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IER

Summary

Compatibility of renewable energies and nuclear power in the generation portfolio

Technical and economical aspects

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The present document is an English translation of the summary of the study "Verträglichkeit von erneuerbaren Energien und Kernenergie im Erzeugungsportfolio : Technische und ökonomische Aspekte". It is a service provided by E.ON Energie AG in order to make the study's results accessible to a broader audience. Only the German text written by the authors is authentic, however.

Executive summary

In discussions of the future of nuclear power, particularly in recent months, the argument has been advanced that there is a fundamental conflict between a further expansion of renewable energies and the continued operation of nuclear power plants in Germany given a lifting of the lifetime reduction. According to this argument, an extension of the lifetime of nuclear power plants would impede the expansion of renewable energies. The argument is also advanced that nuclear power plants are not sufficiently flexible to be operated compatibly given large short-term fluctuations in electricity generated from wind converters and photovoltaic systems.

The study on which this summary is based examines two aspects of this debate, which are explained below:

– Are there any technical and/or operational limitations which in case of a high percentage of fluctuating electrical supply from renewable energies might conflict with the integration of this generated supply assuming a lifting of the lifetime reduction?

– What are the economic and emissions-related (CO_2) effects of a lifetime extension for an electricity system with a large share of renewable energies?

For purposes of this discussion it is assumed that the Federal Government intends to extend renewable energies for electricity generation (app. 30 or 40 % of electricity generation in 2020 and 2030), which assumes that the predominant share is being generated by supply-contingent utilisation systems such as wind converters and photovoltaic systems. In considering the future, it is also assumed that there will be a privileging of electrical supply from renewable energies, with the result that the conventional, and primarily thermal, generation mix will at all times have to just cover the remaining share of the demand for electricity. Unit commitment is examined from a technical-operational standpoint for a generation mix that could result in the event of a "phaseout" of nuclear power and a "lifetime extension" of the existing power plants. Further, the economic and emissions-related (CO_2) effects of both variants "nuclear power phaseout" and "lifetime extension" are estimated.

Up to now nuclear power plants in Germany have been primarily run in continuous operation at nominal (rated) power, with only a few running in load-following mode. However, the facility for load-following operation is a determinant design criterion, and core monitoring and reactor control are accordingly designed so that no subsequent reinforcement of the systems is required. Nuclear power plants can be operated within a range of 50 to 100 % of nominal electrical capacity with power gradients between 3.8 to 5.2 percent of nominal power output per minute in normal operation with low-strain operating mode. Nuclear power plants thus allow for similar power gradients as coal-fired condensation power plants. Altogether, the existing pressurised water reactors and boiling water reactors can contribute to load following operation within 15 minutes at an output of up to 9.6 GW.

Investigations of the selected years 2020 and 2030 show that the residual load in the two scenarios “nuclear power phaseout” and “lifetime extension” (high share of gas fired power plants or nuclear power plants, respectively), which is increasingly volatile on account of the increasing electrical supply of renewable energies, can still be reliably covered from an operational standpoint. In both variants, extreme gradients and levels in the residual load can be dealt with. An essential role is played here by storage technologies that are used to homogenise the residual load and by a reliable prognosis of the stochastic electrical supply from wind converters and photovoltaic systems. In the event of a lifting of the lifetime reduction, nuclear power plants would be increasingly used for load-following operation and their dispatch would be reduced compared to their current operating mode.

Neither of the two scenarios “nuclear power phaseout” or “lifetime extension” is clearly superior with respect to the flexibility of the conventional thermal generation mix. The assertion that the level of operational flexibility necessary to meet the residual load at a high share of electricity generation from renewable energies could not be guaranteed with a lifetime extension of nuclear power plants, is unjustified.

However, assuming an even greater portion of electricity generation from wind converters and photovoltaic systems for 2030 than is assumed here – regardless of whether nuclear power plants are part of the generation mix or not – a control of fluctuating electrical supply from renewable energies, or the construction of additional storage systems, will be required to cover the electricity demand with the necessary level of supply reliability.

A reduction of yearly system operating costs of 31 % in 2030 can be achieved in the “lifetime extension” scenario as compared to the “nuclear power phaseout” variant. This is primarily owing to reduced expenditures for fuels and CO_2 certificates. The phaseout of nuclear energy would further be accompanied by new construction requirements for power stations with a net bottleneck capacity of app. 22 GW, and that would in turn entail additional costs.

There are also considerable differences to be taken into account with respect to wholesale prices for electricity. Assuming a balanced electricity exchange and constant CO_2 certificate prices, the wholesale prices in 2030 are approximately 16 % less in the “lifetime extension” scenario than in the “nuclear power phaseout” scenario. A phaseout of nuclear energy would result in additional emissions of 70 mil. tCO_2 in the year 2030. If we compare the cumulative CO_2 emissions in years 2010 to 2030, additional emissions of 1280 mil. tCO_2 (+ 36 %) result in the “nuclear power phaseout” scenario.

In summary, the assertion that a lifetime extension of nuclear power plants would be a stumbling block for the expansion of renewable energies cannot be supported from a technical standpoint. In fact, from an economic and emissions (CO_2) perspective a nuclear energy phaseout would even be counterproductive.

Background and objective

Discussions have intensified in recent months concerning the future use of nuclear energy in Germany, in particular the topic of lifting the lifetime reduction for German nuclear power stations. Here, in addition to questions on the effects on electricity prices and CO_2 emissions, the debate has focused in particular on the effects on future utilisation and expansion of renewable energies. Examples of this include statements and arguments found in publications from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [2–4]. There it is stated that a lifetime extension of the nuclear power stations will have a curbing effect on the expansion of renewable energies, because nuclear power and renewable energies are incompatible in the interconnection of power systems.

Often cited as a primary reason for this supposed incompatibility of nuclear power and renewable energies is insufficient operational flexibility on the part of nuclear power plants. Nuclear power plants, it is claimed, are "difficult to regulate" and the frequent switching on and off is "avoided wherever possible based on safety considerations alone". Nuclear power plants, it is argued, are "constructed to run smoothly at 100 % load, and thus to generate the same amount of power at all times – whether it is needed or not" [2].

A similar argument, which holds that the required expansion of renewable energies is incompatible with a large percentage of baseload plants (coal and/or nuclear energy), is also made in the current report of the German Advisory Council on the Environment (SRU) [12] and in a study by Fraunhofer IWES commissioned by the German Renewable Energy Federation (BEE) [8]. In both publications the argument is made that on account of the increasing fluctuation[1] in the electrical supply from renewable energies the operation of baseload plants will in the future be limited, for both economical and technical reasons, and that a lifetime extension for German nuclear power plants will interfere with the integration of renewable energies.

With this in view, two aspects of the debate concerning the lifetime extension of nuclear power stations are examined more closely in the study that is summarised here [10]. First, the question is explored as to whether in case of a lifetime extension for German nuclear power plants there are technical and/or operational limitations that may complicate the integration of a high percentage of fluctuating electrical supply from renewable energies. Second, the economic and emissions-related (CO_2) effects of a lifetime extension of nuclear power plants are estimated for an electricity system with a high percentage of fluctuation in the production from renewable energies. The analysis explicitly excludes

[1] Utilisation systems of fluctuating renewable energies (wind converters, photovoltaic systems) for electricity generation are also called "non-controllable" or "non-regulatable" systems. Technically speaking, this term is only partly correct since an increase in electrical supply can be avoided through regulation. From an economic standpoint, the electrical supply of renewable energies is privileged in Germany through the Renewable Energy Sources Act.

the basic question of whether the desired expansion in the electricity supply from renewable energies is the correct path towards an economical, environmentally and climatically sustainable, and reliable electricity supply in Germany.

To answer the above questions, an analysis is conducted using the years 2020 and 2030 as an example, based on the assumption of an expansion of electricity generation from renewable energies in Germany, which, going by Federal Government expectations, results in a share of approximately 30 % of the demand for electricity in 2020 and 40 % in 2030. Using as a basis historical curves for demand load, wind energy supply, and solar radiation supply in Germany, the historical curves for demand load and for electrical supply from wind converters and photovoltaic systems are determined for the years 2020 and 2030, as well as the resulting historical curve for the residual load[2] to be covered through the conventional (primarily thermal) generation mix. The coverage of this residual load is then examined for a generation mix that may result in case of a "nuclear power phaseout" and a "lifetime extension" for existing nuclear power plants. In addition to the technical and operational aspects of unit commitment with a large share of electricity generation from renewable energies also the economic and emissions-related (CO_2) effects of both variants "nuclear power phaseout" and "lifetime extension" are determined.

Energy economic assumptions

The energy economic assumptions have been made for this study in the context of current studies and of both internal reports and estimates [6, 7]. A few simplifying assumptions are required on account of the limited regional scope under consideration and to ensure the simplest possible mutual comparison of the two scenarios, and wherever possible these have been made to ensure that estimates remain conservative – i.e. intensified for the situation of baseload power plants, in particular nuclear power plants.

This analysis is based on the assumption that in 2012, in keeping with an economic recovery, the domestic net electricity demand in 2012, at app. 542 TWh, will return to the levels of the years 2007 and 2008 and will then remain constant. Future electricity exchange balances of zero are assumed. Given a continuation of historical net losses, these assumptions are consistent with a net electricity generation (without pumping) of approximately 571 TWh in 2020 and 2030. For purposes of the current discussion, these assumptions are conservative because the level of fluctuating residual load will decrease on account of an increasing electrical supply from renewable energies and this will not include any allowance for potential homogenising effects from the electricity exchange.

For future trends in energy carrier prices, both the "nuclear power phaseout" and "lifetime extension" scenarios are based on the assumption of a moderate increase in raw oil prices, following the drastic price collapse in 2008, to 75 $US\$_{2007}$ by 2030, which is then used to derive price trends for heating oil, natural gas, and coal. The CO_2 allowance price

[2] Residual load as used in the following refers to the electrical demand load minus the electrical supply from wind converters and photovoltaic systems.

of 30 €$_{2007}$/tCO_2 is assumed for both points in times under consideration. Table 1 provides an overview of the assumptions, which with regard to energy carrier prices represent a more conservative estimate considering system operating costs of a primarily fossil-thermal generation mix.

	2007	2020	2030
Heating oil	55.9	33.8	37.4
Natural gas	26.3	19.3	20.5
Coal	9.2	7.7	7.9
Lignite	3.8	4.1	4.4
Nuclear fuel	2.5	2.5	2.5
CO_2 allowance price	0.6	30.0	30.0

Table 1: Trends in energy carrier prices, free plant [€$_{2007}$/MWh] and CO_2 allowance prices [€$_{2007}$/tCO_2].

A significant increase is assumed for electricity generation from renewable energies in 2020 and 2030, with the result that, according to Federal Government targets, a share of approximately 31 % of electricity generation[3] is achieved in 2020. The share will increase to approximately 42 % by 2030.

	2007	2020	2030
Wind	40	102	154
...offshore	-	36	88
...onshore	40	65	65
Photovoltaics	3	13	19
Biomass	24	37	41
Run-of-river and hydro storage	21	24	24
Total	88	176	238
Share	0.15	0.31	0.42

Table 2: Trend of net electricity generation from renewable energies [TWh] and its share of overall net electricity generation.

Table 2 provides an overview of assumptions concerning future use of renewable energy sources for electricity generation. According to our assumption, the supply-contingent electricity generation from wind energy rises from 40 TWh in 2007 to 154 TWh in 2030 with approximately 88 TWh generated in offshore wind converters. With regard to the electricity generation from photovoltaic systems, which also fluctuates, the assumption is that it will increase to 13 TWh by 2020 and to 19 TWh by 2030. It is generally assumed that in the future there will continue to be a privileging of electrical supply from utilisation systems of renewable energies. The more intensive utilisation of wind converters at the sea envisioned by the Federal Government is only feasible assuming a significant expansion of the electricity grid. For that reason it is also assumed that in the future it will be possible, owing to the recently effected Power Grid Expansion Act (EnLAG), to avoid possible congestion in the transmission grid when integrating the electrical supply from offshore wind converters.

[3]The rates in this analysis are shown as a share of net electricity generation without pumping.

Dynamics of residual load

The structure of the residual load in the years 2020 and 2030 on which the analysis is based is obtained by scaling selected historical time variation curves of hourly demand load, quarter-hourly wind supply, and semi-hourly solar radiation to each of the relevant assumed energy quantities of the electrical demand load and supply from wind converters and photovoltaic systems [9]. For the historical load curve of electricity demand, data from ENTSO-E (formerly UCTE) has been used, which however has been scaled to the overall net electricity generation (excluding pumping). The historical curve of wind supply was created using historical data (actual wind supply inside the transmission network areas and wind speeds at the sea in 2008) and taking into consideration a variable path towards expansion for wind converters inside the country and at the sea (onshore and offshore). Figure 1 shows the resulting curve for electrical demand and residual load, broken down by quarter hour for the year 2030.[4]

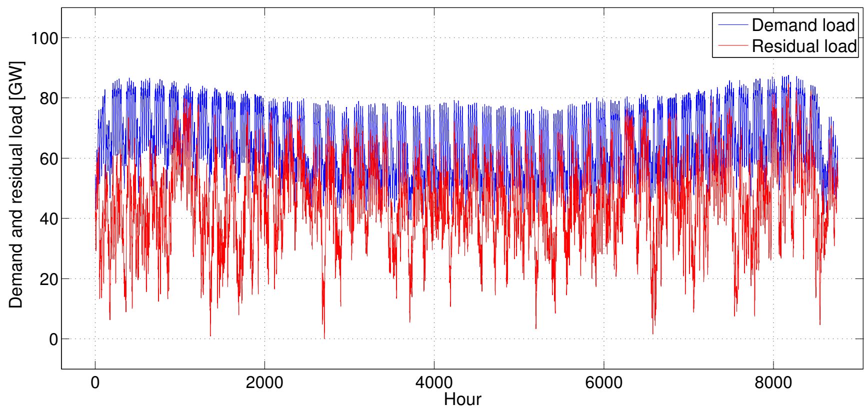


Figure 1: Time variation curves of electrical demand load and residual load in the year 2030 (Basis: scaled historic wind generation profile 2008).

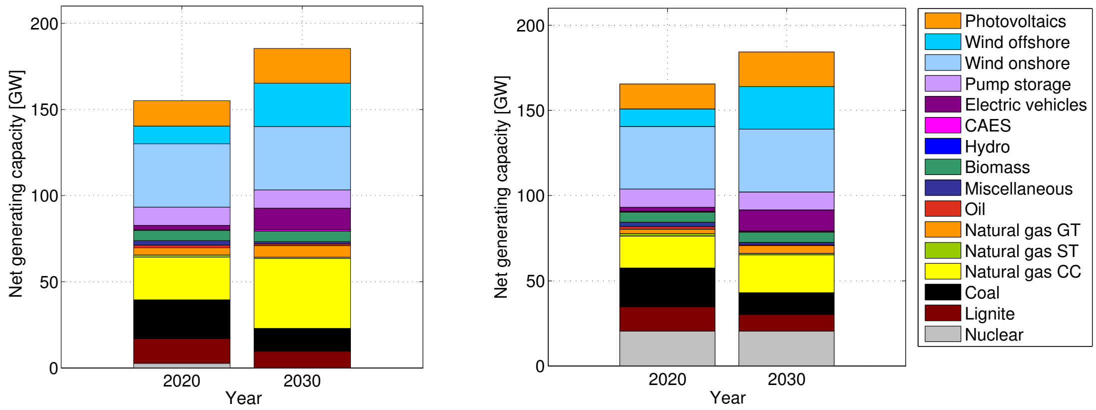
The overwhelming majority (over 90 %) of residual load gradients that occur fall within a range of –2.3 to +2.4 GW/15 min, but extreme gradients of the residual load also occur (caused by extreme gradients in wind supply) from up to –12 or +11 GW/15 min.

Generation mix in 2020 and 2030

Based on the energy economic assumptions outlined above, the power plant capacities shown in Figure 2 for Germany, which include as an exogenous parameter power plant projects that are currently underway [5], are obtained for the years 2020 and 2030 as part of a cost-oriented expansion plan. The currently remaining lifetimes have been assumed

[4]Use of wind generation profiles based on other historical years can result in different outcomes in the distribution of the residual load. The fundamental characteristics however should be the same.

for the "nuclear power phaseout" scenario; for the "lifetime extension" scenario it was assumed that the current power plants will still be in operation in the year 2030.



(a) "Nuclear power phaseout" **(b)** "Lifetime extension"

Figure 2: Power plant capacities in Germany in the year 2020 and 2030.

To homogenise the fluctuating electrical generation from renewable energies, storage systems will gain in importance. In this projection, three storage technologies are explicitly considered: (i) pump storage power plants, (ii) compressed-air energy (CAES) storage gas-turbine power plants (as endogenous construction option) and (iii) mobile battery storage in electric vehicles.

Existing *pump storage power plants* in Germany, including systems[5] run by German operators in neighbouring countries, are examined in eight different power plant classes, with a total electrical output of 6.7 GW. Of the two new construction projects which are currently in the planning phase in Atdorf and Forbach, only the first has been included for implementation in 2020. It is assumed with regard to *compressed-air energy storage gas-turbine power plants* that beginning in 2015 a maximum of 800 MW/a in additional system capacity can be added to the system in Huntdorf. Assumptions concerning the availability of *mobile battery storage in electric vehicles* are based on targets from the Federal Government, which predicts one million vehicles on German roads by the year 2020 and five million by 2030, vehicles which, depending on their usage profiles, may be partially available for use in storing electrical energy.

Load-following capability of German nuclear power plants

The current infrastructure of the German electricity supply system allows for nuclear power plants to be run primarily in continuous operation at nominal power and for only

[5]This includes a total of five systems in Austria, Luxembourg, and Switzerland with a total electrical power output of approximately 2.8 GW.

selected stations (Unterweser, Phillippsburg 1, and Neckarwestheim 1) to be run in load-following mode [1]. In France some 40 nuclear power plants are run in load-following mode for purposes of covering load demand in the electricity grid with an equivalent supply of electricity [13].

In Germany both boiling water reactors and pressurised water reactors are used for electricity generation from nuclear energy. With both reactor types, load-following operation must be compatible with the systems of reactor monitoring and control. This was a determining design factor for the reactors that are currently in operation, and thus core monitoring and reactor control instrumentations were designed accordingly so that no subsequent reinforcement of the systems would be required [11]. The output power control for the pressurised water reactor (app. 70 % of installed nuclear power output in Germany) is based on the use of control rods and the soluble boric acid in the reactor coolant and moderator, and for boiling water reactors it is primarily based on the mass flow of the coolant and moderator that is used.

This study is based on a more conservative set of assumptions for power gradients and minimum power output than is found in the operating manuals of the correspondent power plants, which contain comprehensive technical and safety instructions for power plant operation. Based on the design of the systems currently in use, nuclear power plants in Germany can be organised into three construction configurations for pressurised water reactors and two lines for boiling water reactors (cf. Table 3). The configurations are distinguished by their slightly different load-following capabilities.

Type of reactor	Configuration	Power output
Pressurised water reactor	2	4,537 MW
Pressurised water reactor	3 (“Vor-Konvoi”)	5,437 MW
Pressurised water reactor	4 (“Konvoi”)	4,039 MW
Boiling water reactor	69	3,885 MW
Boiling water reactor	72	2,572 MW
Total		20,470 MW

Table 3: Construction configurations of German nuclear power stations.

Pressurised water reactors are capable to increase or decrease the power output in a power range of 50 % of the nominal electrical capacity ($P_{min} \geq 50$ %) within a time period of a quarter of an hour. An even higher load-following capability is possible in the range above 80 % of nominal electrical capacity ($P_{min} \geq 80$ %) with maximum power gradients of up to 10 % of nominal power output per minute. In addition, the operating manuals for the construction lines “Vor-Konvoi” and “Konvoi” allow for power output changes of up to 80 % of nominal electrical capacity ($P_{min} \geq 20$ %). Although the power output of a boiling water reactor can be more easily controlled through the effects of the moderator density by means of the steam void content of the coolant and moderator through the core flow, boiling water reactors can only contribute 40 % of nominal electrical capacity ($P_{min} \geq 60$ %) to load-following operation. In the upper capacity range ($P_{min} \geq 90$ %), boiling water reactors can be controlled with power gradients comparable to the pressurised water reactors. Certain operating modes on boiling water reactors can result in limited power gradients and may reduce the load-following capability to about one percent of nominal power output per minute.

With regard to the technical potential for load-following operation, it is possible to run nuclear power plants in Germany with power gradients of 3.8 to 5.2 percent of nominal (rated) power output per minute in normal operation assuming a low-strain operating mode. Nuclear power plants thus reach power gradients that are comparable to coal-fired condensation power plants. Load-following of up to 10 % of nominal power output per minute can even be achieved in the upper power output range above 80 % of nominal electrical capacity. Pressurised water reactors (at app. 7 GW) and boiling water reactors (at app. 2.6 GW) in Germany can contribute to load-following operation within 15 minutes with a total output of up to 9.6 GW.

Unit-commitment of conventional power plants to cover residual load

The following description of the integration of fluctuating electricity generation from renewable energies and the coverage of the resulting altered residual load with different thermal power plant portfolios in both the "nuclear power phaseout" and "lifetime extension" scenarios is based on a mixed-integer and a relaxed linear optimisation model. Using an hourly breakdown, these models specify the optimal (minimum) cost unit commitment and dispatch for the two existing power plant portfolios. Here such operational restrictions as the following are considered at each point in time: minimum power output, minimum operating- and shut-down times, the demand for heat to be covered through combined heat and power, primary- and secondary control reserve, start-up- and generation costs, and available storage options.

The integration of the fluctuating supply of renewable energies is possible in a reliable manner in both the "nuclear power phaseout" and "lifetime extension" scenarios. The remaining residual load profile can be covered at all hours in both variants. In the "lifetime extension" scenario nuclear power plants participate in the load-following operation.

Figure 3 shows yearly net electricity generation in the year 2030, including pumping, by the energy carrier being used. Based on the existing power plant capacities in the two scenarios, a significant decrease can be observed in the share of electricity generation through fossil-fuelled power plants in the "lifetime extension" scenario as compared to the "nuclear power phaseout" scenario. While the electricity generation of fossil-fuelled power plants makes up a 56 % share in the "nuclear power phaseout" scenario, it only amounts to 29 % in the "lifetime extension" scenario. Further, the capacity utilisation of the individual fossil-fuelled power plants decreases in comparison to the "nuclear power phaseout" scenario. In the "lifetime extension" scenario nuclear power plants represent 27 % of total yearly electricity generation. In addition, the two variants under consideration result in a different usage of the storage technologies outlined. Thus pump storage power plants contribute 5.3 TWh to load coverage in the "nuclear power phaseout" scenario and 8.3 TWh in the "lifetime extension" scenario. This increase in the "lifetime extension" variant is attributable to the greater opportunity for storage of electricity generation from nuclear power plants as compared to generation from systems with comparatively high variable generation costs. However, the mobile battery storage with low storage volume indicates a comparable generation of 5.2 and 4.6 TWh respectively. The generation of compressed-air energy storage gas-turbine power plants is marginal, with 0.09 TWh in the "nuclear power phaseout" scenario and 0.03 TWh in the "lifetime extension".

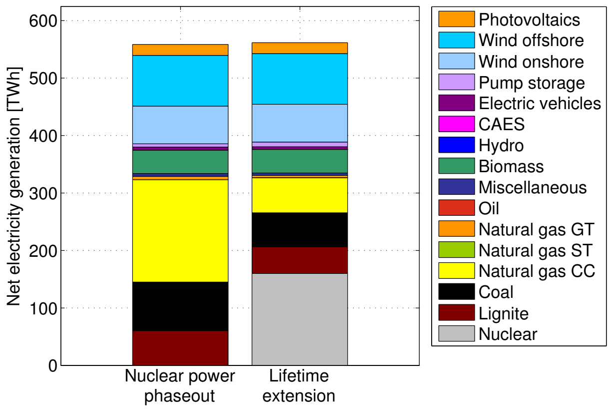


Figure 3: Yearly electricity generation by energy carrier in both scenarios "nuclear power phaseout" and "lifetime extension" in the year 2030.

To facilitate our characterisation of the load-following operation of conventional power plants during time ranges with extreme residual load characteristics, we will below examine more closely the time range with the lowest residual load for the year 2030 for purposes of example.

The unit commitment in the hour with the lowest residual load of 0.1 GW (hour 14 on the 3rd day) and on the surrounding days is shown in Figure 4a for the "nuclear power phaseout" scenario and in Figure 4b for the "lifetime extension" scenario. In this hour 37.8 GW are fed in from wind converters and 11.5 GW are supplied from photovoltaic systems.

In the "nuclear power phaseout" scenario (see Figure 4a) we initially observe a gradual reduction in the power output of the thermal power plants. As expected, this initially affects the gas-fired combined cycle (CC) power plants, and starting at hour 10 of the second day it affects the coal-fired power plants as well. In the neighbouring time range of the hour with the lowest residual load, the production of thermal power plants remains at a low level. Local extremes in the residual load are covered through the subsequent loading and unloading of the pump storage power plants, and through the mobile battery storage (electric vehicles).

In the "lifetime extension" scenario (see Figure 4b) there is a significant reduction in the power output of the nuclear power plants beginning at the eleventh hour of the second day. During the time segment under consideration there are three nuclear power plants

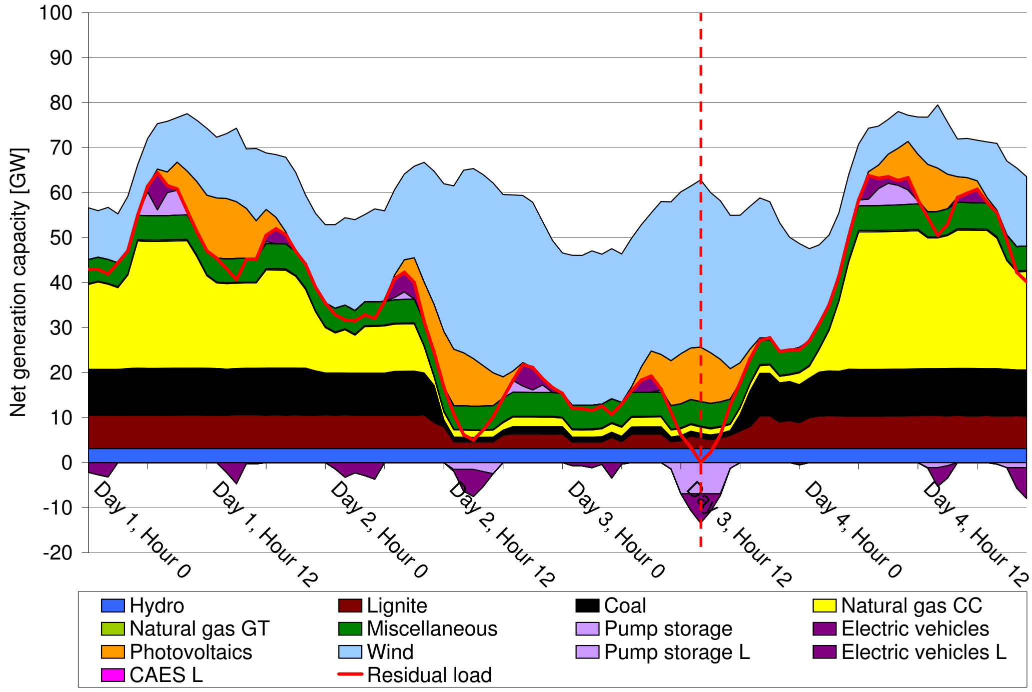


Figure 4a: Cost optimal unit commitment and dispatch during the time period of lowest residual load in the year 2030, scenario "nuclear power phaseout".

with varying output during operation and these contribute to the compensation for the fluctuating electrical supply of renewable energies inside the time range of lowest residual load. The other nuclear power plants are temporarily switched off. Fossil-fuelled power plants are also switched off during the hours before and during the lowest residual load, with the exception of certain combined heat and power systems. The subsequent rise in the residual load is initially covered primarily through nuclear power plants. Thus nuclear power plants contribute to load-following operation and the compensation for the fluctuating electrical supply of renewable energies. Similarly to the "nuclear power phaseout" scenario, here the existing storage systems enable the smooth operation of the thermal power plants. However, in the event that the share of electricity generation from wind converters and photovoltaic systems for 2030 is greater than assumed here – regardless of whether nuclear power plants are part of the generation mix or not – the control of electrical supply from renewable energies, or the construction of additional storage systems, will be required to cover the electricity demand with the required level of supply reliability (ensuring a sufficient primary- and secondary control reserve).

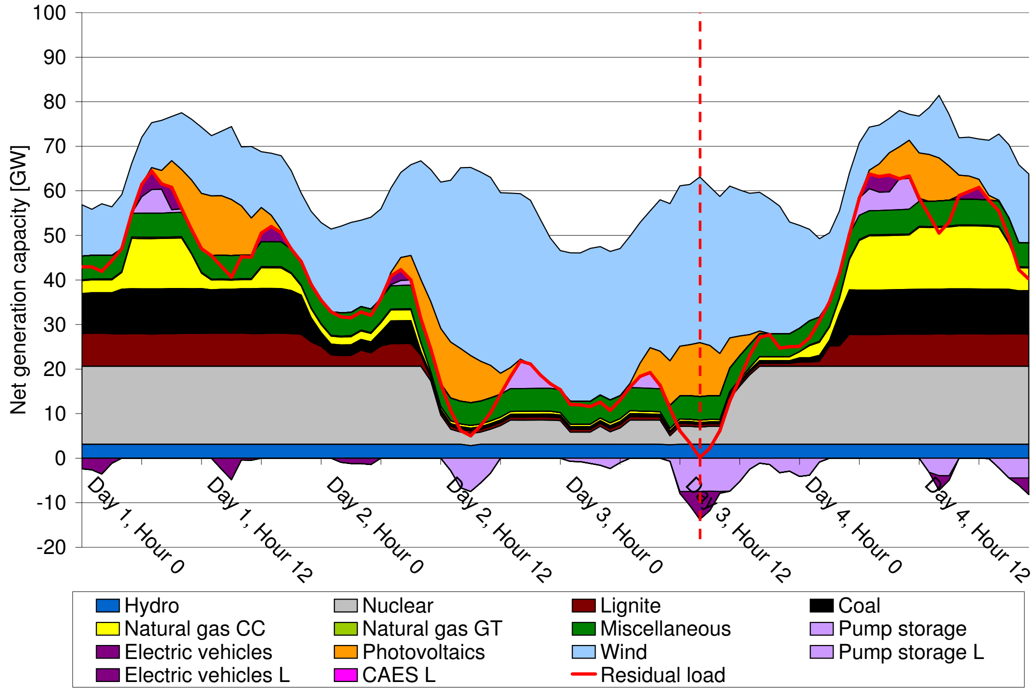


Figure 4b: Cost optimal unit commitment and dispatch during the time period of lowest residual load in the year 2030, scenario "lifetime extension".

Load-following capability of the power plant portfolio

The analyses of unit commitment and dispatch for the years 2020 and 2030 have shown that changes in the residual load can be tracked at each hour in both the "nuclear power phaseout" and "lifetime extension" scenarios. However, more significant changes occasionally occur on a sub-hourly basis than can be observed in a purely hourly breakdown. For that reason, for this study times with extreme sub-hourly changes in residual load have been identified using quarter-hourly curves as a basis. Estimation calculations are used to determine the maximum potential that the generation units currently in operation (or that could be activated) can contribute at these times within 15 minutes of a drop or an increase in output. The estimates show that at almost all times only the collective of thermal power plants in the two "nuclear power phaseout" and "lifetime extension" scenarios would be able to change the total power output more inside of 15 minutes than the gradients of the residual load require.

Table 4 indicates the increasable generation of spinning (i.e. those generating synchronically) and stationary power plants within a quarter hour for the time with the greatest gradient of residual load of +10.9 GW/15 min. In the latter case only those plants were recorded which could be started up within a maximum of 15 minutes.

Table 4: Analysis of the load-following operation for the time with the greatest positive gradients of residual load of +10.9 GW/15 min in the year 2030 (numbers indicated in GW/15 min).

Type of power plant	Nuclear power phaseout			Lifetime extension		
	Spinning		Quickly activable	Spinning		Quickly activable
Coal ST	0.5	(10.4)†	0.0	0.5	(9.9)	0.0
Natural gas CC	0.9	(32.7)	0.0	1.3	(10.9)	0.0
Natural gas GT	0.1	(0.2)	6.4	0.1	(0.1)	4.2
Natural gas ST	0.0	(0.2)	0.0	0.0	(0.1)	0.0
Lignite ST	0.6	(7.1)	0.0	0.7	(6.9)	0.0
Nuclear fuel ST	-	-	-	0.0	(20.5)	0.0
Other	1.0	(5.2)	0.6	1.0	(5.2)	0.3
Subtotal	*3.0*	*(55.8)*	*7.0*	*3.6*	*(53.6)*	*4.50*
Storage	22.0 (1.1)			19.6 (3.3)		
Total	32.0			27.7		

† The values shown in parentheses indicate the generation outputs of the power plants that are in operation at the time of the analysis.

It becomes clear that at this time – when the residual load is also at a relatively high level – the collective of thermal power plants in both the “nuclear power phaseout” and “lifetime extension” scenarios can easily follow the gradient of the residual load together with the available storage systems.

Economic effects and CO_2 emissions

The results for the “nuclear energy phaseout” and “lifetime extension” scenarios show significant divergences in total yearly system operating costs in the years 2020 and 2030 (see Figure 5). As compared to the “nuclear power phaseout” scenario, the “lifetime extension” scenario shows a reduction in yearly operating costs of 26 % in 2020 and 31 % in 2030. This reduction is primarily due to reduced expenditures for fuel and CO_2 emissions certificates. In addition, it is possible in the “lifetime extension” scenario to avoid additional expenditures for investments in new power plants with an installed net bottleneck capacity of app. 22 GW.

Furthermore, the two scenarios affect projected wholesale prices for electricity in different ways. Figure 6 can be used to perform a qualitative comparison of the ordered annual electricity price duration curves in the two scenarios “nuclear power phaseout” and “lifetime extension” for the years 2020 and 2030. Assuming a balanced foreign trade and constant CO_2 allowance prices for purposes of simplicity, electricity prices will decrease in the “lifetime extension” scenario as compared to the “nuclear power phaseout”

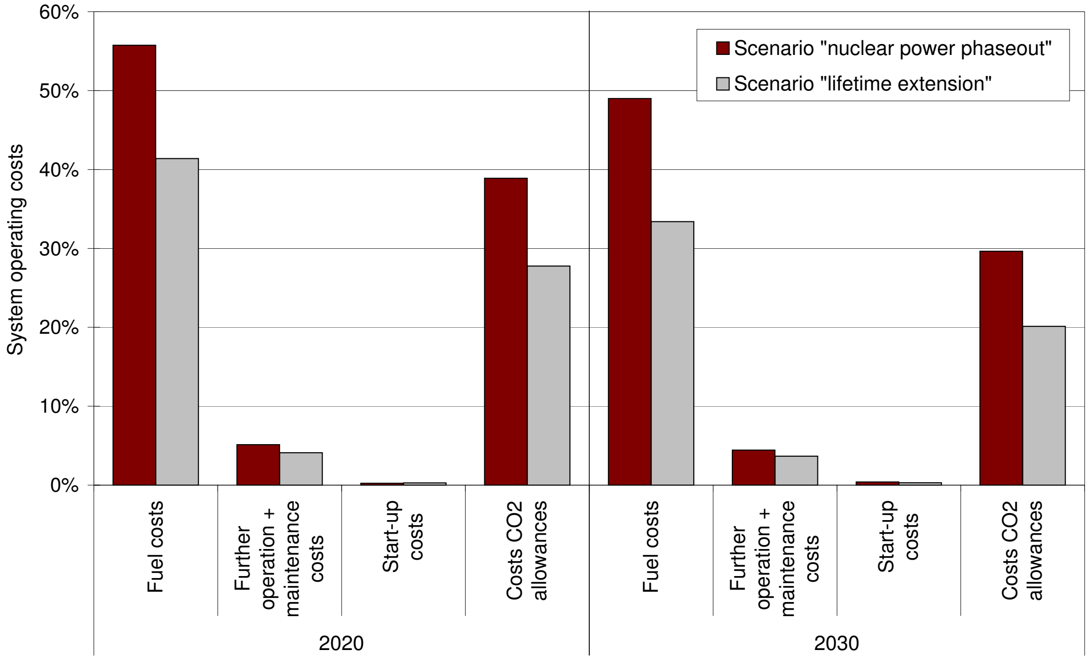
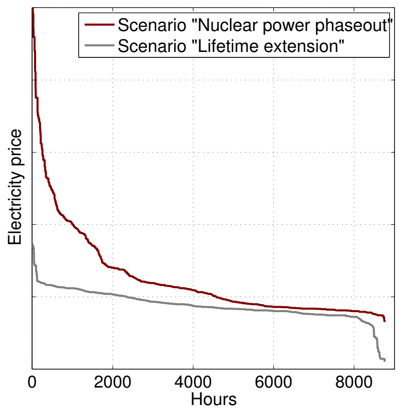
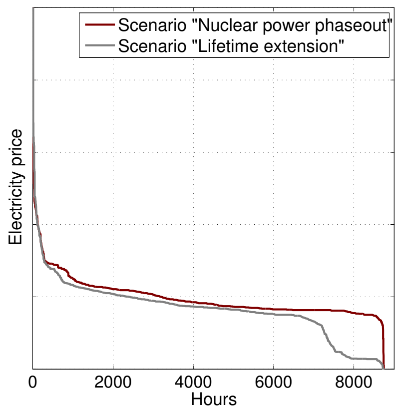


Figure 5: Comparison of system operating costs by components in the scenarios "nuclear power phaseout" and "lifetime extension" for the years 2020 and 2030. Standardised representation on the basis of total system operating costs of the year 2020 in the scenario "nuclear power phaseout".

scenario. The reduction in the average wholesale price for electricity is app. 30 % in 2020 and app. 16 % in 2030.



(a) Year 2020



(b) Year 2030

Figure 6: Comparison of annual electricity price duration curves in the scenarios "nuclear power phaseout" and "lifetime extension" for the years 2020 and 2030.

The two scenarios yield different CO_2 emissions on account of their different production structures. In 2020 the CO_2 emissions in the "nuclear power phaseout" scenario, which are 286 mil. tCO_2, are approximately 82 mil. tCO_2 higher than in the "lifetime extension" scenario. At 218 mil. tCO_2, the "nuclear power phaseout" scenario results in CO_2 emissions that are 70 mil. tCO_2 greater than the "lifetime extension" scenario in the year 2030. If we compare cumulative CO_2 emissions, we obtain additional emissions in the "nuclear power phaseout" scenario of 555 mil. tCO_2 (+27 %) between 2010 and 2020 and 1,280 mil. tCO_2 (+36 %) between 2010 and 2030.

Conclusion

An expansion of utilisation systems of renewable energies for privileged electricity generation will, according to current Federal Government plans, result in a considerably more extreme distribution of the residual load that must be covered by the conventional power plant mix. The gradients of the residual load will in some cases more than triple their current levels, and overall the distribution of the residual load will become significantly more volatile and drop in level altogether.

By virtue of their technical design, the nuclear power plants currently in operation in Germany are thoroughly capable of being used for load-following operation. By conservative estimates, there is an power output range of up to 9.6 GW for all nuclear power plants with power gradients of 3.8 to 5.2 %/min, with which they are capable of being used for load-following operation without limitations.

The analyses of power plant operation with a large percentage of electricity generation from renewable energies (app. 42 % in 2030), which were based on the years 2020 and 2030 as an example, indicate that there is no clear superiority with respect to the flexibility of the thermal power plant mix in either the "nuclear power phaseout" or "lifetime extension" scenario. The assertion that the level of operational flexibility necessary to meet the residual load at a high share of electricity generation from renewable energies could not be guaranteed with a lifetime extension of nuclear power plants, is unjustified from a technical perspective.

Given increasing portions of fluctuating electricity generation and steep distributions of the residual load, nuclear power plants will also contribute to load-following operation given a lifetime extension. Extreme gradients and levels in the residual load can be dealt with.

In none of the time segments in the years 2020 and 2030 that were closely examined for this study would it have been impossible to integrate the fluctuating electrical supply from wind converters and photovoltaic systems into the electricity system. An essential role is played here by storage technologies that are used to homogenise the residual load and by a reliable prognosis of the stochastic electrical supply from wind converters and photovoltaic systems. However, assuming an even greater portion of electricity generation from wind converters and photovoltaic systems for 2030 than is assumed here – regardless of whether nuclear power plants are part of the generation mix or not – a control of fluctuating electrical supply from renewable energies, or the construction of additional storage systems, will be required to cover the electricity demand with the necessary level of supply reliability.

When the matter is considered from an economic and emissions-related (CO_2) perspective, it becomes clear that a lifetime extension of German nuclear power plants (based on the assumptions made in this analysis) will result in reduced expenditures for fuels, less CO_2 emissions, and thus, reduced expenditures for CO_2 allowances. This would have the effect of significantly reducing system operating costs overall. The phaseout of nuclear energy would also entail a greater need for new power plants to be constructed. Furthermore, under present assumptions a nuclear power phaseout would likely result in significantly higher wholesale prices for electricity.

In conclusion, the assertion that a lifetime extension of nuclear power plants would be a stumbling block for the expansion of renewable energies cannot be supported from a technical standpoint. In fact, from an economic and emissions (CO_2) perspective a nuclear energy phaseout would even be counterproductive.

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