allocation

We use “imbalance settlement” as an umbrella term for processes in the balancing system that take place after real time (that is, the activation of control power). This involves two closely connected steps: the determination of the imbalance price (*Ausgleichsenergiepreis*) – the price that BRP have to pay for being out-of-balance, and the allocation of remaining costs or profits.

The imbalance price is crucial for economic efficiency, since it is the incentive for BRP to keep their portfolio balanced. A too low imbalance price leads to underinvestment in forecasts and adjustments of BRP schedules and a too high imbalance prices leads to overinvestments.

Vandezande et al. (2009) and Borggrefe & Neuhoff (2011) discuss different types of balancing settlement systems. ENTSO-E (2012a) provide an overview of balancing mechanisms and price determination in Europe. Van der Veen et al. (2010) compare the German and the Dutch settlement systems.

Usually, imbalanced BRPs that are on the “wrong” side (increase the control area imbalance) pay an imbalance price, while BRPs that are on the “right” side (decrease the control area imbalance) receive a payment. There is a large variety of pricing mechanisms in place: imbalance prices can be based on the average or the marginal costs of control power; can be differentiated between short and long BRP (two-price system) or not (one-price system); can be calculated based on the energy price of activating control power or include the cost of capacity reservation; and can include ad-hoc mark-up during critical situations.Sometimes prices are also determined as a function of the spot market price.

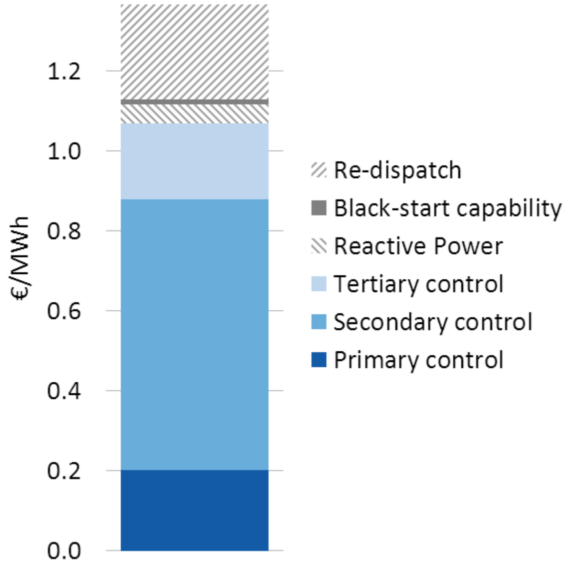

Figure 10. Control power is by far the largest ancillary service in terms of market size (2011).

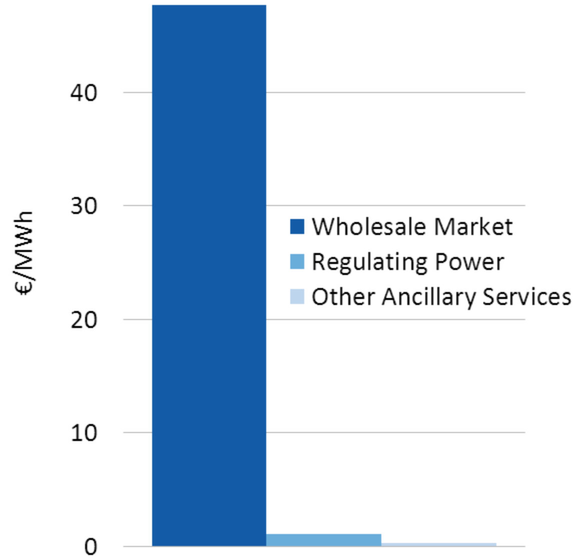

Figure 11. Control power is a very small market when compared to the wholesale market for energy (2011).

5.1. *Imbalance Prices and Cost Allocation Mechanism in Germany*

Just as control power market design, the determination of the German imbalance price is regulated by the Bundesnetzagentur and has been adjusted several times during the past years. The latest reform came into force in December 2012.[5]

The German imbalance price system is a one-price system, based on the average costs of control energy, and settled for time intervals of 15 minutes, corresponding to BRP schedules (Consentec 2012). The system is designed to be cost-neutral such that all costs for control energy are paid for by unbalanced BRPs. Since 2012, the price includes a mark-up of at least 100 €/MWh if more than 80% of all control power is activated. The revenues generated during those times are distributed to consumers via reduced grid fees.

The costs for control power reservation, however, are distributed to all electricity consumers on a pro-rata (€/MWh) basis.

There are two major sources of inefficiency in the German market design: first, economic theory suggests the imbalance price should be based on the *marginal* cost of control energy provision, not the average cost. Second, the costs of capacity reservation should be borne by those BRP that cause the need for power provision. Vandezande et al. (2009) propose to add the costs of capacity on the imbalance price and even propose to avoid capacity payments when procuring control power because costs are difficult to allocate. Both flaws cause the imbalance price to be too low[6] and constitute a positive externality. Hence, BRPs receive a too weak incentive to balance their portfolios. Specifically, VRE generators have a too weak incentive to forecast accurately.

5.2. *Incentives for Accurate Wind and Solar Forecasts*

TSOs and regulators often view the imbalance price primarily from a cost allocation perspective: the price is set in a way that the costs of control power are allocated and no profits or losses remain with the system operators. However, from an efficiency perspective, cost allocation is not the issue.

The crucial role of the imbalance price is that it provides a signal to BRP. For efficiency, it should reflect the marginal economic costs of solving imbalances by means of control power. In the welfare optimum, these marginal costs are identical to the marginal costs of avoiding imbalance by means of better forecasting and intra-day balancing.

While this is true for all sources of imbalance (section 3.1), it might be especially relevant for wind and solar power. Relative to their output, imbalances are larger than for other generators. In addition, forecasting methodology is relatively young and progressing quickly. Both for static and dynamic efficiency it is important that VRE generators see the true costs of forecast errors.

Summing up the results from this section, we find that balancing settlement systems should provide correct price signals to BRP, especially VRE generators. Therefore, the balancing prices should be a one-price system without punitive charges, based on the marginal costs of control energy deliver, and include the costs of control power provision. In Germany, the imbalance price is currently inefficiently low, because it is based on the average cost of control energy, and does not include the costs of capacity reservation.

6. Conclusions and Policy Recommendations

In this paper, we have compiled a broad overview on balancing system, focusing on the role and impact of variable renewables.

Four important results emerge from this study. Firstly, the required amount of reserved capacity depends on a multitude of factors. Wind and solar power forecast errors

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[5] Bundesnetzagentur BK6-12-024, www.bundesnetzagentur.de/DE/DieBundesnetzagentur/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6/2012/BK6-12-001bis100/BK6-12-024/BK6-12-024_Beschluss_2012_10_25.pdf

[6] More precisely, the price deviation between spot prices and imbalance prices is too small. Imbalance prices in times of scarcity are too low and imbalance prices in times of oversupply are too high.

power are only one of several important drivers. Secondly, the empirical correlation between reserved capacity and installed wind and solar capacity is weak. Specifically, German control power reserves could be decreased by 20% between 2008 and 2012, despite a doubling of VRE capacity during that time. Thirdly, the design of imbalance markets determines the incentives for BRPs for balance their portfolios. Specifically, it sets the incentives for VRE generators for forecast accurately. In Germany, two major external effects cause the imbalance price to be too low. Finally, the design of control power markets determines the incentives for VRE generators to provide control power themselves.

This leads to two conclusions. On the one hand, even significant amounts of variable renewables can be add to power systems without necessarily affecting the costs of control power provision dramatically. Control power supply does not seem to be a major issue for wind integration, at least not during the coming years. On the other hand, in Germany and elsewhere a lot can be done to improve incentives by changing the market design of control power markets and imbalance settlement systems.

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