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The Cost of Phasing Out Nuclear Power

A quantitative assessment of alternative scenarios for Germany

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Non-Technical Summary

In the debate on the premature 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 excess costs of different regulatory approaches as a function over time and investigate the implied competitive effects at the plant as well as at the company level. We find that alternative phase-out regulations which effectively lead to the same date for an ultimate shut-down of nuclear power generation exhibit large differences in total costs. The competitive distortions across companies also vary considerably with the chosen regulation depending on how the respective cost implications at the plant level get distributed at the company level via the specific ownership.

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 and methodological approaches presented in this paper may be important for other industrialized countries which also contemplate a premature nuclear phase-out.

1 Introduction

A major objective of Germany's government on the field of energy and environmental policy is the premature 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 a premature 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 a premature phase-out. The utilities insist on a 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 *all* power plants must be shut down.

This paper addresses 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 nuclear power plants and competing utilities.

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 a premature phase-out of nuclear power at a given point in time followed by full-load year regulation and then calendar-year regulation. The reason is that under the target-year approach at any point in time the capacity for nuclear power generation is highest. In the same vein – accounting for historical downtimes – the available capacity under full-load regulation is higher than under calendar-year regulation, even when both approaches achieve the same date for the ultimate shut-down of nuclear power.
2. the various regulation schemes differ significantly in their competitive effects. Across nuclear power plants, the relative distortions are less pronounced the more "equal" plants are treated with respect to their admissible effective use of power generation capacities. This suggests that - ceteris paribus - the target-year approach induces the highest competitive distortions followed by calendar-year regulation and then full-load year regulation. Across companies, the distortionary effects of the alternative regulation schemes depend on the specific ownership of power plants. In the German case, we find that the relative distortions across utilities are highest under a calendar-year regulation followed by a full-load year regulation. A target-year approach causes the smallest competitive distortions across utilities.

There have been several studies on the economic costs of a premature phase-out 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 plant as well as at the company level, but we also quantify the excess costs of the phase-out as a *function over time*. In this regard, we can easily read off how the *insurance premium* against the risks of nuclear power operation changes with the timing of a premature phase-out.

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 and methodological approaches presented in this paper may be important for other industrialized countries which also contemplate a premature 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 premature 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 mainstream 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 interference 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 and an increased degree of utilization in the middle and peak load to cover the base-load gap caused by a nuclear phase-out play an inferior role due to the high costs and low potentials involved. Independent of a nuclear phase-out, the increased cost pressure among competing utilities on the European electricity markets has significantly reduced stand-by power.

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.

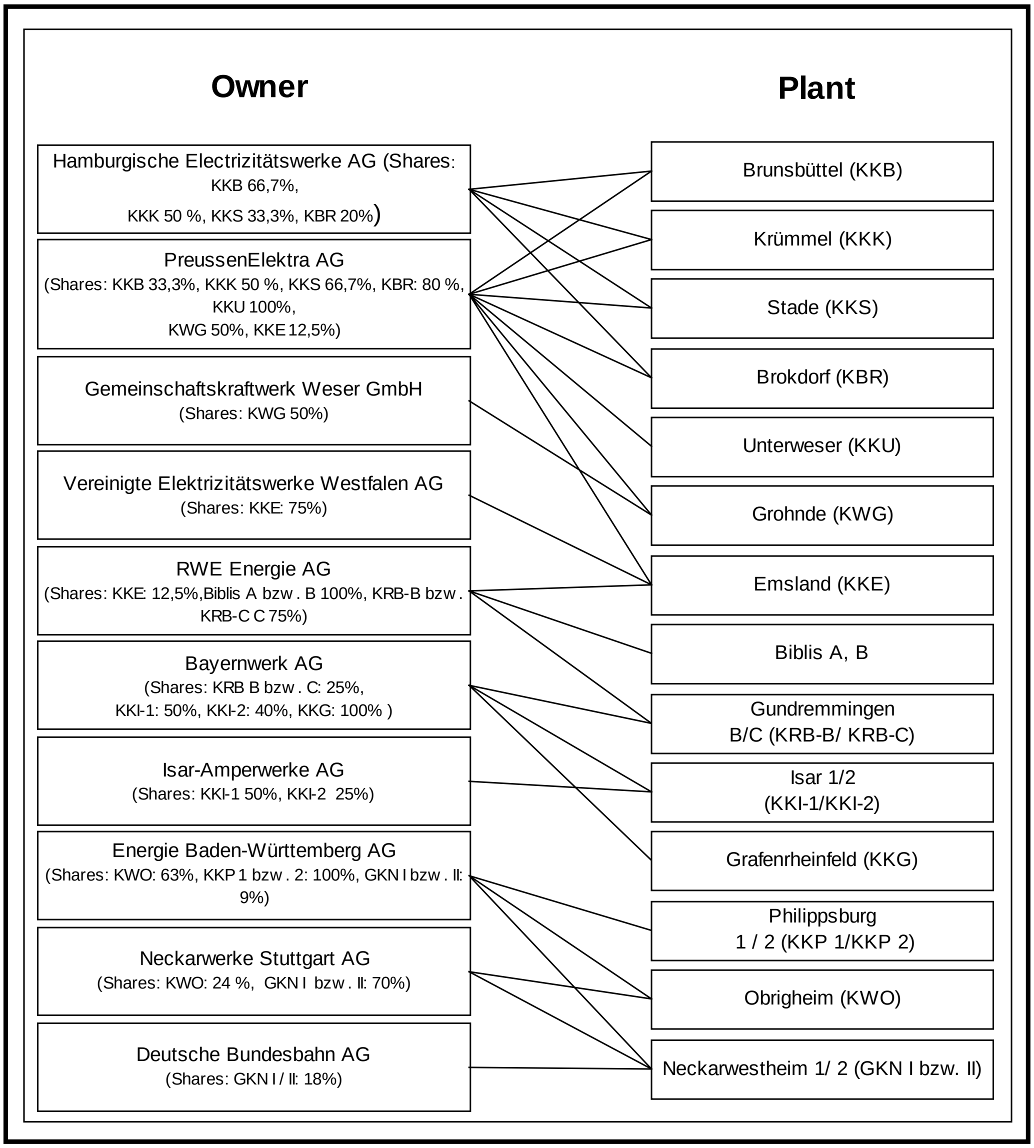
The average availability, which we measure as the ratio between „consumed“ full-load years and „consumed“ calendar years, is lowest for Brunsbüttel, Biblis-A and Biblis-B. These power plants have operated on average less than 6500 full-load hours per year. On the other end, there are Grohnde, Emsland 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 downtimes delay the shut-down of the power plants in the future.

	"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)[1]

[1] Potential mergers between Bayernwerk AG and PreussenElektra AG as well as between RWE and VEW are not reflected in Figure 1. 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 4.3), we will discuss the implications of the potential mergers.

3. Analytical Framework and Parametrization

3.1 Analytical Framework

Our model is designed to investigate the additional costs associated with a premature phase-out of nuclear power plants. Focusing on the replacement decision for nuclear power plants, the model determines the least-cost non-nuclear power back-up to fill the supply gap which is caused by the retirement of nuclear power plants. The model includes detailed technological information (efficiency factor, capacity limits, etc.) and economic data (fixed and variable costs, investment costs, etc.) on operating nuclear power plants and current as well as future non-nuclear plant types for electricity generation (Vögele, 2000).

Our analytical framework accounts for the vintage structure of all power plants. Each existing power plant is explicitly characterised by its remaining technical lifetime, which sets the upper bound for the economic lifetime. Phasing out competitive nuclear power plants requires earlier replacement investment as would be the case for the unconstrained use of existing nuclear power. Consequently, at any given time, the vintage structure of the installed power plants in the phase-out scenario differs from the baseline vintage structure without a premature nuclear phase-out. Figure 2 illustrates the vintage effect of the phase-out policy. Depending on their profitability over time, replacement technologies in the baseline may or may not be of the same type as in the phase-out scenario. Note that a nuclear back-up of existing nuclear power plants is already excluded for policy reasons in the baseline such that all replacement technologies are non-nuclear.

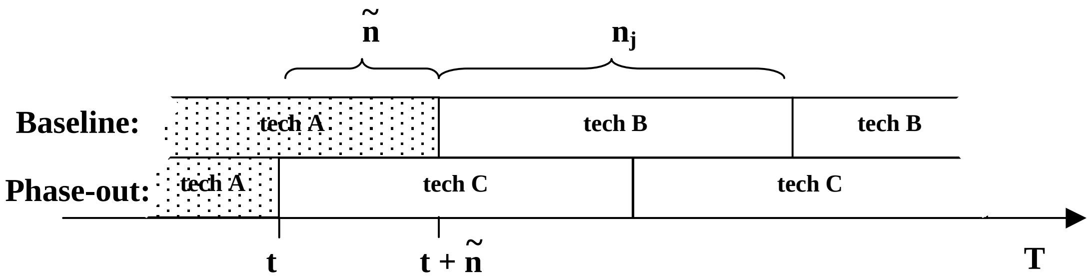


Figure 2: **Vintage Effect of Phase-Out Policies**

Given the phase-out date *t* for a nuclear power plant (*tech A*), this plant would be operated for another $\tilde{n}$ years in the baseline and then be replaced by some non-nuclear plant (*tech B*). In the phase-out scenario, replacement must already occur in *t* with a non-nuclear plant (*tech C*) which is not necessarily of the same type as the back-up technology in the baseline (tech *B*).

To calculate the cost of phasing out nuclear power, we employ standard dynamic investment calculus (Stelzer, 1992; VDEW, 1993; Betge, 1998): All revenues and expenditures associated with an investment or a combination of investments are discounted to a base-year yielding the net present value of the corresponding investment or investment combination. The comparison of different investment alternatives identifies the most profitable investment as well as the additional expenses incurred if other alternatives are chosen. A cost-benefit analysis for alternative investment schemes with a finite horizon model poses the problem of a consistent comparison between payment streams differing in their duration beyond the model horizon. One common approach (Blohm and Lüder, 1995) is to assume that the replacement of an exiting power plant takes place through an endless series of the chosen replacement technology (see Figure 2 above). In our analysis, we measure the cost of a premature phase-out in period *t* as the difference in the present values of the baseline investment stream C_0^I (without administered premature phase-out) and the policy-induced investment stream C_0^{II} :

$$C_0^{phase-out}(t) = C_0^I(t) - C_0^{II}(t) \qquad \textbf{(1)}$$

The present value of the baseline investment stream C_0^I in period *t* is given as:

$$C_0^I(t) = \sum_{j=1}^{m} \tilde{C}_o^j(t) + \sum_{j=1}^{m} \left((1+i)^{-\tilde{n}_j} C_0^j(t+\tilde{n}_j) \cdot \overset{\infty}{F}_j \cdot \frac{\tilde{L}^j}{L^j} \right) \qquad \textbf{(2)}$$

where:

m	:=	number of nuclear power plants (with *j* as the running index),
$\tilde{C}_o^j(t)$	:=	present value of the nuclear power plant *j* in period t,
i	:=	interest rate,
$\tilde{n}_j$	:=	remaining lifetime years for the nuclear power plant *j*,
$C_o^j(t+\tilde{n}_j)$	:=	present value in period $t+\tilde{n}_j$ of non-nuclear power plant *j* replacing the existing nuclear power plant *j* in period $t+\tilde{n}_j$,
n_j	:=	lifetime of a the non-nuclear replacement power plant *j*,
$\tilde{L}^j$	:=	capacity of nuclear power plant *j*,
L^j	:=	capacity of non-nuclear power plant *j*.

$\overset{\infty}{F}_j$ is used for calculating the present value of an infinite investment stream for the non-nuclear replacement power plant *j* where:

$$\overset{\infty}{F}_j = \frac{(1+i)^{n_j} \cdot i}{(1+i)^{n_j} - 1} \cdot \frac{1}{i} = \frac{(1+i)^{n_j}}{(1+i)^{n_j} - 1} \qquad \textbf{(3)}$$

To put it plainly: The factor $\overset{\infty}{F}_j$ transforms the present value $C_o^j(t+\tilde{n}_j)$ of the non-nuclear plant *j* into the present value of the infinite investment series. Note, that we weigh the present value

$C_o^j(t+\tilde{n}_j)$ with the quotient $\frac{\tilde{L}^j}{L^j}$ to account for the potential difference in capacities between the replacing plant and the replaced nuclear power plant.

The present value $\tilde{C}_o^j(t)$ of the nuclear power plant *j* in period *t* is:

$$\tilde{C}_0^j(t) = \sum_{tt=1}^{\tilde{n}_j} \Big(\Big(p(t+tt)\cdot h(t+tt) - (\tilde{f}c_j(t+tt) + \tilde{v}c_j(t+tt)\cdot h(t+tt) + \tilde{s}c_j(t+tt)\Big)\cdot \tilde{L}^j \cdot (1+i)^{-tt}\Big) \quad \textbf{(4)}$$

where:

$p(t+tt)$	:=	electricity price in DM /kWh in period $t+tt$,
$h(t+tt)$	:=	hours plant *j* is operated in period $t+tt$,
$\tilde{f}c_j(t+tt)$	:=	fixed payments in period $t+tt$ in DM/kW,
$\tilde{v}c_j(t+tt)$	:=	variable payments as a function of plant utilization in period $t+tt$ in DM/kWh,
$\tilde{s}c(t+tt)$	:=	fixed repayments and interest payments in period $t+tt$ in 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).

The present value of the non-nuclear replacement plant $C_0^j(t+\tilde{n}_j)$ is calculated as:

$$C_0^j(z) = \sum_{tt=1}^{n_j} \Big(\Big(p(z+tt)\cdot h - (fc_j(z+tt) + vc_j(z+tt)\cdot h + sc_j(z+tt)\Big)\cdot L^j \cdot (1+i)^{-tt}\Big) \quad \textbf{(5)}$$

where:

$z := t+\tilde{n}_j$.

The present value of the premature phase-out investment stream is given as[2]:

$$C_0^{II}(t) = \sum_{j=1}^{m}\left(C_0^{j}(t)\cdot \frac{\tilde{L}^{j}}{L^{j}} \cdot \overset{\infty}{F} \right) - \sum_{j=1}^{m}\sum_{tt=1}^{\tilde{n}_j}\left(\tilde{s}c_j(t+tt)\cdot \tilde{L}^{j}\cdot (1+i)^{-tt} \right) \qquad \textbf{(6)}$$

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 until 2030.

The projections on world market prices for fossil fuels, as given in Table 2, are based on FEES (FEES, 1999). With respect to additional electricity imports to cover the base-load gap for phased-out 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. The technical lifetime of nuclear power plants is set to 40

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[2] 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).

[3] The data base employed for the study can be obtained from the authors on request.

[4] Liberalisation on European electricity markets is likely to increase import capacities. The implications of changes in import capacities on our results are reported in section 4.3.

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]

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 fossil fuel prices (Source: FEES 1999)

[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 calculated costs represent an upper limit.

[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.

4. Scenarios and Results

4.1 Scenario Definition

In our simulations, we distinguish three alternative settings 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.

The costs of a premature 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

[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.

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 power plant will be shut down before 2005.

4.2 Simulation Results

Figure 3 visualizes the costs of a premature phase-out 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]

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 of a premature phase-out at a given point of time. FLY, on the other hand, is cheaper compared to CAY, which induces the highest excess costs. Simply put, at any given point in time, the capacity for power generation of nuclear power plants is highest under TAY followed by FLY and CAY.

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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.

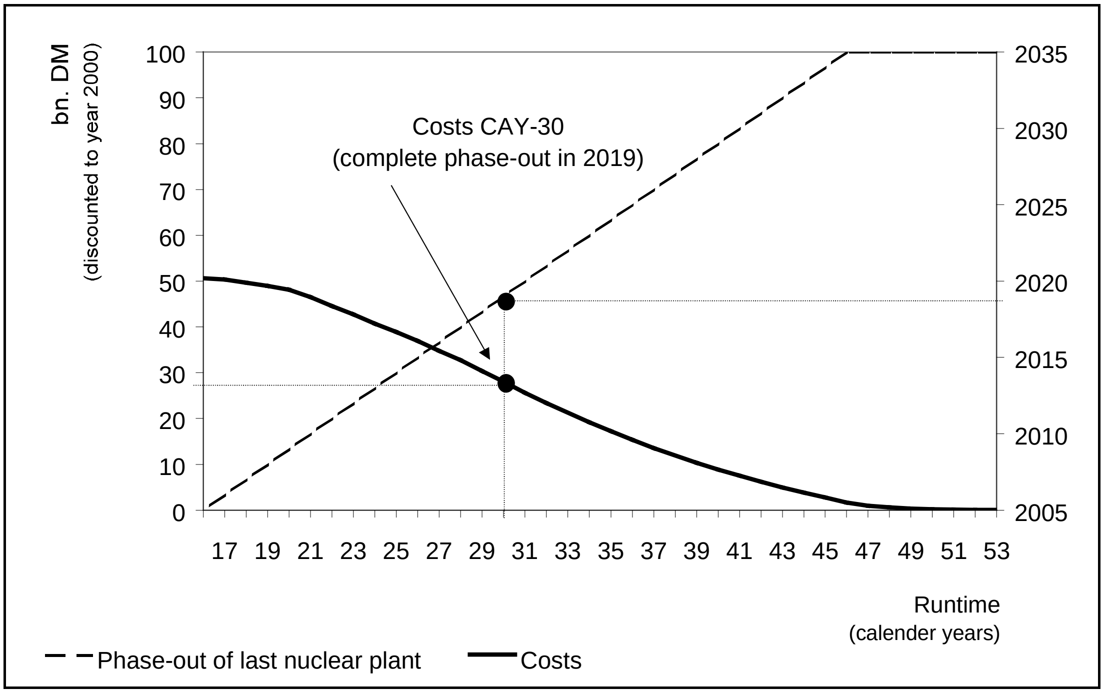

Figure 3a: **Phase-out costs under calendar-year regulation (CAY)**

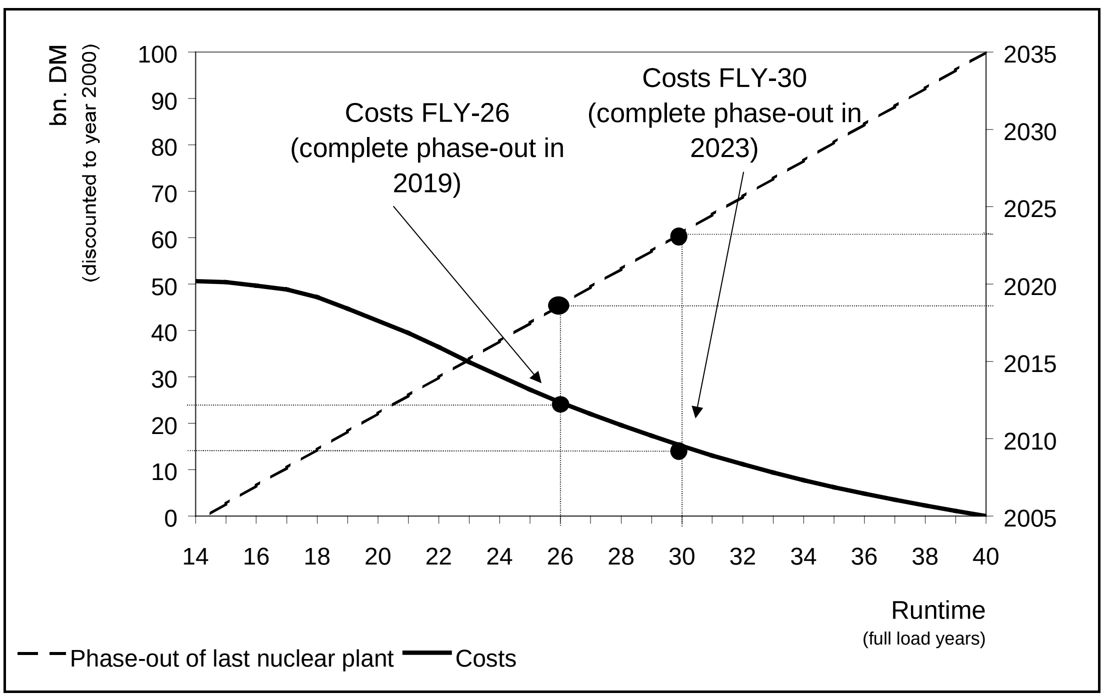

Figure 3b: **Phase-out costs under full-load year regulation (FLY)**

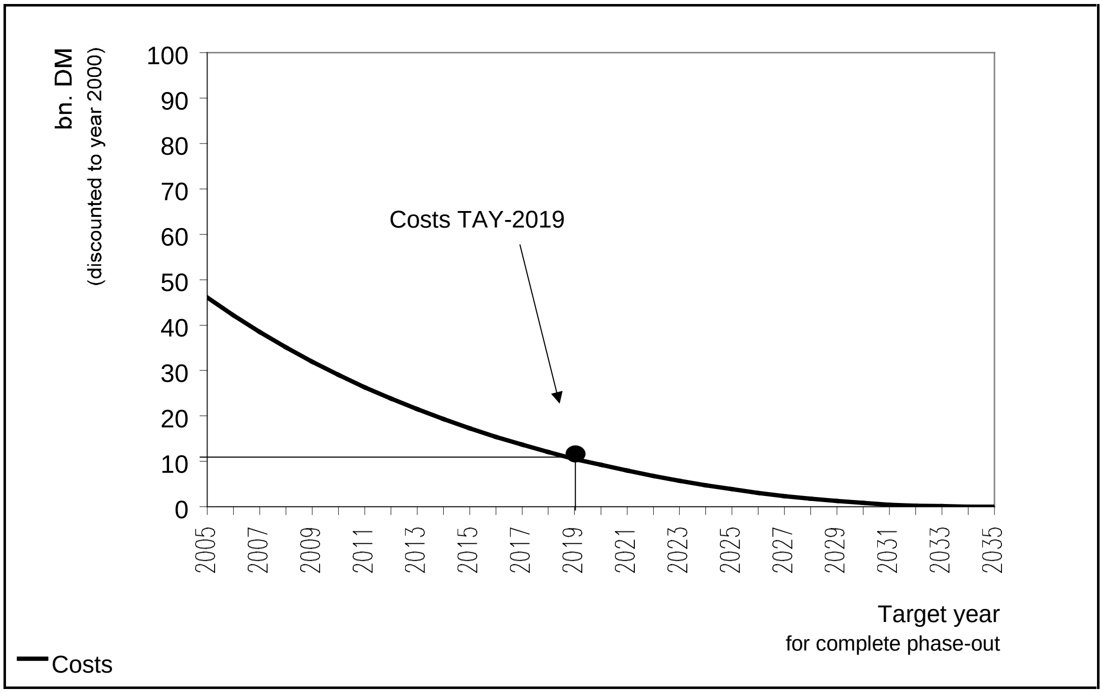

Figure 3c: **Phase-out costs under target-year regulation (TAY)**

The capacity, in turn, is directly associated with the cumulative electricity production of competitive nuclear power plants. TAY, then, implies the lowest foregone profits compared to the baseline. To put it differently: For a given date of ultimate shut-down, TAY effectively delays the replacement of each nuclear power plant as compared to FLY or CAY.

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 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 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 less pronounced, the more similar the vintage structures of the nuclear power plants are. The major differences between CAY and FLY then stem from different historical degrees of utilization across the plants. The more equal the historic utilization factor for plants, the less distinct the differences in costs are for the plant-specific phase-out scenarios.

In principle, the costs of a premature phase-out can be associated with the cumulated electricity production from nuclear power plants, which is feasible under the respective regulation approach. Figure 5a illustrates this relationship for the case of an ultimate phase-out of all nuclear power plants in 2019. We see that CAY-30 allows for a total electricity production of 1.9 PWh, whereas FLY-26 concedes 2.1 PWh and TAY-2019 even 3 PWh.

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[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).

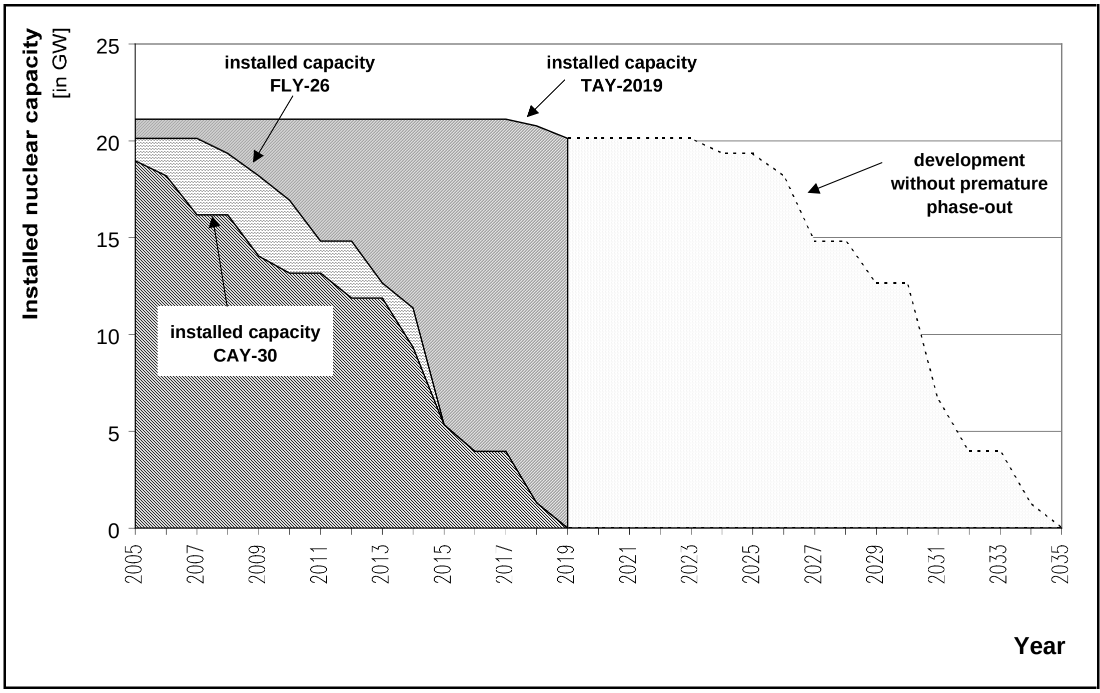

Figure 4: Development of installed nuclear capacities under TAY-2019, CAY-30 and FLY-26 regulation

CAY and FLY, designed to lead to the same cumulated electricity production, cause only slight differences in the date of the ultimate phase-out and the total costs. As compared to these plant-specific regulations, TAY will always cause lower costs for the same given amount of electricity and accommodate an earlier date for the ultimate phase-out. Figure 5b illustrates our reasoning. Let us consider the concrete case where the government concedes a cumulated production of 1.9 PWh, which corresponds to the CAY-30 scenario. The FLY regulation, which is equivalent in terms of cumulated electricity production, would then save about 4 billion DM and allow the shut-down of the power plants one year earlier as compared to CAY. The equivalent target-year regulation – in this case TAY-2012 – would save another 2.5 billion DM compared to FLY and accelerate the phase-out for another 6 years. In other words, for a given cumulated electricity production from nuclear power, TAY will not only reduce costs compared to FLY and particularly CAY, but also speed up the phase-out date.

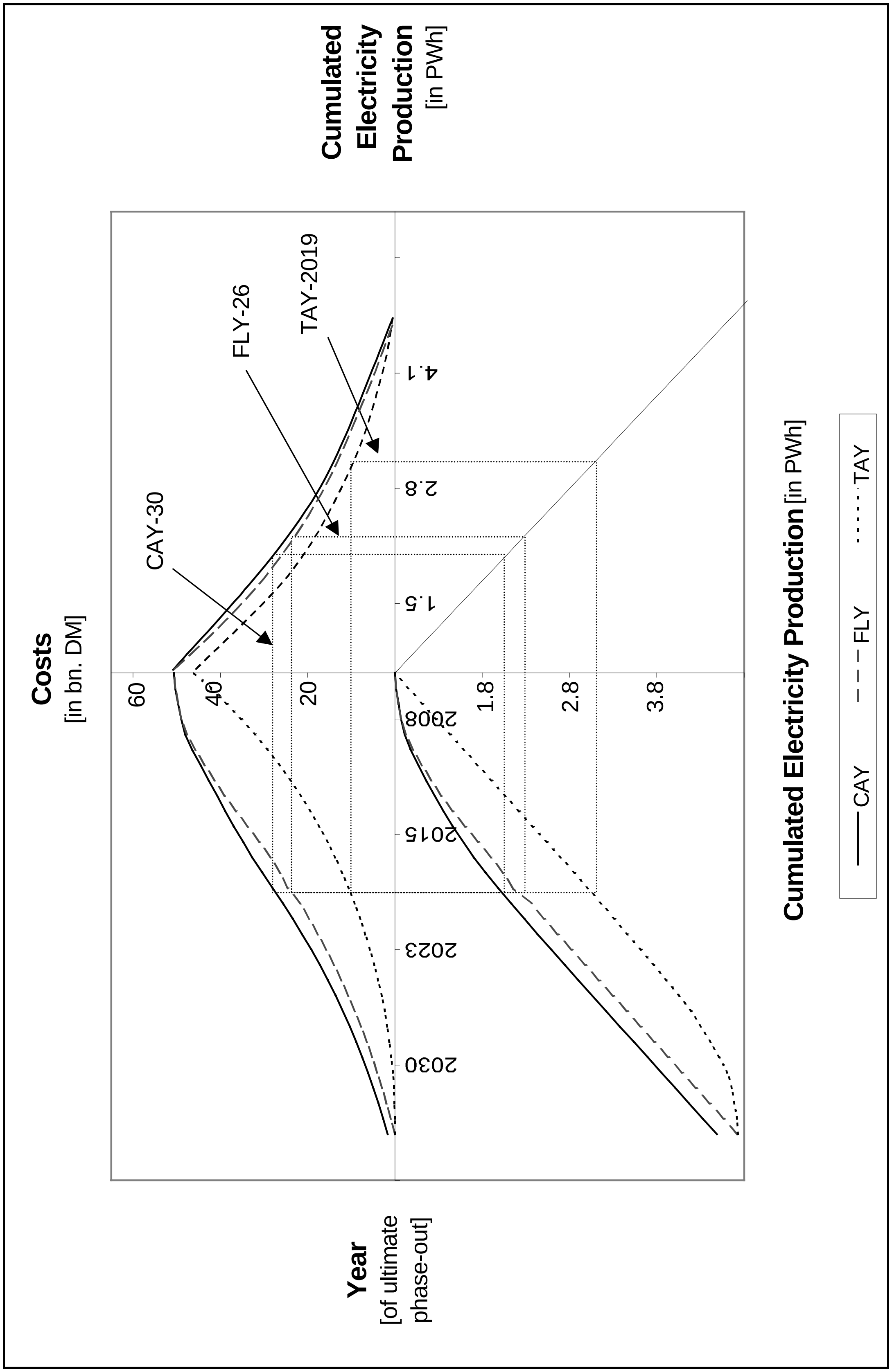

Figure 5a: **Costs and cumulated electricity production for the phase-out regulations CAY-30, FLY-26 and TAY-2019**

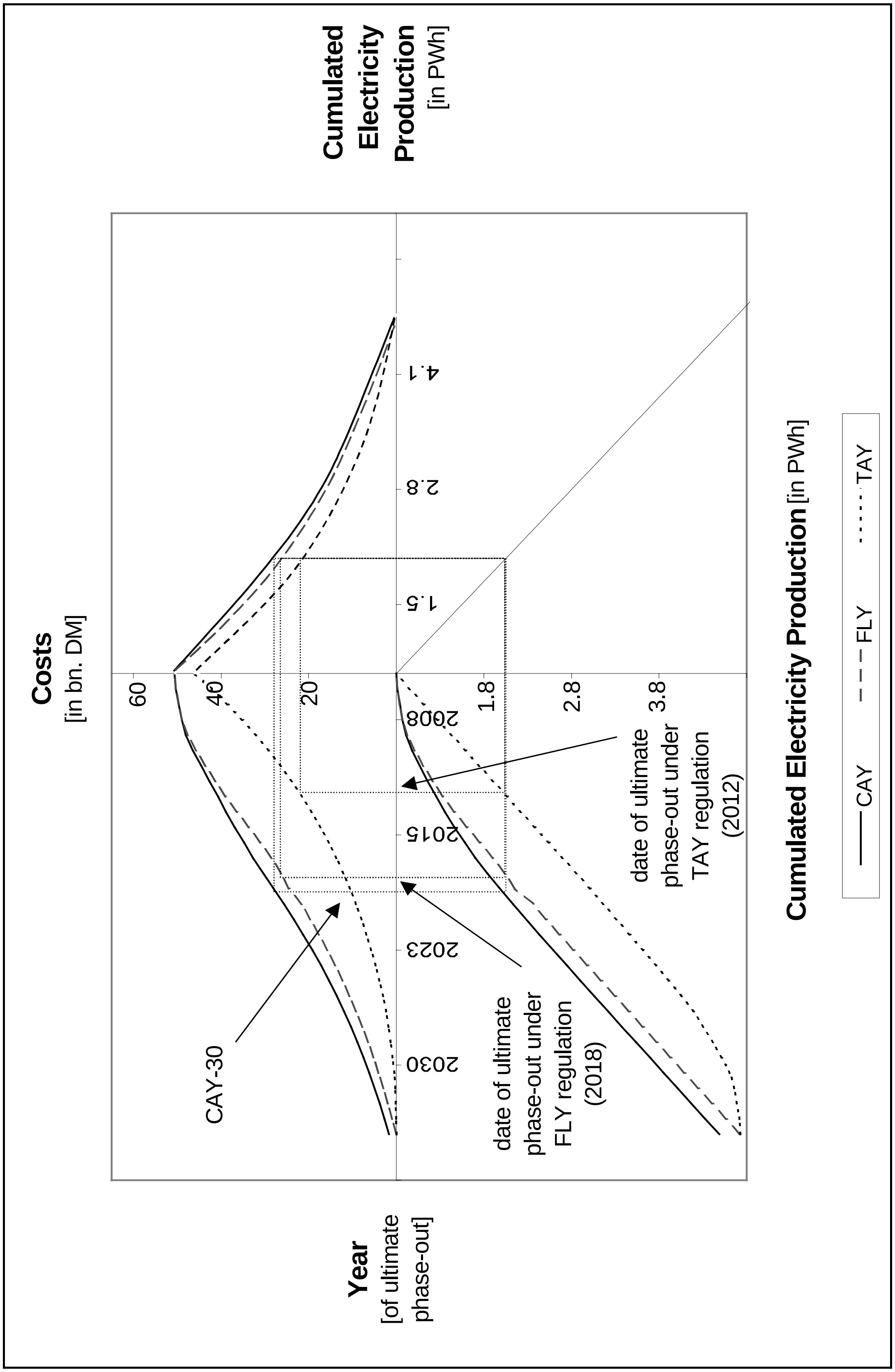

Figure 5b: **Costs and cumulated electricity production for different phase-out regulations designed to lead to the same cumulated electricity production.**

Table 3 provides a spill down of 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.[11] 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. 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 case of Obrigheim and 1.8 million DM/KW in the case of Stade.

[11] 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: Years	Difference to CAY-30: bn. DM	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	Difference to CAY-30: bn. DM	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	Difference to CAY-30: 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)

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.

	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
Bayernwerk AG / Isar - Amperwerke AG / PreussenElektra AG	10,58	0,55		5,99	0,31		9,71	0,50		4,03	0,21	
RWE Energie AG / Vereinigte Elektrizitätswerke Westfalen AG	8,15	0,50		3,90	0,24		6,45	0,40		2,75	0,17	
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)

We see, e.g., that in absolute monetary terms, RWE Energie AG and Preussen Elektra AG will be most affected by the premature phase-out for all regulation schemes. These companies hold stakes in several nuclear power plants with relatively high specific phase-out costs. When we account for potential mergers in the electricity sector (see footnote 1), the differences in total costs between the merged utilities and other companies get even more pronounced (see last two rows in Table 4).

However, absolute cost figures are a misleading indicator for the potential market distortions induced by a premature 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.[12]

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 3). We see from Table 4 that CAY induces the largest differences in relative 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.

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

4.3 Sensitivity Analysis

Table 5 summarizes the robustness of our results with respect to changes of different key parameters. For the sake of brevity and transparency, we focus on those regulation scenarios that lead to an ultimate phase-out in the year 2019.

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 5: Sensitivity Analysis Results for phase-out costs

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 although we do not report the concrete quantitative results here to save journal space.

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 premature 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 as well as in the baseline all imports are used to replace those power plants (here: Obrigheim and Stade) which are not affected, anyway, from a premature phase-out regulation under TAY-2019.[13]

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.

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

5 Conclusions

In the debate on the premature phase-out of German nuclear power plants, there is an intense 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 then allows for a significant cut-back of economic costs (i.e. a reduction of the potential compensation claims by the utilities). 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 cost-cut when it is tailored to achieve the same effective point of total phase-out 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. The reason is that under the target-year approach for any given point in time the capacity for nuclear power generation is highest.

Our total estimates can be interpreted in two ways: On the one hand, they indicate the magnitude of potential compensation claims by the utilities. On the other hand, they can be regarded as the social insurance premium against the reduced risks of nuclear power. In the same vein –

accounting for historical downtimes – the available capacity under full-load regulation is higher than under calendar-year regulation even, when both approaches achieve the same date for the ultimate shut-down of nuclear power.

Alternative regulations on the duration and reference point for the operating time also impose significant changes in the competitive effects of a premature phase-out, i.e. the distribution of costs across plants and companies. The latter explains why the different companies will not necessarily follow the same path in the negotiations with the government on alternative regulation schemes. The government, then, is challenged to come up with a phase-out regulation which does not only minimize total costs but takes into account the induced distortionary effects across companies.

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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