Computation of the Levelized Cost of Electricity under Uncertainty and Endogeneities in Inputs

By Thomas Geissmann

Thomas Geissmann is in the Department of Management, Technology and Economics, Centre for Energy Policy and Economics, Swiss Federal Institute of Technology Zurich (ETH). He maybe reached at tgeissmann@ethz.ch. **He wishes to acknowledge and thank Prof. Dr. Massimo Filippini, Dr. Oriana Ponta, Dr. Adan Cruz-Martinez and Dr. Fabian Heimsch for their helpful comments.**

See footnotes at end of text.

INTRODUCTION

Aside security issues and the level of political support, the question of the economic viability of nuclear energy in today's increasingly liberalized western 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. 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. These cases exemplify the inherent uncertainty in projected costs of nuclear plants in the western world.

The estimation of a power project's economic viability by calculating the levelized cost of energy (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 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 Monte Carlo simulation (MCS) method. These issues have been neglected in previous studies.

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

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 et al. (2006) mention the possibility to control for such correlations, but no study yet effectively accounts for correlations when applying MCS techniques to estimate LCOE.

Source	Technology	MCS	Discounting options	External costs
Branker et al. (2011)	Solar	—	yes	—
Short et al. (1995)	Renewables	—	yes	—
Du and Parsons (2009)	Nuclear/Coal/Gas	—	—	—
Darling et al. (2011)	Solar	yes	—	—
Anderson (2007)	General	yes	—	—
Hogue (2012)	Nuclear/Coal/Gas	—	—	yes
Feretic and Tomsic (2005)	Nuclear/Coal/Gas	yes	—	—
Roques et al. (2006)	Nuclear/Coal/Gas	yes	—	—
Linares and Conchado (2013)	Nuclear	—	—	—
Ahmad and Ramana (2014)	Nuclear/Gas/Solar	—	—	—

Note: The table summarizes which power generating technologies a study considered, whether a MCS method was used and whether discounting options or the role of external costs were discussed.

Table 1: Overview of selected literature

MODEL

This study formulates a business oriented LCOE model, i.e., potential external costs of the technology are not internalized. The methodology applied to the LCOE calculation is based on Du and Parsons (2009). The authors define LCOE as the constant real wholesale price such that debt lenders and electric utilities are compensated their re-quired rate of return, 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 cost 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 (2009), p. 20). The model is demonstrated for the case of a nuclear power project in Switzerland. The LCOE in 2014 prices is given on busbar level. Variable descriptions are given in Table 2.

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. Post-closure cost, decommissioning cost and final waste storage cost provisions (PCP, DCP and FWCP) are constant over time and compounded yearly (emphasized by the exponent *y*). The interest earned on provisions implies some of the costs being covered by working capital. Finally, the LCOE is represented by the electricity price (ElPrice) that yields a net present value of the project equal to zero. By this procedure, the cost and revenue cash flows are discounted at the same rate, implying that both cash flows face the same risks.

Distributional assumptions represent the inherent uncertainty in some variable specifications. They are based on subjective judgment and therefore represent subjective probabilities, accommodating for the modest insight that there is a bounded set of information to build upon. Construction is planned such that the plant 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., the same type that is currently under construction in Olkiluoto (Finland) and Flamanville (France), and which is in discussion to be built in Britain at Hinkley Point. The parameter specifications used for the LCOE simulations are listed in Table 2. 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. The LCOE formula given in the previous section is now embedded it into a Monte Carlo setting using Latin hypercube sampling, which applies the technique of stratified sampling without replacement[2]. The simulation procedure is depicted in Figure 1. Endogeneities account for the probability of some variables to vary in a systematic way. Predefined correlations between variables are introduced into the simulation process by using Spearman's rank-order correlation. Given that the number of iterations is known beforehand, the variable pairs to be correlated are drawn, i.e., the scores are generated, and then ranked in advance of the simulation in a fashion that yields the predefined correlation value.[3]

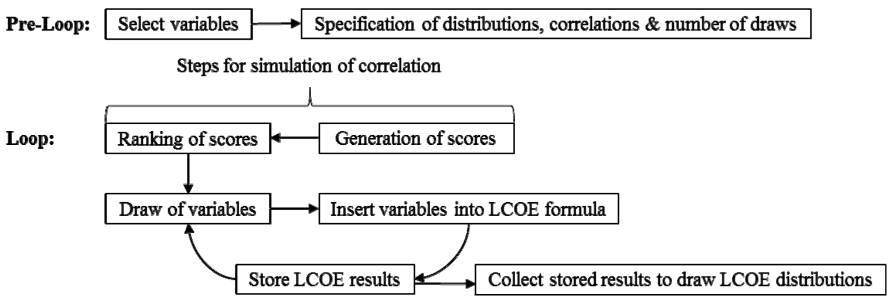

Figure 1: Simulation procedure.

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. The 2014 present value of after tax capital costs, including construction costs, incremental capital costs, post-closure, decommissioning and final waste disposal costs form 74 percent of the total lifetime costs of the project. These ratios signify the high capital intensity of nuclear power. MCS is based on $3 \cdot 10^5$ replications. Figure 2 depicts the estimated LCOE probability density functions for the project under a consideration of correlations.

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. Additional insights are gained via a sensitivity analysis, visualized in Figure 3, with the center line indicating the mean LCOE value. 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 those effects will help to reduce the risk of either project.

The importance of accounting for endogeneities between input variables is exemplified by correlating the two variables construction costs and construction time. For demonstrating purposes, it is assumed that the initial investment costs and the construction time are positively correlated. In this paper, a correlation of 0.9 is assumed. 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 Figure 2 (accounting for endogeneities) and Figure

Parameter	Unit	Nuclear
Electrical capacity (net)	[MW]	1600
Capacity factor	[%]	PERT(80, 90, 95)
Hours per year	[h]	8760
Heat rate	Btu/kWh	10400
Initial investment (overnight)	[$/kW]	Tr(5500, 6500, 7500)
Fixed O&M	[$/kW/a]	Tr(120, 140, 155)
Variable O&M	[$/MWh/a]	Tr(.95, 1.1, 1.4)
O&M real escalation	[%/a]	0.75
Intermediate waste disposal	[$/kW/a]	Tr(45, 55, 80)
Fuel costs	[$/MMBtu]	Tr(.35, 0.43, .5)
Fuel costs real escalation	[%/a]	0.5
Capital increment (1st half)	[$/kW/a]	1% of overnight costs
Capital increment (2nd half)	[$/kW/a]	2% of overnight costs
Post-closure phase costs	[$/kW]	Tr(515, 575, 725)
Decommissioning costs	[$/kW]	Tr(950, 1100, 1450)
Final waste disposal costs	[$/kW]	Tr(2600, 3200, 4200)
Equity ratio	[%]	PERT(40, 50, 50)
Equity rate (nominal)	[%/a]	Tr(8, 10, 12)
Debt rate (nominal)	[%/a]	6.5
WACC	[%/a]	8.25*
Discount rate	[%/a]	= WACC
Inflation rate	[%/a]	2
Real interest on provisions	[%/a]	2
Corporate tax rate	[%/a]	21
Depreciation time	[a]	16
Construction time	[a]	Discrete years=[6; 7; 8; 9; 10] prob=[.1; .4; .2; .15; .15]
Plant lifetime	[a]	60

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 ; $N(\mu,\sigma^2)$ ≡ Normal distribution ; prob ≡ probability. All values are given in real USD 2014 terms. Choices of values and distributions are described in greater detail in the appendix.

* Given the highest probability values of the two debt and equity rate triangular distributions. The WACC varies according to: WACC = Equity rate · Equity ratio + Debt rate · (1 – Equity ratio).

Table 2. Parameter and distribution assumption

4 (not accounting for endogeneities) illustrates the correlation's effect on the estimated LCOE values.

The mean LCOE estimate is 1.5 percent higher than under negligence of the single correlation, with the difference being statistically highly significant at a level of 1 percent. Also, the ordering of the variables' leverage on the mean LCOE estimate changes considerably. 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. Construciton time falls behind in its importance on fourth place.

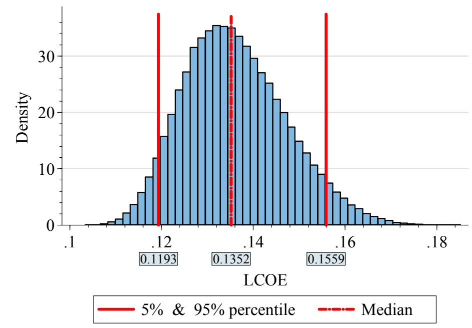

Figure 2. Nuclear LCOE probability density

Mean	**0.1361**	**Median**	**0.1351**
Std Dev	**0.0111**	**Variance**	**0.0001**

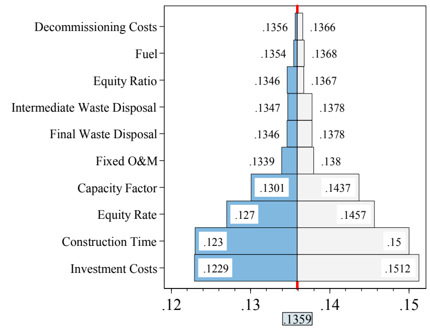

Figure 3. Inputs sorted according to influence on nuclear LCOE

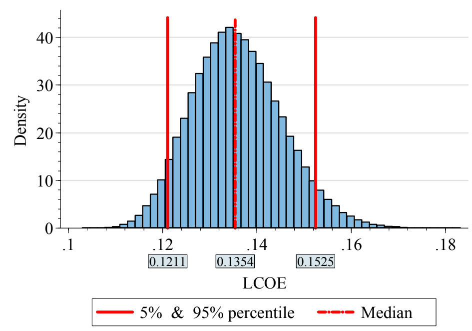

Figure 4. Nuclear LCOE probability distribution without accounting for endogeneities

Mean	**0.1359**	**Median**	**0.1354**
Std Dev	**0.0100**	**Variance**	**0.0001**

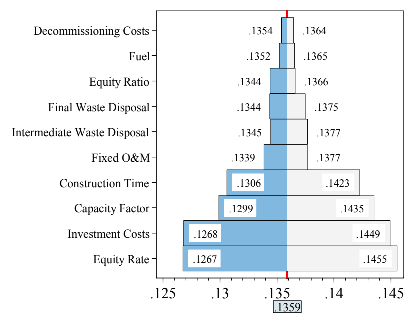

Figure 5. Inputs sorted according to influence on nuclear LCOE without accounting for endogeneities

CONCLUSION

LCOE estimation 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. 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. 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.

Footnotes

[1] See Linares and Conchado (2013) for a general discussion of the economics of new power plants in liberalized electricity markets.

[2] For further details of this method see Vose (2000), for instance.

[3] 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.

Literature

Ahmad, Ali and M. V. Ramana. 2014. Too costly to matter: Economics of nuclear power for saudi arabia. Energy, 69, 682-94.

Anderson, D. 2007. Electricity generation costs and investment decisions: A review. London: UK Energy Research Centre.

Branker, K.; M. J. M. Pathak and J. M. Pearce. 2011. A review of solar photovoltaic levelized cost of electricity. Renewable and Sustainable Energy Reviews, 15(9), 4470-82.

Darling, Seth B; Fengqi You; Thomas Veselka and Alfonso Velosa. 2011. Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science, 4(9), 3133-39.

Du, Yangbo and John E Parsons. 2009. Update on the cost of nuclear power. Center for Energy and Environmental Policy Research (CEEPR) No, 09-004.

Feretic, Danilo and Zeljko Tomsic. 2005. Probabilistic analysis of electrical energy costs comparing: Production costs for gas, coal and nuclear power plants. Energy Policy, 33(1), 5-13.

Hogue, MT. 2012. A review of the costs of nuclear power generation. Bureau of Economic and Business Research (BEBR), David Eccles School of Business, University of Utah, accessible at: www. bebr. utah. edu/Documents/studies/Nuclear_Report_Final_Web_7Mar2012. pdf.

Linares, Pedro and Adela Conchado. 2013. The economics of new nuclear power plants in liberalized electricity markets. Energy Economics, 40, Supplement 1(0), S119-S25.

Roques, Fabien A; William J Nuttall and David MG Newbery. 2006. Using probabilistic analysis to value power generation investments under uncertainty. University of Cambridge, Electricity Policy Research Group.

Short, W.; D.J. Packey and T. Holt. 1995. A manual for the economic evaluation of energy efficiency and renewable energy technologies. Golden CO: National Renewable Energy Laboratory.

Vose, D. 2000. Risk analysis: A quantitative guide. New York, N.Y.: John Wiley.