BÜRO FÜR TECHNIKFOLGEN-ABSCHÄTZUNG
BEIM DEUTSCHEN BUNDESTAG

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Load-following capability of German nuclear power plants

Summary

March 2017
Background paper no. 21

The Office of Technology Assessment at the German Bundestag (TAB) is an independent scientific institution which advises the German Bundestag and its committees on questions of scientific and technological change. TAB has been operated by the Institute for Technology Assessment and Systems Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT) since 1990. It has been cooperating with the Helmholtz Centre for Environmental Research – UFZ, the IZT – Institute for Futures Studies and Technology Assessment and VDI/VDE Innovation + Technik GmbH since September 2013.

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2017

The complete TAB background paper no. 21 is available as PDF file in German language on http://www.tab-beim-bundestag.de/de/untersuchungen/u9600.html

Summary

Initial situation and commissioning

Triggered by plans of the German Federal Government aiming at prolonging the lifetime of nuclear power plants (NPPs) so as to build a bridge into a future era of renewable energies, there has been an extensive and controversial debate in politics, science and the public since autumn 2009. This debate focused on one central issue: Is the planned expansion of renewable energies (RE) for generating electricity – particularly photovoltaics and wind power – compatible with the operation of NPPs in the medium and long term?

Against this background, the Office of Technology Assessment at the German Bundestag (TAB) has been commissioned by the Committee on Education, Research and Technology Assessment of the German Bundestag to carry out a study dealing with this subject. The objective of the TAB project was to review and concisely summarise the status of scientific knowledge and the current debate. The results were intended to serve as an input to structure the discussion for two expert workshops that were planned to take place in March/April 2011. Due to changes in German energy policy triggered by the Fukushima disaster, however, these workshops were cancelled.

Though, due to these developments, there is a considerable and easily comprehensible loss of political and economic relevance regarding the subject of the TAB project, the TAB considers that the results are still interesting and relevant enough to be published at this point in time:

The question regarding the flexibility of the power plant fleet is still topical. In this respect, the analyses presented here regarding the question of what a dynamic expansion of fluctuating renewable electricity generation demands from the (conventional) power plant fleet are still highly relevant.

In other countries with a substantial share of nuclear power in their generation portfolio and plans for an expansion of renewable energies, the issues examined here are raised with utmost urgency. For this reason, it could be helpful to contribute the findings obtained to the international debate on energy policy.

Central issues

Nuclear power plants (NPPs) are predominantly operated in continuous mode at nominal power to cover the so-called base load. In contrast, the feed from photovoltaics and wind power is subject to strong daily and seasonal fluctuations. A large share of the fluctuating electricity feed from renewable energies imposes stringent requirements on the remaining conventional power plant fleet that have to be met in order to ensure a stable and reliable supply.

An assessment of whether or not NPPs can meet these demands depends to a large extent on the answers given with regard to two tangible questions:

- Is it possible to adjust the power output of NPPs to different load situations at a sufficiently high speed? How quickly and over which range is it possible to increase or reduce the electrical power fed in?
- How often would it be necessary to shut down NPPs completely in case of low demand and high feed of electricity from renewable energies and is this technically feasible?

Beyond technical and operational questions, there are also some significant economic aspects to be considered with regard to the operating mode meeting all these requirements – the so-called load-following operation. Possibly, NPPs are technically suited for load-following operation, but cannot be operated profitably in this mode due to their cost structure (high investment costs and low operating costs).

In addition, it is of fundamental significance to know whether the permanent change of operatingstates (temperature and pressure changes in the cooling circuits, frequent operation of controlling devices and the like) results in increased stress and wear of components and thus finally might involve implications regarding the safety of reactor operation.

How flexibly can German NPPs be operated?

In Germany, 17 NPPs with an installed total capacity of approximately 20 GW (net) were in operation in 2010. These NPPs can be divided in three construction series of pressurized water reactors (PWR) and two construction series of boiling water reactors (BWR), see table Z.1. Particularly the differentiation between PWR and BWR is of high significance, as these reactor types are principally very different with regard to their technical properties.

According to their operating manuals, NPPs show a quite remarkable flexibility with regard to the speed at which the power can be adjusted: At almost full load (above 80 % of nominal power [P_{nom}] for PWR and above 90 % for BWR), the power output can be increased or reduced by up to 10 % of the nominal power per minute. In the upper load range (above 50 % P_{nom} for PWR and above 60 % for BWR), the PWR construction series can be adjusted by 3.8 to 5.2 %/min and the BWR construction series by 3.8 to 4.6 %/min (for BWR, this value is reduced to approx. 1 %/min if individual fuel rods are defective). For comparison: For lignite-fired power plants, this value is approx. 3 %/min, for coal-fired power plants it is approx. 4 %/min and for (natural) gas-steam or combined cycle power plants it is 6 %/min. Only gas-turbine power plants with a value of 12 %/min can be adjusted much more quickly.

Table Z.1 Construction series of German nuclear power plants

Construction series		Installed net capacity (MW)
PWR 2	Biblis A, Biblis B, Neckarwestheim 1, Unterweser	4,537
PWR 3 (pre-Konvoi)	Grafenrheinfeld, Philippsburg 2, Grohnde, Brokdorf	5,437
PWR 4 (Konvoi)	Isar 2, Emsland, Neckarwestheim 2	4,049
BWR 69	Brunsbüttel, Isar 1, Philippsburg 1, Krümmel	3,885
BWR 72	Gundremmingen B and C	2,572

Information compiled by TAB

According to the operating manuals, the lower load range (between 20 and 50 % for PWR, respectively 60 % for BWR, respectively) can also be used. However, discussions with power plant operators showed that this lower load range is not being used for normal operation so far (except for start-up and shut-down operations).

The possible speed of power changes and the minimum load are not the only parameters characterising the operational flexibility of NPPs. Another important factor are start-up times required to start up a reactor again from its shut-down condition or from operation at very low power. Thus, for example, the start-up operation of a cold reactor takes 1 to 2 days. From the condition «no-load, hot« (reactor is subcritical, coolant temperature is high), this takes approximately 1 to 2 hours and in case of a longer standstill up to 6 hours. A reactor generating only electricity for its own consumption needs approximately 1 hour until the full power output is available. Basically, shut-down operations can be controlled more quickly, i. a. for safety reasons. In this case, the power is reduced from 100 % to 0 % within a shut-down time of 30 minutes. Further cooling down of the reactor takes another 4 to 5 hours.

Another factor to be considered is the number of cycles that can be run with the plants. Each load cycle stresses the material and will result in signs of material fatigue if frequently repeated. The NPPs have been designed for a certain maximum number of cycles. In the upper load range – e. g. reducing the power from 100 % of the nominal power to 80 % and back (100-80-100) – coolant temperature and pressure hardly change. For this reason, the power plants are designed for up to 100,000 of such cycles. In the lower load range, however, the alternating stress of the components increases and the maximum number of cycles is reduced. The cycle «100-40-100« must not be run more often than 12,000 times. For the cycle «nominal load – no-load, hot – nominal load« (100-0-100), the maximum permissible number of cycles is 400. Assuming a power plant lifetime of 40 years, this would correspond to 10 of these operations per year.

Is the operation of NPPs compatible with plans for an expansion of renewable energies?

To be able to evaluate whether further operation of NPPs is compatible with the planned expansion of electricity generation from renewable energy sources, a model-based analysis of the future power generation system has been carried out. For this purpose, framework data have been assumed (i. a. the future electricity demand, energy carrier prices, renewable energies expansion path) which are based on the assumptions given in the scenarios for the German Federal Government's Energy Concept (Prognos/EWI/GWS 2010) or in the Pilot Study of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) (DLR/IWES/IfnE 2010).

A power plant fleet has been simulated for the model years 2020, 2025 and 2030 by minimising the total system costs for the addition of further power plants and storage facilities. The combined operation of NPPs, fossil power plants and renewable energy systems has been analysed using a model of the electricity market.

Based on the above-mentioned technical capacities regarding the load-following operation of NPPs, three possible future operating strategies have been defined and examined in the different scenarios:

Conditionally flexible operation: Here, routine load change cycles of type 100-50-100 (PWR) or 100-60-100 (BWR) are allowed, i. e. the minimum load does not fall below 50 % (PWR) or 60 % (BWR) of the nominal power. Experience regarding this operating strategy has been already gained in some German NPPs.

Flex20 operation: In this case, it is assumed that the NPPs can also be run flexibly in the lower load range. For PWR, a minimum load level of 20 % has been set as suggested in the specifications of the operating manuals. For BWR, based on expert discussions, a value of 40 % has been assumed as minimum load.

Flex0 operation: In addition, even short-term downtimes are allowed for this mode of operation. To consider start-up and shut-down times, a minimum downtime of 3 hours and a minimum operating time of 1 hour have been set here.

As a measure for flexibility of the conventional power plant fleet (including NPPs), the different scenarios use the quantity of electricity from renewable energies that must be curtailed respectively. A summary of the results for the model year 2030 will be given in the following. Here, as can be found in the Pilot Study of the BMU, the share of renewable energies in electricity generation is approximately 65 %. The scenario without lifetime extension of NPPs shall serve as a reference case, i. e. electricity generation by means of NPP is zero. Nevertheless, approx. 12 TWh of electricity from renewable energies would have to be curtailed in this scenario.

In case of the lifetime of NPPs being extended by 12 years, this value will be increased to approx. 21 TWh, whereas it will be increased even to 28 TWh if the NPP lifetime is extended by 20 years. For this scenario, a conditionally flexible operation is assumed. This illustrates the potential for conflict between a high market penetration with renewable energies and a continued operation of NPPs.

It becomes clear that compliance with the minimum load is the decisive limiting factor, if this assumption is weakened and a Flex20 operation is assumed (i. e. the minimum load is only 20 % for PWR and 40 % for BWR). For the scenario with a 12-year lifetime extension, the electricity quantity to be curtailed then is reduced from 21 TWh for conditionally flexible operation to 14 TWh (Flex20). If, in addition, short-term downtimes are allowed (Flex0), this value falls below 10 TWh. What is remarkable is that this is less than the electricity quantity that would have to be curtailed without NPPs (12 TWh). This means that in the Flex0 scenario electricity from renewable energies even can be better integrated into the system than without NPPs, as in this case the NPPs could be operated more flexibly than the fossil power plant fleet.

To illustrate what the operation of an NPP under these conditions would be like, the number of cycles that would have to be run in the different load ranges has been calculated. In the scenario with a lifetime extension of 12 years, approximately 350 cycles of type 100-60-100 in conditionally flexible operation would be requiredin the year 2030. In Flex20 operation, it would be approx. 200 cycles of type 100-20-100 and another 200 cycles of type 100-60-100. In Flex0 operation, each NPP would run the cycle from full load to no load and back again (100-0-100) on average 100 times a year. Altogether, this would result in approx. 2 to 3 start-up operations per week for each NPP.

Economic aspects

Although it might seem paradoxical at first sight, there is a phenomenon occurring regularly and currently more and more often on the electricity market in its current form: negative prices. During hours when the electricity offer is higher than the corresponding demand, electricity producers are paying money for consumers buying their electricity.

In case of electricity that is remunerated via the mechanism of the German Renewable Energy Sources Act (»EEG«), the responsible grid operators are obliged to buy it for a negative price of up to -150 EUR/MWh (status as of 2010). The difference to the feed-in remuneration paid is added to the German renewable energy surcharge (»EEG surcharge«) and thus will be paid by the consumer. However, this price also applies to conventionally generated and marketed electricity. This means that power plants that continue producing cannot throttle their power for operational or other reasons and thus will incur losses. For this reason, the occurrence of negative prices is an indicator for insufficient flexibility of the power plant fleet.

Among other things, the modelled scenario shows that the current design of the electricity market will reach its limits in case of a high penetration with fluctuating renewable energies, as negative prices occur for approximately 1,950 hours in the model year 2030 even without the lifetime of NPPs being extended. With lifetime being extended (12 years, conditionally flexible operation), this situation is further aggravated by reaching 2,600 hours. Using a highly flexible operation of NPPs (Flex0), however, the number of hours with negative prices can be slightly reduced to approx. 1,800.

Conditionally flexible operation forces NPPs to generate electricity even in hours with negative prices, as short-term load reductions are not possible for the NPPs. If the existing regulation of the German Renewable Energy Sources Act requiring to primarily feed in and remunerate electricity from renewable energy sources would be overturned, renewable energy facilities would have to be curtailed for economic reasons as soon as the market price drops below zero. Thus, the number of hours with negative prices would be reduced and, as a consequence, the operation of NPPs would become significantly more attractive: In the model, the annual profit per installed MW of EUR 180,000 (with priority of renewable energies according to the EEG) would increase to EUR 330,000 in case of the priority rule being abolished. Thus, given a limited flexibility of the NPPs, there is a high interest of the operators in putting the priority rule up for discussion.

Safety aspects of load-following operation

In the TAB project, questions with regard to the possible implications of an increased use of load-following operation for nuclear safety are dealt with in the form of theses. It was not intended to provide final evaluations regarding these theses, as the TAB does not have sufficient competence to deal with this kind of highly complex specialist issues.

The objective was to discuss the theses in an expert workshop with experts from different backgrounds in order to identify areas where a consensus can be reached and to find out where disagreement prevails. Representatives of reactor manufacturers and operators, scientists covering a wide range of opinions with regard to the issue of using nuclear energy and representatives of licensing and supervisory authorities already confirmed to participate in the workshop. However, as mentioned before, the workshop had to be cancelled.

The theses involved are based on the – fictitious – assumption that in the future NPPs will increasingly be operated in a load-following mode that also covers the lower load range (Flex20 and Flex0). This clearly constitutes a breach regarding the operating strategies currently used. So far, no practical experience is available regarding such a kind of operation – at least in Germany.

Abstract of theses with regard to safety aspects of load-following operation

Reactor core: During regular load-following operation, certain thermal, mechanical and corrosive stresses occur at different points inside the reactor. These include, for example: Signs of wear and fatigue regarding the control rod mechanisms, swelling of the control rod ends due to increased neutron densities, thermal stresses due to temperature gradients with the possible consequence of cladding tube damages.

Thermohydraulic components (pumps, valves, pipes etc.): Load-following operation involves a higher level of stress resulting in signs of material fatigue, erosion, corrosion and wear and thus impacting the correct functioning and integrity of components. The top nozzle of the hot and cold legs at the reactor pressure vessel or at the steam generators are particularly affected by processes of thermal stress fatigue. Temperature gradients involve fluctuations of water chemistry which in turn lead to increased erosion and corrosion of the components.

Monitoring and replacement of components: It is ensured that the degradation of components due to ageing and stress is detected in good time by the implemented monitoring and detection systems. Component-specific measurement, however, is limited in principle with regard to spatial and temporal resolution. Except for the reactor pressure vessel, all components in a NPP can be replaced. Shorter replacement intervals involve frequent downtimes of the plant. Due to the technical design, signs of wear and fatigue regarding the pressure vessel are negligible.

Control und regulation processes: Load-following operation is a more complex operating mode than constant load operation. The demands made on the staff are higher and there is an increased probability of human errors. Load-following operation may require adjustments of the fuel assembly loading strategy. As a consequence, the reactors then are not optimised for load-following operation.

Probability and handling of accidents: In the context of load-following operation in the upper load range, previous investigations and model calculations could not prove an increased probability of accidents. Currently, however, there are no investigations, model calculations and experience regarding the question of what the probability of accidents would be like for load-following operation also covering the lower load range.

Licensing procedures: There is disagreement on whether load-following operation (as it is defined here) has to be understood as a modified operating mode and, as a consequence, whether or not it is covered by regulatory licenses applied to date.

The theses have been prepared by the team of experts from the Chair of Nuclear Technology at the Technical University of Munich (Ecofys 2011, p. 65 et seqq.) commissioned by the German Bundestag.

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