The future of nuclear power in France: an analysis of the costs of phasing-out

AUTHORS

Raimund Malischek (EWI)

Johannes Trüby (EWI)

EWI Working Paper, No 14/15

November 2014

Institute of Energy Economics at the University of Cologne (EWI)
www.ewi.uni-koeln.de

Institute of Energy Economics
at the University of Cologne (EWI)

Alte Wagenfabrik
Vogelsanger Straße 321
50827 Köln
Germany

Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.de

ISSN: 1862-3808

The future of nuclear power in France: an analysis of the costs of phasing-out

Raimund Malischek[a,*], Johannes Trüby[a]

[a]*Institute of Energy Economics, University of Cologne; Vogelsanger Strasse 321, 50827 Cologne, Germany*

Abstract

Nuclear power is an important pillar in electricity generation in France. However, France's nuclear power plant fleet is ageing, and the possibility of reducing its share in power generation or even a complete phase-out has been increasingly discussed. Our research therefore focuses on three questions: First, what are the costs of phasing-out nuclear power in France under different scenarios? Second, who has to bear these costs, i.e., how much of the costs will be passed on to the rest of the European power system? And third, what effect does the uncertainty regarding future nuclear policy in France have on system costs? Applying a stochastic optimization model for the European electricity system, we show that additional system costs in France of a nuclear phase-out amount up to 76 billion €$_{2010}$. Additional costs are mostly borne by the French power system. Surprisingly, we find that the costs of uncertainty are rather limited. Based on our results, we conclude that a commitment regarding nuclear policy reform is only mildly beneficial in terms of system costs.

Keywords: Nuclear policy, uncertainty, investment, France, electricity market modeling

JEL classification: C61, Q40, Q48, L94

1. Introduction

Nuclear power is an important technology in the global electricity system, comprising a share of 13% of global power generation (IEA, 2012). Its contribution to electricity generation is currently substantially higher in OECD countries (21% versus 4% in non-OECD countries; IEA, 2012) where nuclear power has

*Corresponding author

Email address: `raimund.malischek@ewi.uni-koeln.de; +49 221 277 29 220` (Raimund Malischek)

been widely deployed since the 1960s in an effort to reduce the import dependency on fossil fuels, diversify the power mix and reduce power system costs.

A key feature of nuclear power is that its electricity generation is virtually carbon-free. Therefore, nuclear power is thought to play a key role in mitigating climate change (IEA, 2012, 2013). Despite its potential to contribute to the de-carbonization of the power sector, nuclear power is a politically sensitive topic in many countries due to the inherent risk of nuclear accidents and subsequent environmental catastrophes.

The public resentment towards nuclear power has been strongly aggravated in the aftermath of the Fukushima-Daiichi accident, especially in Japan and Europe. Politicians in Japan and Germany reacted rapidly and introduced moratoria on the operation of nuclear power plants in their countries. While discussions about a complete phase-out of nuclear power are still ongoing in Japan, the governments of Germany and Switzerland have already decided to fully abolish the use of nuclear energy by 2022 and 2035, respectively. Nuclear policy was a major topic in the French presidential elections in spring 2012, and several other countries such as Italy, Belgium and the United Kingdom have participated in lively public debates on the future of nuclear power.

With only four nuclear power plants currently under construction and more than 10 GW of existing nuclear plants set to retire in the coming decade (IEA, 2012), nuclear power is losing its share in the European power sector. Maintaining the current level of nuclear power generation, let alone increasing its share in order to reduce the carbon intensity of the power sector, would require several firm investment decisions for new plants by the end of the decade given the long construction time for such plants. Nuclear investments are comparably capital intensive due to the large size of the power station, with the specific investment cost ranging between 3000 to 5000€/kW – roughly three times more than a typical coal-fired plant and about four times more than a combined-cycle gas turbine (CCGT). Building a nuclear power plant is a long-term investment with the expected lifetime of a station ranging between 50 and 60 years. The capital-intensity of nuclear investments typically requires either a larger cash-flow per output (price spread) or a longer amortization period than an investment in a coal or gas-fired plant. While the former is basically a market risk that all investors in liberalized power markets face, the latter is closely related to political uncertainty. In order to earn money, nuclear power plant operators need to run their plant – and generate cash-flows – for decades. What if nuclear policy mandates a sudden phase-out?

We focus on France in the following as France faces several additional challenges and particularities related to nuclear power. First, nuclear power contributes to roughly 75% of the electricity generation in France, the highest share of nuclear power in electricity generation in the world. Second, most (37 out of

58) French nuclear power plants were built in the time period between 1975 and 1985. Thus, these plants will reach the end of their lifetime between 2025 and 2035 and will need to be either replaced by new plants or retro-fitted via investments in order to prolong their lifetime. Finally, France faces the political challenge of keeping CO_2 emissions from power generation low while public resentment towards nuclear power grows and renewable energies are still too costly and variable to replace base-load technologies on a large scale. Public resentment and recent political debates, such as the one in the presidential elections of 2012, have introduced political uncertainty toward future nuclear policy in France, which could impede investments in nuclear technology and raise system costs.

In our analysis, we focus on three main research questions: First, what are the costs of a nuclear phase-out in France? To this end, we look at two possible phase-out paths (an immediate phase-out and an extended phase-out over 15 years) as well as examine the effect of lifetime prolongations of existing nuclear power plants. Second, who picks up the bill of a nuclear phase-out in France, i.e., will some of the costs be passed down from the French to the rest of the European power system? And third, what is the effect of political uncertainty regarding future French nuclear policy on nuclear power investments and system costs?

In order to address these questions, we apply a stochastic linear programing model of the European power system. The model allows for the calculation of the least-cost dispatch of power plants and investment in new generation technologies across Europe, accounting for power exchange between the individual regions. Additionally, our approach allows us to model uncertainty regarding future nuclear policy in France, i.e., investment decisions are made without knowing *if* and *when* a future government mandates a nuclear phase-out.

We investigate different scenarios of nuclear policy in France. To answer the first two research questions, we compute deterministic benchmark scenarios in which we identify the cost and necessary modifications of the system under perfect foresight, i.e., all investors know what will happen in the future and when. These scenarios are complemented by three stochastic cases that vary in the probability (high, low and medium) of a phase-out decision in the time up to 2050. In these scenarios, the investors in nuclear power have information about the probability of a nuclear phase-out at any given time. The uncertainty about future nuclear policy leads to different investment decisions and system costs compared to the deterministic cases, allowing us to answer our third research question.

The findings of our analysis are manifold: We find that complying with a phase-out of nuclear power leads to higher system costs in France. The additional costs of a nuclear phase-out depend strongly on how the phase-out policy is designed, totaling a maximum of 76 billion €$_{2010}$[1] (which is roughly 2.5% of GDP in France in 2012).[2] Costs are generally highest if the phase-out is immediate, i.e., nuclear plants are required to shut down immediately after the decision is made, not allowing for a transitory period. Regarding our second research question, we find that the costs of a nuclear phase-out are mainly borne by the French power generators. A phase-out reduces infra-marginal rents in the French system as base-load plants with low marginal costs that have fully recovered their investment expenditure are replaced by plants with higher marginal costs (or imports), while the price-setting plants are hardly affected. Neighboring countries are also affected by a French phase-out. A French phase-out leads to higher conventional power production and stronger investments in conventional power plants in the rest of Europe. Concerning the third research question, we find that costs of uncertainty are rather small in the scenarios, reaching a maximum of 6 billion €$_{2010}$. The costs of uncertainty are mitigated by allowing for lifetime-prolonging investments. Moreover, costs of uncertainty may be mitigated if phase-out policies allow for a transitory period. Political uncertainty typically reduces investments in nuclear power; yet find that additional lifetime-prolonging investments are a rational choice under uncertainty. Such investments are not as capital-intensive and are therefore to a lesser degree exposed to the risk of a phase-out harming the economic viability of the investment.

Our analysis bears relevant implications for policy makers who are often confronted with demands for long-term commitments. In addition to in most cases being unrealistic and probably even undesirable from an information-theoretic point of view as it would require the neglecting of future information, our analysis shows that at least in our application a lack of commitment does not come at a high cost.[3]

The paper is structured as follows: Section 2 provides an overview of the related literature. Section 3 describes the applied approach; Section 4 explains the most important technical and political assumptions. Scenario results for France and the rest of Europe are discussed in Section 5. Section 6 concludes.

2. Literature Overview

Several studies analyzing nuclear and energy policy *in France* have been published[4]: RTE (2011) identifies the risks of an imbalance between electricity demand and supply within a timeframe up to 2030. The authors

[1]€$_{2010}$ denotes real Euros based on 2010 values.

[2]An absolute labelling of such cost figures is difficult as it would require an assessment of the risk-costs of nuclear power plant operation, for which there is no reliable data available.

[3]Under asymmetric information, similar reasoning applies. As shown by Höffler and Wambach (2013) in an application to infrastructure investments, regulators face a trade-off between early commitment and the aim to elicit information in later stages of the game.

[4]For recent publications on nuclear policy and nuclear phase-out scenarios in other countries, we refer to Kannan and Turton (2012) for Switzerland, Park et al. (2013) for Korea, Hong et al. (2013) for Japan and Fürsch et al. (2012a) for Germany.

apply a probability-based simulation model and compare scenarios with different shares of nuclear generation in the electricity mix; however, none with a full phase-out from nuclear power.

CAS (2012) analyzes four different scenarios for nuclear power plant operation in France ranging from an immediate exit from nuclear generation to a continued use of the technology. In summary, the authors calculate the cost of an immediate exit from nuclear power to amount to about 100 billion € in the timeframe between 2010 and 2030.

CDC (2012) assesses all costs of nuclear power generation in France presenting past, present and future costs. Concerning future costs of nuclear, the study compares four scenarios with different assumptions regarding nuclear power generation in France.

UFE (2011) analyzes different possible policy choices based on climate, social, economic and financial criteria. The authors compare three scenarios with different shares of nuclear generation in the period up to 2030. In a scenario with 20% nuclear generation, the authors calculate a required investment expenditure of 434 billion €.

As we show in the following, our results are generally in line with previous results presented in the literature. A difference in the magnitude of the results can be explained by the different scenario assumptions, research focus and methodology applied. Our approach contributes to the existing stream of literature in at least three ways: First, our scenario definition is novel to the literature since it systematically highlights the effects of different phase-out periods and lifetime prolongations. Second, we draw attention to the distribution of costs between the French and the European power system. And third, we incorporate a new type of uncertainty into the literature, namely political uncertainty regarding nuclear policy, and rigorously analyze its effect on costs and investment behavior.

3. Implementation

Previous research on uncertainty in energy markets has focused primarily on uncertainty with respect to demand evolution (e.g., Gardner, 1996; Gardner and Rogers, 1999), fuel and CO_2 price development (e.g., Roques et al., 2006; Patino-Echeverri et al., 2009), portfolio and risk management (e.g., Morales et al., 2009; Gröwe-Kuska et al., 2003) and renewables expansion, both regarding short-term (e.g., Nagl et al., 2012; Swider and Weber, 2006; Sun et al., 2008) and long-term uncertainties (e.g., Fürsch et al., 2012b).

Our approach, in contrast, focuses on long-term uncertainties associated with nuclear policy in France. In doing so, we employ a stochastic linear programing model of the European power system. Given a set of input parameters and constraints, the model calculates dispatch and investment decisions in such a way that residual electricity demand is satisfied and total *expected* discounted system costs in the European power system are minimized.[5] Uncertainty enters the model in the form of whether or not there is a nuclear phase-out decision in France at a particular point in time.[6]

Incorporating uncertainty in a deterministic investment and dispatch model typically influences model results. Informally speaking, while in the deterministic setting the social planner has perfect foresight and can optimally adjust decisions according to his single view of the world, in the multistage stochastic setting the social planner has to make decisions taking several different states of the world into account. This usually leads to deviations from the deterministically-optimal decisions and thus to increasing costs. In our analysis, we quantify these deviations and interpret their implications.

The timeframe of our analysis is up to 2050 in five-year steps. In order to derive consistent investment decisions throughout the outlook period, the optimization is extended to 2070. The dispatch in each modeled year is represented by three representative days per season consisting of six time-slices taking into account load and renewable generation. Investments take place on an annual granularity.

Nuclear phase-out decisions in France (denoted "D" in Figure 1) can occur in every five-year time interval between 2015 and 2035 (mimicking the legislative period of the French government). We assume that no phase-out decision can be made after 2035 in order to have consistent and comparable results for the time period up to 2050. Moreover, this simplification also helps to reduce computer runtime.[7] We thus consider four states, denoted by State 1 (phase-out decision between 2015 and 2020) to State 4 (phase-out decision between 2030 and 2035), in which a phase-out from nuclear power in France occurs as well as an additional state without a phase-out, denoted by State 5. Obviously, we do not allow for investments in nuclear power in France after a phase-out decision has been made.

The benchmark scenarios (denoted by "exit_2020", "exit_2025", "exit_2030", "exit_2035" and "no_exit" in Table 1) are deterministic cases in which we identify the costs and necessary modifications of the system under perfect foresight, i.e., all investors know what will happen in the future and when. These scenarios are complemented by three stochastic cases that vary in the probability of a phase-out decision during the time up to 2050 (denoted by "high_prob", "low_prob" and "medium_prob" in Table 1).

We perform two sensitivity analyses: The first deals with the *form* of the phase-out decision, i.e.,

[5]Residual demand refers to the demand met by conventional generation. It is equivalent to total demand minus generation from renewables (RES-E).

[6]The model is a stochastic extension of the deterministic linear programing model DIME. Bartels (2009) provides a detailed description of DIME including all model equations. The stochastic extension is straightforward and implemented as discussed in Shapiro et al. (2009).

[7]The model is implemented in GAMS and solved using CPLEX. Solving the model on an Intel(R) Xeon(R) (2 processors, each 2.67 GHz) with 96.0 GB RAM takes on average (depending on the scenario setting) between 12 and 24 hours.

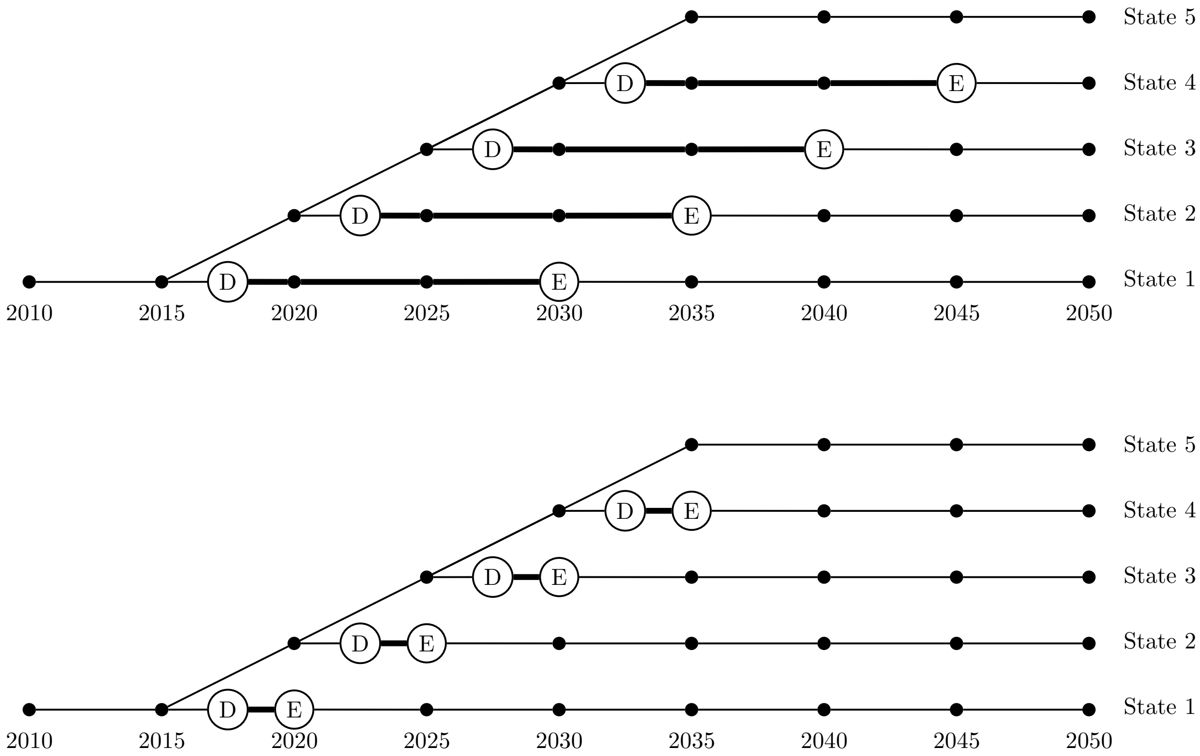


Figure 1: Scenario trees for an extended and an immediate exit from nuclear power in France

whether the phase-out/exit (denoted by "E" in Figure 1) takes place *immediately* after the decision or *over an extended* period of 15 years (see Figure 1). The second sensitivity analysis introduces the possibility of a prolongation of lifetimes of existing nuclear power plants in France. In the sensitivity analysis, lifetimes of existing French nuclear power plants can be prolonged beyond their license period of 40 years. In order to fulfill the required safety standards for a lifetime prolongation, significant investments have to be made. Previous studies have estimated additional costs for a prolongation of nuclear power plant lifetimes by another 20 years in France to amount to 55 billion € (Lundgren and Patel, 2012). Based on these figures, we estimate nuclear retrofit costs in France to amount to 870 $€_{2010}$/kW. By way of comparison, the German government in 2010 assumed retrofit costs for existing nuclear power plants in Germany of 500 €/kW for a lifetime prolongation of 20 years (Prognos, 2010).

We use the following abbreviations for our model runs: "15y_w/o_prolongation" indicates the upper scenario tree without the option for prolongation of existing nuclear power plants in France; "15y_prolongation" indicates that we allow for prolongation. Abbreviations for the lower scenario tree are defined analogously.

Table 1: Probabilities of the different states in the model runs

	State 1	State 2	State 3	State 4	State 5
high_prob	0.05	0.05	0.05	0.05	0.80
medium_prob	0.125	0.125	0.125	0.125	0.5
low_prob	0.2	0.2	0.2	0.2	0.2
exit_2020	1	0	0	0	0
exit_2025	0	1	0	0	0
exit_2030	0	0	1	0	0
exit_2035	0	0	0	1	0
no_exit	0	0	0	0	1

4. Assumptions

The main parameter assumptions entering the model are demand development, fossil fuel and CO_2 prices, technical and economic parameters of the power plants (in particular, investment and retrofit costs) as well as the development of renewable power deployment. The presentation of data in this section is based on the assumptions in Fürsch et al. (2012a) and Prognos (2010).

4.1. Electricity demand

We assume a slightly increasing electricity demand in France, rising to 543 TWh_{el} in 2030 and decreasing moderately decrease to 522 TWh_{el} in 2050, predominantly driven by the uptake of energy efficiency measures (see Table 2). Concerning the rest of Europe, we assume moderate growth rates of on average 0.9% p.a. between 2010 and 2050, resulting in a net electricity demand in the modeled regions (excluding France) of 3089 TWh_{el} in 2050.[8]

Table 2: Net electricity demand in TWh_{el} in France and Europe (excluding France)

	2010	2020	2030	2040	2050
France	501	513	543	533	522
Europe (excl. France)	2161	2455	2666	2871	3089

4.2. Fuel and CO_2 prices

Fuel prices for power plants are based on international market prices plus transportation costs to the power plants (see Table 3). Prices for hard coal and natural gas are assumed to increase in the long run up to 14.2 $€_{2010}/MWh_{th}$ and 31.6 $€_{2010}/MWh_{th}$, respectively.

CO_2 prices are assumed to be the same in all model runs and states. They are assumed to increase in the long run up to 75.1 $€_{2010}$/t CO_2 in 2050 from 23.9 $€_{2010}$/t CO_2 in 2020.

[8]The modeled regions cover France, the United Kingdom, Spain, Portugal, Italy, Germany, Austria, Switzerland, Belgium, the Netherlands, Poland, the Czech Republic and Denmark-West.

Table 3: Fuel costs in €$_{2010}$/MWh$_{th}$ and CO_2 prices in €$_{2010}$/t CO_2

	2010	2020	2030	2040	2050
Coal	11.0	10.1	10.9	11.9	14.2
Natural gas	17.0	23.1	25.9	28.8	31.6
Oil	39.0	47.6	58.0	69.0	81.4
CO_2	14.0	23.9	41.3	58.7	75.1

4.3. Technical and economic parameters for power plants

We assume the introduction of several new or improved conventional technologies as well as decreasing investment costs over time due to learning effects (see Table 4).

Table 4: Specific investment costs for thermal power plants in €$_{2010}$/kW

	2020	2030	2040	2050
Nuclear	3,000	3,000	3,000	3,000
Coal	1,300	1,300	1,300	1,300
Coal (innovative)	2,250	1,875	1,700	1,650
CCGT	950	950	950	950
OCGT	400	400	400	400
IGCC-CCS	-	2,039	1,986	1,782
CCGT-CCS	-	1,173	1,133	1,020
Coal-CCS	-	1,848	1,800	1,752
Coal -CCS (innovative)	-	2,423	2,263	2,102

4.4. Development of RES-E

RES-E development is treated exogenously in our analysis and is not optimized over time within the model. We assume a strong expansion of RES-E generation in France, reaching 277 TWh in 2050 up from 152 TWh in 2020 and 85 TWh in 2010 (see Table 5). This expansion is driven mainly by photovoltaics and wind power technologies. RES-E development is assumed to be the same in all model runs and states.

For the other European countries, we assume a continuous increase of RES-E generation within the coming decades. This development is driven by an increased deployment of wind farms, mainly in Denmark, the United Kingdom, Poland and the Netherlands. Electricity generation from photovoltaics increases primarily in Southern Europe, and geothermal energy is assumed to play an important role for electricity generation only in Italy because of its potential for high enthalpic resources. In 2050, RES-E generation in the European countries accounted for in this analysis (excluding France) is assumed to amount to 1616 TWh compared to approximately 797 TWh in 2020.

5. Scenario results: Implications for France and Europe

In Sections 5.1 and 5.2, we present the deterministic costs of a phase-out from nuclear power in France and the effect on costs across the rest of the European power system. Section 5.1 specifically deals with the

Table 5: Development of RES-E generation in France in TWh

	2010	2020	2030	2040	2050
Hydro	53	56	56	56	56
Wind onshore	14	47	94	104	100
Wind offshore	0	25	35	40	66
Photovoltaics	1	6	19	28	35
Biomass + Waste	17	17	17	17	17
Geothermal	0	1	3	3	3
Total	85	152	224	247	277

costs of prohibiting the prolongation of lifetimes of existing nuclear power plants in France. Furthermore, in Section 5.2, we look at the cost differences between a deterministic phase-out scenario (i.e., "exit_2020" to "exit_2035") and a deterministic scenario with nuclear power available in France until 2050 (i.e., "no_exit"). These values reflect the costs of having to substitute nuclear power plants in France with other conventional fossil-fueled power technologies in France and Europe under perfect foresight. In Section 5.3, in order to better assess the effects of uncertainty on costs, we analyze the impact of uncertainty on investment behavior in nuclear power plants in France. Section 5.4 explores the effect of uncertainty on system costs. Costs of uncertainty are given in our analysis by comparing a stochastic scenario state to the corresponding deterministic scenario (e.g., cost differences between State 3 in model run "high_prob" and the deterministic model run "exit_2030"). These costs reflect the inefficiency that is arising in the system due to political uncertainty.

5.1. The cost of prohibiting the prolongation of nuclear power plant lifetimes in France

The costs of prohibiting lifetime prolongations for existing nuclear power plants in France are significant. In a scenario without phase-out, these costs amount to 19 billion €$_{2010}$ and are mainly driven by higher investment costs as well as higher import costs/lower export revenues (see Figure 2).[9] The former is due to the lack of comparably low-cost nuclear lifetime prolongations which, if available, would reduce investment needs in newly built capacity, particularly newly built base-load capacity (e.g., nuclear), in the intermediate term in France. Note that not all nuclear capacity reaching the end of its licensing period is replaced by newly built (nuclear or other fossil fuel) capacity in France in the scenario without lifetime prolongations. Therefore, power generation in France is lower than in the scenario allowing for lifetime prolongations, resulting in lower exports and higher imports.

Additional system costs in the European power system (including France) amount to 20 billion €$_{2010}$ and are, as seen in the previous results, of the same magnitude as additional costs in France. This reveals

[9]Costs refer to the discounted costs for the whole power system and for the French power system, accumulated over the time horizon up to 2050. A discount rate of 10% has been assumed.

that costs are hardly passed from the French to the rest of the European system, i.e., France has to accept the financial burden of prohibiting lifetime prolongations. European costs are mainly driven by higher investment costs (primarily due to higher investment costs in France) and, in addition, by higher variable costs due to an increased utilization of conventional power plants in the rest of Europe (see middle bar in Figure 2).

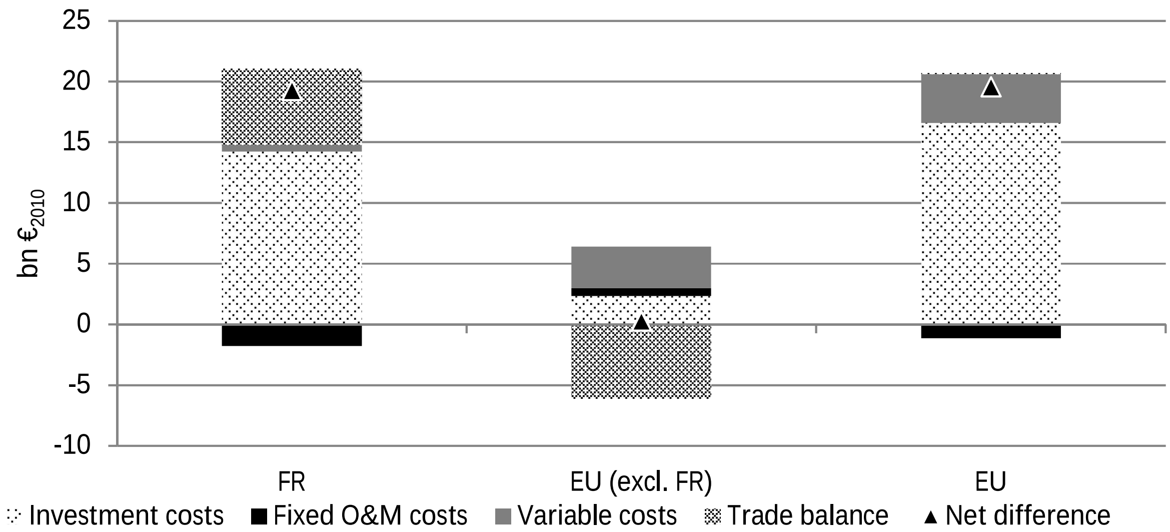


Figure 2: Accumulated (discounted) system cost differences differentiated by cost categories in bn $€_{2010}$ (2010-2050): Deterministic cost difference – w/o_prolongation vs. prolongation

5.2. The deterministic costs of a nuclear phase-out in France

The French power system can adapt to a phase-out from nuclear power at the expense of higher system costs in France and Europe (see Figures 3 to 6). The cost differences in this section reflect the costs of having to substitute (cost competitive) nuclear power plants in France with other conventional fossil-fueled power technologies in France and Europe under perfect foresight.

Additional (deterministic) costs in France of a phase-out can be significant, amounting to 76 billion $€_{2010}$ in a scenario with an immediate nuclear phase-out in 2020 compared to a scenario without nuclear phase-out and the possibility of prolonging the lifetime of existing nuclear plants (see Figure 6).

Deterministic cost differences in France are mainly driven by higher variable costs due to increased utilization of existing and newly built fossil-fueled power plants as well as a reduction in export revenues/higher import costs. The latter is due to lower exports and higher imports (in particular, from Germany) as not all phased-out nuclear generation is replaced by other generation technologies within France. Investment costs

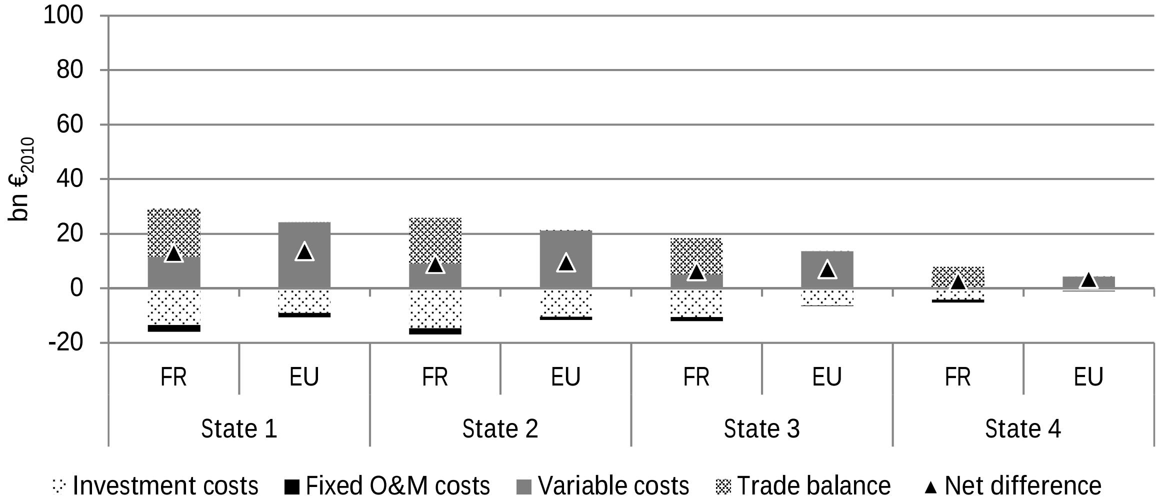


Figure 3: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 15y_w/o_prolongation

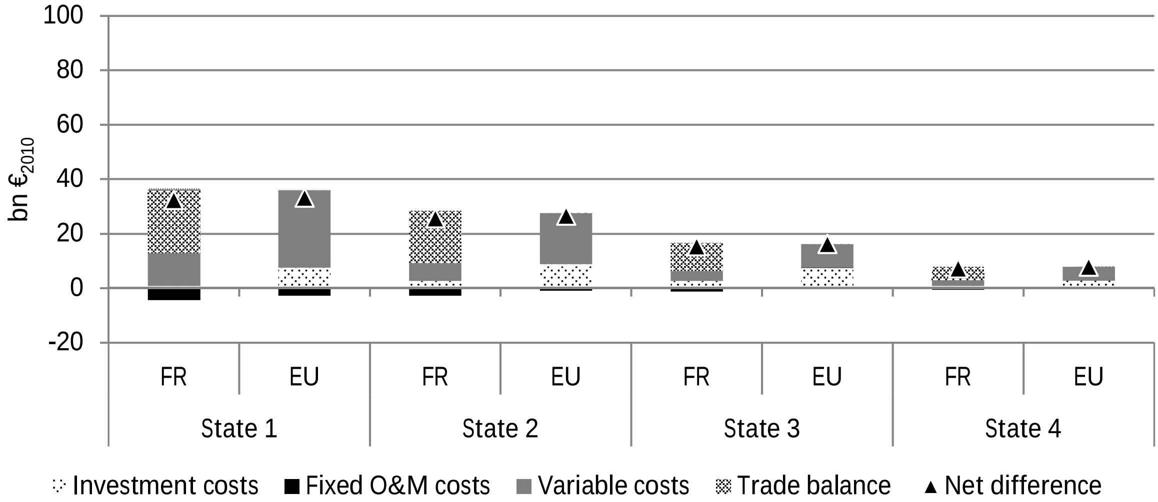


Figure 4: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 15y_prolongation

are lower in phase-out scenarios without prolongation opportunities due to the non-availability of nuclear power plant investments. Nuclear power plants, with comparably high investment costs, are in part replaced by other fossil-fueled power plants. Investment costs are typically higher in phase-out scenarios with prolongation opportunities, indicating that nuclear capacity is prolonged even though it has to be replaced by newly built (fossil fuel) capacities after the phase-out.

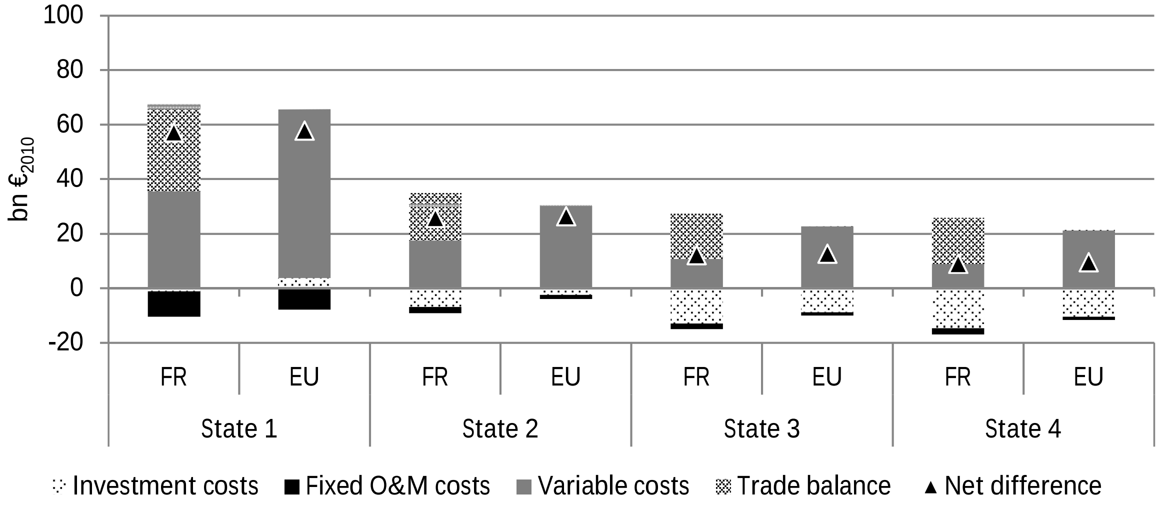


Figure 5: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 0y_w/o_prolongation

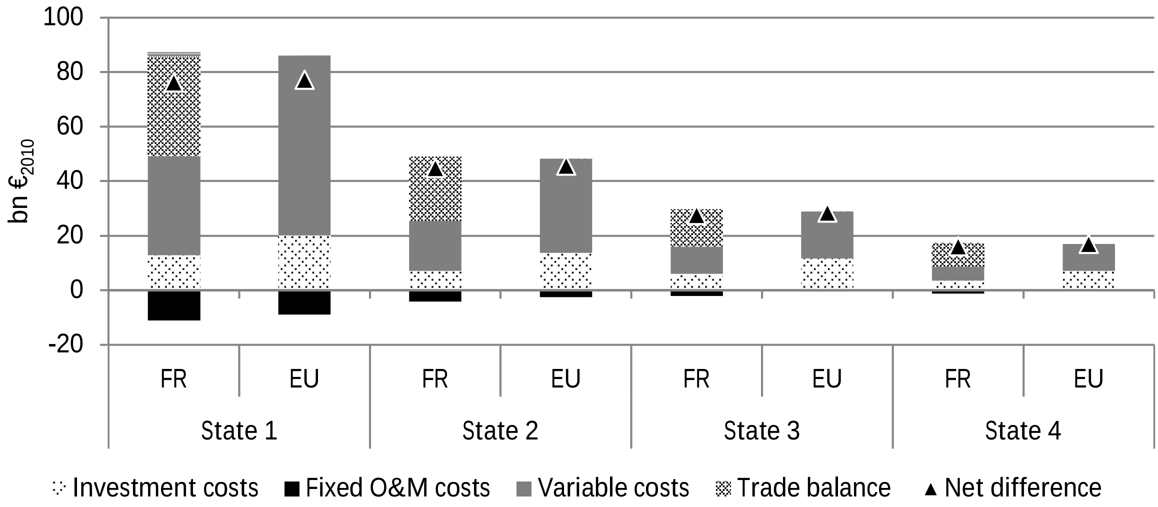


Figure 6: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 0y_prolongation

Additional (deterministic) costs in the European system (including France) of a French nuclear phase-out are incurred to a large extent by the French power system, with only a small fraction being passed onto the rest of the power system (see Figures 3 to 6).[10] Additional costs in the European system are mainly driven

[10]In the figures shown in this section as well as the following, we refrain from showing the cost components for Europe excl. France for better readability since the cost components follow a similar pattern to the one displayed in Figure 2. For the stochastic cases, data may be found in the Appendix.

by higher variable costs due to the non-availability of low-cost nuclear power in France. Conventional fossil-fueled power plants are utilized more often in France and the rest of Europe leading to higher CO_2 emissions in the European power system. Total investment costs in Europe follow a similar pattern as the one described above for the French system, i.e., total investment costs are typically lower in the case of no prolongation opportunities and higher otherwise.

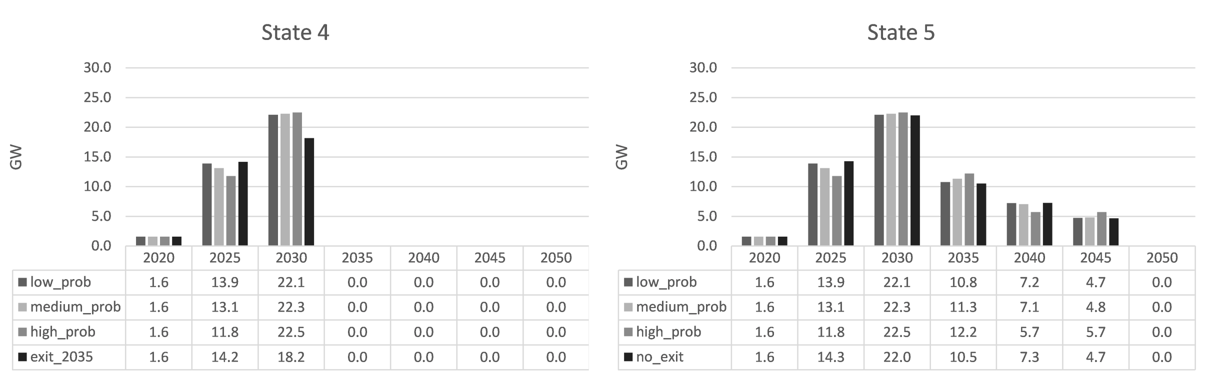
We find that deterministic cost differences in France and Europe follow two main patterns: First, they are clearly higher under an immediate phase-out (see Figures 5 and 6) compared to a scenario with a prolonged phase-out (see Figures 3 and 4). Second, the later the phase-out occurs, the stronger the reduction in system cost differences will be. The first point bears a clear policy implication: Policy makers are well-advised to opt for extended phase-out periods if a phase-out is to be introduced. Additional costs are substantially lower in this case.

5.3. Investment in nuclear power under uncertainty

We observe significant deviations from deterministically socially-optimal investments under uncertainty. Intuitively speaking, one would expect over-investment in nuclear power and under-investment in alternative base-load technologies under uncertainty in states with an early phase-out. Analogously, intuition suggests that uncertainty leads to under-investment in nuclear power in states with either no or a late phase-out. However, deviations from this intuition are possible due to the possibility of prolonging the lifetimes of existing nuclear power plants in certain model runs. Obviously, the high number of model runs computed does not allow for a discussion of all arising patterns. Figures 7 to 10 therefore illustrate the typical investment patterns that may arise and that help to clarify the system cost effects described in the next section.

Uncertainty may lower investments in new nuclear capacity in 2025 for scenario states with either no or a late nuclear phase-out (i.e., States 4 or 5) under a setting with no possible lifetime prolongations. In the example presented in Figure 7, this in turn leads to catch-up effects after 2030 once the uncertainty (in the model) has been resolved. The level of this effect is correlated to the probability of a phase-out occuring, i.e., investments in 2025 are lower in the model run "high_prob" than in "low_prob", followed by a more pronounced catch-up effect in "high_prob" than in "low_prob".

Allowing for lifetime prolongations, a greater amount of existing nuclear capacity may be prolonged under uncertainty in scenario states with either no or a late nuclear phase-out (see State 5 in Figure 8). Less nuclear capacity is typically retrofitted under uncertainty in scenario states with an early phase-out (see State 3 in Figure 8). The investments in 2020 are basically retrofit investments in existing nuclear capacity,



State 4:

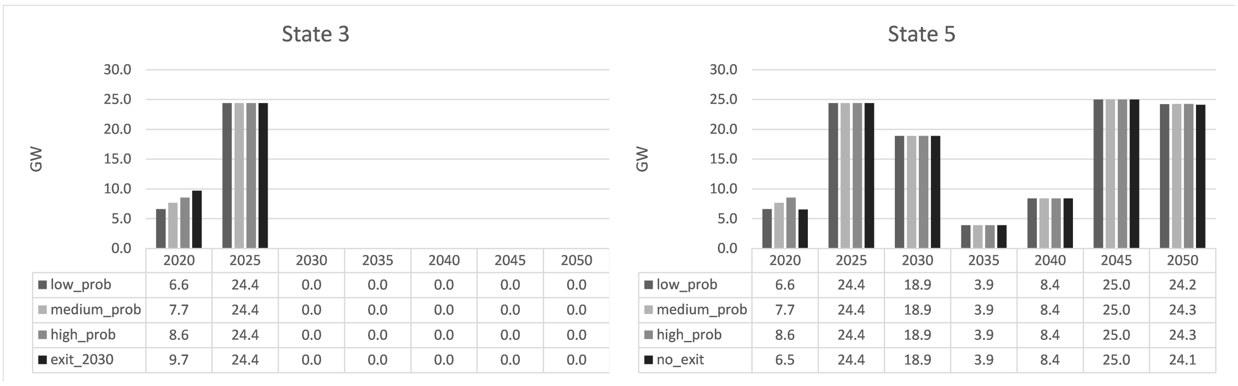
	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	13.9	22.1	0.0	0.0	0.0	0.0
medium_prob	1.6	13.1	22.3	0.0	0.0	0.0	0.0
high_prob	1.6	11.8	22.5	0.0	0.0	0.0	0.0
exit_2035	1.6	14.2	18.2	0.0	0.0	0.0	0.0

State 5:

	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	13.9	22.1	10.8	7.2	4.7	0.0
medium_prob	1.6	13.1	22.3	11.3	7.1	4.8	0.0
high_prob	1.6	11.8	22.5	12.2	5.7	5.7	0.0
no_exit	1.6	14.3	22.0	10.5	7.3	4.7	0.0

Figure 7: Investment in nuclear power in France in GW: 15y_w/o_prolongation

with 1.6 GW being newly-built capacity. Here, the nuclear power plant Flamanville is assumed to be online in the model. New nuclear power plants are only built in State 5 after 2040. Remarkably, the increase in retrofit investments in 2020 in State 5 appears to have no effect on new nuclear power plant investments or retrofit investments thereafter.



State 3:

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	24.4	0.0	0.0	0.0	0.0	0.0
medium_prob	7.7	24.4	0.0	0.0	0.0	0.0	0.0
high_prob	8.6	24.4	0.0	0.0	0.0	0.0	0.0
exit_2030	9.7	24.4	0.0	0.0	0.0	0.0	0.0

State 5:

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	24.4	18.9	3.9	8.4	25.0	24.2
medium_prob	7.7	24.4	18.9	3.9	8.4	25.0	24.3
high_prob	8.6	24.4	18.9	3.9	8.4	25.0	24.3
no_exit	6.5	24.4	18.9	3.9	8.4	25.0	24.1

Figure 8: Investment in nuclear power in France in GW: 15y_prolongation

Investment levels may be much higher under uncertainty than what is considered to be deterministically socially optimal. In State 4 in Figure 9, investment levels at the social optimum under uncertainty are between investments in the model runs “exit_2035” and “no_exit”.[11] Investments in the “low_prob” model run thus amount to 11.4 GW in 2025 and 22.3 GW in 2030 compared to no investment in “exit_2035”. The maximum difference in State 5 is achieved in the years 2025 and 2030, at which time we see no investments in nuclear power plants in France in “high_prob” compared to the deterministically socially-optimal levels of 14.3 GW in 2025 and 22.0 GW in 2030 in “no_exit”.

Figure 10 illustrates investment patterns under uncertainty with prolongation opportunities. Allowing

[11] Higher investment levels in 2030 compared to the “no_exit” level are again due to catch-up effects.

Figure 9: Investment in nuclear power in France in GW: 0y_w/o_prolongation

for the prolongation of existing nuclear capacity, more capacity lifetimes are prolonged in State 3 in the "low_prob" case due to the high investment levels in "no_exit". However, with higher probability of phasing-out, even less capacity is prolonged in State 3 in "high_prob" than in "exit_2030".

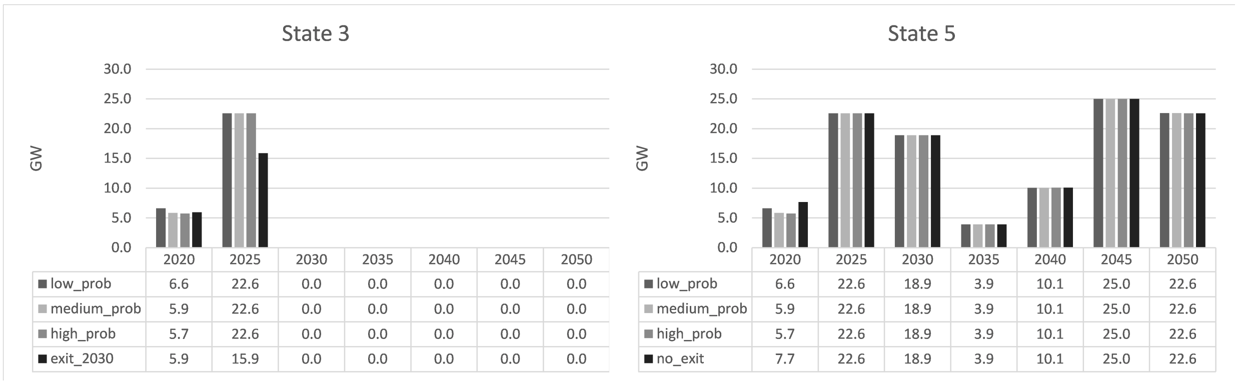


Figure 10: Investment in nuclear power in France in GW: 0y_prolongation

5.4. Costs of uncertainty

Costs of uncertainty are given by comparing a stochastic scenario state to the corresponding deterministic scenario. Due to the large number of calculations performed, we only show selected results in this section. Cost figures for all model runs can be found in the Appendix.

Costs of uncertainty in France and Europe are rather small in most model runs and states. In fact, costs can amount to 6 billion €$_{2010}$ in a setting with a high probability of a phase-out and no possibility of prolongation for existing nuclear power plants (see model run "high_prob" in Figure 11).

Costs of uncertainty in France in the case of no phase-out from nuclear power and a setting without prolongation opportunities are to a large extent driven by a change in the trade balance (i.e., lower export revenues and higher import costs) and lower investment costs (see Figures 11 and 12). The effect concerning variable costs is not unique: While variable costs are higher under uncertainty in model run "high_prob" in Figure 11, they are lower in "low_prob" and "medium_prob".

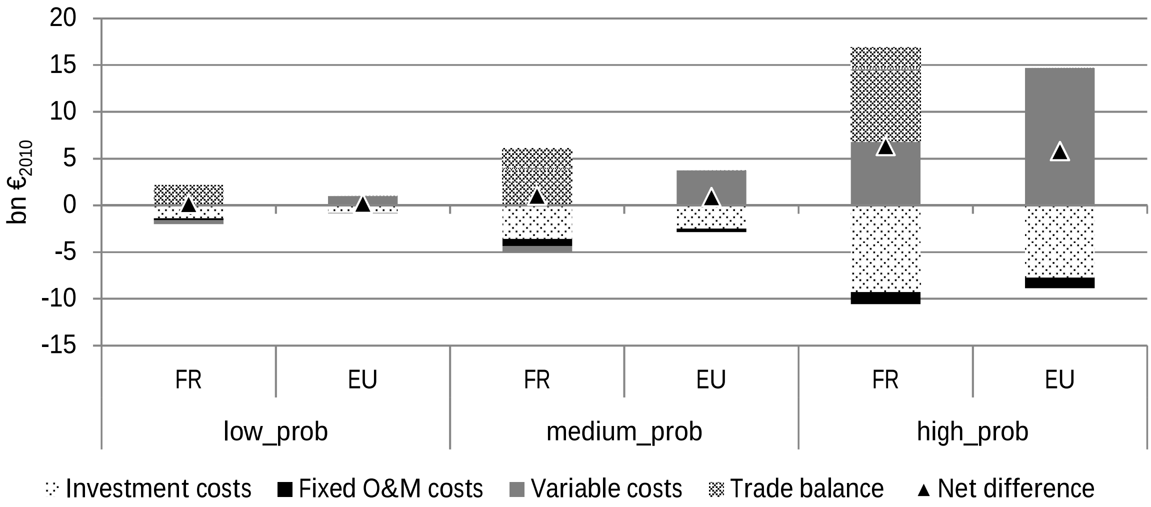


Figure 11: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y_w/o_prolongation – State 5

Costs of uncertainty in France follow two main patterns: First, costs are typically lower in scenarios with an extended phase-out period of 15 years than in scenarios with an immediate phase-out from nuclear power (compare Figures 11 and 12). Second, costs of uncertainty typically increase with increasing probability of a phase-out in states with either no or a late phase-out (see Figure 11). Similarly, costs of uncertainty increase with decreasing probability of phasing-out in states with an early phase-out (see Figure 13).

Costs of uncertainty for the European power system (including France) follow similar patterns. Costs are typically lower in scenarios with an extended phase-out period. Additional costs are mainly caused by higher variable costs under uncertainty in the case of either no or a late phase-out without the possibility of lifetime prolongations (see Figures 11 to 12). When allowing for prolongation, the effect concerning variable and investment costs is ambiguous. For instance, investment costs may be higher in the case of an early phase-out (see Figure 14) due to over-investment in nuclear power plants in France, as illustrated in Figure 10. However, lower investment costs are also possible in the case of an early phase-out (see Figure 13) due to fewer prolongations of existing nuclear power plant lifetimes under uncertainty.

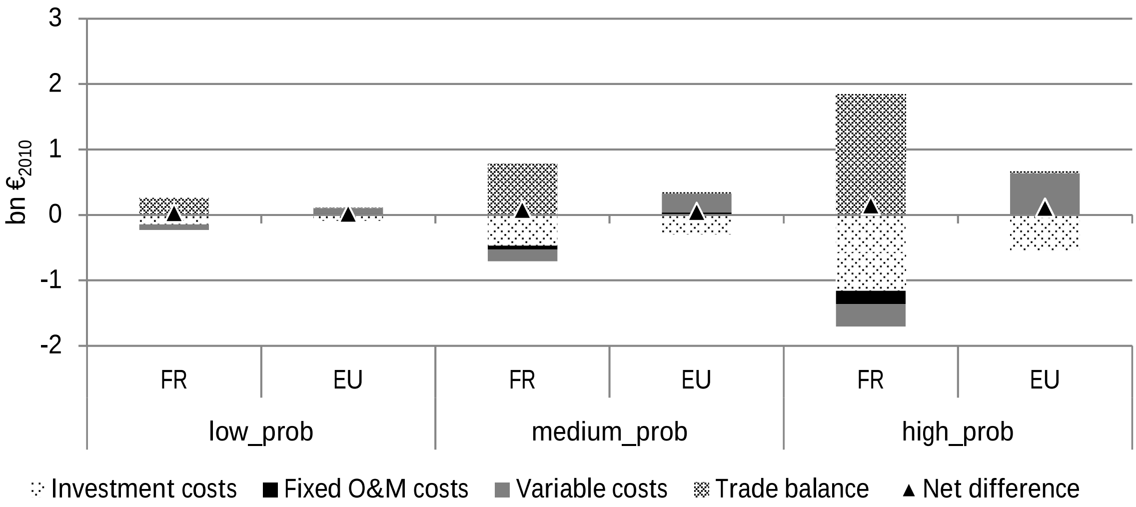


Figure 12: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y_w/o_prolongation – State 5

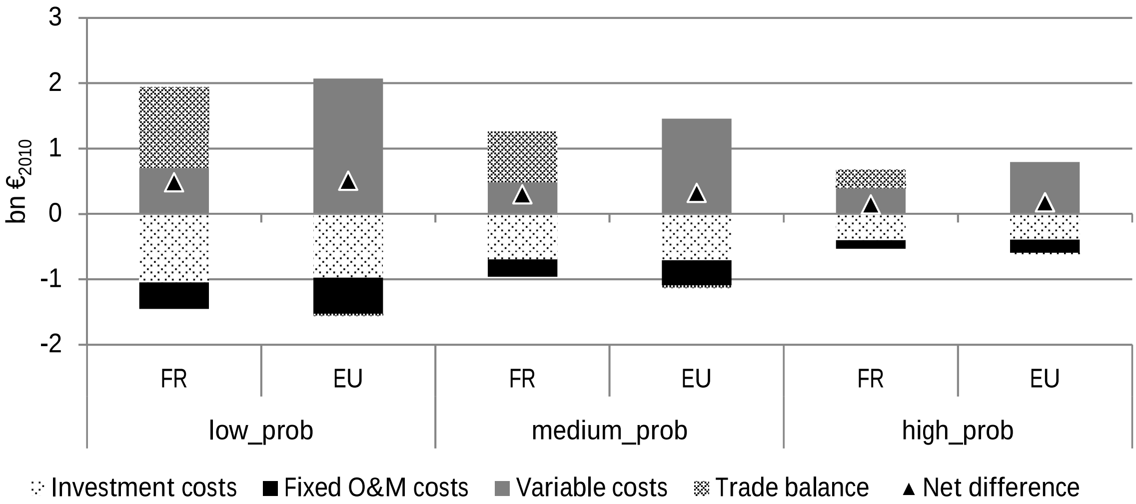


Figure 13: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y_prolongation – State 2

6. Concluding Remarks

This paper provides a model-based analysis of the possible future role of nuclear power in France. We have investigated different scenarios of nuclear policy in France, both under perfect foresight and under uncertainty. We have shown that a phase-out from nuclear power in France leads to higher system costs in the power sector. These costs are mainly borne by the French system, and the cost effects for the rest of

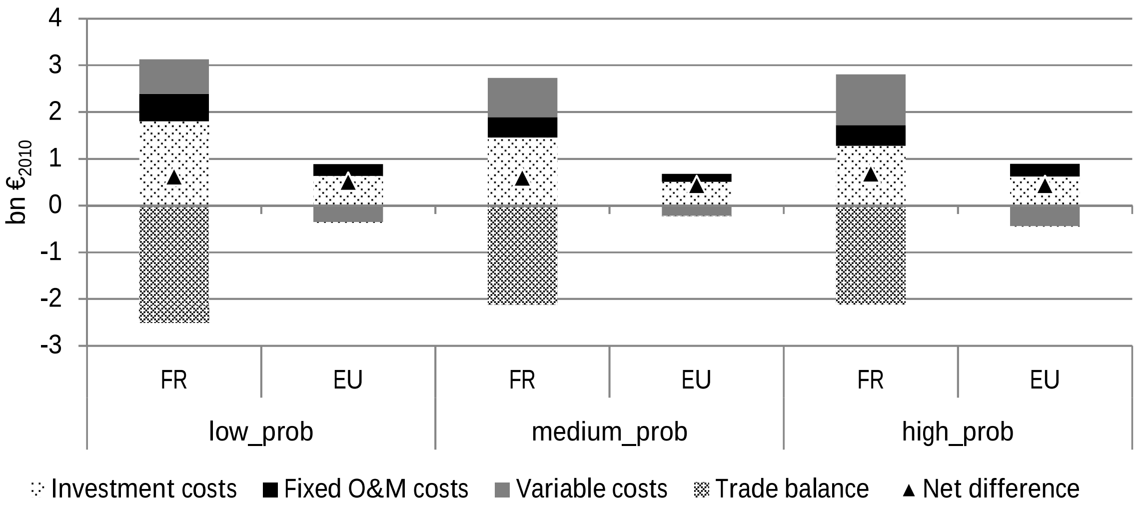


Figure 14: Accumulated (discounted) system cost differences differentiated by cost categories in bn $€_{2010}$ (2010-2050): Cost of uncertainty – 0y_prolongation – State 3

the European power system are rather limited.

Our finding that extended phase-out periods lead to lower costs is in line with the examples of Belgium and Switzerland as these countries have opted for extended phase-out periods. Furthermore, our analysis suggests that the costs of uncertainty are surprisingly low when compared to the costs of phasing out. Further, supported by information theoretic arguments, this finding presents a strong case, at least in this application, against a long-term commitment by policy makers to future nuclear policy.

Further research could address the full costs of nuclear power operation. Such an analysis should include an investigation of the risk-costs of nuclear power plant operation. A further promising research avenue may be the investigation of the possible additional burden of a phase-out for different consumer groups in France and Europe. Bearing in mind that most of the heating in France is electricity based, rising wholesale prices for electricity as a result of increasing system costs in France are of particular political and social relevance. We emphasize that our analysis could also be applied to other forms of political uncertainty such as government intervention in the market through support schemes for renewables, capacity markets or the introduction/extension of CO_2 cap-and-trade schemes.

References

Bartels, M., 2009. Cost Efficient Expansion of District Heat Networks in Germany. Oldenbourg Industrieverlag, Munich.
CAS, 2012. English version - Note de synthèse 263 - Énergies 2050. Tech. rep., CAS.
CDC, 2012. The costs of the nuclear power sector, Thematic public report. Tech. rep., CDC.
Fürsch, M., Lindenberger, D., Malischek, R., Nagl, S., Panke, T., Trüby, J., 2012a. German nuclear policy reconsidered: implications for the electricity market. Economics of Energy & Environmental Policy 1 (3), 39–58.

Fürsch, M., Nagl, S., Lindenberger, D., 2012b. Optimization of power plant investments under uncertain renewable energy deployment paths: a multistage stochastic programming approach. Energy Systems 5 (1), 85–121.

Gardner, D. T., 1996. Flexibility in electric power planning: Coping with demand uncertainty. Energy 21 (12), 1207–1218.

Gardner, D. T., Rogers, J., 1999. Planning electric power systems under demand uncertainty with different technology lead times. Management Science 45 (10), 1289–1306.

Gröwe-Kuska, N., Heitsch, H., Römisch, W., 2003. Scenario Reduction and Scenario Tree Construction for Power Management Problems. Paper accepted for presentation at 2003 IEEE Bologna Power Tech Conference.

Höffler, F., Wambach, A., 2013. Investment Coordination in Network Industries: The Case of Electricity Grid and Electricity. Journal of Regulatory Economics 44 (3), 287–307.

Hong, S., Bradshaw, C. J. A., Brook, B. W., 2013. Evaluating options for the future energy mix of Japan after the Fukushima nuclear crisis. Energy Policy 56, 418–424.

IEA, 2012. World Energy Outlook 2012. IEA Publications Paris.

IEA, 2013. World Energy Outlook 2013. IEA Publications Paris.

Kannan, R., Turton, H., 2012. Cost of ad-hoc nuclear policy uncertainties in the evolution of the Swiss electricity system. Energy Policy 50, 391–406.

Lundgren, K., Patel, T., 2012. Edf advances most in 2 $\frac{1}{2}$ months on nuclear extension report: Paris mover. URL `http://www.bloomberg.com/news/2012-02-13/edf-rises-most-in-2-1-2-months-on-nuclear-report-paris-mover.html`

Morales, J. M., Pineda, S., Conejo, A. J., Carrión, M., 2009. Scenario reduction for futures market trading in electricity markets. IEEE Transactions on Power Systems 24 (2).

Nagl, S., Fürsch, M., Lindenberger, D., 2012. The Costs of Electricity Systems with a High Share of Fluctuating Renewables: A Stochastic Investment and Dispatch Optimization Model for Europe. Energy Journal 34 (4), 151–179.

Park, N., Yun, S.-J., Jeon, E.-C., 2013. An analysis of long- term scenarios for the transition to renewable energy in the Korean electricity sector. Energy Policy 52, 288–296.

Patino-Echeverri, D., Fischebeck, P., Kriegler, E., 2009. Economic and environmental costs of regulatory uncertainty for coal-fired power plants. Environmental Science and Technology 43 (3), 578–584.

Prognos, 2010. Energieszenarien für ein Energiekonzept der Bundesregierung. Tech. rep., Prognos AG, EWI and GWS.

Roques, F., Nuttall, W. J., Newberry, D. M., de Neufville, R., Connors, S., 2006. Nuclear power: A hedge against uncertain gas and carbon prices? Energy Journal 27 (4), 1–24.

RTE, 2011. Generation adequacy report 2011. Tech. rep., RTE.

Shapiro, A., Dentcheva, D., Ruszczynski, A., 2009. Lectures on stochastic programming: Modeling and theory.

Sun, N., Ellersdorfer, I., Swider, D. J., 2008. Model-based long-term electricity generation system planning under uncertainty. Int. Conference on Electric Utility Deregulation and Re-structuring and Power Technologies (DRPT 2008).

Swider, D. J., Weber, C., 2006. The costs of wind's intermittency in Germany. European Transactions on Electrical Power 17 (151-172).

UFE, 2011. Electricity 2030: The choices for France. Tech. rep., UFE.

Appendix

Table 6: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y_prolongation

			Investment Costs	Fixed O&M Costs	Variable Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
State1	low_prob	France	0.2	-0.1	-1.3	1.1	-0.2
State1	low_prob	Europe excl. France	0.2	-0.1	1.2	-1.1	0.2
State1	low_prob	Europe incl. France	0.4	-0.2	-0.2	0.0	0.1
State1	medium_prob	France	0.2	-0.1	-1.4	1.2	-0.1
State1	medium_prob	Europe excl. France	0.2	-0.1	1.3	-1.2	0.2
State1	medium_prob	Europe incl. France	0.4	-0.2	-0.1	0.0	0.1
State1	high_prob	France	0.1	-0.1	-1.1	0.9	-0.1
State1	high_prob	Europe excl. France	0.2	-0.1	0.9	-0.9	0.2
State1	high_prob	Europe incl. France	0.3	-0.1	-0.1	0.0	0.0
State2	low_prob	France	-1.0	-0.4	0.7	1.2	0.5
State2	low_prob	Europe excl. France	0.1	-0.2	1.4	-1.3	0.0
State2	low_prob	Europe incl. France	-1.0	-0.6	2.1	0.0	0.5
State2	medium_prob	France	-0.7	-0.3	0.5	0.8	0.3
State2	medium_prob	Europe excl. France	0.0	-0.1	1.0	-0.8	0.0
State2	medium_prob	Europe incl. France	-0.7	-0.4	1.5	0.0	0.3
State2	high_prob	France	-0.4	-0.1	0.4	0.3	0.1
State2	high_prob	Europe excl. France	0.0	-0.1	0.4	-0.3	0.0
State2	high_prob	Europe incl. France	-0.4	-0.2	0.8	0.0	0.2
State3	low_prob	France	-1.0	-0.5	0.1	1.6	0.2
State3	low_prob	Europe excl. France	0.1	0.0	1.7	-1.6	0.2
State3	low_prob	Europe incl. France	-0.9	-0.5	1.8	0.0	0.4
State3	medium_prob	France	-0.6	-0.3	0.0	1.1	0.1
State3	medium_prob	Europe excl. France	-0.1	0.0	1.3	-1.1	0.2
State3	medium_prob	Europe incl. France	-0.7	-0.4	1.4	0.0	0.3
State3	high_prob	France	-0.4	-0.2	0.2	0.5	0.1
State3	high_prob	Europe excl. France	0.0	0.0	0.5	-0.4	0.0
State3	high_prob	Europe incl. France	-0.4	-0.2	0.8	0.0	0.2
State4	low_prob	France	0.0	0.0	0.0	0.0	0.0
State4	low_prob	Europe excl. France	0.1	0.0	-0.1	0.0	0.0
State4	low_prob	Europe incl. France	0.1	0.0	-0.1	0.0	0.0
State4	medium_prob	France	0.3	0.2	-0.1	-0.3	0.1
State4	medium_prob	Europe excl. France	0.0	0.0	-0.4	0.3	-0.1
State4	medium_prob	Europe incl. France	0.3	0.2	-0.5	0.0	0.0
State4	high_prob	France	0.5	0.4	0.1	-0.8	0.2
State4	high_prob	Europe excl. France	0.0	0.0	-1.1	0.8	-0.2
State4	high_prob	Europe incl. France	0.6	0.4	-1.0	0.0	0.0
State5	low_prob	France	0.0	0.0	0.0	0.0	0.0
State5	low_prob	Europe excl. France	0.1	0.0	-0.1	0.0	0.0
State5	low_prob	Europe incl. France	0.1	0.0	-0.1	0.0	0.0
State5	medium_prob	France	0.3	0.2	-0.1	-0.3	0.1
State5	medium_prob	Europe excl. France	-0.1	0.0	-0.4	0.3	-0.1
State5	medium_prob	Europe incl. France	0.2	0.2	-0.5	0.0	0.0
State5	high_prob	France	0.5	0.4	0.1	-0.8	0.2
State5	high_prob	Europe excl. France	0.0	0.0	-1.1	0.8	-0.2
State5	high_prob	Europe incl. France	0.6	0.4	-1.0	0.0	0.0

Table 7: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y_prolongation

			Investment Costs	Fixed O&M Costs	Variable Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
State1	low_prob	France	0.4	-0.2	0.2	-0.3	0.1
State1	low_prob	Europe excl. France	0.3	-0.2	0.0	0.2	0.3
State1	low_prob	Europe incl. France	0.6	-0.4	0.1	0.0	0.4
State1	medium_prob	France	0.2	-0.2	0.4	-0.3	0.1
State1	medium_prob	Europe excl. France	0.2	-0.2	-0.1	0.2	0.2
State1	medium_prob	Europe incl. France	0.4	-0.4	0.3	0.0	0.3
State1	high_prob	France	0.0	0.0	0.6	-0.7	-0.1
State1	high_prob	Europe excl. France	0.1	-0.2	-0.4	0.7	0.1
State1	high_prob	Europe incl. France	0.1	-0.2	0.2	0.0	0.1
State2	low_prob	France	1.8	0.4	-1.0	-1.0	0.2
State2	low_prob	Europe excl. France	-0.2	-0.1	-0.5	0.9	0.1
State2	low_prob	Europe incl. France	1.6	0.3	-1.5	0.0	0.3
State2	medium_prob	France	1.5	0.3	-0.8	-0.9	0.2
State2	medium_prob	Europe excl. France	-0.2	-0.1	-0.5	0.8	0.0
State2	medium_prob	Europe incl. France	1.2	0.3	-1.3	0.0	0.2
State2	high_prob	France	1.4	0.4	-0.5	-1.1	0.3
State2	high_prob	Europe excl. France	-0.2	-0.1	-0.8	1.1	0.0
State2	high_prob	Europe incl. France	1.2	0.3	-1.3	0.0	0.2
State3	low_prob	France	1.8	0.6	0.7	-2.5	0.6
State3	low_prob	Europe excl. France	-1.2	-0.3	-1.1	2.5	-0.1
State3	low_prob	Europe incl. France	0.6	0.3	-0.3	0.0	0.5
State3	medium_prob	France	1.5	0.4	0.8	-2.1	0.6
State3	medium_prob	Europe excl. France	-0.9	-0.3	-1.1	2.1	-0.2
State3	medium_prob	Europe incl. France	0.5	0.2	-0.2	0.0	0.4
State3	high_prob	France	1.3	0.4	1.1	-2.1	0.7
State3	high_prob	Europe excl. France	-0.7	-0.2	-1.5	2.1	-0.2
State3	high_prob	Europe incl. France	0.6	0.3	-0.4	0.0	0.4
State4	low_prob	France	0.6	0.2	0.5	-1.0	0.3
State4	low_prob	Europe excl. France	-0.4	-0.1	-0.5	1.0	-0.1
State4	low_prob	Europe incl. France	0.2	0.1	0.0	0.0	0.3
State4	medium_prob	France	0.4	0.0	0.8	-0.8	0.4
State4	medium_prob	Europe excl. France	-0.3	-0.1	-0.6	0.8	-0.1
State4	medium_prob	Europe incl. France	0.1	0.0	0.1	0.0	0.3
State4	high_prob	France	0.4	0.1	1.2	-1.1	0.6
State4	high_prob	Europe excl. France	0.0	0.0	-1.4	1.1	-0.3
State4	high_prob	Europe incl. France	0.3	0.1	-0.2	0.0	0.3
State5	low_prob	France	-0.3	-0.2	0.4	0.1	0.1
State5	low_prob	Europe excl. France	0.1	0.0	0.0	-0.1	0.0
State5	low_prob	Europe incl. France	-0.2	-0.1	0.4	0.0	0.1
State5	medium_prob	France	-0.5	-0.3	0.7	0.4	0.3
State5	medium_prob	Europe excl. France	0.3	0.1	-0.2	-0.4	-0.1
State5	medium_prob	Europe incl. France	-0.2	-0.2	0.5	0.0	0.2
State5	high_prob	France	-0.5	-0.3	1.1	0.2	0.5
State5	high_prob	Europe excl. France	0.6	0.2	-1.0	-0.1	-0.2
State5	high_prob	Europe incl. France	0.1	0.0	0.1	0.1	0.2

Table 8: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y_w/o_prolongation

			Investment Costs	Fixed O&M Costs	Variable Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
State1	low_prob	France	0.1	0.0	0.2	-0.2	0.0
State1	low_prob	Europe excl. France	0.1	-0.1	-0.3	0.2	0.0
State1	low_prob	Europe incl. France	0.2	-0.1	-0.1	0.0	0.0
State1	medium_prob	France	0.0	0.0	0.1	-0.1	0.0
State1	medium_prob	Europe excl. France	0.1	0.0	-0.1	0.1	0.0
State1	medium_prob	Europe incl. France	0.1	0.0	0.0	0.0	0.0
State1	high_prob	France	0.0	0.0	0.0	0.0	0.0
State1	high_prob	Europe excl. France	0.0	0.0	0.0	0.0	0.0
State1	high_prob	Europe incl. France	0.0	0.0	0.0	0.0	0.0
State2	low_prob	France	0.1	0.0	0.2	-0.3	0.0
State2	low_prob	Europe excl. France	0.0	-0.1	-0.2	0.3	0.1
State2	low_prob	Europe incl. France	0.1	-0.1	0.0	0.0	0.0
State2	medium_prob	France	0.0	0.0	0.1	-0.1	0.0
State2	medium_prob	Europe excl. France	0.0	0.0	0.0	0.1	0.0
State2	medium_prob	Europe incl. France	0.0	0.0	0.0	0.0	0.0
State2	high_prob	France	0.0	0.0	0.0	-0.1	0.0
State2	high_prob	Europe excl. France	0.0	0.0	0.0	0.1	0.0
State2	high_prob	Europe incl. France	0.0	0.0	0.1	0.0	0.0
State3	low_prob	France	2.6	0.3	-0.8	-2.5	-0.4
State3	low_prob	Europe excl. France	-0.2	0.1	-2.2	2.5	0.2
State3	low_prob	Europe incl. France	2.4	0.3	-2.9	0.0	-0.2
State3	medium_prob	France	2.2	0.3	-0.6	-2.2	-0.4
State3	medium_prob	Europe excl. France	-0.1	0.1	-2.0	2.2	0.2
State3	medium_prob	Europe incl. France	2.1	0.3	-2.6	0.0	-0.2
State3	high_prob	France	1.6	0.2	-0.5	-1.6	-0.3
State3	high_prob	Europe excl. France	0.0	0.1	-1.5	1.6	0.2
State3	high_prob	Europe incl. France	1.6	0.3	-2.0	0.0	-0.2
State4	low_prob	France	1.4	0.2	0.0	-1.6	0.0
State4	low_prob	Europe excl. France	-0.8	-0.2	-0.7	1.6	-0.1
State4	low_prob	Europe incl. France	0.5	0.0	-0.6	0.0	-0.1
State4	medium_prob	France	0.9	0.2	-0.1	-0.9	0.1
State4	medium_prob	Europe excl. France	-0.6	-0.1	-0.3	0.9	-0.1
State4	medium_prob	Europe incl. France	0.3	0.0	-0.4	0.0	-0.1
State4	high_prob	France	0.1	0.0	-0.2	0.2	0.1
State4	high_prob	Europe excl. France	-0.3	-0.1	0.4	-0.1	-0.1
State4	high_prob	Europe incl. France	-0.1	0.0	0.2	0.0	0.0
State5	low_prob	France	-0.1	0.0	-0.1	0.3	0.0
State5	low_prob	Europe excl. France	0.1	0.0	0.2	-0.3	0.0
State5	low_prob	Europe incl. France	-0.1	0.0	0.1	0.0	0.0
State5	medium_prob	France	-0.5	-0.1	-0.2	0.8	0.1
State5	medium_prob	Europe excl. France	0.2	0.1	0.5	-0.8	0.0
State5	medium_prob	Europe incl. France	-0.3	0.0	0.3	0.0	0.0
State5	high_prob	France	-1.2	-0.2	-0.3	1.8	0.1
State5	high_prob	Europe excl. France	0.6	0.2	1.0	-1.8	0.0
State5	high_prob	Europe incl. France	-0.6	0.0	0.6	0.0	0.1

Table 9: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y_w/o_prolongation

			Investment Costs	Fixed O&M Costs	Variable Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
State1	low_prob	France	0.0	0.0	0.6	-0.7	-0.1
State1	low_prob	Europe excl. France	0.1	-0.2	-0.4	0.6	0.1
State1	low_prob	Europe incl. France	0.1	-0.2	0.2	0.0	0.1
State1	medium_prob	France	0.0	0.0	0.5	-0.5	0.0
State1	medium_prob	Europe excl. France	0.0	-0.2	-0.3	0.5	0.1
State1	medium_prob	Europe incl. France	0.0	-0.2	0.2	0.0	0.1
State1	high_prob	France	0.0	0.0	0.3	-0.4	0.0
State1	high_prob	Europe excl. France	0.0	-0.2	-0.1	0.4	0.1
State1	high_prob	Europe incl. France	0.0	-0.1	0.2	0.0	0.0
State2	low_prob	France	0.0	0.0	0.0	-0.1	0.0
State2	low_prob	Europe excl. France	0.0	0.0	0.0	0.1	0.0
State2	low_prob	Europe incl. France	0.0	0.0	0.0	0.0	0.0
State2	medium_prob	France	0.0	0.0	0.0	0.0	0.0
State2	medium_prob	Europe excl. France	0.0	0.0	-0.1	0.0	0.0
State2	medium_prob	Europe incl. France	0.0	0.0	-0.1	0.0	0.0
State2	high_prob	France	0.0	0.0	-0.1	0.1	0.0
State2	high_prob	Europe excl. France	0.0	0.0	0.0	-0.1	0.0
State2	high_prob	Europe incl. France	0.0	0.0	0.0	0.0	0.0
State3	low_prob	France	9.0	1.0	-0.9	-5.4	3.7
State3	low_prob	Europe excl. France	-0.1	0.3	-5.3	5.5	0.3
State3	low_prob	Europe incl. France	8.9	1.3	-6.2	0.0	4.0
State3	medium_prob	France	5.8	0.8	-1.0	-3.3	2.2
State3	medium_prob	Europe excl. France	-0.2	0.2	-3.3	3.3	0.0
State3	medium_prob	Europe incl. France	5.6	0.9	-4.4	0.0	2.2
State3	high_prob	France	0.0	0.0	0.0	0.1	0.0
State3	high_prob	Europe excl. France	0.0	0.0	0.0	-0.1	0.0
State3	high_prob	Europe incl. France	0.0	0.0	-0.1	0.0	0.0
State4	low_prob	France	15.5	1.2	-4.1	-7.6	5.0
State4	low_prob	Europe excl. France	-1.0	0.1	-6.5	7.7	0.3
State4	low_prob	Europe incl. France	14.5	1.3	-10.6	0.0	5.2
State4	medium_prob	France	11.8	0.7	-4.6	-3.7	4.3
State4	medium_prob	Europe excl. France	-0.4	0.1	-3.4	3.7	0.1
State4	medium_prob	Europe incl. France	11.4	0.9	-8.0	0.0	4.4
State4	high_prob	France	-0.8	-0.3	-0.7	1.9	0.1
State4	high_prob	Europe excl. France	0.4	0.2	1.3	-1.9	0.0
State4	high_prob	Europe incl. France	-0.3	-0.1	0.6	0.0	0.1
State5	low_prob	France	-1.4	-0.2	-0.4	2.2	0.2
State5	low_prob	Europe excl. France	0.6	0.2	1.4	-2.1	0.0
State5	low_prob	Europe incl. France	-0.8	0.0	1.0	0.0	0.2
State5	medium_prob	France	-3.6	-0.7	-0.7	6.1	1.1
State5	medium_prob	Europe excl. France	1.2	0.3	4.5	-6.1	-0.2
State5	medium_prob	Europe incl. France	-2.5	-0.4	3.7	0.0	0.9
State5	high_prob	France	-9.3	-1.3	6.8	10.1	6.4
State5	high_prob	Europe excl. France	1.5	0.2	7.9	-10.1	-0.5
State5	high_prob	Europe incl. France	-7.7	-1.1	14.7	0.0	5.8