The Cost of Phasing Out Nuclear Power

A quantitative assessment of alternative scenarios for Germany

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Abstract

In the debate on the phase-out of nuclear power generation in Germany, there is an intense dispute on the effective operating time for the existing nuclear power plants. This paper addresses the question of how alternative phase-out regulations affect both the magnitude of total economic costs and the distribution of these costs across nuclear power plants and competing companies. Based on a dynamic partial equilibrium analysis of power supply options, we quantify the costs of different regulatory approaches as a function over the phase-out time and investigate the implied competitive effects at the company level. We find that alternative regulations leading to the *same phase-out date* exhibit large differences in total costs which are mainly associated with the respective differences in permissible cumulative nuclear power production. The cost differences diminish to a large extent when authorities prescribe the *same cumulative threshold for nuclear power production* instead of the phase-out year. Adopting power production as a proxi for the risk of operating nuclear plants, our quantitative figures may then be interpreted as an insurance premium. We show that the distribution of total phase-out costs across companies changes considerably for the various regulation schemes. Energy policy makers, hence, are not only challenged with efficiency but also with equity considerations. Our quantitative results refer to nuclear phase-out scenarios for Germany and its specific plant structure as well as plant-ownership by companies. However, the issues raised in this paper may be important for other countries which also contemplate a phase-out of nuclear power.

1 Introduction

A major objective of Germany's government on the field of energy and environmental policy is the phase-out of nuclear power. The government argues that the risks associated with the peaceful use of nuclear energy are uncontrollable, and that an "irreversible“ and "comprehensive“ nuclear phase-out should be performed as soon as possible (Bundesregierung 1999). Protagonists of nuclear power, particularly the power utilities, claim control over these risks and point to the potential economic costs imposed by the phase-out of nuclear power. Although they are not able to change the fundamental policy decision against nuclear power, they have entered into an intense dispute on the concrete policy design of the phase-out. The point at issue concerns the operating time of the existing nuclear power plants. The latter serves as a starting point for the potential compensation claims of the utilities, offsetting their opportunity costs induced by an accelerated phase-out. The utilities insist on an operating time of 40 *full-load* years in order to minimize these opportunity costs, whereas the government offers a ceiling of 30 *calendar years* (Maier-Mannhart, 2000). The proposals, hence, not only differ with respect to the nominal number of years, but also with respect to the reference point for the operating time. Adopting calendar years as the reference point implies that power plants are taken off the grid as soon as the given number of calendar years has passed since their initial start-up. In contrast, regulation based on the full-load year approach only considers the *effective* use of power plants. In other words, downtime due to fuel make-up, routine or unscheduled repair work, etc. is not accounted for. This means, that - ceteris paribus - a full-load year regulation allows for a longer utilization of power plants as compared to the calendar-year regulation. Both approaches provide runtime operating rules at the plant level. Alternatively, the government could administer a *target year* in which the last existing power plant must go off the grid.

In this paper we address the question of how alternative phase-out regulations on the nominal runtime and its reference points affect both the magnitude of direct economic costs and the distribution of these costs across competing companies. Based on a dynamic partial equilibrium analysis of electric power supply options, we find that

1. the target-year approach provides the cheapest way for the phase-out of nuclear power *at a given point in time* followed by full-load year regulation and then calendar-year regulation. For example, an ultimate phase-out of nuclear power in 2019 (which reflects the government's current proposal) causes additional costs under the target-year approach of roughly 10 billion DM as compared to a baseline operation time of 40 full-load years. These costs increase by 14 billion DM under the full-load regulation, and additional 3.5 billion DM under calendar-year regulation.
2. the various regulation schemes differ significantly in their competitive effects across companies which own the nuclear power plants. In the German case, the relative distortions across utilities are highest under a target-year regulation followed by a full-load year regulation. A calendar-year approach causes the smallest competitive distortions across utilities. Considering the phase-out of nuclear power in 2019, the calendar-year regulation imposes additional costs per KWh which vary between 0.50 Pf and 1.40 Pf across companies (i.e. a *max-min-ratio* of 2.8 between the maximum and the minimum cost mark-up). Under full-load regulation the cost increase ranges between 0.40 Pf and 1.20 Pf (*max-min-ratio*: 3.0), and between 0.17 Pf and 0.54 Pf (*max-min-ratio*: 3.2) for target-year regulation.

The policy scenarios above describe a trade-off between the date of the phase-out and the incurred costs. However, the cost differences across alternative regulatory regimes leading to the *same* phase-out date are mainly caused by the respective differences in cumulative nuclear power production. These cost differences diminish to a large extent when authorities prescribe the *same cumulative threshold for nuclear power production* instead of the phase-out year. Adopting power production as a proxi for the risk of operating nuclear plants, our quantitative results then can be interpreted as the necessary willingness-to-pay for the risk reduction from nuclear power.

There have been several studies on the economic costs of a phasing out nuclear power in Germany (e.g. Pfaffenberger and Gerdey, 1998; Schade and Weimer-Jehle, 1999; Schmitt, 1999; Horn and Ziesing, 1997). Compared to these studies, which focus on the total costs for a very narrow set of phase-out scenarios, our analysis provides more comprehensive insights. Not only do we investigate the competitive effects at the company level, but we also quantify the phase-out costs as a function over time.

Our quantitative results refer to nuclear phase-out scenarios for Germany and its specific plant structure as well as plant-ownership by companies. However, the issues presented in this paper may be important for other countries which also contemplate a nuclear phase-out (e. g. Sweden, Switzerland or Belgium).

The remainder of the paper is organized as follows. Section 2 provides background information on the electricity supply options and the role of nuclear power in Germany. Section 3 presents the analytical framework and its parameterization. Section 4 defines the scenarios and discusses our results. Section 5 concludes.

2 Background

2.1 Options for closing the nuclear gap

At present, 19 nuclear power plants are operating in Germany which produced around 160 billion kWh in 1999. Nuclear power has covered roughly a third of Germany's electricity demand over the last few years. An administered accelerated phase-out of nuclear power would induce a supply-side gap which can be reduced or closed using four key options:

(i) reduction of energy demand,

(ii) increased utilization of existing power plants,

(iii) increased electricity imports, or

(iv) construction of new non-nuclear power plants.

A significant decline in electricity demand is unrealistic given expert analyses which indicate a slight increase in future electricity demand (see e.g. Prognos/EWI, 1999). A decrease in electricity demand would require policy measures such as taxes on energy or electricity (see e.g. Gruber et al., 1995). The recent green tax reform in Germany foresees a continuous increase in energy taxes over the next years. There are, however, several reasons why there is little prospect that this reform will induce a decrease in electricity demand: First, the tax increase for electricity generation is rather modest and accompanied by tax increases for other competing fossil fuels. This means that fuel-switches away from electricity towards other fuels (e.g. in process or space heating) will be rather small. Second, the tax reform includes special rules for energy-intensive industries that basically work as tax exemptions. Third, liberalization on European electricity markets has already led to a significant fall in electricity prices, which is expected to continue throughout the next years (particularly with respect to the prices paid by households).

Load shifting or increasing the degree of utilization in the middle and peak load may cover some of the base-load gap caused by a nuclear phase-out. Yet, both measures are rather costly and limited in overall scope.[1] There are, hence, two options left to close the power supply gap: increased electricity imports on the one hand, or the construction and operation of new non-nuclear power plants on the other. In both cases, companies will face additional costs which are driven by the difference between the unrestricted economic operating time of their plants and the concrete utilization constraint imposed by the respective phase-out regulation.

2.2 Age Pattern of Nuclear Power Plants

Table 1 gives an overview of the age pattern for Germany's nuclear power plants in regard to “consumed” calendar years and full-load years, respectively. The difference ranges up to 9 years for the case of Brunsbüttel. In the past, the average availability, which we measure as the ratio between "consumed“ full-load years and "consumed“ calendar years, has been lowest for Brunsbüttel, Biblis-A and Biblis-B. These power plants have operated on average less than 6500 full-load hours per year. On the other end, there are Grohnde, Emsland and Neckarwestheim-2, which have operated for more than 7800 full-load hours per year. As mentioned above, in the case of a full-load year regulation, downtime does not reduce the effective operation time, i.e. past times of no-use delay the shut-down of the power plants in the future.

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[1] Note that, independent of a nuclear phase-out, the increased cost pressure among competing utilities on the European electricity markets has already significantly reduced stand-by power.

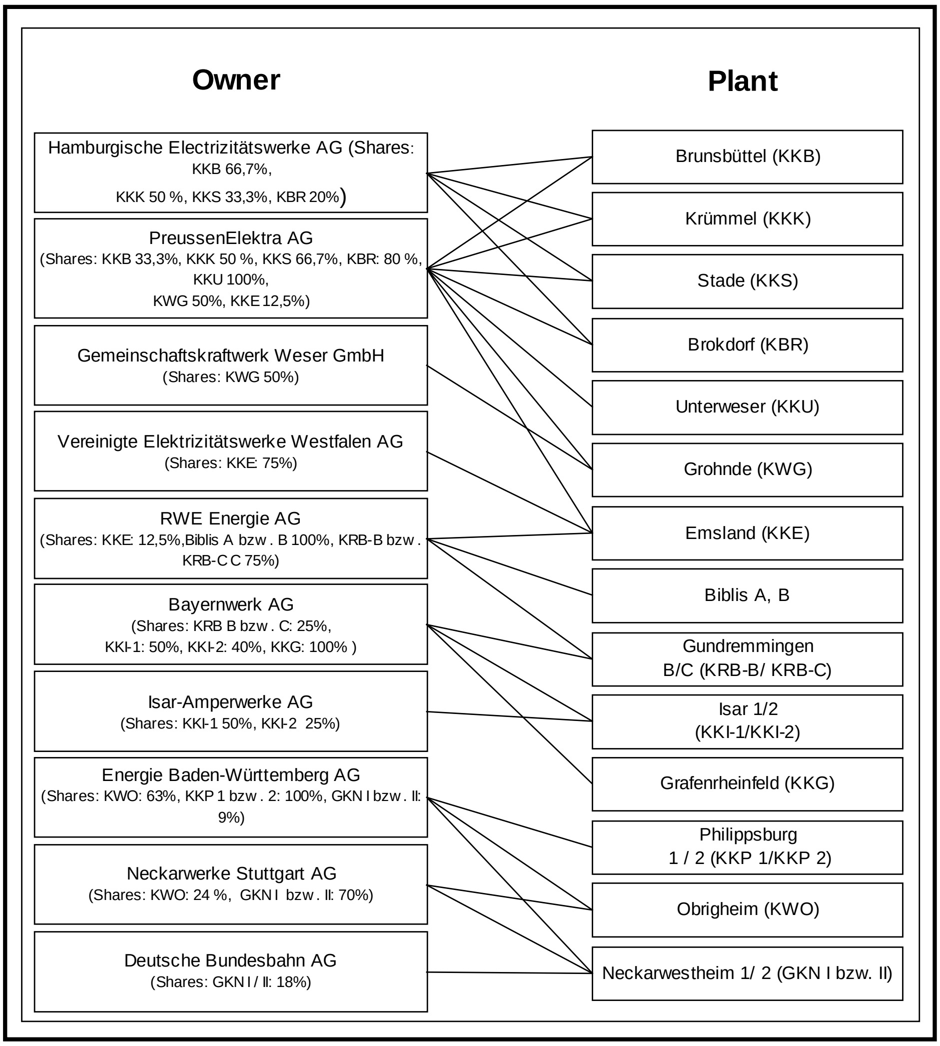
The historical differences in "consumed" calendar years and "consumed" full-load years play a key role in explaining the disproportionate cost incidence of calendar-year regulation versus full-load regulation as reported in section 4 below.

	"Consumed" calendar years **(A)**	"Consumed" full-load years **(B)**	Average degree of utilization **(B:A)**
Obrigheim	30	24	80%
Stade	27	23	84%
Biblis A	24	17	71%
Neckarwestheim 1	23	18	80%
Biblis B	22	16	74%
Brunsbüttel	22	13	57%
Unterweser	20	16	80%
Isar 1	20	16	78%
Philippsburg 1	19	14	75%
Grafenrheinfeld	17	14	85%
Gundremmingen B	15	13	87%
Krümmel	15	12	83%
Grohnde	14	13	91%
Philippsburg 2	14	12	89%
Gundremmingen C	14	12	86%
Brokdorf	13	11	87%
Emsland	11	10	93%
Isar 2	11	10	89%
Neckarwestheim 2	10	9	93%
Average	**17**	**14**	**82%**

Table 1: “Consumed” calendar years and full-load years in 1999 (source: Deutsches Atomforum, 1999)

2.3 Ownership of Nuclear Power Plants

In order to calculate the incidence of the nuclear phase-out at the company level (see section 4.2), we need information on the ownership of plants, which is given in Figure 1.



Note: For the sake of transparency we omit a number of small shareholders such as Energieversorgung Ostbayern (KKI-2: 10 %), Stadtwerke München (KKI-2: 25 %), Zementwerke Lauffen – Elektrizitätswerk Heilbronn (GKNI/II: 3 %); 12 % of shares in KWO are held by nine further companies.

Figure 1: Ownership of the German nuclear power plants (source: Siemens AG, 1999; Pfaffenberger and Gerdey, 1998)

We see that several companies hold multiple ownership in plants. Having calculated the cost incidence of alternative regulation schemes at the plant level, we can infer the implied cost for the companies by distributing the cost at the plant level across companies according to their respective shares in plants. Potential mergers between Bayernwerk AG and PreussenElektra AG as well as between RWE and VEW are not reflected in Figure 1[2]. Isar–Amperwerke is now an associated company of Bayernwerk AG but still treated separately here. In the analysis of the cost incidence of alternative regulations at the company level (see section 4.2), we will discuss the implications of the mergers.

3. Analytical Framework and Parametrization

3.1 Analytical Framework

Our dynamic linear programming model is designed to investigate the additional costs associated with an accelerated phase-out of existing nuclear power plants as compared to a baseline scenario where these plants can be used until the end of their economic lifetime. The model minimizes the costs of covering the supply gap which is caused by the retirement of nuclear power plants subject to technological as well as policy constraints (Vögele, 2000). It includes detailed technological information (efficiency factor, capacity limits, etc.) and economic data (fixed and variable costs, investment costs, etc.) on existing nuclear power plants as well as current and future non-nuclear plant types for electricity generation (KFA, 1994). Appendix A includes an algebraic model summary.

[2] The term "potential" refers to the fact that the mergers still require final approval on behalf of the German cartel office.

3.2 Parametrization

Data on operating, maintenance and investment costs as well as technical information on power plants stem from IKARUS (KFA, 1994), a comprehensive techno-economic data base which has been developed for the German Ministry for Technology and Research over the last few years.[3]

Our partial equilibrium model employs exogenous data on energy demand, international energy prices, and upper limits on electricity imports throughout the time horizon.

The projections on world market prices for fossil fuels, as given in Table 2, are based on FEES (FEES, 1999).

Fuel	Unit	1995	2000	2005	2010	2020	2030
Hard coal	DM_{95}/GJ	2.58	3.00	3.41	3.59	3.96	4.37
Crude oil	DM_{95}/GJ	4.36	5.11	5.85	6.47	7.71	9.68
Light heating oil	DM_{95}/GJ	5.31	6.25	7.18	7.85	9.20	11.46
Heavy heating oil	DM_{95}/GJ	3.52	4.14	4.75	5.23	6.18	7.74
Natural gas	DM_{95}/GJ	4.06	4.37	4.68	5.31	6.56	8.58

Table 2: Development of international fossil fuel prices (Source: FEES 1999)

With respect to *additional* electricity imports to replace nuclear power, we assume an upper capacity bound of 2 TWh at an average import price of 0.06 DM_{95}, including transmission costs.[4] The interest rate is set to 7.5 %, which reflects the market price of borrowed capital.

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[3] The database employed for the study can be obtained from the authors on request (for a brief overview of non-nuclear power plants employed in our calculations see Appendix B).

[4] The implications of a further increase in import capacities on our results are reported in section 4.3.

The technical lifetime of nuclear power plants is set to 40 full-load years (Majewski, 1999; Nuclear Energy Agency, 1992).[5] The utilization factor of nuclear power plants in the core simulations amounts to 85.6 %, i.e. the nuclear power plants are effectively operated over 10.27 months per year.[6]

4. Scenarios and Results

4.1 Scenario Definition

In our simulations, we distinguish three scenarios with respect to the operating time of nuclear power plants:

Calendar years (CAY): The phase-out regulation is based on calendar years.

Full-Load Years (FLY): The phase-out regulation is based on full-load years. The effective runtime in calendar years is obtained when historical and future degrees of utilization are taken into account.[7]

Target year (TAY): Instead of administrating plant-specific operating times (either in terms of full-load years or in terms of calendar years), the government sets a target year in which all power plants must be shut down.

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[5] Opponents of nuclear energy argue for lower lifetimes (Franken, 2000) which – ceteris paribus - would induce smaller phase-out costs. From their point of view, the choice of 40 full-load years implies that the costs presented in our core simulations represent an upper limit (see section 4.3 for a sensitivity analysis with respect to the technical lifetime).

[6] This means that a power plant with a runtime of 40 full-load years can be operated for 46.72 calendar years. The factor is slightly above the historical value. We assumed higher values for the future because downtimes in the past were often caused by a lack of experience with nuclear technology.

[7] Obviously, nuclear power plants which were operated with a low degree of utilization in the past are particularly benefiting from FLY as compared to CAY given the same nominal number of runtime years.

The costs of the nuclear phase-out are measured with respect to a baseline scenario where we assume that existing nuclear power plants can be run until the end of their economic lifetime. The baseline already excludes the construction of new nuclear power plants, which reflects rather persistent social preferences in Germany.

Accounting for the historical degree of utilization, the remaining plant-specific operating time for each nuclear power plant is calculated according to the following rule: First, we subtract the number of *consumed* full-load years from the upper limit of 40 full-load years, which yields the remaining lifetime in terms of full-load years. The latter is then divided by the assumed future degree of utilization, i.e. 85.6 %, to obtain the effective operating time in calendar years. According to this calculation, the last nuclear power plant (Neckarwestheim-2) will be shut down in 2034. Further, we assume that a ceiling of 30 calendar years provides a lower bound for the operating time of power plants. This means that no existing nuclear power plant will be shut down before 2005.

4.2 Simulation Results

Figure 3 visualizes the phase-out costs as a function of the runtime for CAY, FLY and TAY.[8] By definition, FLY coincides with the baseline scenario for a runtime of 40 full-load years, thus, the additional costs in that specific case are zero. A runtime of 40 full-load years based on FLY is equivalent to a maximal runtime of 53 calendar years based on CAY after accounting for past and future downtimes of power plants.[9]

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[8] Note: 1 billion DM = 10^9 DM.

[9] The maximum of 53 years is achieved by Brunsbüttel which had very high historical downtimes – see Table 3 below.

Not surprisingly, the costs of a phase-out for all scenarios become higher the shorter the permitted operating time compared to the baseline case, because the foregone utilization of competitive power generating capacities is increasing.

When comparing across different regulation schemes, TAY provides the cheapest way for a phase-out at a given date, followed by FLY and then CAY. The simple reason for this cost ranking is that at any point in time competitive nuclear capacities are higher under TAY as compared to FLY, and higher in FLY as compared to CAY. TAY, then, implies the lowest foregone profits with respect to the baseline. To put it differently: For a given date of phasing out the *last* nuclear power plant, TAY effectively delays the replacement of each nuclear power plant as compared to FLY or CAY.

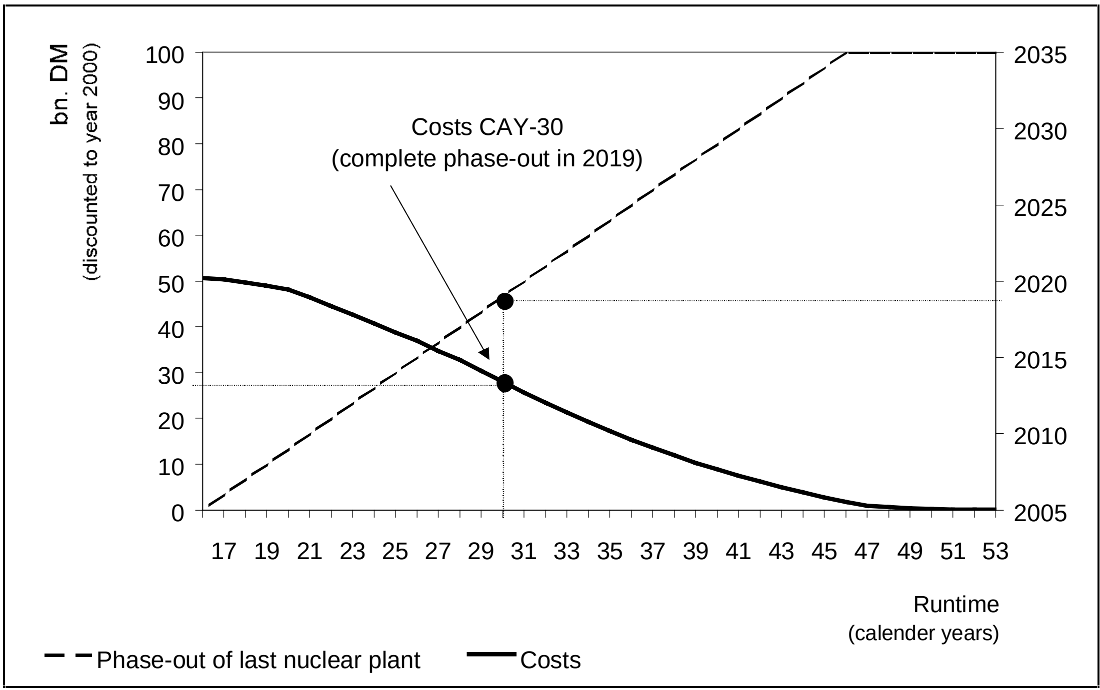


Figure 3a: **Phase-out costs under calendar-year regulation (CAY)**

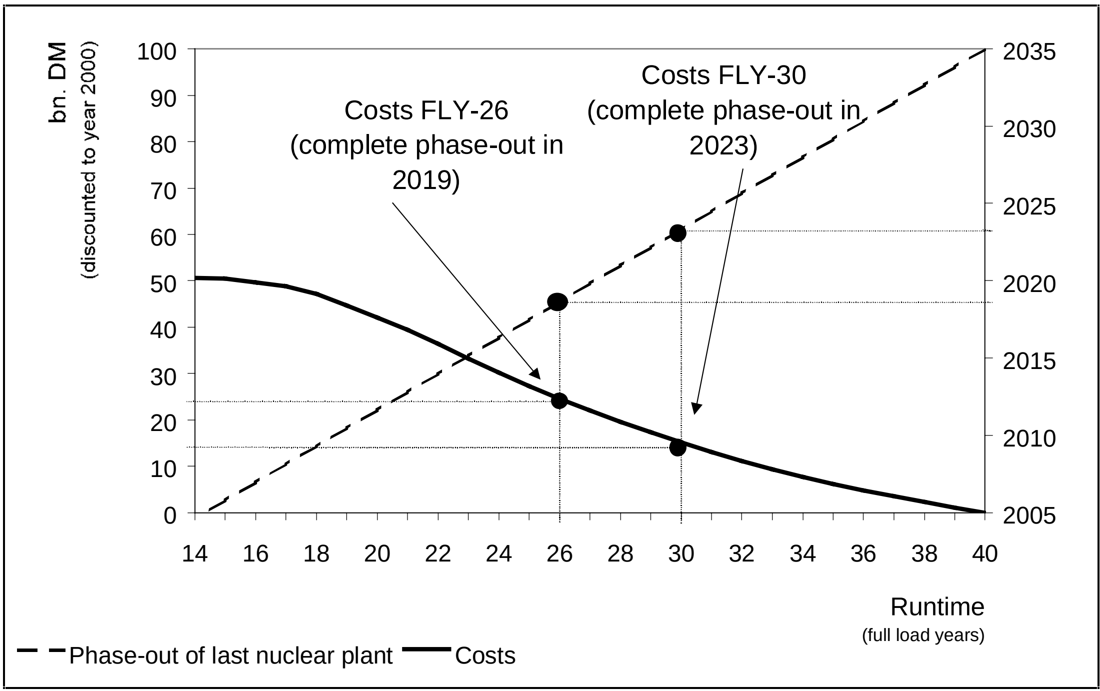


Figure 3b: Phase-out costs under full-load year regulation (FLY)

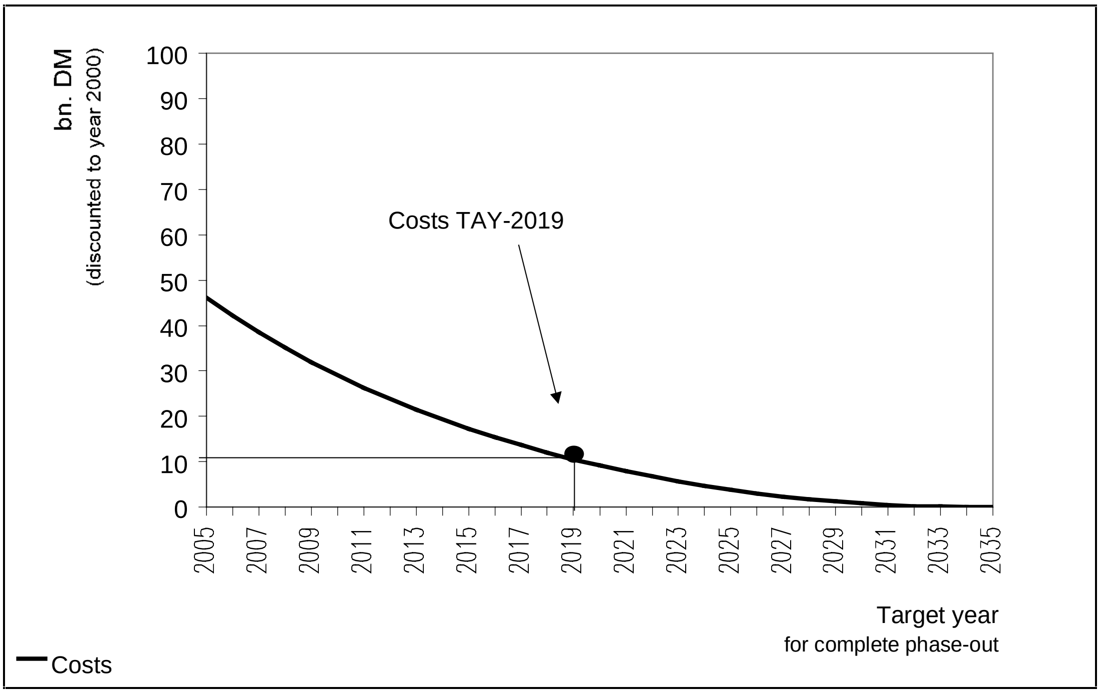


Figure 3c: Phase-out costs under target-year regulation (TAY)

Let us consider in more detail the highly policy-relevant scenario, where the government concedes 30 calendar years for the permissible operating time of existing power plants. As we can see from the final row in Table 3, this scenario (CAY-30) imposes phase-out costs of roughly 28 billion DM; the last nuclear power plant (Neckarwestheim-2) will be shut down in 2019. When we allow instead for 30 full-load years (FLY-30) the costs of the phase-out decline by roughly the half to 15 billion DM. However, the reduction in costs comes along with delaying the ultimate phase-out of nuclear power by four calendar years (when Isar-2 and Neckarwestheim-2 will be taken off the grid). On the other hand, we could achieve the ultimate phase-out of nuclear power in 2019 under FLY when we set the permissible operating time in terms of full-load years to 26 (FLY-26). Though FLY-26 achieves the same date for the ultimate phase-out as CAY-30, it saves 3.5 billion DM. The reason is that some power plants can be operated longer than 30 calendar years under FLY-26 depending on their specific degrees of utilization.[10]

Finally, from the point of total costs, TAY-2019, which also assures an ultimate phase-out of nuclear power in 2019, imposes by far the smallest excess burden. As indicated above, this is due to the additional capacity available. Figure 4 illustrates the reason for our cost ranking with respect to the concrete regulations CAY-30, FLY-26 and TAY-2019. When we postulate the same calendar year for an ultimate phase-out, the quantitative differences in total costs between TAY and plant-specific approaches CAY and FLY become more pronounced -ceteris paribus - the more nuclear power plants differ in age. The major differences between CAY and FLY then stem from different historical degrees of utilization across the plants. The more equal the historic

[10] Brunsbüttel, for example, will get shut down in 2007 under CAY-30, but only in 2014 under FLY-26 (see Table 3). Due to a low utilization of some power plants in the past the operating time under FLY-26 is longer by 1.5 calendar years as compared to CAY-30 (i.e. 31.5 calendar years instead of 30 calendar years).

utilization factor for plants, the less distinct the differences in costs are for the plant-specific phase-out scenarios.

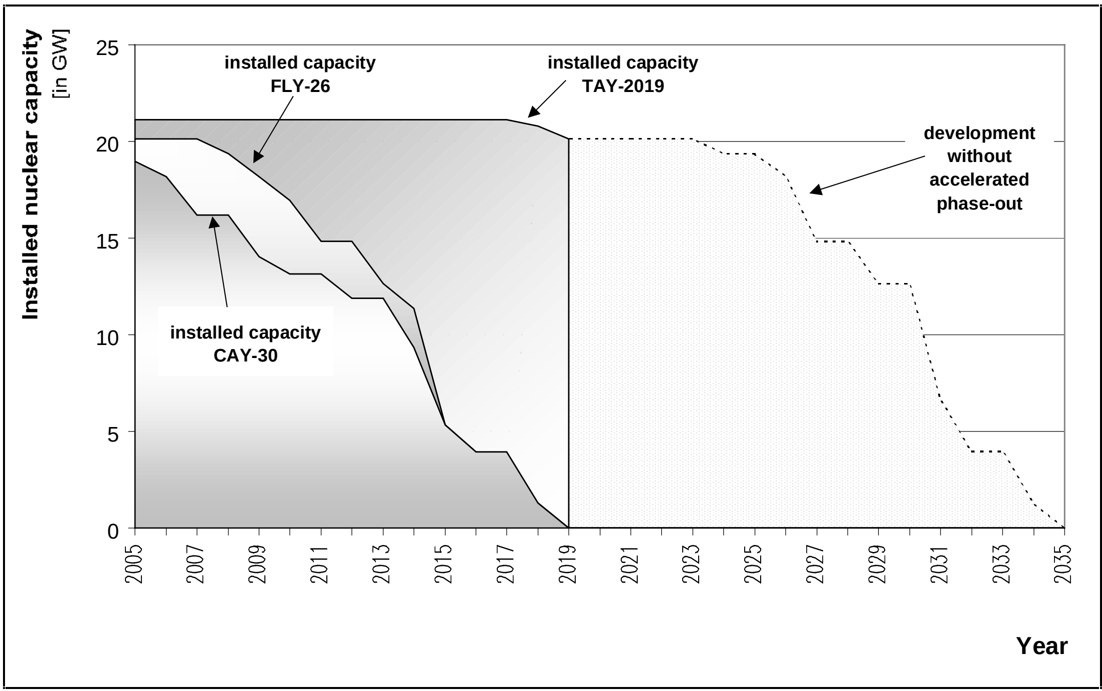
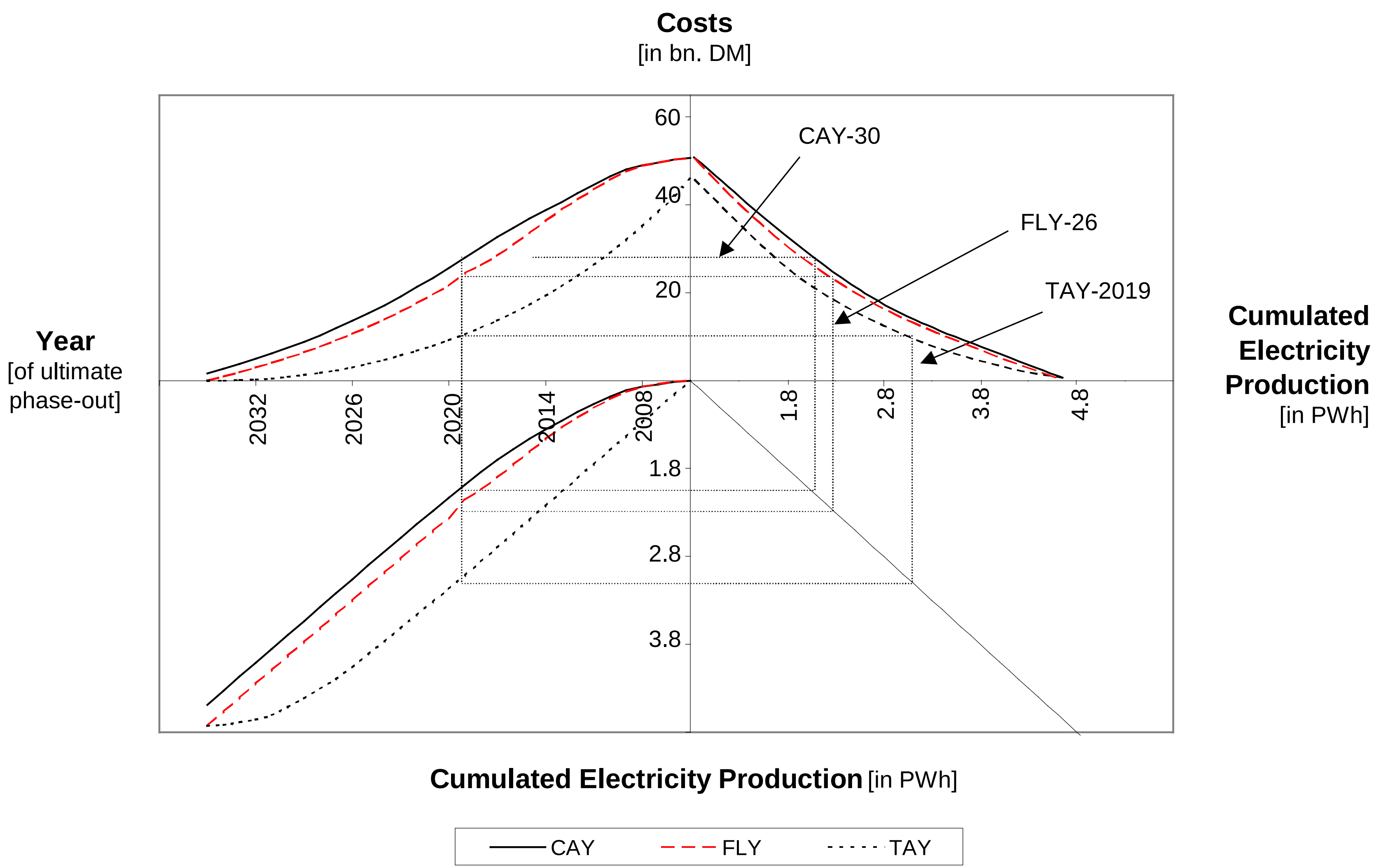


Figure 4: Development of installed nuclear capacities under TAY-2019, CAY-30 and FLY-26 regulation

The cross-comparison of scenarios so far has focused on the cost differences with respect to a given date for the shut-down of the last nuclear power plant in Germany. It must be noted, however, that the cost differences across alternative regulatory regimes which lead to the *same* phase-out date are mainly caused by the respective differences in cumulative nuclear power production. The cost differences diminish to a large extent when authorities prescribe the *same cumulative threshold for nuclear power production* instead of the phase-out year. This means that the alternative regulation schemes converge in cost-effectiveness as we select the risk from nuclear power operation (measured in terms of produced PWh) as a decision criterion rather than the phase-out date. Figures 5a and 5b illustrate our reasoning.


Costs
[in bn. DM]
60
40
20
1.8
2.8
3.8
CAY-30
FLY-26
TAY-2019
Year
[of ultimate phase-out]
2032
2026
2020
2014
2008
1.8
2.8
3.8
4.8
Cumulated Electricity Production
[in PWh]
Cumulated Electricity Production [in PWh]
CAY
FLY
TAY

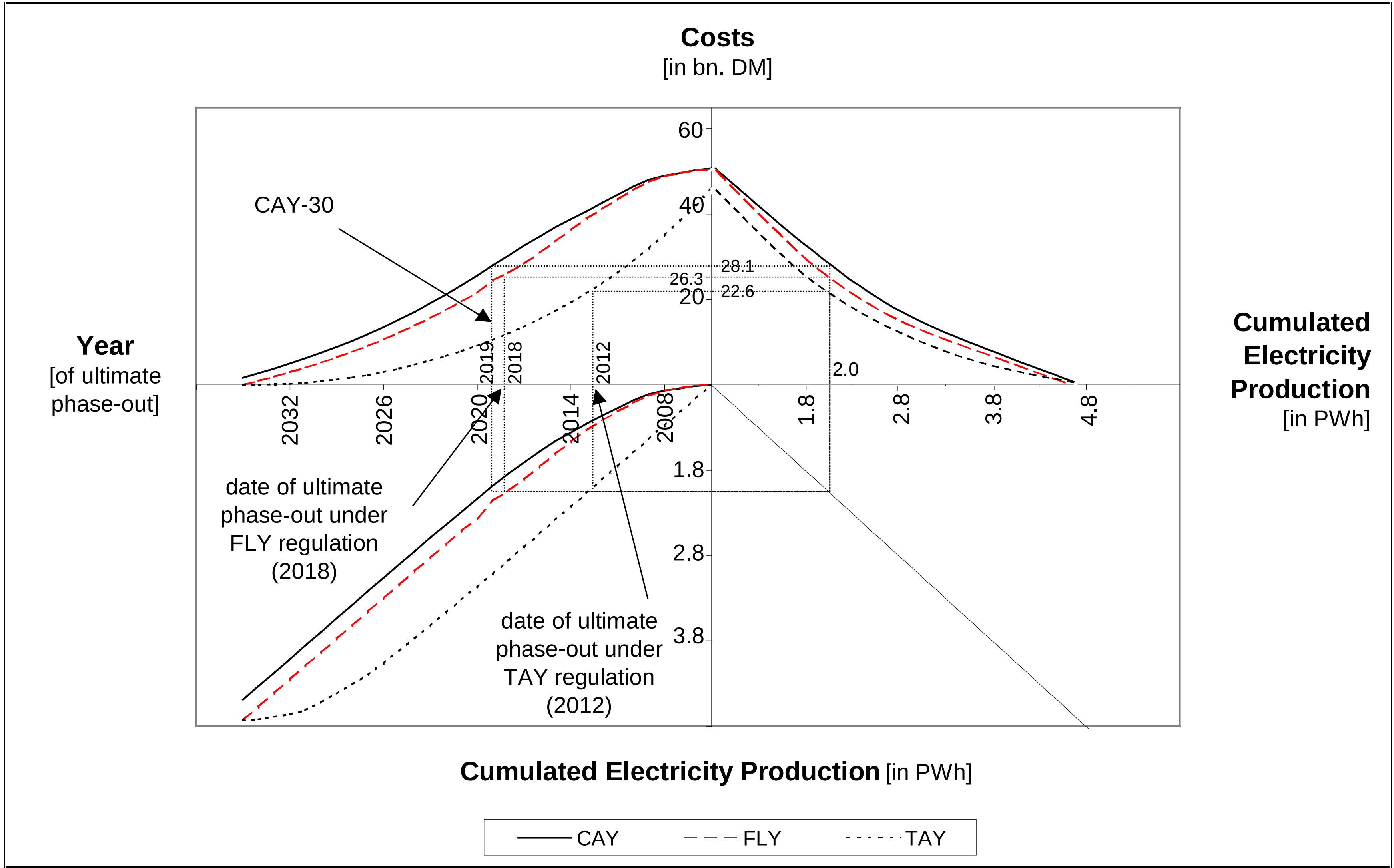


Figure 5b: **Costs and cumulated electricity production for different phase-out regulations designed to lead to the same cumulated electricity production.**

Given an ultimate phase-out of nuclear power in 2019 (see Figure 5b), CAY-30 allows only for a total electricity production of 2.0 PWh (additional costs: 28 billion DM), whereas FLY-26 concedes 2.1 PWh (additional costs: 24 billion DM) and TAY-2019 accommodates 3 PWh (additional costs: 10.5 billion DM). When the government, instead, restricts the cumulative electricity production to 2.0 PWh, which corresponds to the CAY-30, the equivalent FLY regulation would then save only about 1.8 billion DM (Figure 5b) and the equivalent target-year regulation - TAY-2012 – another 3.7 billion DM.[11]

Table 3 splits up the total costs at the plant level. We see that alternative regulatory approaches not only affect significantly the total costs, but also the distribution of costs across the different nuclear power plants. This means that changes in the regulation may have important implications for the competitive effects across the owners of plants. As with total costs, the plant-specific costs decline when we switch from CAY-30 to FLY-26 and then TAY-2019. However, the changes in costs at the plant level are not uniform. The TAY regulation does not account for differences across plants with respect to their operating time so far.[12] While TAY is most attractive from an overall cost point of view, it is potentially most distortionary with respect to the relative cost incidence across plants, as it favours rather old plants.

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[11] Note that in this case FLY phases out nuclear power one year earlier as compared to CAY whereas TAY abbreviates the phase-out for an additional 6 years.

[12] In fact, TAY does not distinguish between a “ young” power plant which just went into operation and an “old” power plant which is at the end of its lifetime.

	Scenario CAY-30			Scenario FLY-30					Scenario FLY-26					Scenario TAY-2019				
	Period of phasing out	Additional costs with respect to baseline scenario in bn.DM	Specific costs in mill. DM/KW	Period of phasing out*	Additional costs with respect to baseline scenario in bn.DM	Specific costs in mill. DM/KW	Difference to CAY-30		Period of phasing out*	Additional costs with respect to baseline scenario in bn.DM	Specific costs in mill. DM/KW	Difference to CAY-30		Period of phasing out	Additional costs with respect to baseline scenario in bn.DM	Specific costs in mill. DM/KW	Difference to CAY-30	
							Years	bn. DM				Years	bn. DM				Years	bn. DM
Obrigheim	2005	0,31	0,9	2006	0,27	0,8	+1	0 (-15%)	2005	0,31	0,9	+0	0 (0%)	2017	0,00	0,0	+12	-0,3 (-100%)
Stade	2005	1,15	1,7	2007	0,88	1,3	+2	-0,3 (-23%)	2005	1,15	1,7	+0	0 (0%)	2018	0,00	0,0	+13	-1,2 (-100%)
Biblis A	2005	2,62	2,2	2013	1,03	0,9	+8	-1,6 (-61%)	2009	1,71	1,4	+4	-0,9 (-35%)	2019	0,43	0,4	+14	-2,2 (-84%)
Neckarwestheim 1	2006	1,56	1,9	2012	0,80	1,0	+6	-0,8 (-48%)	2008	1,33	1,6	+2	-0,2 (-15%)	2019	0,22	0,3	+13	-1,3 (-86%)
Biblis B	2007	2,44	1,9	2015	1,05	0,8	+8	-1,4 (-57%)	2010	1,74	1,4	+3	-0,7 (-29%)	2019	0,51	0,4	+12	-1,9 (-79%)
Brunsbüttel	2007	1,66	2,1	2018	0,51	0,6	+11	-1,1 (-69%)	2014	0,85	1,0	+7	-0,8 (-49%)	2019	0,43	0,5	+12	-1,2 (-74%)
Unterweser	2009	2,06	1,6	2015	1,06	0,8	+6	-1 (-48%)	2010	1,76	1,3	+1	-0,3 (-15%)	2019	0,52	0,4	+10	-1,5 (-75%)
Isar 1	2009	1,43	1,6	2015	0,74	0,8	+6	-0,7 (-48%)	2011	1,22	1,3	+2	-0,2 (-15%)	2019	0,36	0,4	+10	-1,1 (-75%)
Philippsburg 1	2010	1,37	1,5	2017	0,65	0,7	+7	-0,7 (-53%)	2012	1,07	1,2	+2	-0,3 (-22%)	2019	0,42	0,5	+9	-0,9 (-69%)
Grafenrheinfeld	2012	1,68	1,3	2017	0,95	0,7	+5	-0,7 (-43%)	2013	1,57	1,2	+1	-0,1 (-6%)	2019	0,62	0,5	+7	-1,1 (-63%)
Gundremmingen B	2014	1,45	1,1	2019	0,82	0,6	+5	-0,6 (-43%)	2014	1,36	1,0	+0	-0,1 (-6%)	2019	0,70	0,5	+5	-0,8 (-52%)
Krümmel	2014	1,47	1,1	2019	0,84	0,6	+5	-0,6 (-43%)	2015	1,38	1,0	+1	-0,1 (-6%)	2019	0,71	0,5	+5	-0,8 (-52%)
Grohnde	2015	1,40	1,0	2019	0,87	0,6	+4	-0,5 (-37%)	2015	1,45	1,0	+0	0,1 (4%)	2019	0,74	0,5	+4	-0,7 (-47%)
Philippsburg 2	2015	1,41	1,0	2020	0,88	0,6	+5	-0,5 (-37%)	2015	1,46	1,0	+0	0,1 (4%)	2019	0,75	0,5	+4	-0,7 (-47%)
Gundremmingen C	2015	1,37	1,0	2020	0,78	0,6	+5	-0,6 (-43%)	2015	1,29	1,0	+0	-0,08 (-6%)	2019	0,74	0,6	+4	-0,6 (-46%)
Brokdorf	2016	1,32	0,9	2021	0,83	0,6	+5	-0,5 (-37%)	2016	1,37	1,0	+0	0,05 (4%)	2019	0,79	0,6	+3	-0,5 (-40%)
Emsland	2018	1,12	0,8	2022	0,71	0,5	+4	-0,4 (-37%)	2018	1,16	0,9	+0	0,04 (4%)	2019	0,83	0,6	+1	-0,3 (-26%)
Isar 2	2018	1,17	0,9	2023	0,74	0,5	+5	-0,4 (-37%)	2018	1,22	0,9	+0	0,04 (4%)	2019	0,87	0,6	+1	-0,3 (-26%)
Neckarwestheim 2	2019	1,08	0,8	2023	0,68	0,5	+4	-0,4 (-37%)	2019	1,12	0,8	+0	0,04 (4%)	2019	0,88	0,7	+0	-0,2 (-18%)
Sum		28,06	Ø 1,3		15,09	Ø 0,7		-13 (-46%)		24,51	Ø 1,1		-3,5 (-13%)		10,53	Ø 0,4		-17,5 (-62%)

* Rounded to full calendar year

Table 3: Cost-comparison of alternative phase-out scenarios at plant level (discounted to 2000)

When we switch to the plant-specific regulation schemes CAY and FLY, we may expect a more even distribution of costs. As to CAY, the latter only applies when historical downtimes of plants are rather of the same magnitude. FLY, in turn, guarantees an equal treatment across plants as it especially accounts for downtime differences in the past. Let us illustrate our points along some concrete plants. TAY-2019 postulates a phase-out date which is later than the final lifetime year of Obrigheim and Stade. Therefore, these plants do not induce any excess costs with respect to the baseline scenario. On the other hand, CAY-30 and FLY-26 which achieve the same ultimate phase-out date, impose specific excess costs of 0.8 million DM/KW in the case of Obrigheim and 1.8 million DM/KW in the case of Stade.

In order to calculate the incidence at the owner level for the concrete policy scenario above, we must combine Table 3 with the owner-plant-relationships as given in Figure 1. Table 4, then, summarizes the cost incidence at the company level. Obviously, the total costs for a company depend on the number of plants in which it holds stakes, the magnitude of its shares and the plant-specific phase-out costs. We see, e.g., that in absolute monetary terms, RWE Energie AG and Preussen Elektra AG will be most affected by the phase-out for all regulation schemes. These companies hold stakes in several nuclear power plants with relatively high specific phase-out costs. However, absolute cost figures are a misleading indicator for the potential market distortions induced by the phase-out because they do not incorporate information on the respective basis of the total cost incidence. We may better use the implied increase in costs per kWh at the company level as a measure for the competitive effects of alternative phase-out regulations. The latter is calculated under the assumption that the excess costs of the phase-out are uniformly shifted on the supplied electricity over the next 20 years.[13]

	CAY-30			FLY-30			FLY-26			TAY-2019		
	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**
Bayernwerk AG	3,57	0,48	1,70	2,02	0,27	1,53	3,34	0,45	1,54	1,51	0,20	1,27
Energie Baden-Württemberg AG	3,30	0,63	2,23	1,88	0,36	2,01	3,02	0,58	1,97	1,30	0,25	1,55
Hamburger Electricitätswerke AG	2,49	1,40	4,97	1,22	0,69	3,85	1,91	1,08	3,68	0,80	0,45	2,81
Isar-Amperwerke AG	1,01	0,98	3,47	0,55	0,54	3,02	0,92	0,89	3,04	0,40	0,39	2,41
Neckarwerke Stuttgart AG	1,79	1,29	4,58	1,01	0,73	4,09	1,66	1,20	4,11	0,75	0,54	3,39
PreussenElektra AG	6,01	0,55	1,96	3,43	0,32	1,77	5,46	0,50	1,72	2,12	0,20	1,22
RWE Energie AG	7,31	0,55	1,96	3,37	0,25	1,43	5,58	0,42	1,44	2,12	0,16	1,00
Vereinigte Elektrizitätswerke Westfalen AG	0,84	0,28	1,00	0,53	0,18	1,00	0,87	0,29	1,00	0,62	0,21	1,31
Gemeinschaftskraftwerk Weser GmbH	0,70	0,93	3,29	0,44	0,58	3,26	0,72	0,96	3,29	0,37	0,49	3,07
Sum ***	28,06			15,09			24,51			10,53		

* Specific costs as the ratio of total costs over electricity supply by company
** measured as the ratio of costs per kWh over the minimum of costs per kWh
*** including others (see section 2.3 for details)

Table 4: Cost incidence at the company level (discounted to 2000)

Employing the specific cost measure, Table 4 indicates that CAY-30 imposes the highest cost pressure on Hamburgische Electricitätswerke AG and Neckarwerke Stuttgart AG followed by Gemeinschaftskraftwerk Weser GmbH and Isar–Amperwerke AG. When we adopt FLY-26, specific costs are reduced while the cost ranking is rather robust. However, differences in specific costs become less pronounced, which can be interpreted as a reduction in the distortionary effects of the regulation (see columns "relative cost incidence" in Table 4).

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[13] Given the increasing competition on European electricity markets, a total shift of additional costs to the consumer side seems unrealistic. Yet, our measure indicates the additional cost pressure at the firm level emerging from alternative regulations.

We see from Table 4 that CAY induces the largest differences in relative costs measured as the *max-min-ratio* between the maximum and the minimum of additional costs. At the company level, TAY-2019 not only provides a further reduction in specific costs but also minimizes the differences in relative costs. Although TAY-2019 produces the most distinct cost differences at the plant-level the specific owner-plant-relationships reverse this effect. The explanation behind this is that the vintage structures of plants, which belong to the respective companies are rather similar.

When we account for potential mergers in the electricity sector (see section 2.3), the ranking of regulations with respect to the relative cost incidence by company gets reversed (see Table 5): TAY-2019 is most distorting followed by FLY-26 and then CAY-30.

	CAY-30			FLY-30			FLY-26			TAY-2019		
	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**	bn. DM	Pf/kWh*	Relative cost incidence**
Energie Baden-Württemberg AG	3,30	0,63	1,25	1,88	0,36	1,49	3,02	0,58	1,45	1,30	0,25	1,47
Hamburger Electricitätswerke AG	2,49	1,40	2,79	1,22	0,69	2,85	1,91	1,08	2,71	0,80	0,45	2,66
Neckarwerke Stuttgart AG	1,79	1,29	2,57	1,01	0,73	3,03	1,66	1,20	3,02	0,75	0,54	3,21
Gemeinschaftskraftwerk Weser GmbH	0,70	0,93	1,85	0,44	0,58	2,42	0,72	0,96	2,42	0,37	0,49	2,91
Bayernwerk AG / Isar - Amperwerke AG / PreussenElektra AG	10,58	0,55	1,09	5,99	0,31	1,29	9,71	0,50	1,27	4,03	0,21	1,23
RWE Energie AG / Vereinigte Elektrizitätswerke Westfalen AG	8,15	0,50	1,00	3,90	0,24	1,00	6,45	0,40	1,00	2,75	0,17	1,00
Sum ***	28,06			15,09			24,51			10,53		

* Specific costs as the ratio of total costs over electricity supply by company
** measured as the ratio of costs per kWh over the minimum of costs per kWh
*** including others (see section 2.3 for details)

Table 5: **Cost incidence at the company level with respect to mergers in the electricity sector (discounted to 2000)**

Tables 4 and 5 illustrate the point that the competitive distortions *across companies* are extremely sensitive to the concrete owner-plant-relationship which can vary over time.

4.3 Sensitivity Analysis

Table 5 summarizes the robustness of our results with respect to changes of different key parameters.

Variation	Description	CAY-30	FLY-26	TAY-2019
Baseline	See section 3.2	28.1 bn. DM	24.5 bn. DM	10.5 bn. DM
Variation 1 'Operating time'	Max. operating time: 40 calendar years instead of 40 full-load years	- 32 %	- 39 %	- 56 %
Variation 2 'Interest rate'	5 % instead of 7.5 %	+ 30 %	+35 %	+ 45 %
	10 % instead of 7.5 %	- 24 %	- 27 %	- 32 %
Variation 3 'Import capacities'	6 TWh at 0.06 DM/kWh instead of 2 TWh at 0.06 DM/kWh	- 2 %	- 2 %	- 0 %
Variation 4 'Gas price'	Price for natural gas at a level of 70% of the initial values	- 11 %	- 9 %	- 4 %

Table 6: Sensitivity Analysis Results for phase-out costs

For the sake of brevity and transparency, we focus on those regulation scenarios that lead to an ultimate phase-out in the year 2019. We find that our qualitative findings remain robust for changes in key parameters. The ranking of the different regulation approaches is always the same: For a given ultimate phase-out year, TAY causes the lowest phase-out costs followed by FLY and then CAY. Also, our conclusions with respect to the competitive effects remain robust.

Not surprisingly, the assumption about the lifetime of the plants plays a major role for the costs of phasing out nuclear power generation. The longer the lifetime in the baseline, the more costly it gets – ceteris paribus – to phase out nuclear power. If nuclear plants are expected to run only 40 calendar years (i.e. 34.2 full-load years) the costs of CAY-30 and FLY-26 are roughly 30 % and 40 % lower than those of the respective scenarios in the core simulations. For TAY-2019, the costs drop by more than 50 %.

In our core simulations, we have set the interest rate for discounting future monetary flows to 7.5 %. When we assume a lower interest rate of 5 %, the effective costs of a phase-out are less discounted and therefore increase. The opposite holds for a higher discount rate (here: 10 %).

The ongoing liberalization of energy markets may lead to higher electricity import capacities. In the sensitivity analysis, we have tripled the import capacities as compared to the assumptions in the baseline and our core simulations. Increased imports reduce total costs only by 2 % for CAY and FLY. For TAY-2019 an increase in import capacities does not save any additional costs compared to the baseline scenario because in TAY-2019 (like in the baseline) all imports are used to replace those power plants (here: Obrigheim and Stade) which are not affected, anyway, from a phase-out regulation under TAY-2019.[14]

Finally, we assume that world market prices of natural gas are 30 % below our initial level. This implies that gas power plants get more competitive as compared to coal power plants, which reduces total costs by roughly 10 % for scenarios CAY and FLY and by 4 % for TAY.

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[14] Under TAY-2019 Obrigheim and Stade reach the end of their lifetime before the administered phase-out year (see Table 3). Import capacities get fully exhausted, both for TAY-2010 as well as for the baseline, from the same point in time onwards.

5 Conclusions

In the debate on the phase-out of German nuclear power plants, there is a dispute on the effective operating time for the existing power plants. The government (particularly the Green coalition partner) is pushing for a rapid phase-out. The utilities, on the other hand, insist on using existing nuclear power plants until the end of their economic lifetime. Otherwise, they threaten to sue for compensation of incurred opportunity costs.

In this paper, we have assessed how the duration and reference point for the operating time of power plants affect the magnitude and distribution of phase-out costs. Given the same nominal number of years, utilities can run their plants for a longer time under the full-load year approach compared to the calendar-year approach. The former allows for large cut-backs of economic costs. Protagonists of a rapid phase-out, however, stress that the full-load year approach may substantially delay the total phase-out of nuclear power utilization. Yet, regulation based on full-load years even provides a significant cost decrease when it is tailored to achieve the same date of phasing out the last nuclear power plant as under calendar-year regulation. The reason is that several plants with low historical utilization can be used longer than would be permissible under the calendar-year regulation. In comparison with plant-specific regulation schemes, a target-year approach always causes lower costs for the *same date* of an ultimate phase-out because, at any given point in time, it provides a higher capacity for nuclear power generation.

The cost differences diminish to a large extent when we compare the phase-out scenarios with respect to the *cumulative nuclear power production*. In other words: The alternative regulation schemes converge in cost-effectiveness as we select the risk from nuclear power operation (measured in terms of produced PWh) as a decision criterion rather than the phase-out date.

Our quantitative simulations reveal significant changes in the cost incidence across power companies depending on the regulatory approach. This suggests that the various companies will not necessarily follow the same path in the negotiations with the government on alternative regulation schemes. The government, on the other hand, is not only challenged with efficiency considerations but also with equity concerns.

We have omitted several important issues that are inherent to the comprehensive analysis of the economic implications induced by a nuclear phase-out. The partial-analytical framework did not consider spill-over and feed-back effects between the electricity supply market and other markets. Similarly, the question of who bears the burden requires a broader economic perspective. In the mid- to long run, the consequences of a nuclear phase-out must be assessed given global energy resources and environmental constraints. In particular, the question arises how climate policy will cope with the greenhouse gas problem when nuclear power, as a carbon-free energy supply option, will be dropped. Finally, there will be the challenge of harmonizing phase-out strategies at the unilateral level in a consistent way with the continuing utilization of nuclear power in other (particularly developing) countries as well as international trade in nuclear power. We leave analysis of these complex issues for future research.

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Appendix A: Algebraic Model Formulation

The decision, which non-nuclear technologies will back up nuclear capacity in the base load, is based on a dynamic linear programming model. The model minimises investment and operation costs of replacement power plants over the model horizon (in our case 2035) subject to technological as well as policy constraints. The objective function is given as:

$$\min\left\{\sum_{t=1}^{T}\sum_{j=1}^{J(t)} CAN_j(t)\cdot(1+i)^{-t}\cdot\sum_{a=1}^{A}\Delta L_j^a(t)\right\} \qquad \textbf{(1)}$$

where:

t	:=	running index for periods,
T	:=	number of periods in the model,
j	:=	running index for technology type,
$J(t)$	:=	number of different types of capacity available in period t,
a	:=	running index for nuclear power plant
A	:=	number of nuclear power plants,
$CAN_j(t)$	:=	annuity of costs for technology j in period t [DM],
i	:=	interest rate,
$\Delta L_j^a(t)$	:=	capacity of technology j commissioned in period t to back up nuclear power plant a [kW].

The calculation of the annuity is based on dynamic investment analysis (Stelzer, 1992; VDEW, 1993; Betge, 1998). The annuity for technology j is given as:

$$CAN_j(t)=\left\{\sum_{s=1}^{n_j} E_j(t+s)\cdot(1+i)^{-s}\right\}\cdot ANF \qquad \textbf{(2)}$$

where:

n_j	:=	lifetime of capacity of technology *j* [periods].
$E_j(t+s)$	:=	payments in period *t*+*s* resulting from technology *j* commissioned in period *t* [DM/kW],
ANF	:=	annuity factor with: $ANF = \frac{(1+i)^{n_j} \cdot i}{(1+i)^{n_j} - 1}$

Payments $E_j(t+s)$ are defined as:

$$E_j(t+s) = \left(fc_j(t+s) + vc_j(t+s) \cdot \overline{h}_j + sc_j(t+s) \right) \quad \textbf{(3)}$$

where:

$fc_j(t+s)$	:=	fixed payments in period *t*+*s* for technology *j* commissioned in period *t* [DM/kW],
$vc_j(t+s)$	:=	variable payments in period *t*+*s* associated with capacity utilization of technology *j* commissioned in period *t* [DM/kWh],
$\overline{h}_j$	:=	average utilization of technology *j* [hours],
$sc_j(t+s)$	:=	fixed repayments and interest payments in period *t*+*s* for technology *j* commissioned in period *t* [DM/kW].

Fixed payments are composed of personnel expenses and other fixed payments (such as insurance or maintenance costs). Variable payments consist of payments for fuels (incl. fuel taxes) and other variable expenses (e.g. factory supplies).[15]

Total costs are minimised subject to three sets of constraints:

a) Technological constraints:

$$\sum_{a=1}^{A} \Delta L_j^a(t) \leq \overline{L}_j^{tech}(t),\ j = [1, ..., J(t)],\ t = [1, ..., T] \qquad \textbf{(4)}$$

where:

$\overline{L}_j^{tech}(t)$:= maximum capacity for technology *j* commissioned in period *t* to back up nuclear power capacity [[kW].

b) Policy constraints (nuclear phase-out):

$$L_a(t) \leq \overline{L}_a(t),\ a = [1, ...,A],\ t = [1, ..., T] \qquad \textbf{(5)}$$

where:

$\overline{L}_a(t)$:= administered upper bound on capacity of nuclear power plant *a* in period *t* (depending on the phase-out regulation CAY, FLY or TAY) [kW].

[15] Note that repayment and interest payments apply independent of the operation of the existing power plants within the payback-period. For our core simulations we have assumed a payback-period of 20 years (KFA 1994, Hennicke et al. 2000).

c) Nuclear back-up constraints:

$$\sum_{a=1}^{A}\left(L_a^{Baseline}(t)-\overline{L}_a(t)\right)\cdot\overline{h}_{Nuclear}=\sum_{j=1}^{J(t)}\sum_{a=1}^{A}\Delta L_j^a(t)\cdot\overline{h}_j\ ,\qquad t=[1,\ldots,T] \tag{6}$$

where:

$L_a^{Baseline}(t)$:= baseline capacity for nuclear power plant *a* in period *t* [kW].

Appendix B: Overview of Non-Nuclear Power Technologies

Type of technology		available in	Investment costs mil. DM/kW	Efficiency	Fixed Costs mil. DM/kW	Variable Costs DM/kWh
f1	Hard coal (suspension firing)	1989	2476,85	41,08	137	0,014
f10	Compound (hard coal, natural gas)	1989	2354,14	40,57	88	0,017
f11	Hard coal CHP	1989	3343,92	35,67	172	0,028
f12	Hard coal CHP	1989	2481,74	37,51	100	0,014
f16	CCGT (hard coal gasification)	2005	3200,52	45,50	117	0,011
f17	CCGT (brown coal gasification)	2005	3178,89	48,10	152	0,015
f18	CCGT (hard coal gasification)	2005	2790,06	48,50	100	0,010
f20	Compound (hard coal, natural gas)	2005	2760,20	48,36	162	0,013
f21	CCGT (oil)	1989	1454,30	46,90	50	0,007
f22	Hard coal	2005	2595,00	45,47	98	0,010
f3	Brown coal (suspension firing)	1989	2318,69	40,11	88	0,011
f4	Hard coal (fluidized-bed combustion)	1989	2282,41	41,02	132	0,017
f5_1	Natural gas (gas turbine)	1989	558,22	33,26	15	0,012
f5_2	Oil	1989	649,68	31,28	17	0,014
f6	Hard coal CHP (fluidized-bed combustion)	1989	2640,88	44,91	150	0,027
f7	CCGT (natural gas)	1989	1483,70	52,42	67	0,004
f9	CCGT CHP (natural gas)	1989	1931,95	47,50	81	0,005

Table 7: Overview of non-nuclear technologies (source: KFA, 1994)