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Large-Scale Wind and Solar Integration in Germany

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February 2010

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under Contract DE-AC05-76RL01830

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Abstract

This report provides key information concerning the experience of two German transmission system operators with the integration of 25 gigawatts of wind and 7 gigawatts of solar power capacity into their systems, along with their efforts to mitigate its impacts on the electric power system. The report has been prepared based on information provided by managers and engineers from Amprion GmbH and 50Hertz Transmission GmbH to representatives from the Bonneville Power Administration (BPA) and Pacific Northwest National Laboratory (PNNL) during their visit to Germany in October 2009. The trip and this report have been sponsored by BPA's Technology Innovation office. Learning from the German experience could help BPA engineers to compare and evaluate potential new solutions for managing higher penetrations of wind energy resources in their control area. A broader dissemination of this experience will benefit wind and solar resource integration efforts in the United States.

Executive Summary

This work, and the trip to Germany that preceded it, have been sponsored by the Technology Innovation office at Bonneville Power Administration (BPA).

In October 2009, John H. Pease, manager of Technology Innovation at BPA, and Dr. Yuri V. Makarov, chief scientist in the Power Systems Group at the Pacific Northwest National Laboratory (PNNL), visited two major transmission system operators (TSOs) in Germany, including Amprion GmbH (Amprion) in Pulheim, and 50Hertz Transmission GmbH (50Hz-T), formerly the Vattenfall Europe Transmission GmbH, in Berlin, to learn more about their experience with handling large amounts of renewable generation. PNNL's participation was sponsored by the BPA Technology Innovation office.

The visit to Germany was organized by PNNL and Dr. Bernhard Ernst, manager of Front Office System Planning for Amprion and Christian Scholz, Control Area Cooperation for 50Hz-T. During meetings at the TSOs, managers and engineers from Amprion and 50Hz-T provided the U.S. delegation with extensive information about details of the German power system and energy market, which are operated successfully with 25 gigawatts of installed wind power capacity and 7 gigawatts of installed solar power capacity. This report summarizes key elements of these systems based on the information and materials provided by our German colleagues. BPA and PNNL are very grateful to their German colleagues for their help and cooperation in this project.

The BPA currently has more than 3 gigawatts (GW) of installed wind power capacity, and plans to install about 2,500 megawatts (MW) of additional capacity by 2012 [1]. Anticipating potential problems with managing large amounts of wind power in its system, BPA is currently looking for advanced solutions to mitigate negative impacts of variability and uncertainty caused by these resources. In a recent presentation, BPA's executive vice president of corporate strategy, Elliot Mainzer indicated that "BPA is committed to finding innovative solutions to meet the renewable resource objectives of the Pacific Northwest by reliably and cost-effectively extending the integration capability of the BPA balancing authority while honoring our statutory obligations to our preference customers and the operational limitations on the Federal hydroelectric system" [1]. The wind integration team (WIT) at BPA has already proposed and implemented several solutions to help minimize adverse impacts of wind power production. They include:

- implementing transmission system enhancement projects
- introducing wind integration rate charges for wind generators to cover additional balancing costs incurred
- establishing new reliability protocols requiring wind generators to adjust their schedules down to actual output if they substantially under-generate relative to their schedule or reduce output if they substantially over-generate relative to their schedule
- developing a wind forecasting system by March 2010
- adding a BPA "wind desk" to support dispatchers in the efficient use of wind, hydro and other generation; creating sub-hourly transmission scheduling protocols to allow power schedule changes to better match within-hour variations in wind generation

- allowing wind operators to sell power when wind output quickly increases
- allowing wind generators to purchase balancing capacity from suppliers other than BPA
- creating a third-party market for balancing services
- using dynamic schedules to allow wind generators physically located on BPA's system to be remotely balanced by other utilities using electronic signals
- evaluating energy storage and smart grid technologies' potential in the BPA footprint
- implementing the area control error (ACE) diversity interchange (ADI) program
- employing self supply options for within-hour balancing services available for generator owners and operators, and evaluating the benefits of participating in cooperation or consolidation schemes with the other balancing authorities [1], [2].

The BPA Technology Innovation (TI) office focuses on and manages technology initiatives, as well as helps to guide the development of a robust research and development portfolio, drawing from staff that are already engaged in the BPA's dispersed research and development work. The TI statement of work says that "we should be proactive in guiding and supporting the research and development that has the potential to take electric service to new levels in the Pacific Northwest. Further, we should be adapting the successfully researched and developed technologies into demonstration programs and commercial deployments here in the region. If we aren't doing this, then we aren't creating the value that BPA uniquely can deliver for the people of the Pacific Northwest." [3]. The TI project portfolio in the area of renewable resource and wind integration includes multiple innovative projects such as developing forecasting tools (short term, fast ramp, tail events forecast), a scalable energy storage system, improved wind farms modeling, wide-area energy storage and management, a simulation model for the comprehensive analysis of expected wind generation development scenarios, and other important projects [4].

Germany has the largest renewable installed capacity in the world and advanced operational experience with the management of large amounts of wind and solar power in its electric power system. Learning from the German experience will help BPA to compare and evaluate potential new solutions for managing higher penetrations of wind energy resources in its control area. Broader dissemination of this experience will benefit wind and solar resource integration efforts in the United States. In this section, key findings are summarized concerning the German experience with integrating 25 gigawatts of wind and 7 gigawatts of solar energy. These findings can be summarized as follow.

1. Structural Factors Helping to Integrate Large Amounts of Wind & Solar Energy

1.1. Distribution of wind and solar resources in Germany. Higher wind energy potential is observed in the northern and eastern parts of the country; consequently, most of the wind farms are located there. The wind generation fleet consists of multiple wind farms, which help to exploit this diversity in its management. Solar energy potential is, on average, higher in southern Germany, but the sunniest locations are on the islands in the Baltic Sea (North-East coast). Solar generation consists of distributed photovoltaic (PV) energy resources.

1.2. In the past, there has been a strong transmission network in Germany, which minimized the likelihood of congestion problems and simplified energy exchanges within the country. In addition, relatively strong interconnections are in place to neighboring countries through the pan-European Network of Transmission System Operators for Electricity (ENTSO-E) grid. However, with 25 GW of wind power installed within the German grid, the transmission system is reaching its limit.

2. Operational Factors Helping to Integrate Large Amounts of Wind and Solar Energy

2.1. Germany's entire energy market consists of one price area.

2.2. Globalization of wind power production deviations. All wind power production and its deviations in Germany are combined virtually (on a 15-minute average basis), and then distributed to each of four transmission system operators (TSOs). The share of wind energy that each TSO has to balance is proportional to consumption or load in each control area, but not proportional to installed wind power. Solar power (PV) is shared only on an energy level (monthly average).

2.3. The forecast accuracy is very good. The root mean square (RMS) forecast error is below 4.5% for day-ahead forecasts. The TSOs use the services of up to 10 wind forecast service providers at the same time, and then run algorithms selecting the best wind energy forecast in real time.

2.4. German TSOs use 15-minute scheduling intervals within the country. The schedules within the country can change any time before and even after the dispatch interval. The 15-minute schedules are possible within a control area, but its exchanges with the other control areas are scheduled based on 1-hour intervals. Bilateral trades can be 15-minute based.

2.5. Wind production curtailments are possible in the case of jeopardized "security of supply." These events are rare in the transmission system, but happen frequently in the distribution networks.

2.6. TSO Security Cooperation (TSC) in Central Europe includes 12 TSOs. TSC facilitates cooperation and coordination between TSOs in the form of a common TSO data exchange, a TSO security panel of experts, cross-border redispatch, and other wide-area arrangements to handle transmission congestion and other reliability coordination problems [8].

2.7. European Network of Transmission System Operators for Electricity (ENTSO-E) pursues the following main tasks:

- Establishing and elaborating on network codes
- Coordinating network operation by common network operation tools
- Developing a 10-year network development plan
- Publishing an annual work program, annual report and annual summer and winter generation adequacy outlooks

ENTSO-E objectives include:

- Ensuring security of supply
- Meeting the needs of the internal energy market and facilitating market integration
- Promoting relevant R&D and encouraging public acceptance of transmission infrastructure
- Consulting with stakeholders on energy policy issues

ENTSO-E was created in July 2009 by replacing existing TSO associations. Now ENTSO-E integrates 42 TSOs from 34 countries [http://www.entsoe.eu].

2.8. Three German TSOs (excluding Amprion) implemented an imbalance sharing scheme that is similar to the area control error (ACE) diversity interchange (ADI) program in the United States, and operates in real time.

3. Structural Factors That Cause Problems with Integrating Large Amounts of Wind and Solar Energy

3.1. Excessive generation capacity in some control areas (e.g., in the 50HzT area) creates problems with selling wind energy for these TSOs. The problem will be aggravated with 18,000 MW of wind capacity expected in 2017 in the control area of 50HzT, while the system load remains the same or decreases.

3.2. Managing and obtaining information about wind generation connected on the distribution level is difficult.

3.3. The continuing increase of wind and solar energy in Germany, with more offshore wind energy additions, creates new operational problems. For example, in the 50HzT area, about 18,000 MW of wind power capacity is expected (with 10,480 MW connected at the moment). Currently, 14 new offshore wind farms are in the queue, with a total capacity of 3,600 MW (first stage).

3.4. There is no restriction on integrating more wind into the German system except for the limits regulating the distance from wind farms to households.

3.5. Although possible from a legal perspective at most wind farms, there is no direct control over wind generation connected at the distribution level because of the current lack of technical connection between wind farms and the control centers.

4. Operational Factors That Cause Problems with Integrating Large Amounts of Wind and Solar Energy

4.1. Wind and solar power plants produce "must take" energy, except in a few cases when wind power production is curtailed because of the system security conditions.

4.2. Congestion can occur during high wind periods. The NE-SW flows are a pressing and ever increasing problem. Because of the loop flows, congestion on the German-Polish border is also a problem.

4.3. Loop flows that are created by wind and solar energy go through another country's transmission systems, such as Poland and the Czech Republic. France and the Netherlands have installed phase shifting transformers to defend against the loop flows through their systems.

4.4. Negative prices that occur infrequently can reach up to -500 euro/MWh (December 12, 2009). Minus 3,000 euro/MWh is the limit of the Energy Exchange. On October 4, the price was -500 euro/MWh.

4.5. The wind forecasting system is not comprehensive as it does not include all wind farms. Wind forecasts are based on up-scaling of the forecasts provided for about 130 key locations in the country. Solar power production has similar problems.

4.6. Very large forecast errors are rare, but occur once or twice a year.

4.7. There are potential problems with maintaining system inertia on a level required for reliable operation.

4.8. Overloads on transformers connecting the 50HzT area with Poland are due to excessive wind generation in this control area.

5. Changes to Be Made in the German System

5.1. Transition from the bilateral market to a power exchange market structure (applies only for TSOs as required by regulator. There is a large bilateral market between market participants).

5.2. Accommodation of additional amounts of wind capacity will be impossible without major transmission system enhancements. New transmission corridors are needed.

5.2. Bigger systems, super grids, interconnecting the European system with the Russian system are potential solutions to future problems, which are currently under consideration.

5.3. German TSOs are looking for new technologies for energy storage and smart grids.

5.4. A special center for managing the congestion problem on a wide-area basis has been built in Munich [8]. Its name is Central Allocation Office GmbH (CAO).

5.5. Measures need to be developed to handle loop flows, including coordinated solutions, multilateral remedial actions and solutions for cost sharing and cost recovery.

5.6. To address problems with maintaining system inertia, mitigation measures are currently under development. They include assigning must-run units and providing ancillary services from them.

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This work has been sponsored by the Technologies Innovation office at the Bonneville Power Administration (BPA). PNNL participants would like to thank BPA's Technology Innovation office for sponsoring the trip to Germany and their continued support.

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Glossary

Abbreviation	Meaning	Definition
50HzT	50Hertz Transmission GmbH	50Hertz Transmission GmbH is responsible for the operation, maintenance, planning, and expansion of the 380/220 kilovolt transmission grid throughout the German Federal States of Thuringia, Saxony, Saxony-Anhalt, Brandenburg, Berlin, Mecklenburg-Western Pomerania, and Hamburg. The transmission grid operated by 50Hertz covers an area larger than 109,000 km² and runs a length of approximately 9,700 km. It is the technical backbone that reliably supplies power to more than 18 million people as well as to companies contributing approximately 20 percent of German gross domestic product. In 2004, approximately 82 terawatt-hours were transmitted through the area controlled by 50Hertz – enough to provide Berlin with power for about six years. More than 600 employees at 50Hertz work to ensure that this grid remains reliable. Formerly known as Vattenfall Europe Transmission GmbH TSO [5].
Amprion	Amprion GmbH	Amprion GmbH is a leading transmission system operator in Europe and operates a German extra-high voltage grid with a length of 11,000 km. A population of over 27 million is supplied through Amprion's grid from Lower Saxony down to the Alps. Being an innovative service provider, Amprion provides industrial customers and network partners with the security of a highly reliable supply. The network with the voltage levels of 380,000 and 220,000 volts is accessible to all players in the electricity market on a non-discriminating basis and at competitive and transparent terms. Moreover, Amprion is responsible for one of the largest grid areas in Europe and assumes an important task in the European interconnected system [6].
ACE	area control error	The instantaneous difference between a balancing authority's net actual and scheduled interchange, taking into account the effects of frequency bias and correction for meter error.
ADI	ACE diversity interchange	ADI or ACE diversity interchange is the pooling of area control errors (ACE) to take advantage of control error diversity (momentary imbalances of generation and load).
AGC	automatic generation control	Generation equipment that automatically responds to signals from the EMS control in real time to control the power output of electric generators within a prescribed area in response to a change in system frequency, tie line loading, or the relation of these to each other to maintain the target system frequency and/or the established interchange with other areas within the predetermined limits.
AS	ancillary services	Services that are necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of the power system in accordance with good utility practice. Ancillary services include scheduling, system control and dispatch, reactive supply and voltage control from generation sources, regulation and frequency response, energy imbalance, operating reserve – spinning, and operating reserve – supplemental.
BA	balancing authority	The responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a balancing authority area, and supports Interconnection frequency in real time.
BPA	Bonneville Power Administration	The Bonneville Power Administration, headquartered in Portland, Oregon, is a federal agency under the U.S. Department of Energy. BPA serves the Pacific Northwest by operating an extensive electricity transmission system and marketing wholesale electrical power at cost from federal dams, one non-federal nuclear plant and other nonfederal hydroelectric and wind energy generation facilities [7].

CAO	Central Allocation Office GmbH	Central Allocation Office GmbH was established in July 2009 to develop and implement coordinated congestion management solutions in Central Eastern Europe (CEE). CAO is currently implementing a load-flow based explicit allocation process to allocate physical transmission rights for cross-border electricity transmission in the CEE region on behalf of the eight involved transmission system operators. As soon as the implementation is finished and tested, CAO will take over daily operation of the allocation process. CAO is an independent service company and provides the same quality services to all market participants without discrimination. CAO has opened active communications with the electricity market participants and introduced a central helpdesk channel. On behalf of the eight involved TSOs, CAO is implementing a load-flow-based explicit allocation process to allocate capacity transmission rights for cross border transmission of electricity in this region. Market-based, transparent, and non-discriminatory allocations of electricity transmission capacity to the CEE region, respecting the most physical flows, form the principles for the foundation of CAO. To correctly reflect physical flows of electricity in the CEE region and to provide the most efficient calculation of transmission of capacity, the CEE TSOs requested CAO to implement a flow-based capacity calculation and allocation method (FBA) [8].
---	dispatch interval	The interval for which a balancing authority or TSO issues instructions for its generators concerning the level of generation.
DOE	U.S. Department of Energy	The United States Department of Energy (DOE) is a Cabinet-level department of the United States government concerned with U.S. policies regarding energy and safety in handling nuclear material. Its responsibilities include the nation's nuclear weapons program, nuclear reactor production for the United States Navy, energy conservation, energy-related research, radioactive waste disposal, and domestic energy production. DOE also sponsors more basic and applied scientific research than any other US federal agency; most of this is funded through its system of national laboratories [9].
DS	dynamic schedule or dynamic interchange schedule	A telemeter reading or value that is updated in real time and used as a schedule in the AGC/ACE equation and the integrated value of which is treated as a schedule for interchange accounting purposes. Commonly used for scheduling jointly owned generation to or from another balancing authority area.
DWD	Deutscher Wetterdienst	The Deutscher Wetterdienst, commonly abbreviated as DWD, (translated from German as German Meteorological Service), is a scientific agency that monitors weather and meteorological conditions over Germany and offers weather services for the general public as well as specific services (for example nautical, aviation or agricultural purposes).
ECMWF	European Centre for Medium-Range Weather Forecasts	The ECMWF produces operational medium-range weather forecasts. The ECMWF members are from 18 European countries. The objectives of the ECMWF are: (1) development of numerical methods for medium-range weather forecasting; (2) preparation of medium-range weather forecasts for distribution to the member states; (3) scientific and technical research directed to the improvement of these forecasts; and (4) collection and storage of appropriate meteorological data.
EEG	German Renewable Energy Sources Act	The Renewable Energy Sources Act (EEG) regulates the compensation for electricity from renewable energy sources in Germany. The EEG contains a minimum price scheme combined with an obligation for grid operators to purchase electricity from renewable energies at a fixed tariff. The compensation is structured according to the quality of the site. A 20-year running time ensures planning and investment security. The respective nearest operator of a suitable grid must purchase the generated electricity and reinforce the grid as far as necessary and economically reasonable [10].

EEX	European Energy Exchange AG	The European Energy Exchange AG (EEX) is a leading trading market in European energy trading. EEX has evolved into a corporate group which is open for European and international partnerships. The Dutch exchange ENDEX European Energy Derivatives Exchange N.V. has been cooperating with EEX in the clearing sector since 2006. Today, the clearing house ECC provides clearing and settlement for all products traded on ENDEX. In the field of power trading, EEX cooperates with the French Powernext SA. EEX holds 50% of the shares in the joint venture EPEX Spot SE based in Paris which operates short-term trading in power – the so-called spot market – for Germany, France, Austria and Switzerland. German and French power derivatives trading are concentrated within EEX Power Derivatives GmbH, a majority-owned EEX subsidiary with headquarters in Leipzig. Clearing and settlement for all spot and derivatives transactions on power are provided by ECC, which has already been settling the natural gas transactions traded on Powernext since November 2008. Furthermore, EEX holds an interest in store-x GmbH (Storage Capacity Exchange), an internet platform for secondary trading in storage capacities for natural gas, and in trac-x GmbH (Transport Capacity Exchange GmbH), an internet platform for natural gas transport capacities. In addition, EEX holds 20 percent in EMCC GmbH (European Market Coupling Company), a company that performs the congestion management at the German-Danish border [11].
---	Energy & Meteo Systems GmbH	Energy & Meteo Systems GmbH is a German forecast service provider offering innovative services and developments around the integration of renewable energy sources into the power supply. This company processes meteorological data into useful informational and prediction products for the energy community. At the heart of this company's activities lies the wind power prediction system “Previento” – an operational system for calculating a precise 3-day-forecast of a wind farm's power output [17].
ENTSO-E	European Network of Transmission System Operators for Electricity	European Network of Transmission System Operators for Electricity (ENTSO-E) pursues the following main tasks: - Establishing and elaborating network codes. - Coordinating network operation by common network operation tools. - Developing a 10-year network development plan. - Publishing annual work program, annual report and annual summer and winter generation adequacy outlooks. ENTSO-E objectives include: - Security of supply. - Meeting the needs of the internal energy market and facilitating market integration. - Promotion of relevant R&D and public acceptability of transmission infrastructure. - Consultation with stakeholders and positions towards energy policy issues. ENTSO-E was created in July 2009 by replacing existing TSO associations. Now ENTSO-E integrates 42 TSOs from 34 countries [12].
FBA	flow-based allocation	FBA is a method used by eight Central Eastern Europe TSOs to calculate transmission capacity allocation. The method is used by the Central Allocation Office GmbH (CAO). The following principles are used to allocate the capacity: - All TSOs’ available data is used for the calculation (TSOs send their data, models, grid information, etc.) - Calculation is done by CAO - Data from neighboring countries (non-CEE) are also taken into account - Common grid model is used [8].
---	forecast service provider	An organization providing forecasting services.

GFS	global forecast system	The global forecast system (GFS) is a global numerical weather prediction computer model run by the National Oceanographic and Atmospheric Administration (NOAA). This mathematical model is run four times a day and produces forecasts up to 16 days in advance, but with decreasing spatial and temporal resolution over time. It is widely accepted that beyond 7 days, the forecast is very general and not very accurate. The model is run in two parts: the first part has a higher resolution and goes out to 180 hours (7 days) in the future. The second part runs from 180 to 384 hours (16 days) at a lower resolution. The resolution of the model varies in each part of the model. Horizontally, it divides the surface of the Earth into 35 or 70 kilometer grid squares. Vertically, it divides the atmosphere into 64 layers and temporarily produces a forecast for every 3rd hour for the first 180 hours. After that they are produced for every 12th hour.
HIRLAM	high resolution limited area model	HIRLAM, the high resolution limited area model, is a numerical weather prediction (NWP) forecast system developed by the international HIRLAM program. The HIRLAM program is a cooperation between several European meteorological institutes. The aim of the HIRLAM program is to develop and maintain a numerical short-range weather forecasting system for operational use by the participating institutes.
IWES	Fraunhofer-Institute for Wind Energy and Energy System Technology	Fraunhofer-Institute for Wind Energy and Energy System Technology (IWES, formerly ISET) is located in Kassel, Germany. IWES was founded January 1, 2009. It offers research and development along the value chain of wind turbines from material development to grid integration [19].
---	loop flow	The movement of electric power from generator to load by dividing along multiple parallel paths; it especially refers to power flow along an unintended path that loops away from the most direct geographic path or contract path.
---	Météo-France	Météo-France is the French national meteorological service. The agency provides forecasts and warnings in metropolitan France and overseas.
OTC	“over the counter”	“Over the counter” trading option is the same as bilateral trades. Since last August, TSOs have been allowed to trade at the exchange only. Therefore, they don’t need to use OTC anymore.
PNNL	Pacific Northwest National Laboratory	U.S. Department of Energy laboratory located in Washington state. The Laboratory is run by Battelle Memorial Institution [13].
PV	photovoltaic solar generation	PVs are arrays of cells containing a solar photovoltaic material that converts solar radiation into direct current electricity.
RES	renewable energy sources	Energy sources that capture their energy from existing flows of energy, from on-going natural processes, such as sunshine, wind, flowing water, biological processes and geothermal heat flows.
RMS value	root mean square value	The root mean square (abbreviated RMS or rms), also known as the quadratic mean, is a statistical measure of the magnitude of a varying quantity.

---	Previento	Previento is an operational system for predicting the power output of wind farms that allows energy providers, energy brokers, and grid operators to integrate the fluctuating input of wind energy into their daily business in a manner that is both economically and technically efficient. Previento has been developed by Energy & Meteo Systems GmbH. Previento provides a reliable prediction of the expected wind power up to 4 days in advance and with a time resolution of up to 15 minutes for any selected location in Germany and Europe. A wind power prediction depends upon the local conditions in the area of the wind farms as well as on a numerical weather prediction. The entire input of wind-generated electric current from a region is calculated on the basis of selected wind farms. During this process, the representative areas are selected such that they mirror the regional distribution of the wind energy facilities to a very high degree. The exactness of the prediction varies with the weather situation. In contrast to other prediction systems, Previento additionally calculates the margin of error in reference to the actual prediction value dependent upon the current uncertainty in weather conditions. The entire prediction data collected is centrally calculated and relayed to the customers in a standard electronic format via the internet [19].
---	scheduling interval	A time interval for which certain generation schedule or power exchange is provided, usually, in terms of the average power or energy.
TI	Technology Innovation office at BPA	BPA created the Technology Innovation office in 2005 to focus and manage its technology initiatives, as well as to help guide development of a robust research and development portfolio, drawing from staff that are already engaged in BPA's dispersed research and development work [3].
TSC	Transmission System Operator Security Cooperation	TSO Security Cooperation (TSC) is made up of 12 European transmission system operators (TSOs) in Central Europe. This regional initiative strives to foster security of supply within the participating countries and throughout Europe. With the common goal of enhancing overall system security, TSC harmonizes with other intra-European initiatives and cooperation centers. This initiative encompasses a permanent TSO security panel (group of security experts) and implements a shared platform for exchanging data and assessing mutual security needs. TSC helps TSOs to better manage their expanding operations, especially with respect to integrating wind energy and handling increases in cross-border trading and electricity transmission. The TSC tools allow member TSOs to access key data and provide them with access to advanced methods for choosing appropriate remedial actions. These services can be used by TSOs for day-to-day operations in their regions, starting first with day-ahead planning processes. In a second phase, these services will be expanded to grant TSOs nearly real-time control over their operations. [14].

TSO	transmission system operator	As a provider of system services, the transmission grid operator is responsible for maintaining constant line frequency and voltage, balancing power generation with consumption, and ensuring cost-effective power transmission. German law (Energiewirtschaftsgesetz from 07/07/2005), European Parliament Directives and the European "Common Rules for the Internal Market in Electricity" stipulate that each transmission system operator is responsible for operating their controlled area of the transmission grid in a reliable, cost-effective, consumer-friendly, efficient, and environmentally friendly manner. In particular, each TSO is responsible for maintaining the proper system balance as their contribution to reliable power provision. To fulfill these obligations, it is necessary to manage injected energy and power-consuming loads [5]. Transmission system operators (TSOs) are responsible for the bulk transmission of electric power on the main high voltage electric networks. TSOs provide grid access to the electricity market players (i.e., generating companies, traders, suppliers, distributors and directly connected customers) according to non-discriminatory and transparent rules. To ensure the security of supply, they also guarantee the safe operation and maintenance of the system. In many countries, TSOs are in charge of the development of the grid infrastructure too. TSOs in the European Union's internal electricity market are entities operating independently from the other electricity market players [12].
UCTE	Union for the Coordination of Transmission of Electricity	From July 1, 2009 on, the European Network of Transmission System Operators for Electricity (ENTSO-E) took over all operational tasks of the six existing TSO associations in Europe, including the Union for the Coordination of Transmission of Electricity (UCTE).
VE-T	Vattenfall Europe Transmission GmbH	Former name of 50 Hertz Transmission GmbH
WIT	wind integration team at BPA	In 2008, BPA created a cross-agency wind integration team (WIT) to address the challenges of rapid development of wind energy in the BPA balancing authority. The mission of the WIT is to clearly define and execute a plan for integrating wind generation in a manner that allows for the continued highly reliable operation of the federal power and transmission system at the lowest cost consistent with sound business and operations practices [15].

Contents

Figures

Tables

1.0 Introduction

This work, and the trip to Germany that preceded it, have been sponsored by the Technology Innovation office at the Bonneville Power Administration (BPA).

In October 2009, John H. Pease, manager of Technology Innovation at BPA and Dr. Yuri V. Makarov, chief scientist in the Power Systems Group at Pacific Northwest National Laboratory (PNNL), visited two major transmission system operators (TSOs) in Germany, including Amprion GmbH (Amprion) in Pulheim and 50Hertz Transmission GmbH (50Hz-T), formerly Vattenfall Europe Transmission GmbH, in Berlin, to learn more about the German experience with handling large amounts of renewable generation. PNNL's participation was sponsored by the BPA Technology Innovation office.

The visit to Germany was organized by PNNL and Dr. Bernhard Ernst, manager of Front Office System Planning for Amprion GmbH and Christian Scholz from Control Area Cooperation at 50 Hertz. During meetings at the TSOs, German managers and engineers provided the U.S. delegation with extensive information about the German power system and energy market, which are operated successfully utilizing 25 gigawatts of installed wind power capacity and 7 gigawatts of installed solar power capacity. This report summarizes key elements of these systems based on the information and materials provided by our German colleagues. BPA and PNNL are very grateful to their German colleagues for their help and cooperation in this project.

The Bonneville Power Administration has currently more than 3 gigawatts (GW) of installed wind power capacity, and plans to install about 2,500 megawatts (MW) of additional capacity by 2012 [1]. Anticipating potential problems with managing large amounts of wind power in its system, BPA is currently looking for advanced solutions to mitigate the negative impacts of variability and uncertainty caused by these resources. In a recent presentation, BPA's executive vice president of corporate strategy, Elliot Mainzer indicated that "BPA is committed to finding innovative solutions to meet the renewable resource objectives of the Pacific Northwest by reliably and cost-effectively extending the integration capability of the BPA balancing authority while honoring our statutory obligations to our preference customers and the operational limitations on the Federal hydroelectric system" [1]. The wind integration team (WIT) at BPA has already implemented and proposed several solutions to help minimize adverse impacts of wind power production. They include:

- implementing transmission system enhancement projects
- introducing wind integration rate charges for wind generators to cover additional balancing costs incurred
- establishing new reliability protocols requiring wind generators to adjust their schedules down to actual output if they substantially under-generate relative to their schedule or reduce output if they substantially over-generate relative to their schedule
- developing a wind forecasting system by March 2010

- adding a BPA “wind desk” to support dispatchers in the efficient use of wind, hydro and other generation; creating sub-hourly transmission scheduling protocols to allow power schedule changes to better match within-hour variations in wind generation

- allowing wind operators to sell power when wind output quickly increases

- allowing wind generators to purchase balancing capacity from suppliers other than BPA

- creating a third-party market for balancing services

- using dynamic schedules to allow wind generators physically located on BPA’s system to be remotely balanced by other utilities using electronic signals

- evaluating energy storage and smart grid technologies potential in the BPA footprint

- implementing the area control error diversity interchange (ADI) program

- employing self supply options for within-hour balancing services available for generator owners and operators, and evaluating the benefits of participating in cooperation or consolidation schemes with the other balancing authorities [1], [2].

The BPA Technology Innovation (TI) office focuses on and manages technology initiatives, as well as helps to guide the development of a robust research and development portfolio, drawing from staff that is already engaged in BPA's dispersed research and development work. The TI statement of work says that “we should be proactive in guiding and supporting the research and development that has the potential to take electric service to new levels in the Pacific Northwest. Further, we should be adapting the successfully researched and developed technologies into demonstration programs and commercial deployments here in the region. If we aren't doing this, then we aren't creating the value that BPA uniquely can deliver for the people of the Pacific Northwest." [3]. The TI project portfolio in the area of renewable resource and wind integration includes multiple innovative projects such as developing forecasting tools (short term, fast ramp, tail events forecast), a scalable energy storage system, improved wind farms modeling, wide-area energy storage and management, a simulation model for the comprehensive analysis of expected wind generation development scenarios, and other important projects [4].

Germany has the largest renewable installed capacity in the world and advanced experience with handling large amounts of wind and solar power in its electric power system. Learning from the German experience will help BPA to compare and evaluate potential new solutions for managing higher penetrations of wind energy resources in its control area. Broader dissemination of this experience will benefit wind and solar resource integration efforts in the United States. In this report, key findings are summarized concerning the German experience with integrating 25 gigawatts of wind and 7 gigawatts of solar energy.

2.0 Overview of the German System

2.1. Germany has about 25 GW of installed wind capacity (20,300 turbines) and about 7 GW of installed solar power capacity. All solar power in Germany is photovoltaic based. Figure 1 shows the projected growth of wind power capacity in Germany. Most of the growth will be provided by offshore wind capacity additions. Figure 2 illustrates near-term offshore wind capacity additons in the 50HzT system only (in the Baltic Sea) [16].

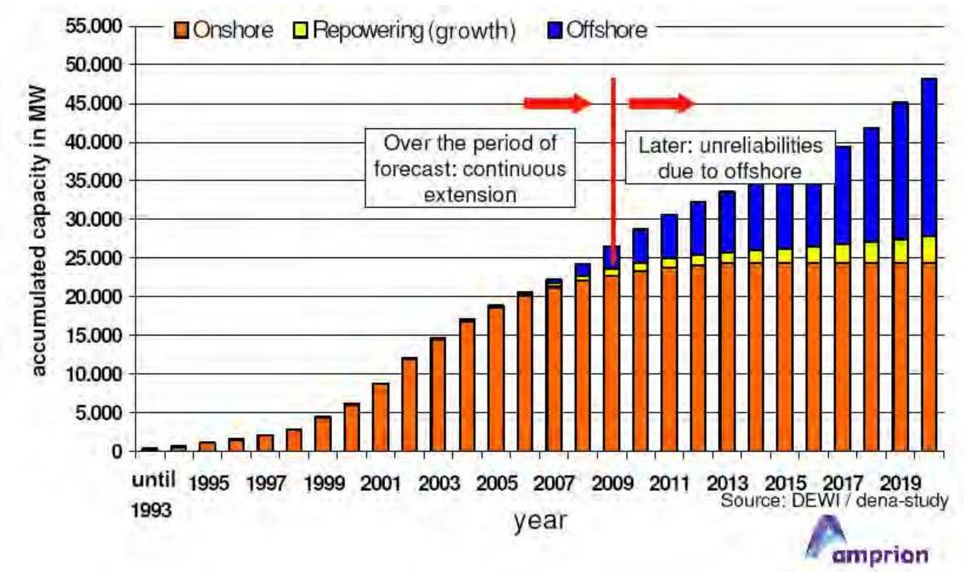

Figure 1. Wind power capacity growth in Germany (Provided by Dr. B. Ernst, Amprion)

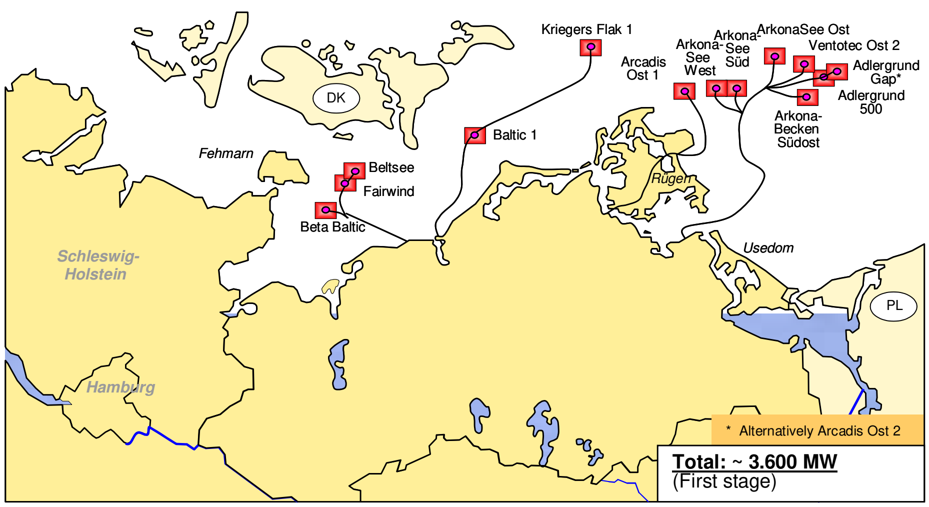

Figure 2. Near-term offshore wind capacity additions in the 50HzT (Provided by H.-P. Erbring, 50HzT)

2.2. Distribution of wind and solar resources in Germany. Wind and solar resources are more or less geographically distributed with most of the wind energy potential observed in northern and eastern parts of the country; consequently, most of the wind farms are located in these parts of the country. Most wind farms in Germany have just a few wind turbines. The wind generation fleet consists of multiple wind farms, which helps to exploit the geographical diversity in its management. Solar energy potential is, on average, higher in southern Germany, but the sunniest locations are found on the islands in the Baltic Sea, off the northeast coast. Solar generation consists of distributed photovoltaic (PV) energy resources.

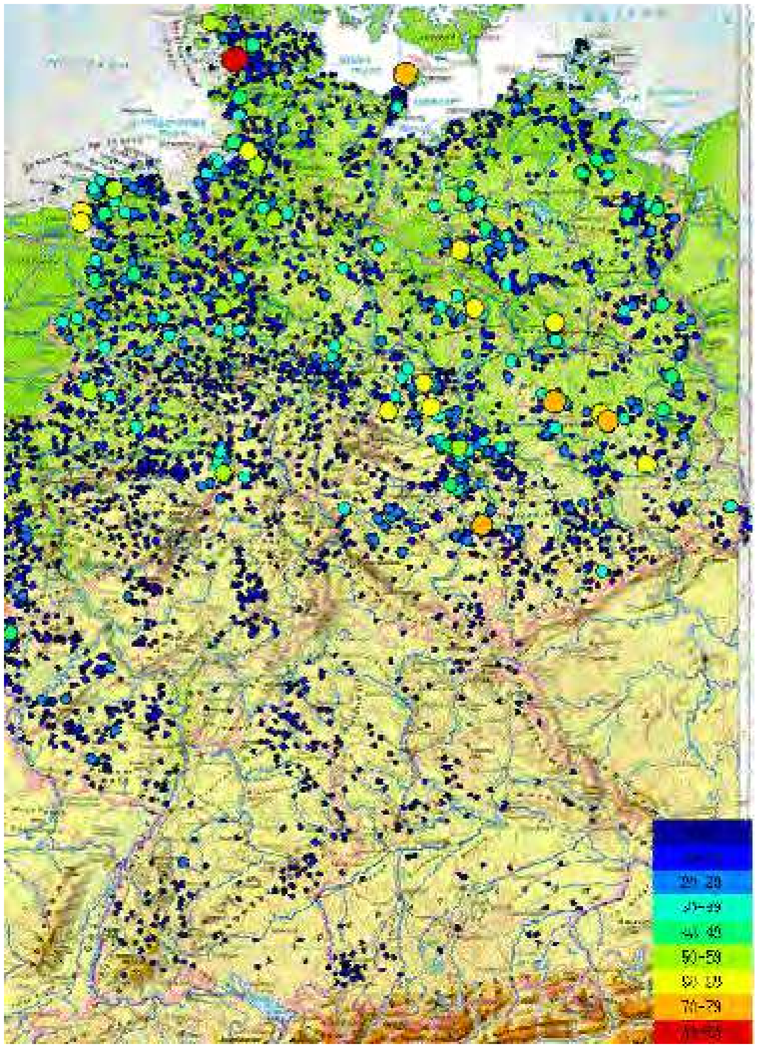

Figure 3. Distribution of wind farms in Germany (Provided by Dr. B. Ernst, Amprion)

2.3. Germany's peak demand is 80 GW, while the minimum demand is only 30 GW.

2.4. One of the largest ramps observed in Germany was 5 GW within 8 hours. See Figure 4. In the 50HzT area, the maximum observed 15-minute wind power ramps were +485 MW and -563 MW. For a 60-minute interval, the most significant wind power ramps were +1,393 MW and -1,824 MW. The maximum observed intraday swing in wind power production was +7,302 MW.

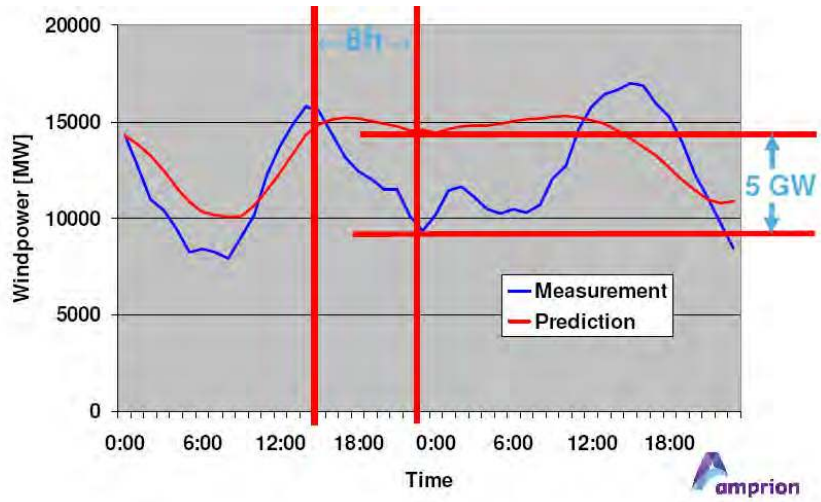

Figure 4. Wind power during a storm front (Provided by Dr. Bernhard Ernst, Amprion)

2.5. TSOs are responsible for balancing deviations for their portion of German renewable resources, as well as other deviations, and use contracted regulation power for this purpose.

2.6. German TSOs, such as Amprion and 50HzT, are independent transmission operators, which do not own power plants. Nonetheless, they do own the transmission system. German energy law requires the TSOs to provide grid access to everybody without discrimination, and to facilitate competition among power producers and energy traders.

2.7. Amprion has 4,266 MW of installed wind capacity (3,736 turbines).

2.8. Capacity factor for wind in the Amprion control area is between 15 and 25%. The capacity factor in the 50HzT area is between 18 and 19%.

2.9. 50HzT has 10,480 MW of installed wind capacity (about 7,500 turbines) and about 300 MW of installed PV capacity. 9,700 MW of wind and all PV capacity are connected at the distribution level. Most of the wind and solar power capacity is connected at the distribution level. 50HzT's load variation is from 3,500 MW to 15,000 MW. The installed generation capacity is about 34,000 MW.

2.10. In the 50HzT area, wind power capacity is expected to be about 18,000 MW (with 10,480 MW in 2009). Currently, 14 new offshore wind farms are in the queue, with a total capacity of 3,600 MW. This is the first stage of increasing wind farm development in the Baltic Sea area.

2.11. Pumped storage is a part of secondary reserve. The pumped storage capacity in the Amprion area is 2,500 MW. However, only a minor part of this is under the control of Amprion. This energy storage has a limited energy capacity, and can provide energy for only a few hours. The pumped storage capacity at 50HzT is 3,100 MW.

2.12. The security package of the European Grid (ENTSO-E[1]) includes:

- Operation handbook
- Multilateral agreements

[1] From July 1 2009 on, ENTSO-E, the European Network of Transmission System Operators for Electricity, took over all operational tasks for the six existing TSO associations in Europe, including UCTE, the Union for the Coordination of Transmission of Electricity.

- Compliance monitoring and enforcement.

2.13. There are no restrictions in terms of capacity for integrating more wind in the German system. There are limits on siting wind farms; new wind farms cannot be placed close to households. In addition, there are many restrictions and rules by local authorities. Getting permission for a wind farm is a long process and not always successful.

2.14. All transmission facilities comply with the N – 1 reliability criterion: if one transmission line trips, the other ones are able to take the additional load.

2.15. TSOs are responsible for investing in transmission system development. Since the beginning of the incentive regulation in Germany in 2009, TSOs can apply for a budget for transmission system upgrades. The regulator decides which measures can be accepted, and based on that a predefined percentage of the investment is conceded to the TSOs. By determining the conceded revenues, the regulator indirectly influences the TSO's ability to make upgrades.

2.16. Critical situations caused by wind appear several times a year. For instance, 50HzT experienced these situations four times in 2008, and three times in 2009 (with wind power production exceeding 7,200 – 8,200 MW). The highest ramp observed in the 50HzT area was 1,000 MW in 15 minutes.

2.17. The TSOs' control measures include:
- Circuit switching, e.g., line trips
- Use of permissible tolerances for voltage and current
- Use of additional reserves
- Demand control management
- Preventive congestion management
- Stopping intraday trading
- Countertrading
- Generation redispatch
- Reductions of already accepted schedules
- Global measures (reduce all generation, or all consumption, or all transfers).

Table 1 shows critical grid situations that have happened in the 50HzT control area since autumn 2008.

Table 1. Critical grid situations since autumn 2008 (Provided by Hans-Peter Erbring, 50HzT)

09.-11.11.2008	**7341 MW**	
15.-16.11.2008	**7274 MW**	
18.-21.11.2008	**8752 MW**	local measures acc. § 13 (2)
02.12.2008	**6069 MW**	local measures acc. § 13 (2)
03.-04.01.2009	**5728 MW**	local measures acc. § 13 (2)
01.-02.02.2009	**6187 MW**	
21.-23.03.2009	**8225 MW**	global measures acc. § 13 (2)

2.18. System balance can be usually achieved in about 2 hours; sometimes the imbalances are observed for half of the day (50HzT).

3.0 Balancing Reserves

3.1. Three types of balancing services are used in Germany: primary, secondary, and tertiary regulation. (All German TSOs additionally use a special wind reserve.) The activation sequence of these reserves is shown in Figure 5 and Figure 6. The idea of the reserve activation sequence is to subsequently replace primary reserve by secondary reserve, and then by tertiary reserve, until the tertiary response is released by generation redispatch. See Figure 6.

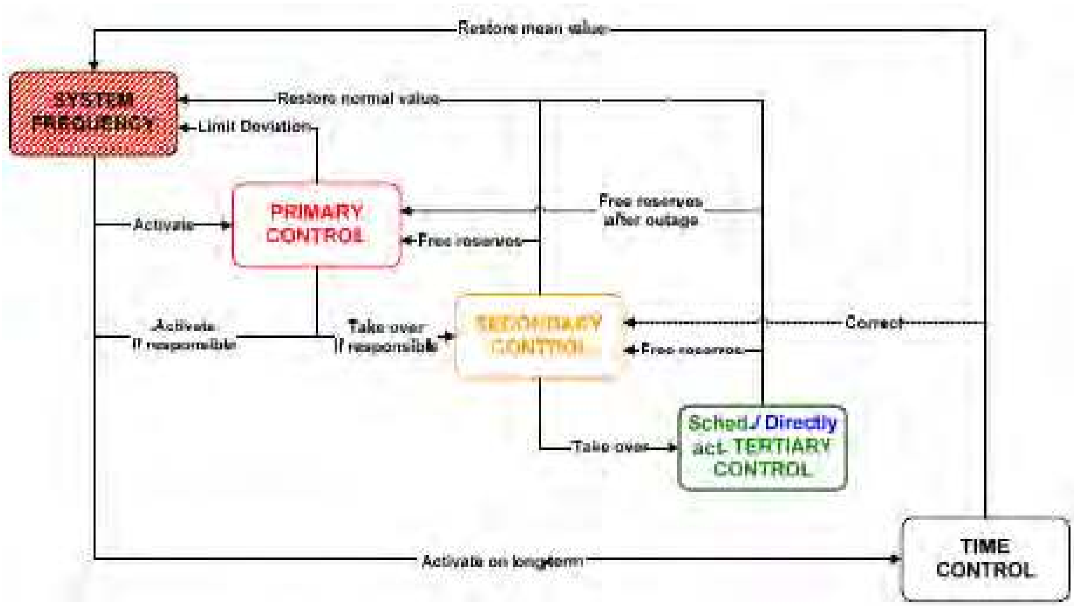

Figure 5. Balancing reserves activation sequence (Provided by Stephan Schlunke, 50HzT)

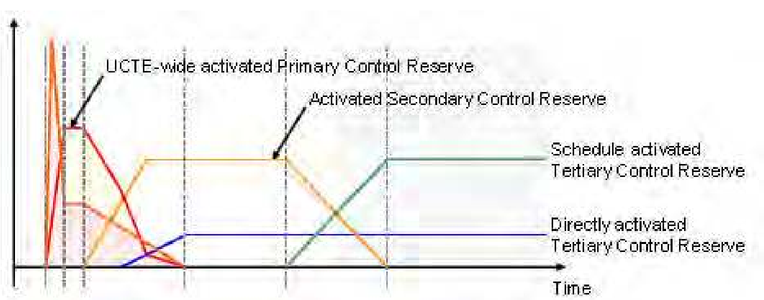

Figure 6. Balancing reserves activation sequence (Provided by Stephan Schlunke, 50HzT)

3.2. Primary regulation (frequency response) responds to frequency variations in a continuous automatic manner. It is provided by generators based on a decentralized principle. All European systems are obligated to provide a total of 3,000 MW of the primary reserve capacity, which should be capable of deploying within 30 seconds. (This corresponds to the outage of two major nuclear power plants with the capacity of 1,500 MW each.) The 3,000 MW primary regulation capacity requirement is distributed to each TSO depending on the size of its served load. The German share in the European primary reserve is 630 MW. The 50HzT share is 135 MW. The primary regulation is procured as capacity reserve based on a market mechanism. Resources providing primary regulation service are paid for their capacity allocated to this purpose, based on the market price. They are not paid for the energy component of this service.

3.3. Secondary reserve (regulation) has a 5-minute deployment requirement. The German TSOs procure about 4,900 MW (-2,200 MW for the regulation down, and +2,700 MW for the regulation up capacity). 50HzT procures from -464 to +532 MW. Secondary regulation is provided by power plants connected to the automatic generation control (AGC) system. These are mainly hydro power plants and pumped hydro plants. It is interesting that the system operators decide if and when a hydro unit should be started or stopped to provide more or less spinning regulation capacity, which is the regulation resource (not necessarily spinning). The secondary regulation resources are paid the market price for both the procured capacity and actual energy provided for regulation.

3.4. Three of the four German TSOs (except Amprion) implemented a shared secondary reserve utilization scheme that helps to minimize the regulation needs in their control areas. The scheme currently includes four modules explained in Table 2. The scheme is similar to the ACE diversity interchange scheme used in the United States, but it is more advanced as a result of sharing of regulation resources between areas and because of the optimization algorithm helping to select the most economical solution in a wide area. Table 3 shows primary and secondary reserve capacity reduction caused by a secondary reserve utilization scheme in the 50HzT control area.

Table 2. Shared secondary reserve utilization scheme (Provided by Stephan Schlunke, 50HzT)

Step/module	Innovation
Module 1:	Since 17.12.2008: Compensation of imbalances in opposite direction in joint control areas
Module 2:	Since 05.05.2009: Mutual support in case of insufficient secondary power in one or more control areas Conclusion: Reduction of secondary power reservation in the joint control areas; Introduction of an equal price for regulation energy within the joint control areas that has to be paid by traders organized in balance groups
Module 3:	Since 01.07.2009: Realisation of the principle that reserve providers reserve resources get the request for activation only from the connecting TSO; ☛Every resource object can be activated for the entire jont contol area by the optimization tool
Module 4:	Since 01.09.2009: Activation of secondary reserve is exclusively made by the optimization tool using the mutual merit order list for SR (MOL)
Module 5:	...

Table 3. Primary and secondary reserve capacity reduction caused by secondary reserve utilization scheme (Provided by Stephan Schlunke, 50HzT)

Kind of control reserve	Reserved for VE Transmission before module 2 was started / now
Primary power reserve	± 135 MW ± 135 MW
Secondary power reserve	+ 630 MW / - 450 MW + 532 MW / - 464 MW
Tertiary power reserve	+ 350 MW / -756 MW + 288 MW / - 532 MW

3.5. Tertiary reserve (load following) must meet a 15-minute deployment requirement. German TSOs procure -2,400 MW of the downward and +2,300 MW of the upward tertiary reserve capacity.

50HzT procures from -532 to +288 MW. The tertiary regulation resources are paid the market price for both the procured capacity and actual energy provided.

3.6. Amprion also procures so called wind reserve of +/- 150 MW. It has a 45-minute deployment characteristic that is activated infrequently. Table 4 summarizes the balancing capacity used in the Amprion and 50HzT systems.

Table 4. Reserve requirements in the Amprion and 50HzT areas

TSO	Peak load	Generation capacity	Wind capacity	Solar capacity	Primary reserve	Secondary reserve (regulation)	Tertiary reserve (load following)	Special wind reserve
Amprion	29,000	47,000 (incl. RES)	4,400	2,000	270	-875 +1,050	-1,070 +700	+/- 150
50HzT	15,000	34,000	10,480	300	135	-464 +532	-532 +288	N/a

3.7. TSOs do not have or use the contingency reserve. Nor do they differentiate between imbalances created by forced generator outages or deviations from bilateral schedules. In the case of an imbalance, the following sequence of reserve deployment is implemented. See Figure 6.

3.8. TSOs pay the market price for these reserves. The energy cost is recovered from the imbalance account, created using payments for deviations from the bilateral schedules by responsible energy market participants. The capacity payments are recovered from the network utilization charges that are collected from the consumers. In the case of wind and solar resources, the TSOs themselves are the responsible parties and are charged for deviations. The renewable energy sources (RES) are excluded from these deviation charges. These imbalances are paid by the TSOs and remunerated via the EEG scheme.

3.9. Power plants must provide reserves to the TSO in emergency situations.

4.0 Energy Market

4.1. Germany's entire energy market is one price area. Energy is bought and sold based on common supply and demand price ladders. Recent prices for energy in Germany are given in Figure 7.

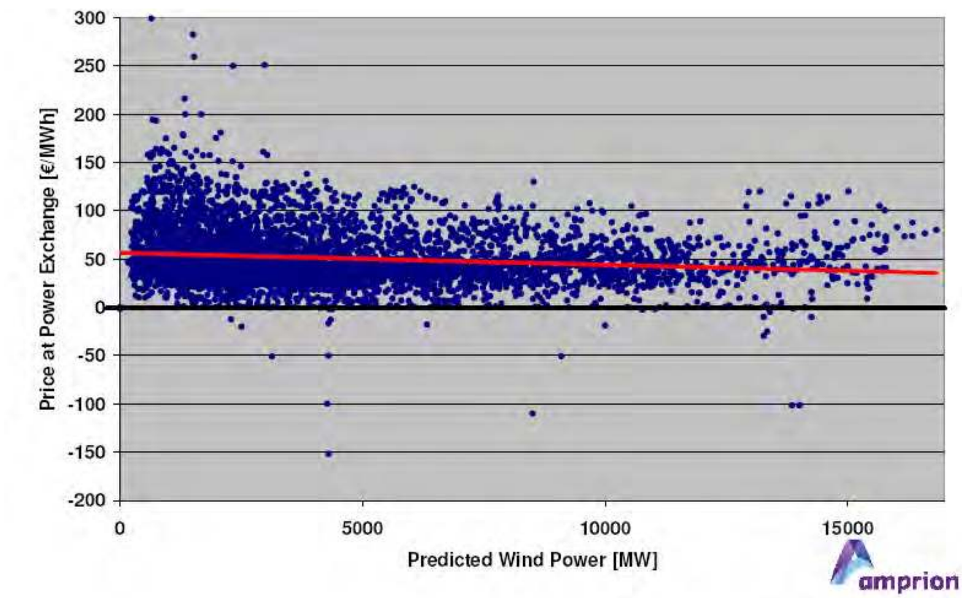

Figure 7. Energy prices in Germany (October 2008 - May 2009, Provided by Dr. Bernhard Ernst, Amprion)

4.2. The market is created by responsible balancing parties (traders, producers, large consumers, distributers). The traders can be located in the same control area, or in different control areas, or even in different countries. Several traders can form "chains" between the power producers and consumer suppliers.

4.3. The market includes the day-ahead market, intraday market, and reserves market.

4.4. The TSOs do not know exact schedules for the next day, the next 15-minute dispatch interval or the next hour. The schedule can change any time within the operating day as well. Moreover, the schedules can be provided to the TSOs the day after the operating day, according to (50HzT). This is only possible for trades within the control area. Trades across control areas must be nominated at least 45 minutes ahead.

4.5. TSOs do not apply an economic dispatch except for the secondary reserve sharing scheme created by three TSOs. The economic dispatch task is addressed by power producers and customers suppliers who participate in the bilateral market. The TSOs simply put the schedules together.

4.6. TSOs determine the imbalance cost, congestion cost, etc. These costs are charged to the consumers. (There is a certain procedure to assess which proportion of the costs can be charged to the consumers. The regulator determines the justified costs for balancing wind energy every year and publishes them in a report.) The TSOs profit is tied to how effectively they manage the system imbalances and congestion.

5.0 Renewable Energy Markets and Mechanisms to Balance Wind and Solar Deviations

5.1. The TSOs put wind energy on the Energy Exchange (EEX), also called the spot market. Beginning in 2010, bilateral or "over the counter" (OTC) deals with renewable energies are not permitted for TSOs. This is a new rule to ensure transparency for the federal regulator.

5.2. An operator of a renewable energy source (RES) can choose between two ways of payment:

- RES Option 1. Fixed price for energy. TSOs are obligated to sell the energy on the EEX market and are responsible for the balancing function.

- RES Option 2. RES operators act as market participants and need to sell the energy by themselves via bilateral trading or trading at the energy exchange. They are responsible for any imbalances. To cover the difference between market costs versus generation costs and costs of imbalances, RES operators get an additional payment per MWh depending on the kind of RES.

Most operators choose model 1.

5.3. Under RES option 1, for selling wind and solar energy, there is a centralized market run by TSOs. Wind and solar power plants produce "must take" energy except for a few cases when the wind power production is curtailed because of system security conditions. Figure 8 shows the TSO functions while marketing wind energy. (The plot corresponds to the energy exchange market design introduced in Germany in 2010). Beginning in 2010, all wind power must be sold on the spot market (power exchange EEX in Leipzig).

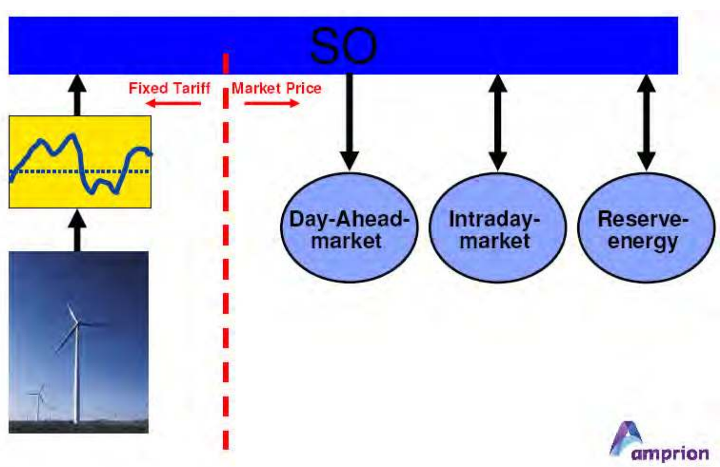

Figure 8. Marketing wind power from 2010 on (Provided by Dr. Bernhard Ernst, Amprion)

5.4. Energy and cost equalization is implemented and used between the TSOs. See Figure 9. This is a provision of the German Renewables Energies Act (2004). The inter-TSO equalization is based on real-time redistribution of renewable energy (power exchange) and associated imbalances proportional to the shares of energy consumption in each control area. Figure 10 shows an example of shares used among the four German TSOs. Figure 11 illustrates the 50HzT wind power exchange window prior to 2010.

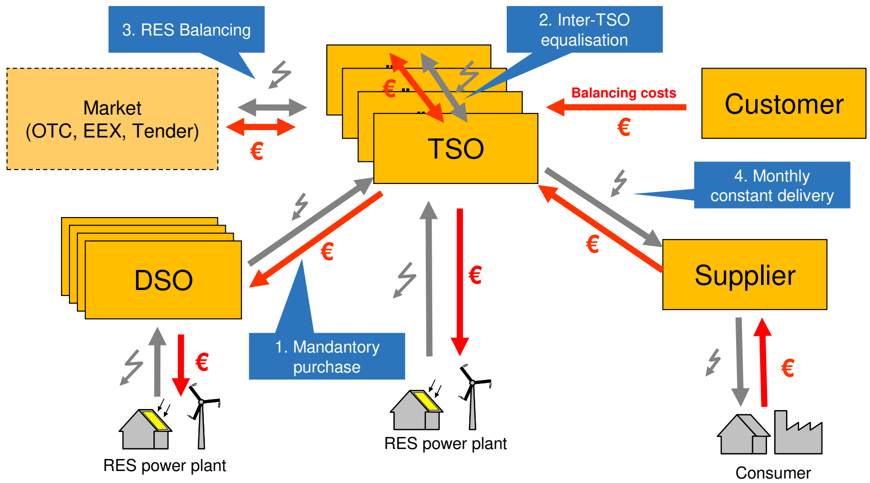

Figure 9. Handling renewable energy in Germany (Provided by Christian Scholz, 50HzT)

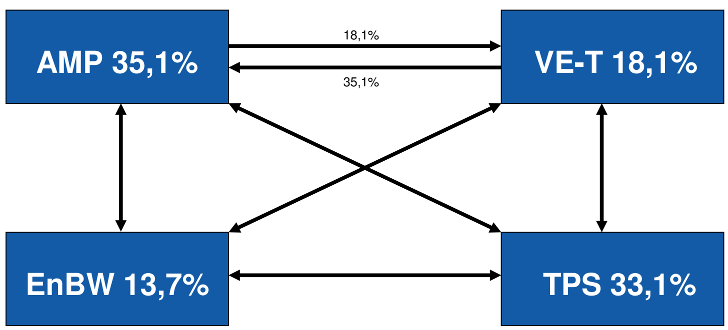

Figure 10. Example of shares used for the TSOs' equalization (Provided by Christian Scholz, 50HzT)

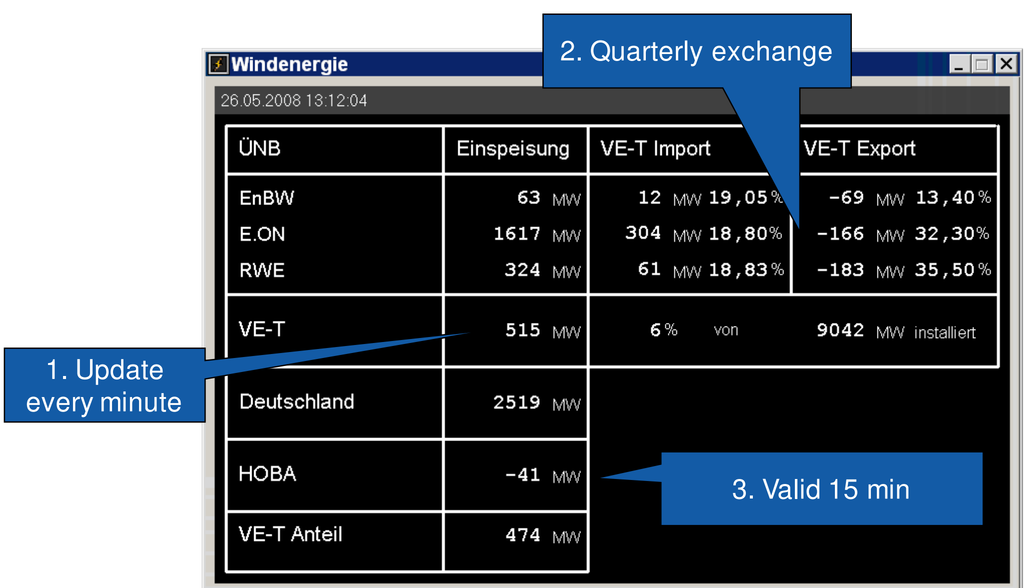

Figure 11. 50HzT power exchange window (Provided by Christian Scholz, 50HzT)

5.5. For the renewable resources, TSOs balance the difference between their 15-minute shares of wind energy and the shares of the actual production. See Figure 12. The TSOs' balancing function consists of cutting production peaks (through the sales of excessive energy), filling the valleys (through purchasing the deficient energy), and delivering the scheduled energy to the customers or their suppliers. See Figure 13. (Figure 13 was valid until 2009. Since 2010, there's trading at EEX instead of delivering to the suppliers.) Since 2010, TSOs do not deliver to customers; they just sell on the power exchange on the day-ahead market. During a day, TSOs adjust their positions by purchasing and selling in the intraday-market based on an updated short-term forecast.

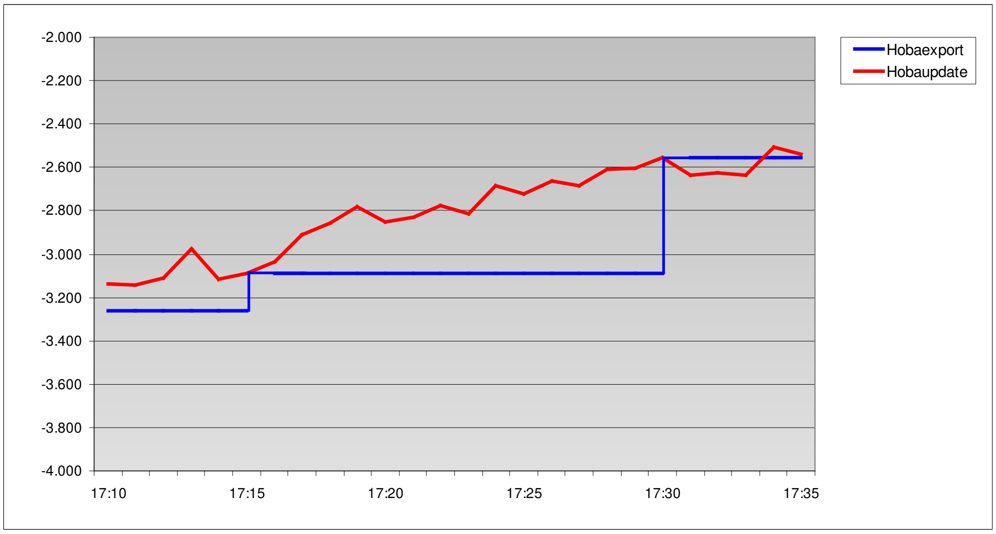

Figure 12. TSOs balance the differences between their 15-minute shares of wind energy and the shares of actual production. (Provided by Christian Scholz, 50HzT)

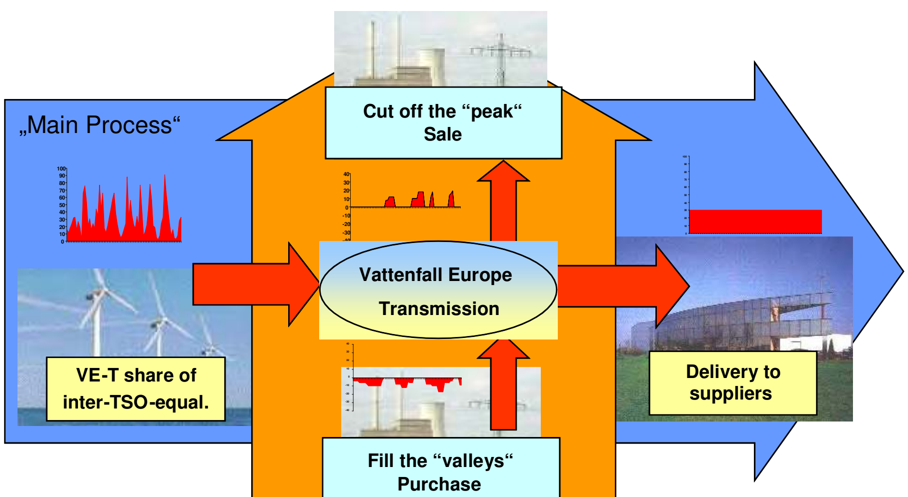

Figure 13. TSOs functioned to balance renewable resources before EEX was implemented in 2010. (Provided by Christian Scholz, 50HzT)

5.6. The balancing process for renewable resources is implemented based on consecutive trading activities on the EEX. The remaining imbalances are settled like the imbalances of any other balancing group in the control area. See Figure 14. An example of the renewable resource balancing is given in Figure 15.

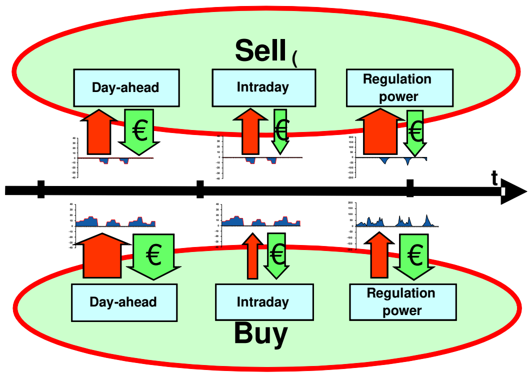

Figure 14. Balancing renewable resources before EEX was implemented in 2010. Since 2010, TSOs only sell energy on the day-ahead market. (Provided by Christian Scholz, 50HzT)

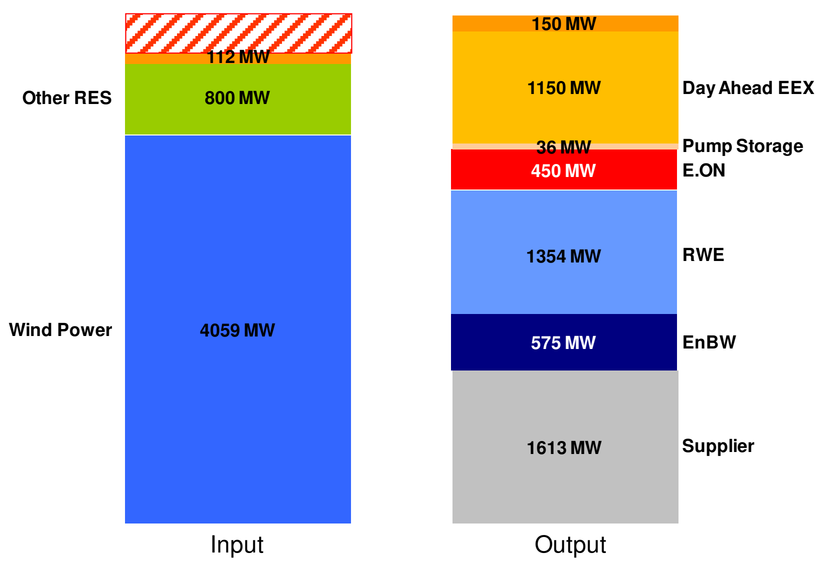

Figure 15. An example of the renewable resources balance (Provided by Christian Scholz, 50HzT)

5.7. Wind and solar energy producers in Germany get remunerated by the TSOs at fixed tariff prices for the energy actually produced. The tariffs vary depending upon generation types (e.g., offshore wind, onshore wind, and PV solar energy). The price depends on the quality of the site; very good sites have a higher digression of the price, i.e., their feed-in tariff is reduced compared to sites with lower potential. For example, 50HzT pays an average of 80 Euro per MWh for onshore wind.

5.8. TSOs are responsible for placing the volume of wind energy on the market. Therefore, the TSOs sell wind and solar energy on the power exchange. If the market price is lower than the tariff purchase price, the TSOs ultimately charge the difference to consumers based on an annual settlement period. Special note: This charge to consumers is not a pass through cost and must be approved by regulators. The TSOs are expected to make an optimal marketing decision and may not be reimbursed for "bad judgment" in the execution of trades to sell "must take" energy. This is the primary reason TSOs use the latest wind and solar techniques to forecast predicted energy.

5.9. If the TSOs need reserves to balance against wind variability, the TSOs first have to use the intraday market of the EEX, and in case of insufficient liquidity they can use the contracted wind reserves.

6.0 Forecasting Wind and Solar Energy

6.1. The TSOs are responsible for predicting wind and solar power production and the remuneration of the forecast service providers. TSOs also compensate for the imbalances caused by wind and solar power production. Therefore, it is essential that accurate wind and solar forecasts be delivered.

6.2. In our opinion, the forecast accuracy is very good in Germany. Amprion provided the following information regarding the root mean square (RMS) error for day-ahead forecasts: single farm: 10-20%; control area 400 km x 400 km – 7.5-10%; all German control areas: 5.5-6% (percent of installed capacity). The RMS forecast error may even be below 4.5% for day-ahead forecasts. (This information was provided by Energy & Meteo Systems). In the 50HzT control area: single area forecast RMSE: 6.3 – 7.2%, combined forecast 5.9%. Maximum forecast errors: -4,000 MW and +2,100 MW. The forecast RMS error for the whole of Germany in 2008 was 4.6% (combined).

6.3. Amprion uses 10 wind forecast service providers, as shown in Figure 16. Their data is entered into a "combination tool," which produces the optimal forecast combinations. The combination tool classifies the weather situation (based on the principal components and cluster analyses) and selects the optimal combination of prediction weights for the identified cluster or situation. The combination box allows reduction of the day-ahead RMS forecast error for the whole of Germany to about 4%. Figure 17 shows a screenshot of the combination tool. The combination tool was developed for Amprion by Energy & Meteo Systems GmbH.

Figure 16. Combining the best forecasts in Europe (Source: Dr. Bernhard Ernst, Amprion, with the plot provided by Energy & Meteo Systems)

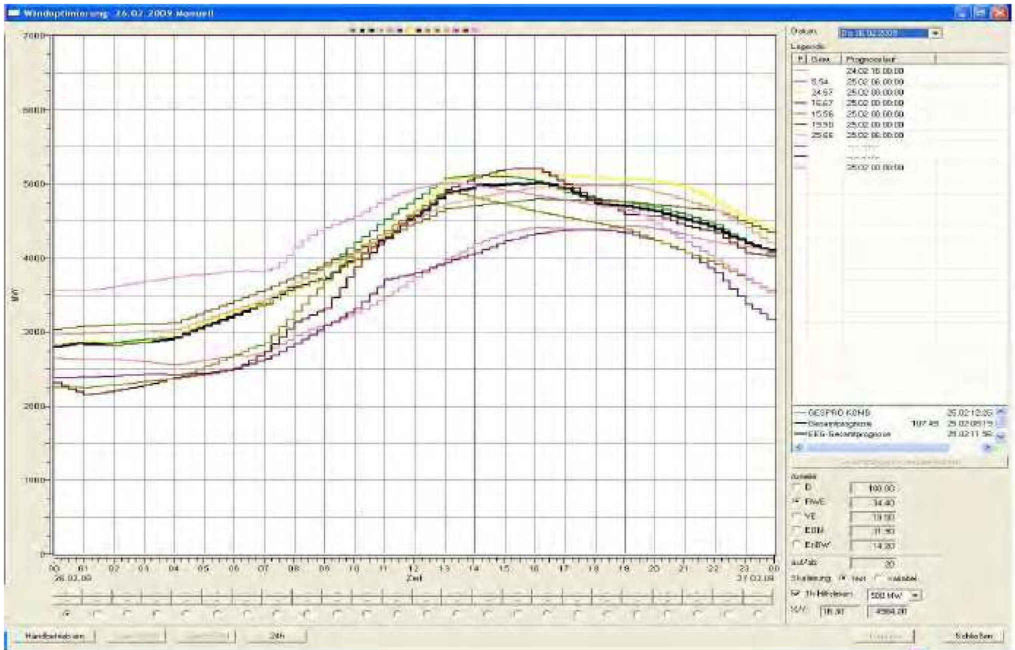

Figure 17. Screenshot of the combination tool (Source: Dr. Bernhard Ernst, Amprion)

6.4. 50HzT's combined forecast is based on services provided by the following sources: Deutscher Wetterdienst[1] (DWD), Global Forecast System[2] (GFS), High Resolution Limited Area Model[3] (HIRLAM), Météo-France[4], and European Centre for Medium-Range Weather Forecasts[5] (ECMWF). 50HzT uses three different forecast tools. A manually adjusted weighted sum is used to combine these three forecasts together. See Figure 18. Forecasts are provided for the whole of Germany, 50HzT's area, and the regions within 50HzT's area. The forecast horizon is 96 hours and beyond that, updated twice a day.

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[1] The Deutscher Wetterdienst, commonly abbreviated as DWD, (translated from German as German Meteorological Service), is a scientific agency that monitors weather and meteorological conditions over Germany and offers weather services for the general public as well as specific services (e.g., nautical, aviation or agricultural purposes). (Source: Wikipedia).

[2] The Global Forecast System (GFS) is a global numerical weather prediction computer model run by the National Oceanographic and Atmospheric Administration (NOAA). This mathematical model is run four times a day and produces forecasts up to 16 days in advance, but with decreasing spatial and temporal resolution over time. It is widely accepted that beyond 7 days, the forecast is very general and not very accurate. The model is run in two parts: the first part has a higher resolution and goes out to 180 hours (7 days) in the future. The second part runs from 180 to 384 hours (16 days) at a lower resolution. The resolution of the model varies in each part of the model. Horizontally, it divides the surface of the Earth into 35 or 70 kilometer grid squares. Vertically, it divides the atmosphere into 64 layers and temporarily produces a forecast for every 3rd hour for the first 180 hours. After that, they are produced for every 12th hour. (Source: Wikipedia).

[3] HIRLAM, the High Resolution Limited Area Model, is a numerical weather prediction (NWP) forecast system developed by the international HIRLAM program. The HIRLAM program is a cooperation between several European meteorological institutes. The aim of the HIRLAM program is to develop and maintain a numerical short-range weather forecasting system for operational use by the participating institutes. (Source: Wikipedia.)

[4] Météo-France is the French national meteorological service. The agency provides forecasts and warnings in metropolitan France and overseas. (Source: Wikipedia.)

[5] The ECMWF has been producing operational medium-range weather forecasts. The ECMWF members are from 18 European countries. The objectives of the ECMWF are: (1) development of numerical methods for medium-range weather forecasting; (2) preparation of medium-range weather forecasts for distribution to the member states; (3) scientific and technical research directed to the improvement of these forecasts; and (4) collection and storage of appropriate meteorological data. (Source: Wikipedia).

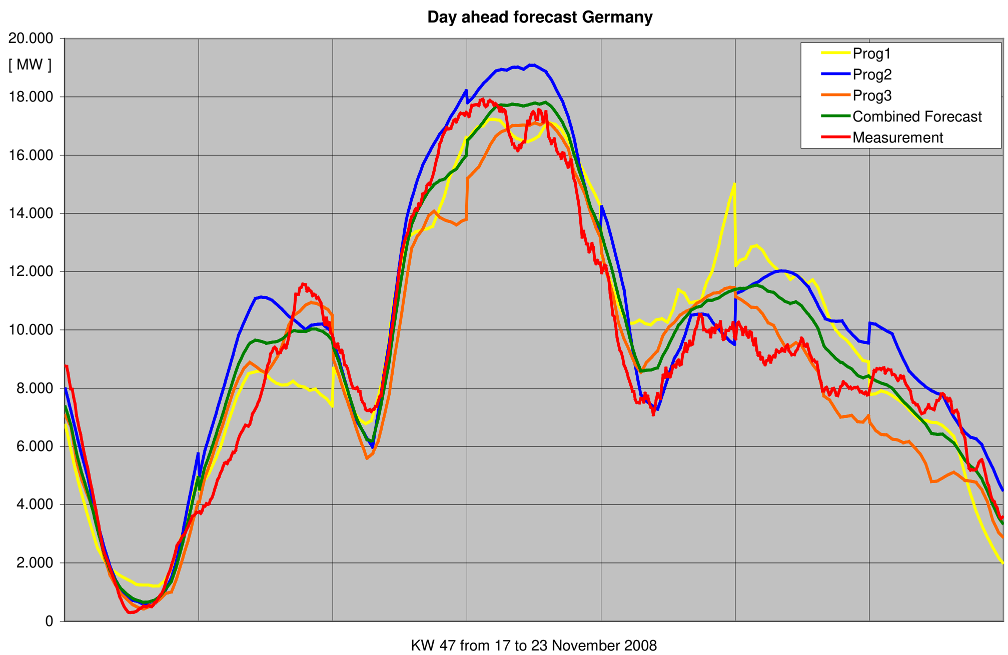


Figure 18. 50HzT wind power forecasts (Provided by Christian Scholz, 50HzT)

6.5. Data from the sites include only MW output from the turbines.

6.6. There is no full online coverage of all wind farms by real-time metering and/or forecasts in Germany, but some wind parks are covered. Wind forecasts are based on upscaling the forecasts provided for about 130 key locations in the country. The upscaling system has been developed by Fraunhofer-Institute for Wind Energy and Energy System Technology (IWES, former ISET), Kassel. The representative online measurements set in the 50HzT area include 2,242 MW of wind power capacity, which is about 23% of the total installed capacity in the 50HzT area. See Figure 19. The approach includes: (1) upscaling of wind generation for each square area of 10 x 10 km; and (2) aggregation of all square areas. The algorithm results in a weighted sum of all online measurements. The upscaling process is rather accurate in terms of its root mean square error (RMSE). See Table 5 and Figure 21a. However, in some cases this error could be very significant. See Figure 21b.

Table 5. The accuracy of the upscaling process (Provided by Christian Scholz, 50HzT)

Power			
	Overestimation	-799	MW
	Underestimation	988	MW
	Average (bias)	0	MW
	Standard deviation	146	MW
	RMSE	1,58	% *
Energy			
	Deficit	450	GWh
	Surplus	451	GWh
	Total	1	GWh

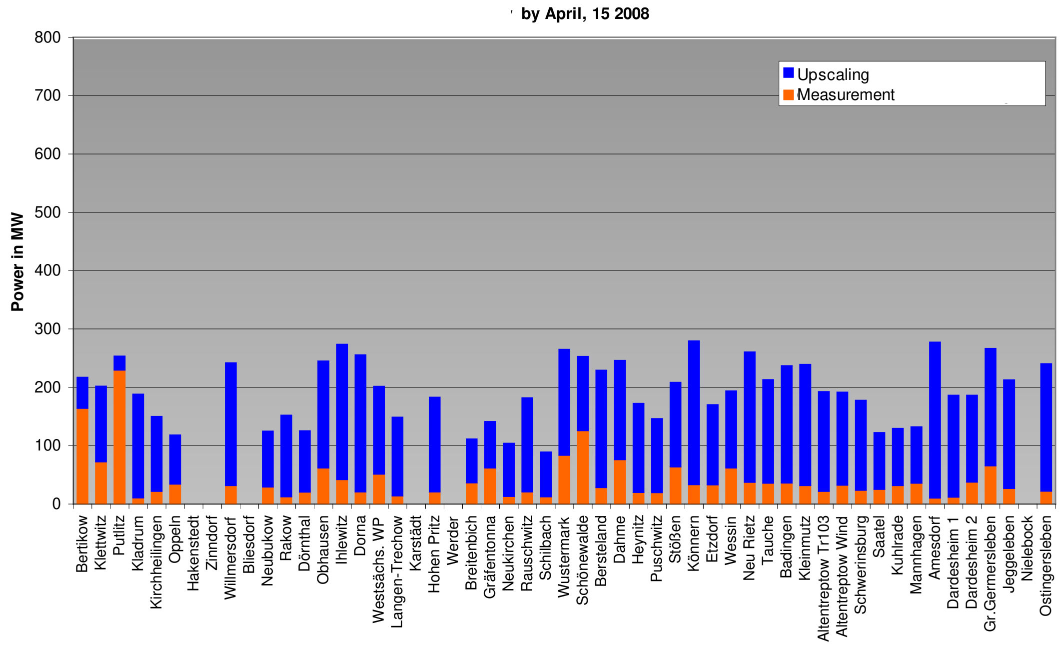


Figure 19. Coverage of the wind farms in the 50HzT area (Provided by Christian Scholz, 50HzT)

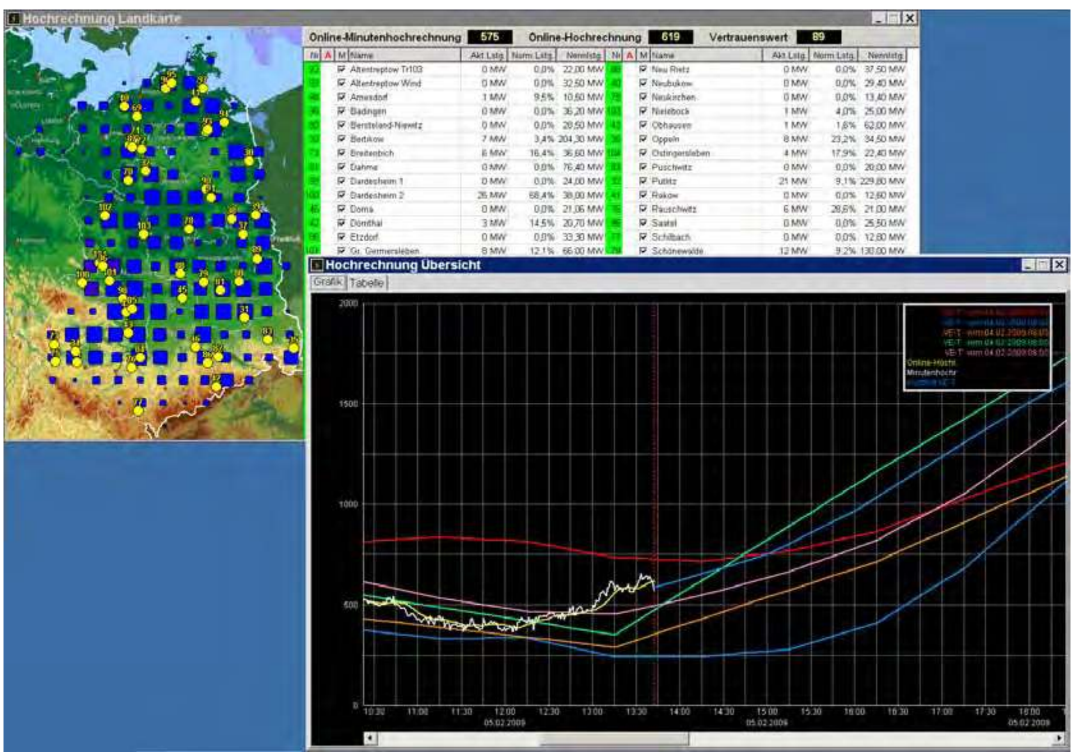
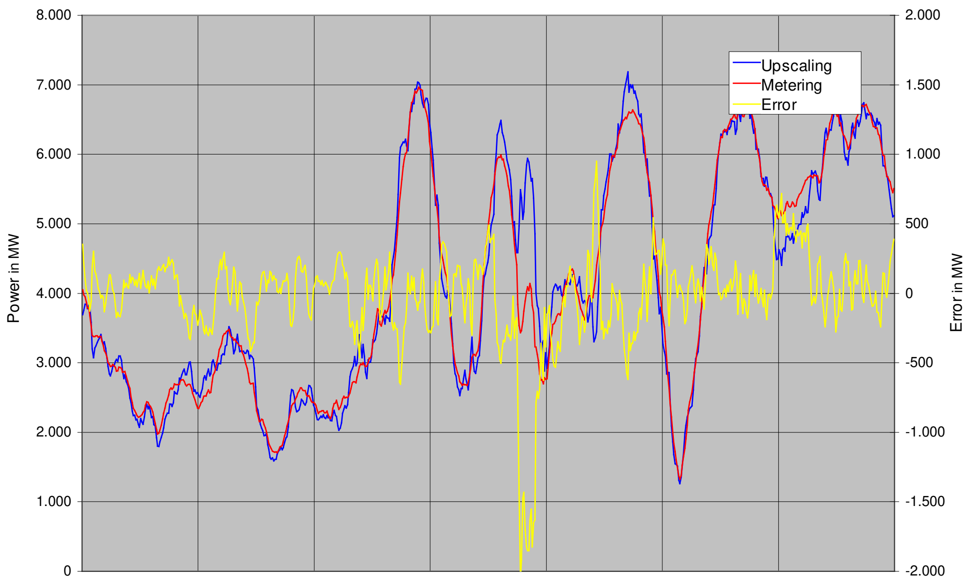
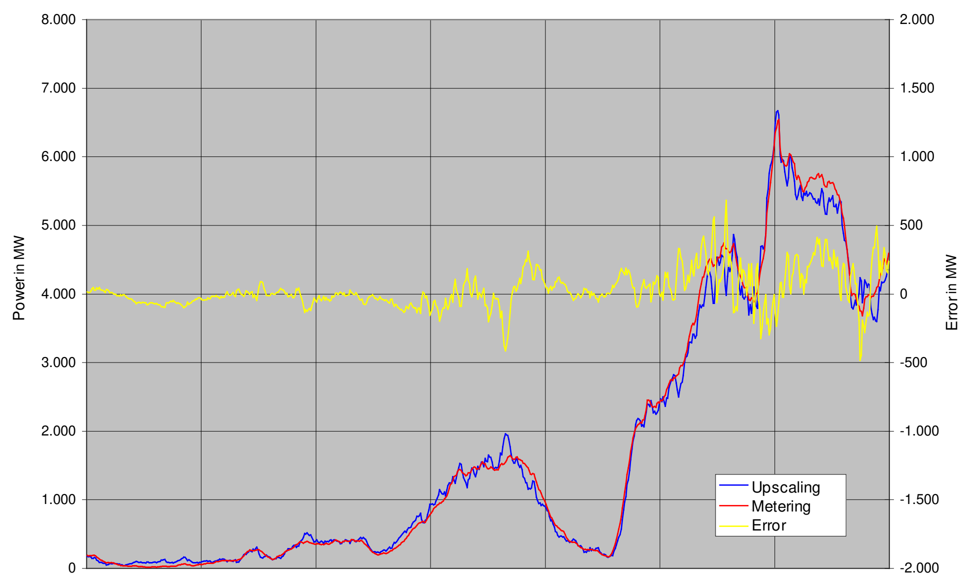


Figure 20. Upscaling tool's user interface (Provided by Christian Scholz, 50HzT)



(a)



(b)

Figure 21. Upscaling error for wind generation (Provided by Christian Scholz, 50HzT)

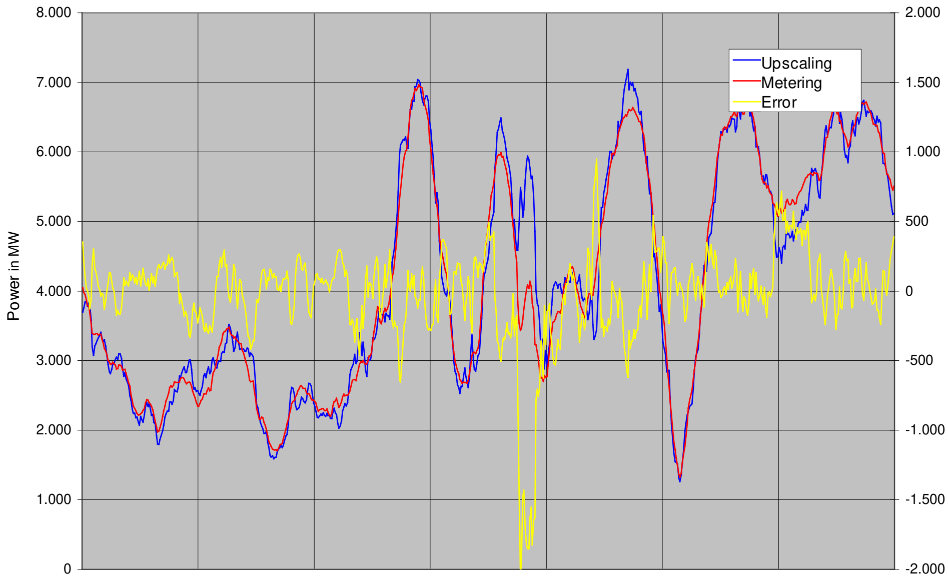


Figure 22. Upscaling error for wind generation (Provided by Christian Scholz, 50HzT)

6.7. Very large forecast errors are rare but occur once or twice a year. Forecast errors occur "slowly" because of the spatial spread of wind farms throughout Germany.

6.8. Forecasts for the German TSO regions are updated four times a day. In addition, the PV forecasting system combines the following information. See Figure 23:

- Weather forecast information from numerical weather forecast models
- Detailed technical data from photovoltaic modules such as
  - inclination
  - tracking to the sun
  - shadowing effects
  - module ventilation.

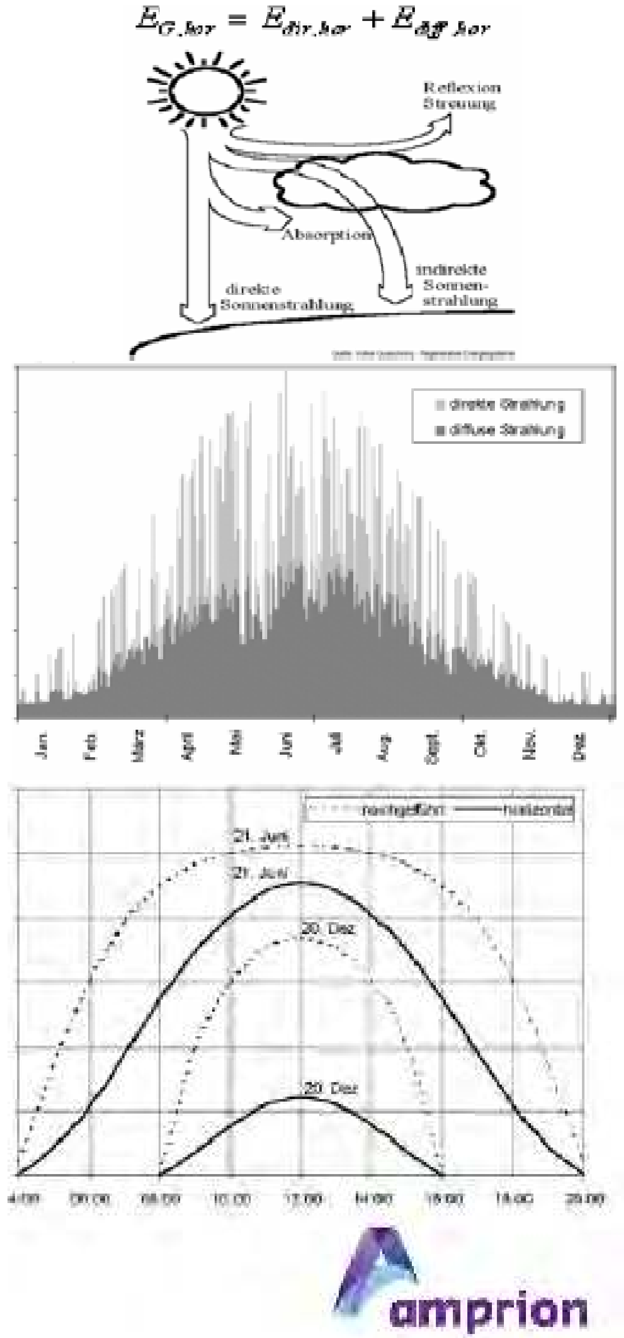


Figure 23. Elements of the PV forecasts (Provided by Bernhard Ernst, Amprion)

7.0 Scheduling Process

7.1. German TSOs use a 15-minute scheduling system. The schedules within the TSO's control areas can change any minute. The 15-minute schedules between TSOs are fixed values and can be updated 45 minutes in advance within the country. For external schedules, border-specific rules apply.

7.2. Energy exchange schedules are based on trades. Currently there are more than 200 traders participating in the German market.

8.0 Handling Wind and Solar Power Deviations from the Forecast

8.1. All wind and solar power production and their deviations in Germany are combined into one pot, and then a share of responsibility for each of four TSOs is determined, e.g., Amprion has a 35% share in the pot.

9.0 Transmission and Congestion

9.1. Sometimes wind generation in the 50HzT area causes overloads on transformers connecting the 50HzT area with Poland. In response, remedial actions are developed and successfully applied to reduce the power production in the 50HzT control area.

9.2. There are problems with maintaining system inertia in the 50HzT control area. Mitigation measures that are currently under discussion include assigning must-run units and providing ancillary services from RES.

9.3. The transmission network in Germany does have congestion problems quite frequently, but it is treated as a no-congestion network by market applications. The NE-SW flows are especially problematic. This leads to challenges in operating the network. Congestion often occurs during high wind periods. Currently, 50HzT has to utilize remedial actions on approximately 150 days a year. Also, there are transmission limits on the interconnectors with the other countries (e.g., Poland), as shown in Figure 24.

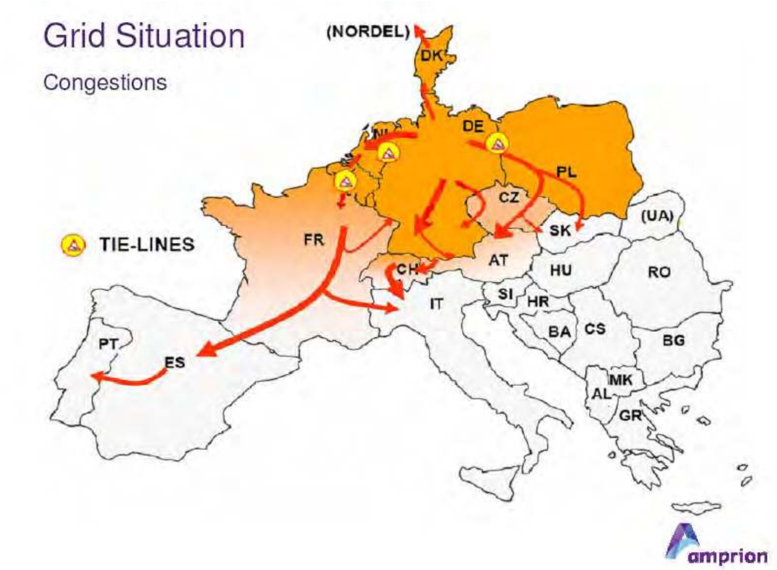


Figure 24. Congestion problems on Germany's tie lines (Provided by Bernhard Ernst, Amprion)

9.4. Within Germany, there are no transmission tariffs, but TSOs sell transmission rights on interconnectors with adjacent countries, such as France.

9.5. Consumers pay only the grid utilization charge based on tariffs established by regulators. The tariffs depend on the area. In the Amprion area, for example, the charge is less than 1.45 European cents per kWh.

9.6. "Security of supply" permits the curtailment of wind production. These events are rare and happen mainly in the distribution networks. There is no direct control over wind generation connected at the distribution level. A "cascading scheme" is employed for informing wind generators and other generators connected at the distribution level about required curtailments.

9.7. In response to congestion problems (when they occur), the TSOs redispatch power plants to manage overloads. Curtailments are done based on information about generators most affecting the congestion problem. Generators that are redispatched because of wind are paid for the lost revenue. Payments are cost based in the form of tariffs. They include the start up and shut down costs. The TSOs pay the redispatch cost although this is not a major cost.

9.8. With the other countries, the congestion is managed based on transmission capacity auctions. A special center for managing the congestion problem on a wide-area basis will be built in nearby Munich.

9.9. Loop flows are created when high wind infeed in northern Germany goes through other countries, such as Poland and the Czech Republic. See Figure 25. This has become an international problem. France and the Netherlands have installed phase shifting transformers to prevent loop flows through their systems. Measures need to be developed to handle loop flows, including such coordinated solutions as multilateral remedial actions and solutions for cost sharing and cost recovery of these actions.

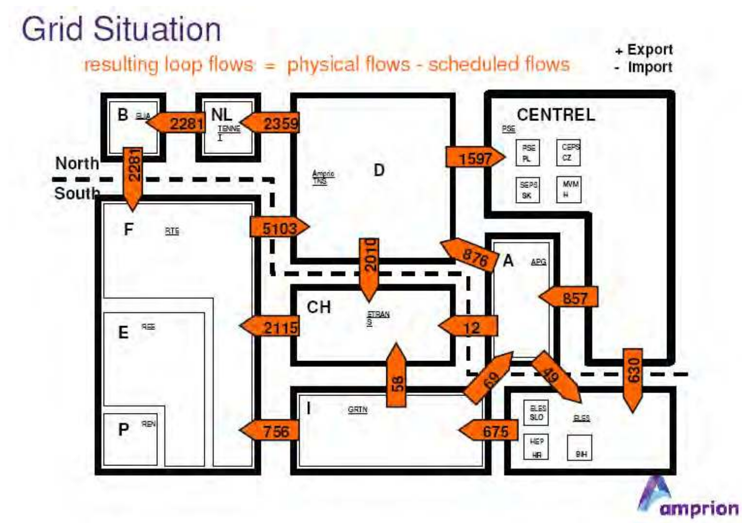


Figure 25. Example of loop flows (Provided by Bernhard Ernst, Amprion)

9.10. TSC - TSO Security Cooperation in Central Europe (includes 12 TSOs). It includes:

- Common TSO data exchange (Elements: forecast data from all TSOs, merging input data, extending grid security calculations, etc.)
- TSO security panel of experts (meets once a month)
- Cross-border redispatch subject to cost sharing and recovery
- Moving from bilateral measures to multilateral measures
- Regional power flow models.

(Different concepts have been developed by France and Belgium).

9.11. Local utilities or distribution companies provide interconnection service for wind generators.

9.12. Accommodation of additional amounts of wind capacity will be impossible without major transmission system enhancements. Thus, 50HzT currently has three major transmission improvement projects.

10.0 Control Performance Criteria

10.1. The frequency tolerance in Europe is 200 millihertz. This corresponds to an outage of two nuclear units with the total capacity of 3000 MW. The frequency response responsibility is distributed over Europe. The German's share of the response is about 700 MW.

10.2. The automatic load shedding begins at 49 Hz. It has five steps. At 47.5 Hz, the last portion of the load is curtailed.

10.3. The ACE equation is essentially the same as the one used in the United States:

$$ACE = \Delta I - k\Delta f$$

50HzT TSO starts a balancing action when the ACE value exceeds +/- 200 MW (Amprion).

11.0 Conclusions

The German experience with operating a system with 25,000 MW of installed wind capacity and 7,000 MW of solar capacity includes multiple technical, organizational and market solutions, which may be of interest to the Bonneville Power Administration and the other U.S. balancing authorities.

In particular, the report demonstrates that solutions that are currently under evaluation or under implementation, or have been already implemented by the BPA Wind Integration Team, and are consistent with the best international experience in the area of wind and solar resources integration. For example, implementing the sub-hourly scheduling process; participating in the ACE sharing (ACE diversity interchange) scheme; incorporating wind energy and wind power ramps forecasts into the BPA operations; and creating sub-hour balancing mechanisms and markets are completely in line with the successful solutions and practices in Germany.

At the same time, the German experience helps to see more clearly problems that BPA might face in the future at higher levels of wind energy penetration in its system. These potential future problems include loop flows and additional congestion created by wind power production outside of its native area; over-generation; infrequent, very significant imbalances caused by large forecast errors ("tail events"); and possible problems with low system inertia. An evaluation of these potential problems could help BPA to be better prepared to face them, as well as to find solutions ahead of time.

Some approaches undertaken by the TSOs in Germany could be of interest for BPA as improvements or even potential new solutions. They include:

- The German experience with accurate forecasting of wind power production underlines again the importance of this topic for a successful integration of large amounts of variable generation. German TSOs use up to 10 forecast services from different providers, and achieve an outstanding accuracy from the resulting forecast by using weighted sums of the forecasts with dynamically adjusted weights.

- The idea of globalizing wind power production deviations among multiple balancing authorities helps to mitigate the impacts of wind. All wind power production and its deviations in Germany are combined virtually in one pot (on a 15-minute average basis), and then a share of responsibility for each of four transmission system operators is determined. This helps to minimize the effort of handling wind power variations and uncertainties.

- The imbalance sharing scheme, which is similar to the ADI where BPA is participating, employs an additional idea of sharing regulating resources so that a particular resource can be selected to provide secondary regulation service for any of the participating TSOs based on merit order, without considering its actual location.

- The European experience with establishing a common frequency response (primary response) reserve standard and with sharing the reserve requirement obligation among the control areas deserves more attention in the United States.

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