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A probabilistic approach to the computation of the levelized cost of electricity

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ABSTRACT

This paper sets forth a novel approach to calculate the levelized cost of electricity (LCOE) using a probabilistic model that accounts for endogenous input parameters. The approach is applied to the example of a nuclear and gas power project. Monte Carlo simulation results show that a correlation between input parameters has a significant effect on the model outcome. By controlling for endogeneity, a statistically significant difference in the mean LCOE estimate and a change in the order of input leverages is observed. Moreover, the paper discusses the role of discounting options and external costs in detail. In contrast to the gas power project, the economic viability of the nuclear project is considerably weaker.

1. Introduction

In the wake of the Fukushima incident in 2011, the future of nuclear energy in the western world has become more than ever unclear. Whilst countries such as Germany proposed to phase out their plants, others are considering building new ones. Notably, the UK and Finland are in the process of finalizing plans for the construction of nuclear power plants in Hinkley Point and Pyhäjoki. In Switzerland, the Federal Council and the two chambers of the parliament decided in 2011 against a replacement of the five Swiss nuclear power plants at end of their lifetimes [1]. As a result, Switzerland's electricity generation—with a current nuclear share of roughly 40 percent—would be nuclear free by 2034. The Federal Council's long term energy strategy therefore expects a future yearly shortage in electricity generation of 48 TWh, planned to be filled half by means of renewable energies and imports and half by increasing energy efficiency [2].

Aside security issues and the level of political support, the question of the economic viability of nuclear energy in today's increasingly liberalized energy markets has not yet reached a consensus in the energy community. In the past, nuclear projects in western countries tended to exceed their projected costs significantly. Falk [3] for instance notes that between 1966 and 1986 the construction costs of new nuclear plants in the US surpassed their projected costs by 200%. The 40 projects finalized after the incident in Three Mile Island in 1979 exceeded projected costs even by 250%, partly due to increased regulatory safety requirements [3]. A similar picture is given by the two nuclear plants currently under construction in Europe: the EPR (European pressurized water reactor) plants in Olkiluoto (Finland) and Flamanville (France). Both construction projects have been surpassing their projected costs since start of construction in 2005 and 2007 by a multiple. While their commissioning was planned for 2009 respectively 2012, their first day of operation still remains unclear today (in 2016) [4]. These cases exemplify the inherent uncertainty in projected costs of nuclear plants in the western world.

This paper demonstrates a model to calculate the levelized cost of energy (LCOE) of a power generating technology applying Monte Carlo simulation (MCS). The estimation of a power project's economic viability by calculating the LCOE is a fundamental initial instrument for investment decisions by companies and for policy makers. However, the methodology bears a range of drawbacks. A prominent difficulty to which the energy literature has repeatedly pointed at is that the LCOE is highly sensitive to investment costs, which, especially in the case of nuclear power, often form one of the

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Table 1
Overview of selected literature.

Source	Technology	MCS	Discounting options	External costs
Branker, Pathak et al. [43]	Solar	–	yes	–
Short, Packey et al. [44]	Renewables	–	yes	–
Du and Parsons [18]	Nuclear/Coal/Gas	–	–	–
Darling, You, et al. [12]	Solar	yes	–	–
Anderson [11]	General	yes	–	–
Hogue [8]	Nuclear/Coal/Gas	–	–	yes
Feretic and Tomsic [13]	Nuclear/Coal/Gas	yes	–	–
Roques, Nuttall, et al. [6]	Nuclear/Coal/Gas	yes	–	–
Ahmad and Ramana [9]	Nuclear/Gas/Solar	–	–	yes
Heck, Smith et al. [10]	Nuclear/Coal/Gas/Renewables	yes	–	yes

Note: This table summarizes literature on the estimation of LCOE, the power generating technologies considered therein, whether a MCS method was used and whether discounting options or the role of external costs were discussed.

biggest component to overall costs. Separate—though very relevant issues when weighing against alternative technology options—are so-called endogeneity issues: for instance, the failure to take into account the correlation between fuel prices and electricity prices or the volume of new investments in the market.[1]

In the following, sensitivity issues of LCOE computations will be addressed by accounting for uncertainty in input variables and potential endogeneities among these uncertainties by simulating a range of alternative project courses through the MCS method. Also, the roles of discounting options and external costs are addressed. These issues have been neglected in previous studies. The MCS-LCOE model is demonstrated for the case of a nuclear and gas power project in Switzerland. Pro-nuclear liberal and right wing parties won the Swiss national elections in October 2015. Before, the political consensus was to not replace the nuclear fleet. However, the legislative might overthrow this decision in the future depending, for example, on the required level of autarky in electricity generation, the need for predictable base load energy and goals in terms of emission abatements. In case the nuclear fleet will not be replaced, gas power plants could help to compensate some of the nuclear electricity generation.

This paper is organized as follows: section 2 summarizes the relevant literature, with a special focus on the accounting for risks in project appraisal. Section 3 describes the model and the parameters' distributional assumptions. The results are analyzed in section 4. Section 5 concludes.

2. Literature

Most of the literature estimating the LCOE of power plant technologies provide single point estimates and sensitivity analyses based on switching values. Especially in the case of nuclear power, the literature disagrees greatly on the future costs, however, with a trend towards higher cost estimates, given the recent experiences made with new nuclear projects in western countries. The number of peer as well as non-peer reviewed studies using MCS methods or accounting for different discounting options or external costs is relatively small (see Table 1).

To emphasize is the tendency of the literature to overlook the role of endogeneities. Roques, Nuttall et al. [6] mention the possibility to control for such correlations, but no study yet effectively accounts for correlations when applying MCS techniques to estimate LCOE. Furthermore, a discussion of the role of external costs or different discounting methods is sparse. As shown by Radetzki [7], the role of external costs is crucial when evaluating the effective costs of a technology. However, only Hogue [8], Ahmad and Ramana [9] and Heck, Smith et al. [10] were found to some extent internalize external costs by including a CO_2 tax in their models. Anderson [11] treats the issue of positive and negative externalities by discussing how they are related to the concept of endogenous technical change and how investment experience affects the costs of carbon abatement technologies.

If MCS is applied, model descriptions frequently fall short of a clear specification of the assumptions underlying the variables' probabilistic distributions and of the experiences these assumptions are based upon. There also seems to be no consent on how many replications to perform. While, e.g., Darling, You et al. [12] use 1 million replications varying 4 variables, Feretic and Tomsic [13] conduct 2000 replications varying 3 variables. Hence, a rule of thumb will be given to derive the minimal number of replications necessary to obtain statistically meaningful results.

2.1. Accounting for risks in power plant projects

A profound estimation of LCOE is complex and based on several assumptions with partly little practical experiences available, e.g., when specifying the costs of final nuclear waste storage. Even if the decision-maker only is interested in a classical single-point LCOE estimate and not in the assessment of risk per se, a fundamental question arises: how should the values of the input factors be chosen when data are lacking, or when making assumptions about future conditions is difficult? In general, the practice of using the mode for each variable does not result in the most likely project performance level, or even the expected value of the performance measure. Additionally, the practice of using conservative values might lead to overly conservative final performance measures, which can be arbitrarily distant from the expected values and thereby leading to biased decisions.

The robustness of a LCOE analysis can be partly assessed by performing sensitivity analysis and calculating the switching values of input factors. These methods are frequently used as the sole tools to address project risk. In the deterministic setting of a sensitivity analysis, the values of variables are varied singularly (or groupwise) and the extent of their influence is quantified, leading to the identification of a group of key variables that have the highest impact on a project's net benefits. Calculating the switching value of a variable implies finding the value at which a project's net present value (NPV) becomes zero [14].

Fundamental drawbacks of the sensitivity analysis and switching values approaches are their failure to take into account the probabilities of the occurrence of relevant critical values as well as endogeneities among variables. Quantitative risk analysis using MCS overcomes these limitations and offers a framework in which

[1] See Linares and Conchado [5] for a general discussion of the economics of new power plants in liberalized electricity markets.

Table 2
Parameters and distributional assumptions.

Parameter	Abbreviation	Unit	Nuclear	Gas (Advanced CC)
Electrical capacity (net)	(*ECap*)	[MW]	1600	400
Capacity factor	(*CapF*)	[%]	PERT(80; 90; 95)	PERT(75; 85; 90)
Hours per year	(*h*)	[h]	8760	8760
Heat rate	(*HeatR*)	Btu/kWh	10,400	6700
Initial investment (overnight)	(*I*)	[$/kW]	Tr(5500; 6500; 7500)	Tr(1000; 1100; 1300)
Fixed O&M	(*fOM*)	[$/kW/a]	Tr(120; 140; 155)	Tr(25; 40; 50)
Variable O&M	(*vOM*)	[$/MWh/a]	Tr(0.95; 1.1; 1.4)	Tr(3; 4.5; 5.5)
O&M real escalation	(*OMreal*)	[%/a]	0.75	0.75
Intermediate waste disposal	(*IWC*)	[$/kW/a]	Tr(45; 55; 80)	–
Fuel costs	(*FC*)	[$/MMBtu]	Tr(0.35; 0.43; 0.5)	N(μ = 6.25; 0.09μ)
Fuel costs real escalation	(*FCreal*)	[%/a]	0.5	1.5
Capital increment (1st half)	(CI_1)	[$/kW/a]	1% of overnight costs	1% of overnight costs
Capital increment (2nd half)	(CI_2)	[$/kW/a]	2% of overnight costs	2% of overnight costs
Post-closure phase costs	(*PC*)	[$/kW]	Tr(515; 575; 725)	–
Decommissioning costs	(*DC*)	[$/kW]	Tr(950; 1100; 1450)	Tr(150; 165; 195)
Final waste disposal costs	(*FWC*)	[$/kW]	Tr(2600; 3200; 4200)	–
Equity ratio	(*ERatio*)	[%]	PERT(40; 50; 50)	40
Equity rate (nominal)	(*ERate*)	[%/a]	Tr(8; 10; 12)	Tr(7.5; 8.5; 9.5)
Debt rate (nominal)	(*DRate*)	[%/a]	6.5	6
WACC	(*WACC*)	[%/a]	8.25[a]	7[a]
Discount rate	(*DRate*)	[%/a]	=WACC	=WACC
Inflation rate	(*IRate*)	[%/a]	2	2
Real interest on provisions	(*IP*)	[%/a]	2	2
Corporate tax rate	(*Tax*)	[%/a]	21	21
Depreciation time	(T_a)	[a]	16	16
Construction time	(T_c)	[a]	Discreteyears = [6–10] prob = [0.1; 0.4; 0.2; 0.15; 0.15]	Discreteyears = [3–5] prob = [0.5; 0.25; 0.25]
Plant lifetime	(T_o)	[a]	60	30

Note: Tr(A; B; C) ≡ Triangle distribution; PERT(A; B; C) ≡ Beta-PERT distribution, whereby A ≡ lowest possible value, B ≡ highest probability value and C ≡ highest possible value; Tp(A; B; C; D) ≡ Trapezoidal distribution, whereby B and C span the range of the highest probability; N(μ,σ^2) ≡ Normal distribution; prob ≡ probability. All values are given in real USD 2014 terms. The choices of parameter values and distributions are described in greater detail in the appendix.

[a] Given the highest probability values of the two triangular debt and equity rate distributions. The WACC varies according to: WACC = Equity rate • Equity ratio + Debt rate • (1 − Equity ratio).

different potential project courses can be analyzed and their potential benefits quantified. Not only does it—in form of the average of the simulated realizations—provide an improved single-point estimate, it offers additionally a detailed measure of the related project risks. For instance, the estimated standard deviation of the LCOE can be used as such indicator, or a variable's probability to be higher than a certain threshold.

The interest in performing risk analysis for investment appraisal has been evolving since the 1960s. At that time, software and computer capacities were such that many risk-analysis tasks could not be performed in a time-efficient manner. The analysis presented in classical works such as Pouliquen [15] and Reutlinger [16] is still relevant and actual, as are many of the main challenges involved in performing risk analysis, such as the choice of probability distributions and correlation among variables. Choosing probability distributions for uncertain input factors amounts to giving a quantitative representation of the information that is available for these factors. This information can stem from surveys, historical data, experienced subjective judgments, or a combination of them. Pouliquen [15] gives empirical backing to the fact that the exact choice of distribution is not critical if the variance is reasonably well estimated. He also offers some guidance for appropriately choosing a probability distribution in specific situations. Clarke and Low [17] argue that even if there is no information to support the specification of a variable's probability distribution, the use of a uniform distribution is still to be preferred over a deterministic framework. Variables for which a distribution has been defined can be correlated to account for their interdependencies. However, the specification of endogeneities is a greater challenge and needs to be carefully addressed.

3. Model

3.1. LCOE formula

Generally, there are two foundations to build a LCOE analysis upon: a societal point of view which includes external costs but excludes any accounting issues like taxation and depreciation. The second is a more business oriented one, where accounting issues play a crucial role, but which tends to overlook the implications of non-internalized external costs. In what follows, the focus lies on a business oriented LCOE model, but not without discussing the role of external costs, i.e. the case is examined where a regulator forces a firm to internalize its external costs.

The methodology applied to the LCOE calculation is based on Du and Parsons [18]. The authors define LCOE as the constant real wholesale price such that debt lenders and electric utilities are compensated their required rate of return,[2] i.e. the LCOE is based on corporate finance's central concept of zero economic profit. Hence, the LCOE represents the price of electricity required, whereby the price is subject to inflation, such that the project yields a net present value of zero. The key benefit of this procedure, where the weighted average costs of capital (WACC) is applied to the unlevered after-tax cash flow, is that even though the debt-to-equity ratio changes over time, the implied risk premium remains constant (see Du and Parsons [18], p. 20).

[2] The required rate of return is assumed a priori. However, as shown by Ederer [19] for the case of offshore wind farms in the UK, the dynamics of the electricity sector might lead to different a posteriori realizations. The MCS accounts for such uncertainties via underlying distributional assumptions.

The LCOE estimates of a nuclear and gas power project in Switzerland are given in 2014 prices and on busbar level, i.e. infrastructure costs are excluded. An unregulated market environment is assumed, i.e. utilities sell their electricity into a competitive power market with no possibility of rolling over costs to consumers. This lack of risk sharing between consumers and utilities increases the perceived financial risk of a project compared to a regional monopoly situation. A comprehensive elicitation of LCOE in a competitive market necessitates the consideration of the role of taxation. This implies the specification of tax-deductible depreciation allowances and inflation rates. However, while, for example, a gas plant could resell contracted fuel on the spot market if it would yield a higher return than transforming the fuel into electricity, no other possibilities to generate revenues than by selling electricity are considered. The following formulae summarize the LCOE model. Variable descriptions are given in Table 2.

Multiplicative factors

$$DF_t = 1/(1+WACC)^{t-t_1}$$
$$IF_t = 1/(1+IRate)^{t-t_0}$$
$$OMF_t = [(1+IRate)\cdot(1+OMreal)]^{t-t_0}$$
$$FCF_t = [(1+IRate)\cdot(1+FCreal)]^{t-t_0}$$
$$CTF_t = [(1+IRate)\cdot(1+CarbonTreal)]^{t-t_0}$$

Note: Time is given by t and the reference year 2014 is represented by t_0. Discounting starts at the year of completion t_1. *WACC* is the weighted average costs of capital, *IRate* is the inflation rate, *OMreal* is the real inflation of operating and maintenance costs, *FCreal* is the real escalation rate of fuel costs and *CarbonTreal* is the carbon tax real escalation rate.

Costs during the construction period T_c ($t \le T_c$)

$$Cost_t = ECap\cdot I\cdot 1000\cdot IF_t\cdot DF_t/T_c$$

Note: Testing, final licensing and certification work is assumed to be completed within construction time. A uniform construction schedule, i.e. a uniform distribution of investment costs over the construction period is assumed for both technologies. *ECap* is the electrical capacity, *I* is the initial investment (overnight), *IF* is the inflation factor, *DF* is the discount factor and T_c is the construction time.

Costs during the operational phase T_o ($T_c < t \le T_c + T_o$)

$$Cost_t = ECap\cdot(1-Tax)\cdot DF_t\cdot[A+B]+C-D$$

where

$$A = 1000\cdot\left(I\cdot CI_{i=\{1,2\}}\cdot IF_t + fOM\cdot OMF_t + IWC\cdot IF_t\right)$$

$$B = CapF\cdot 8760\cdot\left(vOM\cdot OMF_t + \frac{HeatR}{1000}\cdot FC\cdot FCF_t + \frac{CarbonI}{1000}\cdot CarbonT\cdot CTF_t\right)$$

$$D = ExtC\cdot IF_t\cdot(1-Tax)\cdot DF_t + \left(PCP_t^y + DCP_t^y + FWCP_t^y\right)\cdot(1-Tax)\cdot DF_t$$

$$E = \underbrace{\frac{\sum_{T_c} I\cdot ECap\cdot 1000\cdot IF_t/T_c}{T_a}\cdot Tax\cdot DF_t}_{\text{Depreciation tax shield}}$$

Note: ECap is the electrical capacity, *Tax* is the corporate tax rate, *DF* is the discount factor, *CI* is the capital increment in the first half ($i=1$) and second half ($i=2$) of the plant's operational phase, *IF* is the inflation factor, *fOM* are fixed operation and maintenance (O&M) costs, *OMF* is the O&M real escalation factor, *HeatR* is the heat rate, *IWC* are intermediate waste disposal costs, *vOM* are variable O&M costs, *FC* are fuel costs, *FCF* is the fuel costs real escalation factor, *CarbonI* is the carbon intensity, *CarbonT* is the carbon tax, *CTF* is the carbon tax real escalation factor, *ExtC* are other non-internalized external costs, *PCP* are post-closure costs provisions, *DCP* are decommissioning costs provisions, *FWCP* are final waste storage costs provisions, T_c is the construction time and T_a is the depreciation time.

A deferred costs accounting is implemented, i.e. fees for post-closure, decommissioning and final waste disposal costs are collected during the operational phase. It is assumed that a real, tax free interest rate can be earned on these accumulated fees. The compounded provisions match expected future costs at the end of the operational phase. Provisions for post-closure costs, decommissioning costs and final waste storage costs (*PCP*, *DCP* and *FWCP*) are constant over time and compounded yearly (emphasized by the exponent y). Interests earned on provisions imply that some of the costs are covered by working capital.

Generated revenues during operational phase T_o ($T_c < t \le T_c + T_o$)

$$Revenue_t = ElPrice\cdot ECap\cdot CapF\cdot 8760\cdot 1000\cdot IF_t\cdot(1-Tax)\cdot DF_t$$

Note: ElPrice is the electricity price, *ECap* is the electrical capacity, *CapF* is the capacity factor, *IF* is the inflation factor, *Tax* is the corporate tax rate and *DF* is the discount factor.

Finally, the LCOE is represented by the electricity price (*ElPrice*) that yields a net present value of the project equal to zero.

$$LCOE = ElPrice \quad \text{s.t.} \quad \sum_{T_{total}} Cost_t = \sum_{T_{total}} Revenue_t$$
$$T_{total} = T_c + T_o + T_p + T_d + 1$$

Note: ElPrice is the electricity price, T_c is the construction time, T_o is the operating time, T_p is the post-closure time and T_d is the decommissioning time.

By this procedure, the cost and revenue cash flows are discounted at the same rate, implying that both cash flows face the same risks.

3.2. Parameters and distributional assumptions

Distributional assumptions represent the inherent uncertainty in some variable specifications. They are based on subjective judgement and therefore represent subjective probabilities, accommodating for the modest insight that there is a bounded set of information to build upon. Galway [20] describes supporting procedures for eliciting subjective probability distributions and notes that human beings tend to be overconfident in terms of their ability to quantify uncertainty. Pouliquen [15] points out that the specification of a distribution function should make best use of the available information, while not requiring more than what is available. For example, the specification of a normal distribution necessitates the availability of a larger data sample and hence more detailed information than a triangular, trapezoid or discrete distribution. The Beta-PERT distribution could be applied instead of the triangular one for the mean of the distribution to be less affected by boundary values, bringing it closer the distribution's mode.

Construction is planned such that either technology could start producing electricity around 2030, approximately the time when half of the Swiss nuclear capacity will have been taken off grid. The nuclear technology is assumed to be of type generation III + EPR, i.e. of the same type currently under construction in Olkiluoto (Finland) and Flamanville (France), and under discussion to be built in Britain at Hinkley Point.

The parameter specifications used for the LCOE simulations are listed in Table 2 and explained in greater detail in the appendix. The assumptions listed in Table 2 yield a best estimate (the model's static results without running MCS) of total overnight costs of USD 10.4 billion for the nuclear project. This value is in line with cost estimates for the EPR project at Hinkley Point, with Schneider, Froggatt et al. [21] estimating the construction costs of the two projected plants to amount to 7 billion British pounds each.[3] According to the same report, a current cost forecast for the EPR projects at Olkiluoto and Flamanville is 8.5 billion Euros and, due to the ongoing delays, this is not the final price tag.[4] Different to the nuclear case, the combined cycle gas power plant is a proven technology and Swiss specific adjustment costs are assumed to be minor, even though there has not been built a single gas power plant in Switzerland for 50 years. The best estimate of the overnight costs of a 400 MW gas power plant in Switzerland is USD 440 million.[5]

The large investments necessary to build a nuclear power plant increase the perceived risk of such a project to creditors. Also, the sunk cost character of a small salvage value of an unfinished project is risk increasing. As a result, the nuclear and gas projects are non-neutral in terms of financing risks. While some of the economic risk of a nuclear plant is structural, variable risk factors affecting the risk premium (e.g., the status of nuclear power in the western world) are still unclear. It therefore is assumed that in the nuclear case, next to the equity rate, the equity ratio is subject to a probability distribution as well. This line of argument, along with the necessity to account for endogeneities, points to a yet unsolved deficiency of MCS techniques mentioned by Seitz and Ellison [25]: explicitly representing risks associated with certain parameters by probability distributions creates the possibility that such risks will be double counted, particularly in cases where the WACC (which presumably already incorporates these risks) is used as the discount rate.

3.3. Discounting

A discounting scheme reflects the uncertainty of a population in terms of the shape of their future living. There is empirical evidence of hyperbolic discounting, where time preference rates decrease over time (see, e.g., Frederick, Loewenstein et al. [26]). Especially for long term projects, the exponential effect of discounting future costs and benefits plays a crucial role in the evaluation of overall project performance, as cash flows in a distant future quickly become marginal with respect to a project's present value cash flow. The elicitation of a discount rate for long-term investment analysis has been subject of much controversy in the literature. One fundamental aspect is, whether a purely opportunistic cost based approach is taken, or one with a larger societal perspective (which possibly accounts for intergenerational equity). Companies as well as public agencies usually adopt the former approach for their long-term investment choices. They mostly set the discount factor to be equal to the WACC, which requires a specification of the cost of debt, the cost of equity and the debt-equity ratio. The societal perspective has been subject to many academic discussions, where voices have been arguing for a pattern of declining discount rates over time in order to avoid a trivialization of welfare impacts on future generations. This procedure is discussed in Evans [27], OXERA [28] and Pearce, Groom et al. [29] but has hardly ever been implemented in practice, though. An exception are the two latter of the aforementioned studies. However, OXERA [28] finds that their only marginally declining schedule changes the overall LCOE only little.

The literature misses a clear theoretical guideline that shows which decreasing patterns to apply to the cash flow of a nuclear plant. Hence, instead of using decreasing discount rates over time to account for intergenerational equity, the study at hand implements a deferred cost accounting: in Switzerland, nuclear plants are mandated by law to augment funds in their operational phase to cover post-closure, decommissioning and final waste disposal costs. The simulation follows this principle and models the accruing of these funds during the operational phase (instead of accounting for these costs in lump sum form at the operational phase's end). Such procedure has an important implication in terms of discounting and intergenerational equity: even though these costs will become effective in the distant future, the incremental costs are paid by those who instantly make use of the power provided by the nuclear plant. Furthermore, the severe discounting effect when accounting for costs at the end of a plant's lifetime is mitigated.

3.4. Simulation procedure

The LCOE formula given in the previous section is now embedded it into a Monte Carlo setting, where the cumulative distribution function of a stochastic variable $F(x) = P(X \le x)$ assumes only values between 0 and 1. The inverse function G gives for each probability level $y = F(x)$ a value x such that the probability of variable X being below or equal x is exactly y: $G(y) = G[F(x)] = x$. The function G is used for generating random samples for X. First, a random number r between 0 and 1 is generated from a uniform distribution. The function G then is applied to the number r to produce a random sample according to the probability distribution of X: $G(r) = x$. As r is equally likely to be any number in the range from 0 to 1, the generated value x of the stochastic variable X is equally likely to be generated in any percentile range. Proceeding in

[3] Other sources, however, indicate that these costs could rise up to 10.5 billion British pounds [22].

[4] The high delays and cost overruns of these first ever built EPRs in Finland and France are partly excused by alleged "prototype costs". A Swiss EPR also could show some "prototype characteristics", as the plant, e.g., could not be built at sea side or because of specific regulation and certification requirements. Also, there would be no scale effects, as in Switzerland only one reactor would be built at a given site.

[5] This estimate is in line with EIA [23] and Prognos, EWI et al. [24].

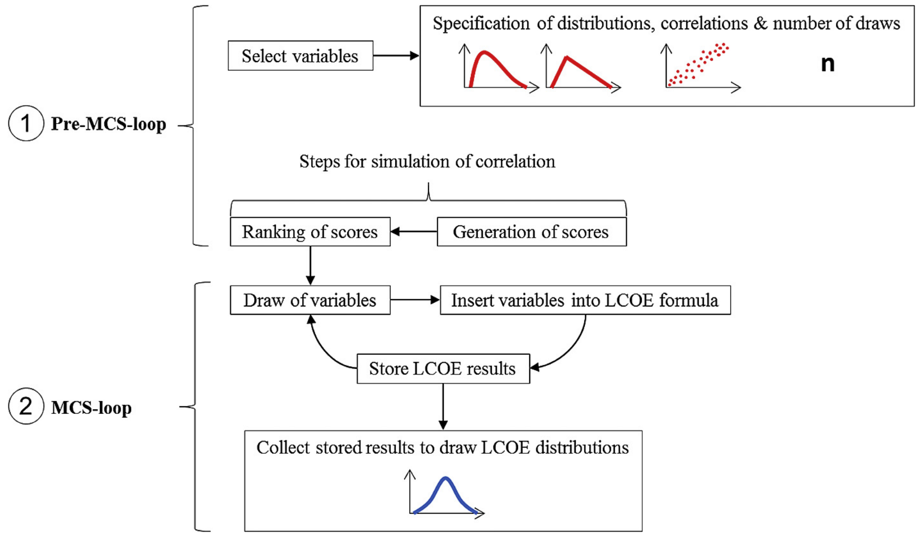

Fig. 1. Simulation procedure.

this way enables the generation of a random sample for any probability distribution for which it is possible to determine the inverse cumulative probability function G. Even though this is not a viable option for all probability functions, for most cumulative probability functions it is indeed possible to calculate the inverse. Other sampling techniques have been developed for situations where this is not the case.[6]

It is worth mentioning such other sampling technique, Latin hypercube sampling, which uses the technique of stratified sampling without replacement.[7] The advantage of Latin hypercube sampling, on which also the MCS simulation in this study is based upon, is that it enables to reproduce the desired distribution in fewer replications by stratifying $F(x)$ and applying random sampling to every of the resulting intervals.

The simulation procedure is depicted in Fig. 1. Endogeneities account for the probability of some variables varying in a systematic way. Predefined correlations between variables are introduced into the simulation process by using Spearman's rank-order correlation.[8] Given that the number of iterations is known beforehand, the variable pairs to be correlated are drawn in a first step (i.e., the scores are generated), and—in a second step—ranked in advance of the simulation in a fashion that yields the predefined correlation value.[9]

The literature on project appraisal so far is lacking a rule of thumb to infer the least number of Monte Carlo iterations necessary to obtain statistically meaningful results in terms of the outcome variable. This number can be inferred as follows: the probability of the percentage error relative to the estimated mean of the distribution lying outside the q percent confidence interval of the true distribution is $p_{1-q} = z_q \cdot s/\bar{x} \cdot \sqrt{n}$, where z_q is the q percent percentile of the standard normal distribution. The necessary number of replications is n, with $\bar{x}$ and s representing the population mean and variance, respectively. As the "true" LCOE values are not known, the latter two variables need to be estimated. However, usually not only one parameter is varied, but several of them (including the outcome variable). For n to hold for all parameters simultaneously, we replace $p_{1-q} = [1-(1-\tilde{p}_{1-q})^k]$ by $\tilde{p}_{1-q} = [1-(1-p_{1-q})^{1/k}]$, where k is the number of parameters varied. Then n is calculated for every k. As a conservative estimate, the highest result can be taken as minimum number of iterations needed to receive a set of estimates that satisfies the predefined level of p_{1-q}, which, e.g., could be 1%.

4. Results

If the best estimates given in Table 2 are used, i.e. if no MCS is applied, the LCOE of the nuclear plant amounts to 13.17 cents per kWh and 8.71 for the gas plant. The 2014 present value of after tax capital costs (including construction costs, incremental capital costs, post-closure, decommissioning and final waste disposal costs) constitute 74% of the total lifetime costs of the nuclear project and 17% in case of the gas project. These ratios signify the high capital intensity of nuclear power.

In a next step, MCS is applied to account for uncertainties in the variables' best estimate as well as potential endogeneities among these uncertainties. The minimal amount of necessary MCS iterations n is approximately $3 \cdot 10^5$ replications.[10] Figs. 2 and 3 depict the estimated LCOE probability density functions for the nuclear and gas power project under a consideration of correlations. Different to single point estimates, the range of the results reflects a project's inherent uncertainty, providing a comprehensive handle to judge a project's economic viability.

In the nuclear case, the power market would have to sustain a uniformly distributed real electricity price of at least 13.61 cents per kWh for 60 years for the project to yield a non-negative net present value. The economic viability of the gas power plant with a mean LCOE of 8.83 is considerably higher. The LCOE density functions not only differ in terms of their mean estimates, but also with respect to

[6] See Law and Kelton [30] and Gentle [31] for a description of many of the alternative methods.

[7] For further details of this method see Vose [32], for instance.

[8] Spearman's rank-order correlation is a nonparametric version of the Pearson product-moment correlation and only requires a monotonic relationship between the variables instead of a linear one.

[9] Balcombe and Smith [26] highlight the issue of serial correlation (also known as cycles) and the need to increase forecast variance over time. However, in what follows, only the possibility for a simple correlation between individual variables will be considered.

[10] In order to estimate the population mean $\bar{x}$ and variance s, $5 \cdot 10^5$ replications were used. It was decided to aim for $p_{1-q} = 1\%$, whereby (when using as example the case displayed in Fig. 2) 13 parameters are varied for the simulation (including the LCOE variable). See section 3.4 for a description of the proposed method to calculate n.

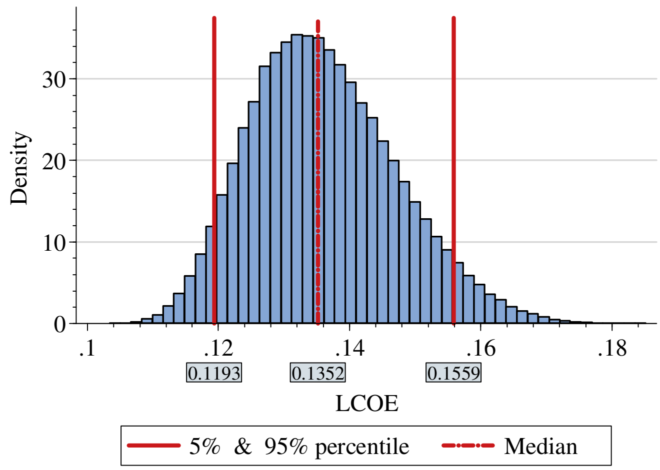

Fig. 2. Nuclear LCOE probability density.

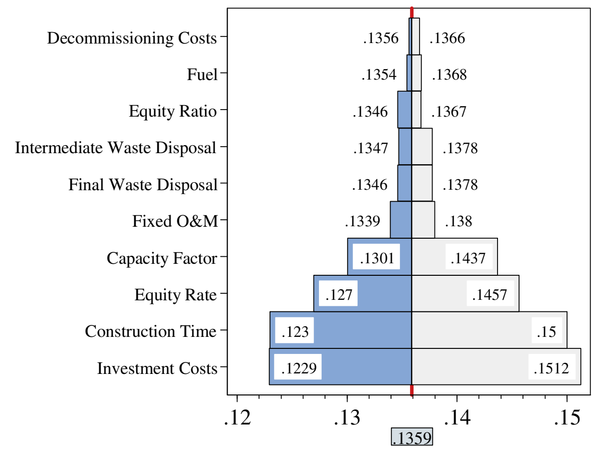

Fig. 4. Inputs sorted according to their leverage on nuclear LCOE.

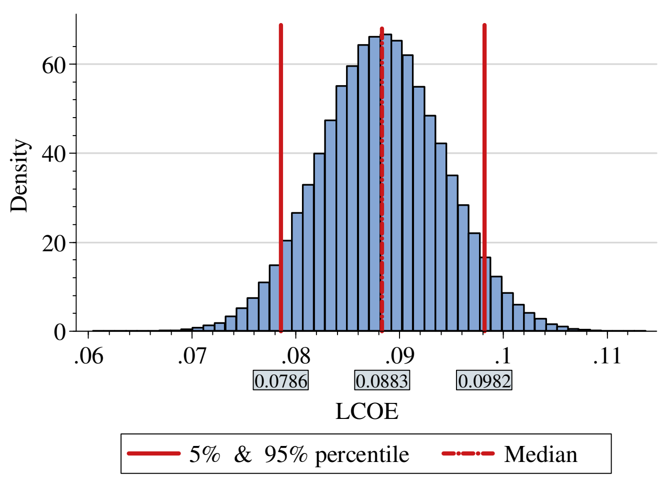

Fig. 3. Gas LCOE probability density.

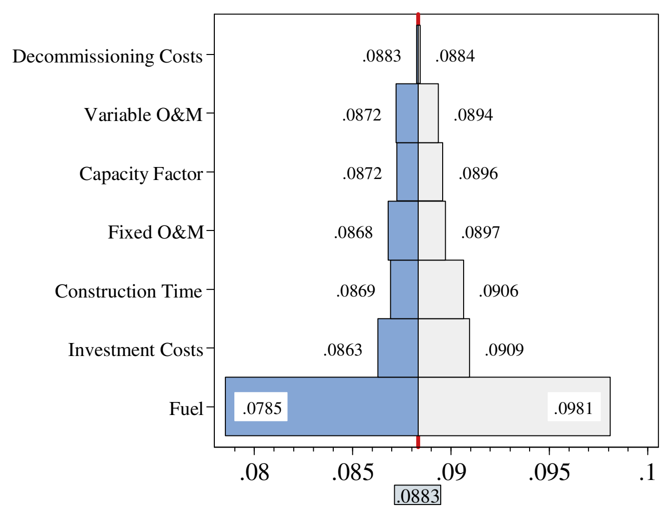

Fig. 5. Inputs sorted according to their leverage on gas LCOE.

their standard deviation. The standard deviation is bigger relative to the mean in the nuclear case, indicating that there are more uncertainties and hence risks buried within this specific project.

Additional insights are gained via a sensitivity analysis, visualized in Figs. 4 and 5 (the center line indicates the mean LCOE estimate). Depicted are the factors driving risk by their relative importance, i.e. how much LCOE mean value estimates change when a single input is varied over its predefined range. Awareness of driving factors helps to reduce the risk of either project.

By causing a variation in LCOE of 2.83 cents per kWh around the mean estimate, the nuclear plant's economic viability is highly dependent on capital costs, especially on upfront investment costs (see Fig. 4). Unsurprisingly, the economic viability of the nuclear plant is much less sensitive to fuel price risks than the gas plant.[11]

The importance of accounting for endogeneities between input variables is exemplified for the nuclear project by correlating the two variables construction costs and construction time.[12] Of course, many other potential endogeneities can be thought of, e.g., between fuel costs and inflation rates or interdependencies due to policies simultaneously affecting several variables. A comparison between Fig. 2 (accounting for endogeneities) and Fig. 6 (not

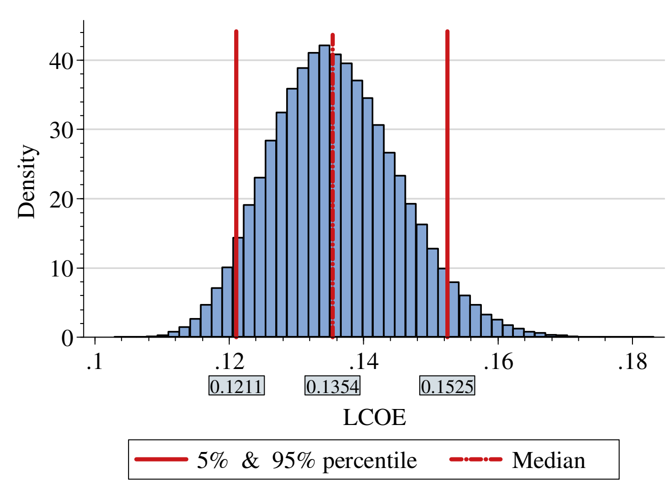

Fig. 6. Nuclear LCOE distribution without accounting for endogeneities.

[11] The effects shown in Figs. 4 and 5 assume a ceteris paribus change of the respective variable and hence do not account for potential endogeneities (i.e., correlations are not double counted).

[12] The choice and specification of the correlation level is explained in greater detail in the appendix.

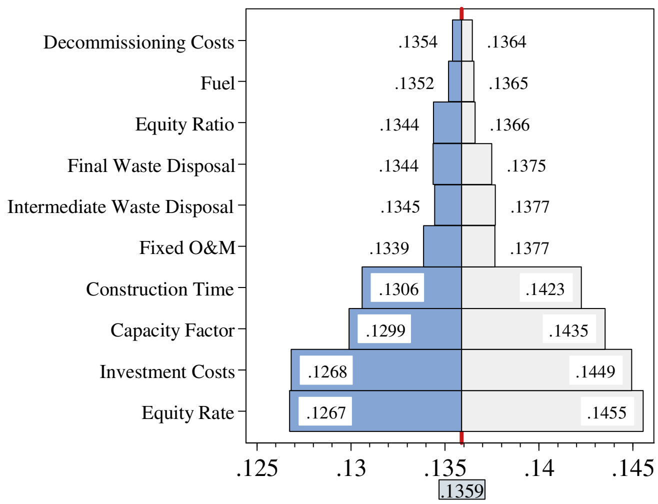

Fig. 7. Inputs sorted according to their leverage on nuclear LCOE without accounting for endogeneities.

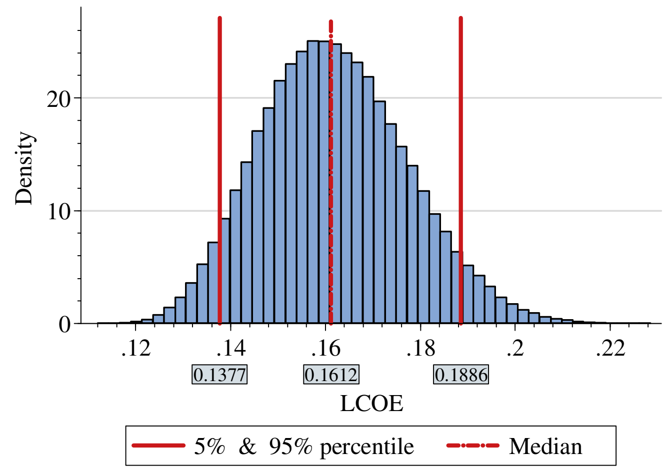

Fig. 8. Nuclear LCOE distribution under consideration of external costs.

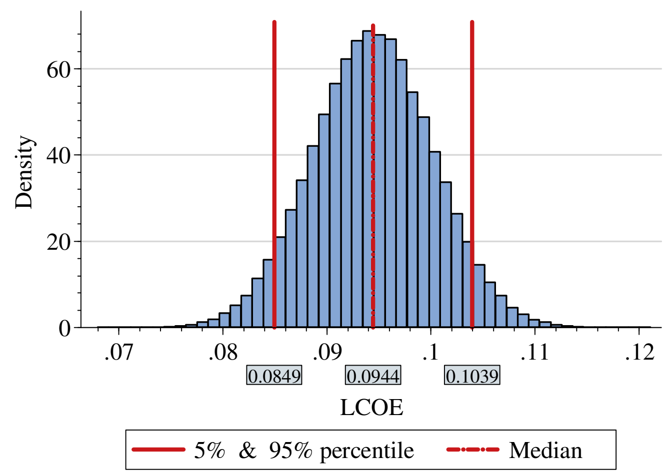

Fig. 9. Gas LCOE distribution under consideration of external costs.

accounting for endogeneities) illustrates the correlation's effect on estimated LCOE values.

The mean LCOE estimate is 1.5% higher than under negligence of the single correlation, with the difference being statistically highly significant at a level of 1%. Also, the ordering of the variables' leverage on the mean LCOE estimate changes considerably (see Fig. 7). Before, investment costs and construction time formed the pair of most influential variables in terms of their leverage on the mean. However, under the negligence of any endogeneities, the equity rate ranks first, followed by the investment costs. Construction time falls behind in its importance on fourth place.

4.1. A remark on external costs

External costs represent risks associated with a power plant project that are not internalized by the project owner, but are implicitly carried by the society. Investors usually do not account for external costs of their project as long as there is no regulation forcing them to internalize these. Power markets are still distorted by non-internalized external costs. Examples are a very low price of carbon certificates in the European Union or a non-insured damage risk of nuclear plants. In what follows, the aim is to provide a LCOE estimate assuming the technologies were forced to internalize some of their external costs. This exemplification has an illustrative character, as there are various sorts of external costs and it is in their nature that their quantification is difficult and connected to large uncertainties. The literature incorporating external costs in LCOE analyses (see Table 1) only focuses on costs related to greenhouse gas (GHG) emissions. In the study at hand, the focus lies on two externalities: external costs associated with life cycle GHG emissions and—relevant for the nuclear project—the risk of an accident.

Figs. 8 and 9 depict the effect on LCOE estimates under an internalization of external costs. Non-surprisingly, if the technologies were forced to carry these costs the resulting LCOE are higher, especially in the case of the nuclear project, where the mean LCOE estimate increases by 19%. The increase for the gas project is 7%. In conclusion, it would be even more difficult for the nuclear project to be economically viable if this technology would be forced to internalize its range of external costs.

Table 3
External costs parameter and distributional assumptions.

Parameter	Abbreviation	Unit	Nuclear	Gas (Advanced CC)
Carbon intensity	(*CarbonI*)	[gCO_2-eq/kWh]	16	469
Carbon tax	(*CarbonT*)	[$/$tCO_2$]	Tp(10; 18; 22; 24)	
Carbon tax real escalation	(*CarbonTreal*)	[%/a]	1	
Other non-internalized external costs	(*ExtC*)	[mills$/a]	PERT(33; 285; 730)	–

Note: PERT(A; B; C) ≡ Beta-PERT distribution, whereby A ≡ lowest possible value, B ≡ highest probability value and C ≡ highest possible value; Tp(A; B; C; D) ≡ Trapezoidal distribution, whereby B and C span the range of the highest probability.
All values are given in real USD 2014 terms. Choices of values and distributions are described in greater detail in the appendix.

5. Conclusion

LCOE estimations are based on a range of assumptions to which a varying degree of uncertainty is attached. Using probability distributions, these uncertainties are approximated, quantified and translated into cost risks [15,16]. MCS subsequently yields comprehensive results about possible project outcomes. In this paper, the traditional approach of calculating LCOE is extended by not only implementing a probabilistic model applying MCS to account for project risks, but also by introducing endogeneities between inputs.

The results allow for several insights. First, given current and past electricity prices, a nuclear project hardly would be economically viable in a liberalized Swiss power market. The LCOE estimates are higher than in most former studies on the LCOE of nuclear projects but in line with the cost estimates for current projects in Finland, France and the UK. Several single parameters are found to be decisive for the project's economic viability: first, keeping capital costs under control will be detrimental, implying a construction schedule not sheering off path. In contrast to the nuclear case, a combined cycle gas power plant is a proven technology with accordingly small technological risks. Here, initial investment costs are lower per unit of installed capacity and quantifiable with less uncertainty. However, the high dependency of the project's economic viability on the future price of natural gas is risk increasing. Roques, Nuttall et al. [33] refer to this effect as the „overlooked option value" of gas power under fuel price uncertainty.

The consideration of endogeneities between inputs is important. By controlling for only a single correlation a statistically significant difference in the mean LCOE estimate and a changing order of the leverage of inputs thereon is observed. Finally, a discussion of the role of discounting options and external costs is given. Nonsurprisingly, if investors would be forced by a regulator to internalize external costs, the economic viability of their project would be weaker.

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Appendix. Details on parameters and distributional assumptions

In what follows, the parameter and distributional assumptions represented in Tables 2 and 3 are explained in greater detail. The best estimate for the nuclear capacity factor of 90% reflects the high availability of the Swiss nuclear fleet, with the 80% lower bound accounting for the case of having persistent difficulties in selling base load electricity. The gas plant would be expected to take over the role of a nuclear plant to some extent, i.e. its best estimate capacity factor is in the higher range, too. The specification of the fuel costs, fixed and variable operation and maintenance (O&M) costs as well as the intermediate waste disposal costs for the nuclear project are based on the respective costs given in the annual reports of the years 2002–2013 of the two newest Swiss nuclear power plants (Gösgen and Leibstadt) and on DECC [34] for the gas project. No possibilities for a hedging of fuel costs are assumed. The O&M real escalation factor for the nuclear project is taken from the annual reports of Gösgen and Leibstadt as well. The assumed value is also supported by Davis and Hausman [35]. In form of a conservative assumption, the same factor is assumed for the gas project.

The abundance of data allowed for the specification of a normal distribution when accounting for uncertainties in the level of future natural gas prices. The normal distribution was calibrated using the real natural gas spot price variation in Germany between 1990 and 2014. Switzerland sources most of its natural gas via Germany. The distribution is not truncated, as no information is available in this regard and tail values are not considered to be statistically relevant. Real gas price escalations are assumed to go hand in hand with IEA [36]'s expected future yearly increase in gas demand in the power sector. Despite the significant drop in uranium prices in the recent years, the moderate real uranium price increase is rooted in the assumption that Switzerland only would consider building a new plant if there is a form of nuclear renaissance.

Incremental capital costs represent annual additions to the asset value of a plant during its operational phase. Based on the annual reports of the two newest Swiss nuclear plants (Gösgen and Leibstadt), these costs are estimated to be 1% of the initial investment costs in the first half of the operational phase and to double in the second half due to an increase in retrofitting activities. For simplicity, the same numbers are assumed for the gas power project. Intermediate nuclear waste disposal costs are considered to be fixed, as the main part of these costs stems from the operation of the intermediate storage facility. The costs estimates for post-closure-, decommissioning and final waste disposal are based on Swissnuclear [37] for the nuclear project and, due to a lack of data, on the assumption of 15% of initial investment costs for the gas project. Decommissioning assumes a "green field" result and does not account for any salvage values at the end of a plant's lifetime. The carbon intensity estimates are based on a life-cycle emission approach and stem from Moomaw, Burgherr et al. [38]. Particularly because of uranium mining and enrichment, nuclear power is not carbon free.

Given the assumption of a competitive power market, the capital recovery period follows a merchant project financing structure. According to Swiss law, the maximum depreciation allowance for nuclear and gas power plants is 6.5% per annum. The implied linear depreciation schedule specifies a, in nominal terms, constant principal repayment over the first 16 years of the operational lifetime of a plant, yielding a yearly allowance of 6.25%. The corporate tax rate is set to the average effective corporate tax level in Switzerland, i.e. it embraces taxes on federal, regional and local level. No special tax policies like investments tax credits or production tax credits are assumed. Post-closure, decommissioning and final waste disposal cost provisions are assumed to yield a real interest rate of 2%, which is the rate currently assumed by the Swiss government for today's provisions of the nuclear fleet.

The quantification of external costs connected with a nuclear accident is as difficult as the one of GHG emissions. Similarly to the latter, it also exhibits a life cycle cost character, as there is a chance of an accident in all associated process steps like uranium processing and enrichment, electricity generation, uranium reprocessing, decommissioning and final waste disposal. However, very limited experiences have been made so far with the later stages of a nuclear plant's life cycle. And given that external costs are accounted for as a thought experiment, only the external costs of an accident connected with the generation of electricity are focused upon. These costs are mainly related to a potential damage of human health—which should include psychological damage—and the impairment of assets. In Switzerland, external costs of small scale accidents are currently internalized via insurances covering costs of damage up to CHF 2.16 billion. However, this is not the case for major accidents like disasters of the scale of Chernobyl or Fukushima. Such costs would be carried by the public without any significant compensation. The difficulty of a monetary valuation of such events lies in the adequate combination of extreme low probabilities and huge damages.

A study of the Swiss Federal Office of Civil Protection conducted in 1995, which is non-public but whose results are cited in Zweifel, Umbricht et al. [39] on p. 25, roughly estimates the total damage of a major accident with a likelihood of occurrence of 1E–7 and with an extensive escape of radioactivity to amount to CHF 4.2 trillion. When specifying an estimate of external costs, the population's risk aversion with respect to a large scale accident also plays a role. However, this aversion, too, is very difficult to quantify and therefore the range of the external costs estimate is accordingly high.

The specification of the Beta-PERT distribution used to model the external costs related to a nuclear plant's accident is as follows: the lower bound and mode are based on the Infras, Econcept et al. [40] external costs estimate of USD 33 million (risk neutral population) and USD 285 million (risk averse population, lowest number under risk aversion given in the study), respectively. The upper bound of USD 730 million stems from the same study's lower range cost estimate under risk aversion. This choice of USD 730 million as the upper limit of the nuclear's external costs distribution is rather conservative, as Infras, Econcept, et al. [40] mention possible costs of up to USD 9.5 billion per year under risk aversion. The external costs are assumed to neither depend on electricity generation nor on installed capacity.

Carbon prices are taken from scenario specifications given in DECC [34] regarding investment costs for a combined cycle gas power plant with combustion carbon sequestration, transport and storage (CCS), i.e. from the marginal costs of the GHG emission backstop technology. All distributions are assumed to keep their initial specification over a project's lifetime.

For demonstrating purposes, it is assumed that the initial investment costs and the construction time are positively correlated. The US nuclear fleet, for example, showed a steady increase in construction costs [41] with an accompanying rise in construction time [42]. Also in case of the first and only two EPR reactors currently under construction in Finland and France, which have sheered well off their expected time and cost path, costs increased monotonically with construction time. For the Finnish case, according to Schneider, Froggatt, et al. [21] on p. 49, construction time has risen approximately by factor 2.75 and costs by factor 2.8. Very similar or even worse experiences are made in France. The study at hand assumes a correlation of 0.9. Since the combined cycle gas power technology is well proven, delays in the construction process are hypothesized to be caused less by costly technological problems, but rather by other circumstances like legal disputes, which on average are expected to be less costly. Vice versa, if a cost increase occurs during the construction period, its impact on the construction time is assumed to be less severe than in the nuclear case. Hence, in an ad hoc manner, the correlation coefficient is assumed to be one third smaller, i.e. 0.6.

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