How to deal with negative power price spikes?—Flexible voluntary curtailment agreements for large-scale integration of wind

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ABSTRACT

For the large-scale integration of electricity from renewable energy sources (RES-E), the German system seems to reach its limits. In 2009, the electricity wholesale market experienced serious negative prices at times of high wind and low demand. The feed-in system in Germany consists of a fixed feed-in price, a take-off obligation and a RES priority rule, and in practice only very restrictive use of RES-E curtailment. Exactly the latter is the problem. We argue that the overall performance of the system would improve seriously by lifting the restrictions on the use of voluntary curtailment agreements, while retaining the priority rule as such. Since generators of RES-E can only improve under this system reform, investment conditions improve, leading to higher installed RES-E capacity. This in turn implies that reduced wind output due to curtailment can actually be offset by higher wind output in all periods in which there is no problem.

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1. Introduction

The support of renewable energy sources (RES) has tradition in Germany and its success shows in large-scale deployment of renewable electricity (RES-E), especially wind energy. The share of RES-E in total gross electricity consumption is ca. 16.4% (BMU, 2010) and is projected to increase to 38.6% by 2020 (German Federal Government, 2010) and targeted at 80% in 2050 (BMWi, 2010). The promotion of RES-E in Germany already started in the 1980s with subsidized R&D and demonstration programs. In 1989, the 250 MW market stimulation program was introduced which called for the installation of wind power and was aiming at direct market diffusion. It guaranteed a fixed payment per kWh of electricity produced, together with investment incentives. The Electricity Feed-in Act was introduced in 1991. Grid operators needed to pay 80% of (average historical) electricity retail prices as feed-in tariffs for electricity generated by certain RES. Furthermore, it required electricity suppliers to accept the electricity fed into the grid. In 2000, the Renewable Energy Sources Act (EEG) replaced the Electricity Feed-in Act.

The key to success for the system has been the consequent and partly very generous pursuit of a feed-in system combining a fixed feed-in tariff, a take-off obligation for RES and a priority rule in case of network congestion. This system design reduced investors' risks and boosted investment (Klessmann et al., 2008). However, on windy days with low demand severe problems occur and the system

reaches its limits.[1] This is not due to "too much" wind energy production but due to a flawed market design. Faced with large-scale integration of RES-E, good market design is increasingly becoming an issue (cf. e.g. Newbery, 2010).

In 2009, the wholesale market in Leipzig experienced a couple of negative price spikes.[2] One problem of the current system in Germany is that the possibilities for curtailment of RES-E production (which is energy-not-supplied) are very restrictive by law. Basically, it is not allowed to curtail wind, while a conventional plant still produces unless in must-run status or is required to operate for system reliability. Clearly then the system constrains the two leverages for the market to operate efficiently: prices and quantities. Prices are fixed through feed-in tariffs (with the result that RES-E suppliers do not respond to market signals) and quantities are fixed by the priority rule and the restrictions on curtailment (voluntary and involuntary). The current policy debate is about how flexible the use of RES-E curtailment should be. The legal authorities opt for a very restrictive use to fulfill the political goals on environmental protection. The reason is if RES-E generators are curtailed while conventional plants are still running for economic rather than reliability reasons, the foregone production of RES-E would impede climate policy goals too strongly. Furthermore, negative prices increase the incentives to invest in flexibility measures (storage, demand side management and plant flexibility). Therefore, negative prices tend to accelerate

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[1] Somewhat surprisingly, the same difficulties are already arising due to photovoltaic feed-in, which has boomed in 2009 (BMU, 2010).
[2] See also Section 2.1 below and (Nicolosi, 2010) for a detailed discussion of these extreme price events.
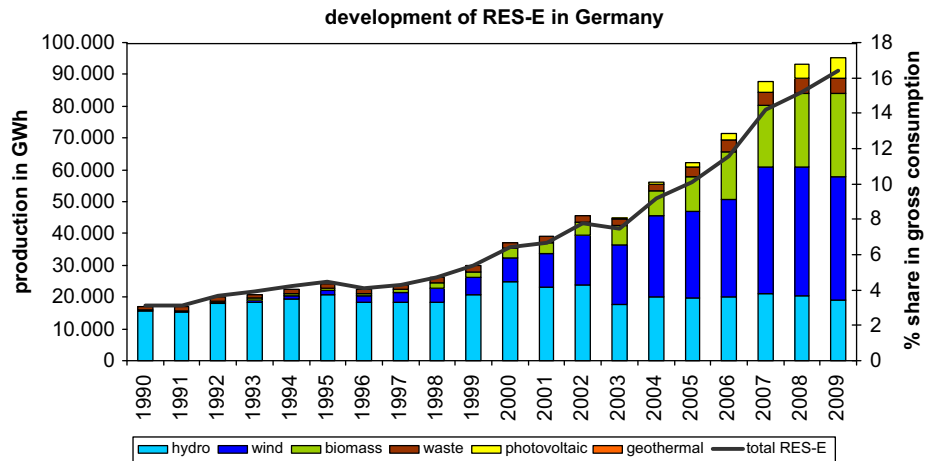
development of RES-E in Germany

Fig. 1. Development of RES-E generation in Germany 1990–2009 (data from BMU, 2010).

the energy transition towards a low-carbon power production. However, these incentives can be inefficiently strong and therefore costly to society.

In this paper, we argue in favor of flexible use of voluntary curtailment agreements (VCA), while leaving the feed-in system and crucially the priority rule intact. The latter secures that RES-E plant operators cannot worsen their situation as compared to the current situation as they can always opt to produce instead of being curtailed. As a result, the RES-E operators will always want to receive at least the feed-in tariff for the curtailed production. Depending on details, they might get more, which we call the "delta effect". The situation for RES-E investments remains stable or could be improved. This in turn means that the RES-E production foregone in these few hours, where RES-E generators might be partially curtailed, can be offset by additional RES-E output in all other hours due to a higher installed RES-E capacity. Lifting the restrictions on voluntary RES-E curtailment, while keeping the RES priority rule, therefore from an economic perspective increases system's efficiency (to the benefit of society as a whole). At the same time, the effect on climate policy targets may be negligibly small or even positive. Moreover, this small change would improve large-scale market integration of RES-E significantly.

With "efficiency" we mean standard micro-economic definition of maximization of social welfare, being defined as the (unweighted) sum of consumer- and producer-surplus. If, for convenience, we take demand to be inelastic, then this is the same as saying 'getting the same output at least cost'. Theoretically the environmental externality of CO_2-emissions should be part of the social welfare function. This approach, however, inevitably leads to an evaluation of the value of environment which is highly controversial. To avoid this difficulty, our approach is to take the environmental effect as a separate goal and stress the policy trade-off between economic efficiency (excluding the externality) and the environmental effect. We then argue that with our proposal the trade-off may be very small or vanish altogether, implying higher economic efficiency without impeding the environmental goal.

In Section 2 we first describe the events of negative prices on the wholesale market in Germany in 2009 and continue with a description of the feed-in system given by the EEG. Section 3 analyses the problem and argues for an approach with flexible VCA for RES-E. We do not discuss alternative systems like a premium system or a system with certificates; these may be good alternatives, but are currently not the focus of the short-term

debate on how to improve large-scale integration of RES-E under a system with feed-in tariffs.[3] Section 4 concludes.

2. Current system and its limits

2.1. Large-scale RES-E production and negative wholesale price

The support scheme to promote and deploy RES-E in Germany relies on a feed-in system with fixed feed-in tariffs. It is considered to be highly effective, with the main argument that the fixed feed-in tariff reduces investors' risks. If we ignore the typical large hydro systems, Germany has among the highest RES-E shares worldwide. Moreover, anticipated and targeted growth is high. Fig. 1 shows the development of RES-E generation in Germany.

It is obvious that especially in the last years the development of RES-E and therefore the support scheme were effective. The share of renewable generation is constantly rising and wind power which is characterized by intermittent feed-in has the highest share among all RES-E.

Yet the system is the victim of its own success. Growth and integration of RES-E were fast and substantial, but the system as it is seems to reach its limits. The large-scale integration of especially wind power, and lately PV, puts the market under stress (Borggrefe and Nüßler, 2009). Whereas until September 2008, spot prices at the EEX in Leipzig were not allowed to be negative, the EEX lifted this restriction and allowed negative bids down to a floor of $-3000€/MWh$.[4] Albeit counterintuitive at first glance, negative prices are basically efficient for non-storable goods such as electricity. Economically speaking, the negative price signals the inflexibility of existing plant stock that has been built in the past. The negative prices actually set strong incentives for future investments in flexible system components and storage opportunities. However, incentives can also be inefficiently strong and thus come at too high costs for society. The key is to find optimal prices, be this positive or negative. Since the allowance of negative prices the power exchange experienced a number of extreme negative price spikes, i.e. down to $-500€/MWh$ on October 4, 2009, as can be seen in Table 1 and Fig. 2.

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[3] A discussion on switching to a premium system will be of interest for the further development of the EEG in 2012.

[4] Before negative prices were allowed, trading was allocated pro-rata whenever the electricity offered at that price would exceed demand.

Table 1
Ten most negative prices at EEX spot market (data from Nicolosi, 2010).

Date	Day	Hour	Price (€/MWh)	Wind (MWh)	Load (MWh)	Residual load (MWh)
22.12.2008	Mon	3	−101.5	15.787	41.763	25.976
22.12.2008	Mon	4	−101.5	15.897	41.845	25.948
22.12.2008	Mon	5	−101.5	16.022	42.919	26.897
08.03.2009	Sun	7	−109.97	8.722	38.488	29.766
04.05.2009	Mon	2	−151.97	4.965	34.922	29.957
04.05.2009	Mon	5	−99.72	4.786	36.973	32.187
04.10.2009	Sun	2	−105.76	17.607	42.051	24.444
04.10.2009	Sun	3	−500.02	17.188	40.874	23.686
04.10.2009	Sun	4	−100.09	17.072	40.176	23.104
24.11.2009	Tue	4	−149.94	17.614	50.041	32.427
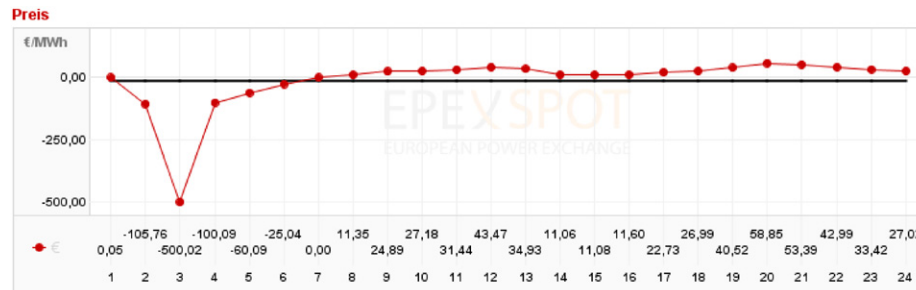
Fig. 2. Negative price spike at EEX on October 4, 2009.
Source: EEX, 2010

Another negative price spike occurred at the end of December 2009, going down to about −250 €/MWh.[5]

Most of these negative prices arose as a result of a combination of low demand due to weekend or national holidays and strong supply of wind energy, creating a situation where the large-scale wind energy production and priority feed-in forced inflexible conventional plants to be ramped down to must-run production. To avoid the costly ramping down, inflexible conventional power plant generators will bid into the market with negative prices.

We see several reasons why inflexible bidders, in most cases these are base load plants, accept negative prices and continue to produce. Firstly, the plant operators are not willing to ramp-down due to high start-up costs and due to opportunity costs. The opportunity costs arise when prices above variable costs occur in the following hours after a possible ramp-down and the plants cannot ramp-up quickly in the hours immediately after the negative price event (Andor et al., 2010a). In other words, running down from 90% to 50% in 1 h with negative prices may miss production in several hours directly after this 1 h. This means not only foregone revenues for plant operators, but also higher system costs and thus inefficient market design. In case wind energy production decreases sharply in these hours this part of demand must be produced by other plants that are more expensive per definition. Secondly, plants may have obligations in different markets such as ancillary services. A generator that is contracted for the provision of negative balancing has to be able to reduce production to a certain extent if needed and thus has to stay running with at least the corresponding production.

The events with negative prices triggered a heated discussion on how to proceed with large-scale integration of intermittent RES-E production. One of the main points in the debate is the priority feed-in and the restrictive rules of RES-E curtailment (voluntary and involuntary). RES-E plants are allowed to be curtailed only as a last resort, for example, if network reliability is threatened otherwise. The priority feed-in of RES-E as well as the rules on curtailment is explained in the next sections.

2.2. System integration of RES-E under the EEG: priority feed-in

Energy supply and market design in Germany rely on the Energy Act 2005 (EnWG, 2005). §1(1) of the Energy Act states that energy supply shall be "secure, affordable, consumer-friendly, efficient and environmentally friendly".[6] Clearly, the mandate is to balance between different policy goals. The law does not describe how to weigh the different, possibly conflicting, goals. For the support of RES-E §1 EEG states that the purpose of the law is to facilitate the sustainable development of energy supply, particularly for the sake of protecting the climate and the environment, to reduce the costs of energy supply to the national economy (also by incorporating external long-term effects), to conserve fossil fuels and to promote the further development of technologies for the generation of electricity from renewable energy sources (EEG 2008).

The RES-E support system relies upon three key elements that are as follows:

1. A fixed feed-in tariff for RES-E, with a take-off obligation.
2. A priority rule for RES-E vis-à-vis non-RES-E.
3. No or only very restricted use of RES-E curtailment.

The EEG guarantees fixed feed-in tariffs for the following RES: hydropower, landfill gas, sewage treatment plant gas and mine gas, biomass, geothermal energy, wind power, solar radiation, e.g. photovoltaic, solar thermal. The feed-in tariffs vary with the generation capacity of the installations and the type of RES. The

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[5] Upon closer examination, it turned out that at this occasion the market did not clear and prices did not fall to −3000 €/MWh only because the Federal Network Agency (BNetzA) reacts and allowed transmission system operators (TSOs) to limit their bids at about −250 €/MWh.

[6] In original EnWG §1(1): "Zweck des Gesetzes ist eine möglichst sichere, preisgünstige, verbraucherfreundliche, effiziente und umweltverträgliche leitungsgebundene Versorgung der Allgemeinheit mit Elektrizität und Gas."
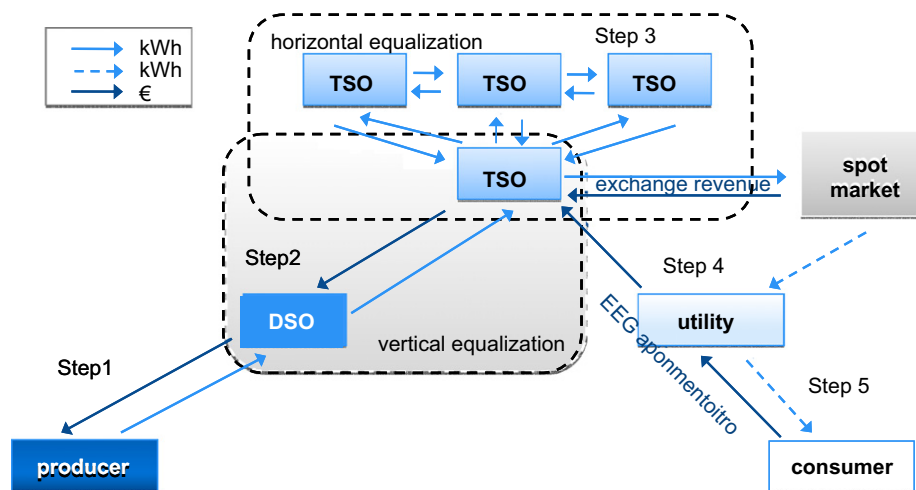
Fig. 3. Equalization scheme (adapted from BNetzA, 2010a).

tariffs are guaranteed for a fixed period of time.[7] Tariffs for newly invested installations are decreased every year by a certain percentage in anticipation of technological learning. The costs of the feed-in tariffs are passed through to the end-users and ultimately find their way into the end-user energy prices.

Following §8(1) EEG, grid system operators shall immediately and with priority purchase, transmit and distribute the entire available quantity of RES-E. Since the revision of the EEG in 2009 RES-E is sold at the European Power Exchange (EPEX)[8] spot markets by the transmission system operators (TSOs), who are in charge of this RES-E marketing. The mechanism to implement this marketing function by the TSOs is arranged in the equalization scheme ordinance (AusglMechV), relying on §64(3) EEG. The AusglMechV regulates the rules for the transmission and distribution of RES-E feed-in between grid system operators (vertical and horizontal equalization) as well as the marketing of RES-E on day-ahead and intraday spot markets by TSOs. Fig. 3 gives an overview of the equalization scheme.

The RES-E producers feed their electricity production into a network node of a grid system operator, mostly distribution system operators (DSO), who pays them the feed-in tariff. As a second step the DSO transmits the RES-E to the next TSO who compensates the paid feed-in tariffs vertically. The horizontal equalization between the four TSOs in Germany conduces to balance the burden of RES-E feed-in. The TSOs then have to market the RES-E feed-in on the spot markets, where the utilities purchase the electricity which they offer to end consumers. The TSO has to accept the market price at the spot market. The monetary difference arising from this can be passed on to consumers as EEG apportionment. The customers are charged with EEG apportionment by their utility which forwards the payments to the TSO for financial equalization. While in 2010 this apportionment charge accounted for 2.0 cents/kWh in the price of electricity consumed, it will increase significantly in 2011 to 3.5 cents/kWh (eeg-kwk.net, 2010).

The key problem is that this support design does not allow an economically efficient and market-compatible integration of large supply of RES-E, especially wind energy (see also Hiroux and Saguan, 2010). We argue in this paper that this is a problem of poor market design, not of "too much" wind. The problem gets more visible if network constraints occur. Wind energy is mostly produced in the coastal regions in the north, whereas the load

centers are further south.[9] The transmission network north–south is increasingly congested and needs to be reinforced to allow large-scale transport of wind energy. If the grid needs to be upgraded, the grid system operator is obliged to reinforce the grid.[10] While in 2005 the necessary reinforcement of the German transmission grid was estimated by the German Energy Agency (dena) at 850 km, it was recently determined between 1700 and 3600 km (dena, 2010). In practice, the required grid reinforcement advances very slowly. This is mainly due to the long permitting procedures for transmission grid construction.

2.3. Rules on RES-E curtailment: voluntary and involuntary

As explained, the TSOs are subject to a RES-E take-off obligation. With large-scale integration of wind, further feed-in of RES-E can sometimes be uneconomical or may threaten system reliability. The conditions under which the TSOs are allowed to curtail RES-E are specified by law and are very restrictive. For the further discussion we have to differentiate between voluntary and involuntary curtailment options.

The TSOs are allowed to curtail RES-E plants with a capacity of over 100 kW involuntarily if the network is already congested with electricity from other RES-E plants (§11 EEG and §12 EEG hardship clause),[11] and every RES-E and conventional plants in case of severe threats to system reliability (§§13(1) and 13(2) EnWG). Every sort of curtailment results in a loss of RES-E production and thereby forgone revenues for the RES-E plant operators. Whether they get compensated for involuntary curtailment, depends on the circumstances which forced the curtailment. In the cases as specified in §11 and 12 EEG the TSO has to compensate at least the forgone feed-in tariff revenue.[12] In cases of the obligated general system responsibility defined in the EnWG especially in §13(2) no compensation is required for losses in feed-in tariff revenues to the RES-E generator. The costs for such feed-in management can normally be socialized through network charges.

According to §8(3) EEG in conjunction with §15 (contractual agreement) the obligations for the grid system operator pursuant to §8(1) shall not apply where RES-E plant operators and grid system operators agree by contract to deviate from priority

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[7] For most technologies this period is 20 years.
[8] Formerly European Energy Exchange (EEX).

[9] The problem will exacerbate with the planned offshore wind installed in the future.
[10] The costs of network reinforcement are socialized over network users.
[11] Newly installed plants need to be equipped with technical provisions for such curtailment.
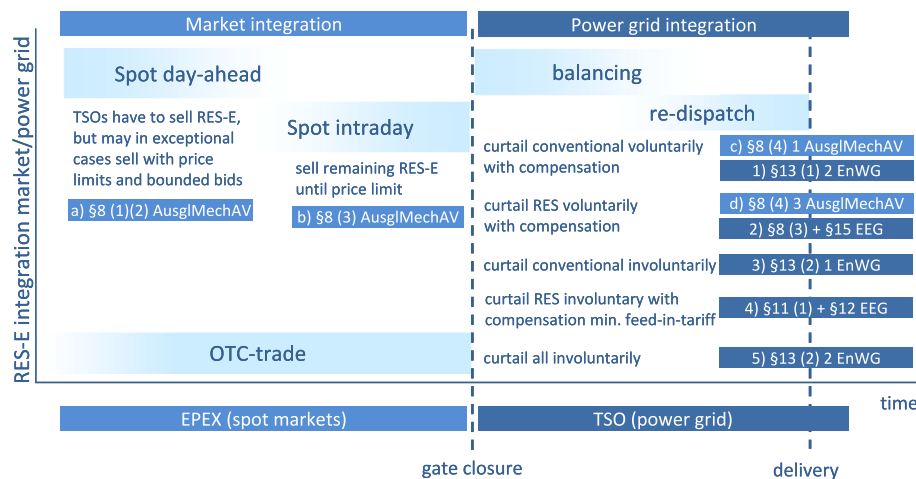[12] Less the expenses saved.

Fig. 4. Curtailment rules and departure from RES-E marketing in the current system.

purchase in order to better integrate the installation into the grid system. This means that at least theoretically there already is a legal possibility for VCA, but the use is restricted by Federal Network Agency (BNetzA) regulation: Firstly, for voluntary curtailment contracts pursuant §8(3) EEG the compensation might be lower than the feed-in tariff because the curtailment tariffs have to be approved efficient[13] by the BNetzA.[14] Secondly, a ranking of feed-in management measures and therefore exceptions from priority feed-in is given in guidelines from the BNetzA (2010b). One of the main messages of these guidelines is that voluntary curtailment of RES-E is considered to be inefficient if the compensation is higher than actual feed-in tariffs and the use might impede the climate policy goals. As before, voluntary curtailment of RES-E is only regarded as a last resort.

Another point is the RES-E marketing obligation held by TSOs. The negative price spikes in the second half of 2009 triggered justified concern for the liquidity of the TSOs. As a result the rules to diverge from this obligation in exeptional cases as set in the ordinance (AusglMechAV 2010, §8) have been adjusted by the end of 2010. Formerly exceptional cases were situations when marketing under the normal procedure is expected to lower the TSOs revenue and disproportionally burdens their liquidity. Especially those hours were brought out when the forecasted wind energy feed-in was predicted to add up to 60% of the total capacity installed in Germany and/or hours when the total load amounted to only 60% of the annual peak load in 2009. With the revision of the ordinance the criteria for exception cases was changed and now a TSO may gradually take predefined counter-measures to ensure system stability whenever a call for second auction at the energy exchange indicates market failure.

To avoid unreasonably negative prices which will cause an unbearable burden, the TSOs are allowed to use price limitations for their bids offered in the day-ahead and intraday market. The price limits shall be set within a bandwidth from -150 to $-350€/$MWh. The specific prices within these limits shall then be determined randomly to prevent strategic action. Information on the hours with price limits and the price limits themselves is published anonymously to increase transparency. The next step, if the problem persists, is the use of VCA with generators and/or

consumers. Here again conventional generation has to be addressed first and only as a last resort RES-E generators may be curtailed.[15] The compensation for such VCAs shall not be higher than the market price which would arise in the curtailment hour on the day-ahead spot market if the curtailed amount was bid into the market as demand (load). As well as in the case of §8(3) EEG the compensation for RES-E curtailment might be lower than the feed-in tariff paid in case of take-off obligation. Therefore, it is very unlikely that RES-E operators will enter voluntary agreements. The RES-E operator will have to assess the likeliness of being curtailed later on involuntarily and without compensation according to §13(2) EnWG.

Fig. 4 sums up the above explained RES-E curtailment rules in the current system. It gives an overview of TSOs' divergence from marketing of RES-E on the power exchange according to §8 AusglMechAV (indicated as a–d) and of exceptions from priority feed-in as given by the BNetzA guidelines for feed-in management (given by number 1–5).

Summing up, we observe that under the current regime, RES-E generators do not directly participate in the electricity market. They receive a fixed feed-in tariff for their electricity production; therefore electricity market prices are not relevant for them and they do not react to changes. Thus RES-E generators are not confronted with the risks and advantages of the electricity market. The main responsibility is taken by the TSOs who are in charge of the integration of RES-E into the grid and into the market. This take-off obligation is the flipside of the fixed feed-in tariff system. Obviously, with feed-in tariffs above market prices, RES-E production would not be taken off without such an obligation. The strict procedure and many restrictions in the law and ordinances to curtail RES-E should ensure a priority feed-in of RES-E into the grid and avoid short-term sacrifice of potential RES-E generation on environmental-political grounds unless absolutely necessary.

However, it is evident that if prices are fixed by the feed-in tariff on the one hand and quantities are fixed by very restricted use of curtailment (voluntary and involuntary) on the other hand, the market loses degrees of freedom to perform its market-clearing function, at the expense of system-wide economic efficiency. In the following we will argue that these restrictions are not necessary and that flexible application of VCA of RES-E can

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[13] The term "efficient" is not specified in the guideline. The context suggests, however, that it does not refer to purely economic efficiency as applied in our paper.

[14] The BNetzA has to examine whether these costs are efficient pursuant to the provisions of the EnWG and if need for curtailment is not owed by the system operator himself.

[15] To make use of these instruments for the exception cases the TSOs have to announce their intention to the BNetzA and the total hours are limited to 100 in total per TSO in 2010.

be left to the market without obvious difficulties in achieving an energy system which fulfils the requirements given by §1(1) EnWG: a secure, affordable, consumer-friendly, efficient and environmentally friendly supply of electricity.

3. Flexible use of VCAs

Above we have seen that the current system design can lead to severe problems; in fact, markets may not clear and therefore prices may, without allowed price limits, go down to the administrative lower limit, which has been set at $-3000€/MWh$. We argue that such extreme negative prices are economically inefficient and are the result of flawed market design; they are not the result of "too much" wind, but result from poor market integration of RES-E.

As already mentioned, the current system of the promotion and integration of RES is characterized by the following three elements:

1. A fixed feed-in tariff for RES-E, with a take-off obligation.
2. A priority rule for RES-E vis-à-vis non-RES-E.
3. No or only very restricted use of RES-E curtailment.

Upon economic reflection, the market flaw is immediately clear. These three conditions taken together imply that both the price and the quantity are fixed. In economic terms, the market does not have sufficient degrees of freedom, because both market adjustment tools (price and quantity) have been constrained. The solution follows quickly; the market needs to have at least one way to be able to adjust. We will argue to lift the restrictions on voluntary RES-E curtailment. We argue to change the system retaining a fixed feed-in tariff for RES-E and a take-off obligation, and retaining the priority rule for RES-E, but allowing flexible VCAs. If the use of voluntary curtailment is allowed in a more flexible way, the market can use quantities to restore market equilibrium. The question arises what the equilibrium outcome of such a system might be?

The key notion is that both the TSOs and the RES-E suppliers should have an adequate incentive to engage in voluntary curtailment if this is profitable and efficient. A RES-E supplier will only want to be curtailed if he receives at least the feed-in tariff which he would have received if he had not been curtailed. Therefore, the minimum price for curtailed RES-E is the associated feed-in tariff.[16] Note that this is a payment for power that is actually not produced. Therefore, RES-E producers can only improve their position. In Coasean terms, the priority rule allocates production rights to RES-E generators. Given the priority rule, RES-E plant operators will be proposed to receive compensation at least as high as the feed-in tariff for being curtailed, because, given the priority rule, they can always opt to produce and receive the feed-in tariff.

Due to their marketing obligation we assume that the TSOs are actually incentivized to minimize the costs. In more practical terms, TSOs may be subject to an incentive-scheme that allows retaining a fraction of profits made. The affected TSO will implicitly or explicitly organize a tender for VCAs. Depending on the competitive pressure on the tender market for VCAs, the RES-E suppliers will be able to receive a mark-up "δ" on top of the feed-in tariff. Therefore, the price paid for RES-E-not-supplied is "feed-in tariff$+\delta$". Moreover, we assume that the feed-in tariff-part of the compensation to be paid out to RES-E plant operators for curtailed quantity are fully passed through to end-users. The TSO may be made eligible to bear the costs of δ payments though.
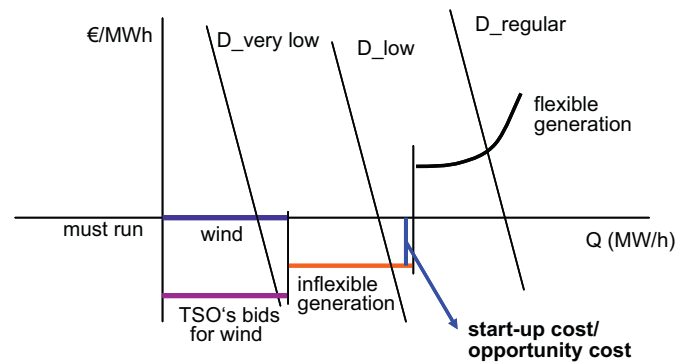

Fig. 5. Merit order without VCA.

Under these two conditions, the TSO starts to curtail if and only if, the price on the market is $-\delta$, and thus depending on the size of δ, at slightly negative market prices.[17] Basically, the price signals to curtail inflexible conventional plants instead of flexible RES-E as soon as it gets more expensive. Market forces will secure that exactly this happens. Hence with VCAs the TSO is given a lever for cost-efficient dispatch and can thus decrease overall system cost. This is actually the economically efficient outcome. The key to see the improved economic efficiency is to realize that the merit order is restored.

We note in conclusion that the possibility of flexible use of VCAs introduces incentives for flexibility addressing both the RES-E suppliers and the TSOs and, as RES-E starts to respond to market conditions, strengthens the market link between RES-E and non-RES-E. Therefore, market compatibility and RES-E integration would substantially be improved. We illustrate the effects on the merit order and on market production graphically taking the example of wind energy feed-in.

In Fig. 5, we depict the merit order *without* flexible VCAs. For convenience, we have excluded all must-run units in this figure. We have depicted three different states of market demand: regular, low and very low. Without VCAs, wind energy production will be utmost left in the merit order before all other suppliers; although the variable production costs are zero, the wind energy suppliers will always receive the feed-in tariff and will not have an incentive to reduce their production. In fact, due to the take-off obligation it is mandatory for the TSOs to bid RES-E into the market. With very low demand and without price limitation, the market will not clear efficiently and prices drop till the administrative lower limit ($-3000€/MWh$) given by TSO's bids for wind in the figure; ultimately the TSO will have to intervene to guarantee system reliability. Focusing on low demand, we have seen above that following the effects of high start-up and opportunity costs, inflexible plants will find it rational to bid negative prices. Although the marginal costs of production of inflexible plants are thus actually negative (i.e. due to opportunity costs, it is costly not to produce), whereas marginal costs of wind energy is zero, wind energy supply would nevertheless be prior to inflexible plants in the bidding schedule.[18] This implies a costly inefficiency for the overall system and for society. From an economic efficiency point of view, we should first curtail wind energy production and then curtail inflexible plants.

Fig. 6 shows the case *with* VCAs. Due to lifting the ban on RES-E curtailment, we find that the merit order is restored again,

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[16] Note that in practice, there exist several different feed-in tariffs, depending especially on technology and age of RES-E plant.

[17] In case the cost for the feed-in tariff paid out for curtailed RES-E should be borne by the TSO, the TSOs start curtailment if the market price is more negative than the curtailment price. The curtailment price (feed-in tariff$+\delta$) would then establish the natural negative price limit on the wholesale market.

[18] As RES-E bids are made by TSOs, we depict the marginal cost of wind and the mandatory bid without price limitation.
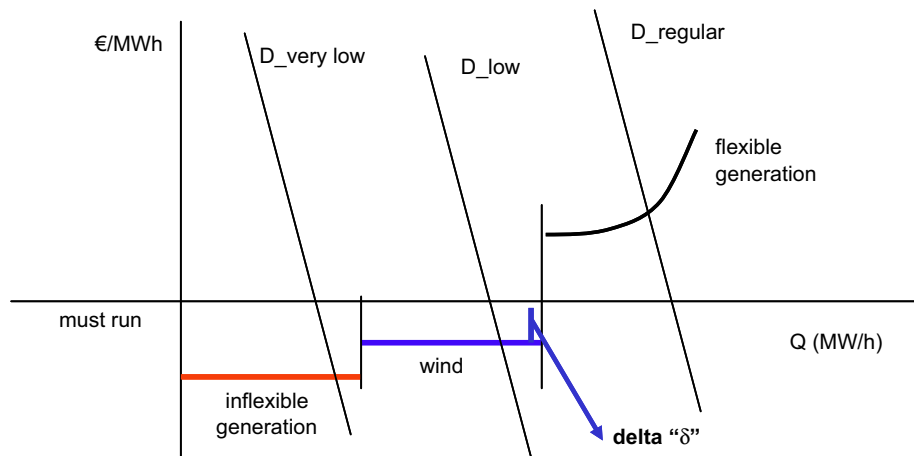
Fig. 6. Merit order with VCA.

thereby establishing a potentially substantial efficiency increase. As derived above, with VCAs, RES-E producers will have a natural incentive to respond to (extreme) market signals and will be voluntarily curtailed if market prices are sufficiently low, which of course is exactly what low prices try to signal. Assuming that the mark-up following from the tender is δ, we find that RES-E will be curtailed if the market price reaches $-\delta$. It is straightforward to see that if opportunity costs of inflexible plants are higher than that, wind will be curtailed first and then only will inflexible plants be curtailed, thereby restoring the merit order. We can conclude that VCAs can substantially improve system-wide efficiency and thereby improve economic performance to the benefit of society as a whole.

If RES-E producers receive the feed-in tariff plus δ for curtailed production, they cannot be worse off. In fact, the "delta-effect" actually improves the situation of RES-E. Consequently, the investment incentives for RES-E remain at least stable and improve ceteris paribus. This is crucial for our main argument. The use of curtailment leads to less RES-E production while it would actually be available and thus this seems to contradict the climate policy goals. The delta-effect mitigates this drawback, and can actually compensate the effect. By improving investment conditions, the delta-effect will increase total installed RES-E capacity. While curtailment happens only in a couple of hours when low demand and high wind cause prices to be negative, the increase in total installed capacity allows more output in all other hours. In sum, the delta-effect can quite easily offset the curtailment effect, with the result that total RES-E production could actually increase. In that case, VCAs would in fact contribute to climate policy goals.

The net effect depends on δ, which depends on tendering; without further details on tendering design, it is impossible to tell how high δ could possibly be. A back-of-the-envelope calculation can roughly illustrate the order of magnitude of additional capacity required to offset the effect of curtailed wind. Between October 2008 and November 2009 there have been 71 h during which the wholesale price for electricity was negative and during these hours the wind feed-in has been not higher than 18 GWh (Nicolosi, 2010) and in many hours less as can be seen in Table 1. Importantly, however, the expected value of curtailed wind within each of these hours is far less than the maximum feed-in at that moment. First, each event with negative prices comprises peak moments with significant curtailment and many hours with insignificant curtailment.[19] Second, in a majority of cases, the

Table 2
Overview of the back-of-the-envelope-calculation of the delta effect.

Number of events with negative prices	71	h/a
Maximum feed-in during these events	18,000	MWh/h
Curtailment factor	0.1	
Curtailed energy to be compensated for	**127,800**	**MWh/a**
Full-load-hours equivalent of a wind turbine	1300	h/a
Lifetime of a wind turbine	20	a
Additional capacity needed for compensation	**4.92**	**MW/a**

events themselves will be insignificant, leading to minor curtailment. We would expect a high probability of hours with low curtailment and a low probability of hours with high curtailment. If we assume that the curtailment factor is 10% (i.e. 0.1 of total wind generation) and if we make the conservative assumption of wind turbine operation equivalent of 1300 full load hours per year, and if we further assume a lifetime of 20 years for the additional capacity, we find that roughly 5 MW additional wind capacity would offset the loss of wind energy due to voluntary curtailment in 1 year (Table 2).[20]

There is a second-order effect which is not captured in the back-of-the-envelop calculation above. If the delta-effect leads to more wind capacity, the number of hours with negative prices increases. Thereby the number of hours with curtailed wind energy would increase and conversely, the number of hours with an offsetting effect decreases as time passes. There are counter-effects though. Firstly, as time passes, inflexible plants will be replaced by flexible plants, and secondly, storage options and flexible demand will start to relieve the problem. Given sufficient time for the system to adjust, we will observe less rather than more events with negative prices.

An important question for policy reform always concerns income effects ("who gains and who loses"), as this usually decisively determines political and social acceptability. We distinguish three different interest groups. First are the RES-E suppliers. As already noted, as long as the feed-in tariff, the take-off obligation and the RES-E priority rule remain, the RES-E suppliers can only gain by VCAs, due to the "delta-effect". Therefore, we argue that RES-E suppliers cannot be worse off, and will likely be better off by δ. Second, we analyze the effects for the conventional power plants. We have to make an assumption on trade and markets. We assume that spot market prices and

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[19] For each single event where negative prices occur, we would expect curtailment to be normally distributed around a peak moment.

[20] The assumption of a 10% curtailment factor is critical. But even if we assume the absolute worst case that whenever prices are negative all wind was curtailed, additional capacity required to offset the missed wind generation is only 50 MW.

contract prices are fundamentally related. Thus, if spot prices are systematically low, this will ultimately be reflected in lower contract prices. Where this is not the case, traders have been surprised by unexpected events which invariably lead to market inefficiencies. Furthermore, we assume for our purposes here that the market functions well and that all cost changes in the value chain are ultimately passed through to end-users. The owners of inflexible plants that still produce with very low or negative prices pay the bill of the system flaw without VCAs. Consequently, if VCAs are introduced they actually gain because market prices will be less negative. To get the perspective right: These producers will not profit more, but they will lose less in the above mentioned hours where voluntary curtailment is needed. Thirdly we examine the end-users. There are two effects to be considered. Firstly, directly or indirectly, end-users gain from negative prices. A negative price means that a user actually receives money for consumption. Large end-users might buy directly from the market or have market-like contracts with flexible prices. Small end-users will benefit ultimately if retailers benefit and if competition secures that these benefits are passed through. If VCAs mean that prices will be less negative, then end-users will lose from a system change. Secondly, if VCAs improve system efficiency, and if efficiency improvements are ultimately passed through to end-users, the end-users might actually benefit from a system change. The increased costs of the RES-E subsidies (the "delta-effect" which even increases if this effects leads to more wind output) will ultimately be borne by end-users. However, if the entire system benefits and markets and the regulator secure that these benefits are ultimately passed through to end-users, we must logically conclude that the end-user will be better off on balance.

The underlying cause of negative prices is that the system contains too much inflexibility, both on supply and the demand side. Many investments have been made in the past, when intermittence and flexibility were not so important. Inflexibilities may have been optimal at the time of investment, but turn out to be the problem now. To repair this, the system can increase flexibility of load and generation as well as develop more storage options. This requires investment, takes time and is costly. Negative prices actually set an incentive for investors to create flexibility. Therefore, less negative prices due to the use of VCAs might reduce the incentives to invest in flexibility. However, the argument is similar to the merit-order argument. As argued, without VCAs prices can be inefficiently negative and VCAs could restore optimality and therefore guarantee more efficient incentives for flexibility.

The overview of the overall assessment of the feed-in system *without* VCAs versus feed-in system *with* VCAs is given in Table 3.[21]

The entries in the table clearly suggest that allowing VCAs, while retaining a feed-in tariff, a take-off obligation and a RES-E priority rule, improves overall performance. Market compatibility improves because RES-E suppliers will respond better to market signals, especially in extreme situations where it gets important. This is also the main advantage over the proposal made by Andor et al. (2010b) who suggest to limit the obligation for the TSOs to market RES-E to those cases when marginal cost is recovered simulating a market situation and thus stabilizing market prices. Compensated curtailment would then occur whenever marginal cost exceed the market price.

[21] It may be pointed out that we do not compare with alternative models for RES promotion, like a premium model (like in Spain) or a certificates-model (like in the UK). These models may have their attractions, but would in Germany require too large a system reform to be politically feasible in the short-run. We note, however, that there is some discussion to introduce a premium model by 2012.

Table 3
Overview of the assessment of a system change.

Criterion	Feed-in *without* VCA	Feed-in *with* VCA
Market compatibility	–	O
Efficiency	–	+
Effectiveness	++	+/++
Integration	–	+
Income redistribution effects		
RES-E suppliers	O	O+δ
Conventional plants	–	O
End-users	+	+/O

System efficiency improves, primarily because the merit order will be restored. The system might get somewhat less effective with respect to achieving climate policy targets in the short term, but we stress that the short-term effect may be offset in the longer run. We have seen that VCAs will reduce RES-E output in the short run, but will increase installed RES-E capacity and may therefore increase overall RES-E output in the long run. Therefore, as the effectiveness of a feed-in system is high because of low risk, we would argue that introducing VCAs would not seriously impede this advantage of a feed-in system. Integration improves substantially as there will be natural lower price limits that are slightly negative and that reflect market conditions. A feed-in system with VCAs is very well able to handle negative prices. Lastly, on balance we would expect that most stakeholders could gain from a system change. Importantly, RES-E suppliers cannot be worse off.

4. Conclusions and outlook

The current feed-in system for RES-E deployment relies on fixed feed-in tariffs, a take-off obligation and a RES-E priority rule, and as mentioned, strongly restrictive rules on RES-E curtailment. This paper contributes to the debate on large-scale integration of RES-E and makes a policy recommendation to improve the feed-in system in general and in Germany specifically. More precisely, we argue in favor of wide use of flexible VCAs for RES-E, while retaining the priority rule for RES-E.

The electricity wholesale market in Leipzig experienced severely negative prices in the second half of 2009. The events occurred on windy days with low demand. Due to restrictions on RES-E curtailment, prices and quantities are fixed, and it is no surprise that the market has difficulties to perform well. These events triggered a debate on how to proceed, leading to a discussion on circumstances under which curtailment of RES-E can be applied. While recognizing the problem, the authorities tend to be very restrictive with (voluntary) curtailment agreements in order to avoid wasting RES-E production while available (using the wind while it blows). We argue to allow more flexibility for VCAs which would improve the market performance considerably.

The key problem is that curtailment of wind energy while wind blows seems at first glance to sacrifice RES-E while they are actually available and thus appears to contradict climate policy targets. We argue that there is a counter-effect which at least mitigates and possibly offsets this effect. Retaining the priority rule implies that RES-E producers will always have the option to produce and collect the feed-in tariff if desired. Therefore, RES-E operators will not want to enter into a VCA if they do not at least receive compensation as high as the feed-in tariff for foregone output. In fact, depending on details, we would expect a delta improvement for RES-E producers to be attracted into VCAs. Thus, RES-E investment conditions improve and therefore we expect larger installed RES-E capacity with the result that there can be

more RES-E output in all hours when the system is not constrained, which can easily offset the curtailed RES-E. Therefore, allowing flexible VCAs, while keeping the priority rule, would increase the total system's efficiency to the benefit of society, while the reduction in total RES-E production may be small or total RES-E supply may actually increase.

A second set of objections to flexible VCAs might be the lower incentives to increase flexibility in the system (storage, DSM and more flexible power plants). The underlying cause of negative prices is that the system contains too much inflexibility, both on the supply and on the demand side. Negative prices actually set an incentive for investors to create flexibility. However we argue that prices without VCAs can reach an inefficient level of negativity and would then undesirably increase system costs. Therefore, the overall system might be too costly. VCAs could restore optimality and thus guarantee more efficient incentives for flexibility.

An issue for further research concerns implementation. One open question arising from the concept of VCAs is about the different steps in the procedure that VCAs could target. It is related to the extent to which the present restrictions can be relieved. As of now renewable electricity can only be curtailed as a last resort after all other market or scheduling options have been exhausted. Leaving the spot markets untouched and implementing VCAs of RES-E equal to the voluntary curtailment of electricity from conventional sources would require the least change to the present procedure described in Section 2.3. The next level would be to allow RES-E to participate in balancing service markets offering an efficient amendment to the use of conventional balancing.

An interesting development is that the same discussion seems to shift towards smart distribution grids. In order to make smart distribution grids work, the system operator will have to have some authority over the system including the network, load and generators. For the smart distribution grids, the latter typically concerns distributed generation which most often is renewable.

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