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Economics of Nuclear Power Plant Investment

Monte Carlo Simulations of Generation III/III+ Investment Projects

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Abstract

This paper analyzes nuclear power plant investments using Monte Carlo simulations of economic indicators such as net present value (NPV) and levelized cost of electricity (LCOE). In times of liberalized electricity markets, large-scale decarbonization and climate change considerations, this topic is gaining momentum and requires fundamental analysis of cost drivers. We adopt the private investors' perspective and ask: What are the investors' economics of nuclear power, or - stated differently - would a private investor consider nuclear power as an investment option in the context of a competitive power market? By focusing on the perspective of an investor, we leave aside the public policy perspective, such as externalities, cost-benefit analysis, proliferation issues, etc. Instead, we apply a conventional economic perspective, such as proposed by Rothwell (2016) to calculate NPV and LCOE. We base our analysis on a stochastic Monte Carlo simulation to nuclear power plant investments of generation III/III+, i.e. available technologies with some experience and an extensive scrutiny of cost data. We define and estimate the main drivers of our model, i.e. overnight construction costs, wholesale electricity prices, and weighted average cost of capital, and discuss reasonable ranges and distributions of those parameters. We apply the model to recent and ongoing investment projects in the Western world, i.e. Europe and the United States; cases in non-market economies such as China and Russia, and other non-established technologies (Generation IV reactors and small modular reactors) are excluded from the analysis due to data issues. Model runs suggest that investing in nuclear power plants is not profitable, i.e. expected net present values are highly negative, mainly driven by high construction costs, including capital costs, and uncertain and low revenues. Even extending reactor lifetimes from currently 40 years to 60 years does not improve the results significantly. We conclude that the economics of nuclear power plants are not favorable to future investments, even though additional costs (decommissioning, long-term storage) and the social costs of accidents are not even considered.

Keywords: nuclear power; nuclear financing; investment; levelized cost of electricity; monte carlo simulation; uncertainty

JEL-Codes: Q40; D24; G00

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1 Introduction

The debate on the role of nuclear power in the global energy mix has intensified recently in the context of climate change strategies. In particular, there is a debate about the potential contribution of nuclear power to policies of climate change mitigation and energy security in both, industrialized (e.g., MIT 2018; IEA 2019) and emerging countries (e.g. Kessides 2014). Recent studies by international organizations suggest a need for more nuclear power as part of a climate protection strategy, such as the IEA (2019) study “Nuclear energy in a clean energy system”. In the special report by the Intergovernmental Panel on Climate Change (IPCC) nuclear generation increases, on average by around 2.5 times by 2050 in the 89 considered mitigation scenarios (de Coninck et al. 2018). However, the traditional economics literature regularly observes that nuclear power plant investments are not competitive under regular market economy, competitive conditions, as Davis (2012) has summarized in a survey of the literature.

In this paper, we update existing analyses of the economics of nuclear power plant investments, by using up-to-date data and a stochastic modeling approach that can accommodate several uncertainties. We focus on investments into third generation reactor technologies (i.e., Gen III, Gen III+) and leave aside (advanced) fourth generation reactors (Gen IV), and small modular reactors (SMRs), as they are still far away from being commercially deployable (MIT 2018, 91), if ever (Schneider et al. 2015, 56; Thomas 2019, 226). There is ample data on recent investments into nuclear power plants of Gen III and Gen III+ that we use in the modeling. The paper focusses on projects carried out in Western countries, mainly Europe and the U.S., with a relatively high level of data reliability, and some electricity market competition. Thus, we exclude non-market institutional contexts from the analysis, where data quality and the levels of subsidies make an economic analysis difficult, such as China (Thomas 2017; Hibbs 2018) or Russia (Thomas 2018). We focus on the perspective of an investor, and thus leave aside the public policy perspective, such as externalities, cost-benefit analysis, proliferation issues, etc.

The topic is not new; on the contrary, economic analysis of nuclear power started in the post-World War II period, and has been updated ever since. When nuclear power for electricity generation was introduced in the late 1950s resp. early 1960s, government, industry, as well as academics were quite enthusiastic that nuclear power would become rapidly economic in the following decade (Ullmann 1958; Pittman 1961) and become the major energy source for electricity generation (Weinberg 1971; Rose 1974). In this (21st) century, two important studies on nuclear power came from the MIT (2003) and the

University of Chicago (2004), respectively, both arguing that nuclear power was not cost competitive with other fossil fuels at the time; these studies were regularly updated (MIT 2009, 2018; University of Chicago 2011). Joskow and Parsons (2009), Rothwell (2011) Linares and Conchado (2013) have provided updates, too, with detailed calculations, though confirming the earlier findings. Davis (2012) provides a broad survey of the literature, including own estimates. The textbook by Geoffrey Rothwell (2016), that we draw on with respect to modeling, provides a very useful account of methodological questions.

The paper thus provides both an update of data, and an application using a model taking into account uncertainties on a variety of parameters. The next section summarizes the state of the art of current and planned NPP projects in Gen III/III+ technologies; from that discussion, we take a variety of data, but also some lessons on cost increases over time. In Section 3, we lay out the investment model that calculates two standard parameters: Net present value (NPV) and the levelized costs of electricity (LCOE) that makes our results comparable with others in the literature. We follow the vast majority of the literature on the economics of nuclear power and focus on the perspective of a private investor (e.g., Rothwell 2016; Thomas 2010a) by employing a Monte-Carlo simulation (MCS) technique. It allows for incorporating uncertainty of crucial parameters, e.g. up-front overnight construction costs (OCC), capital costs, and the wholesale price of electricity. Section 4 introduces the data and the sources, taken from a variety of technical and economic sources, with additional calculations and assumptions of our own. Section 5 provides the results from the Monte Carlo calculations, and discusses them. For most of the scenario runs, the net present values of an investment in a new nuclear power plant are negative. This suggests that an investor would not recover his investment and an expected rate of return, i.e. nuclear power plant investments are not profitable. Off course, the results vary significantly, e.g. with respect to construction duration, and the distribution of the uncertain variables (e.g. uniform vs. normal distribution). The results are robust, however, also against a hypothetical lifetime extension from 40 years to 60 years, which improves the economics, whereas the expected NPV remains highly negative. Section 6 presents the main conclusions and policy implications.

2 Recent trends in NPP investments

2.1 Global trends

In October 2019, the IAEA Power Reactor Information System (PRIS) lists 448 nuclear power plants (NPP) or 393 GW of installed capacity in operation in 31 countries. In 2018, the world nuclear fleet generated 2,536 TWh or 10.15 percent of total electricity generation; of which 70 percent were produced by only five countries: (by rank) the U.S., France, China, Russia, and South Korea. 181 NPP or 78.1 GW are closed, of which only 19 are fully decommissioned (Schneider et al. 2018, 2019). In all regions, except for the Asia Pacific region, reactors under decommissioning are outpacing reactors under construction (see Figure 1). PRIS lists 52 reactors or 53 GW of capacity in 19 countries under construction; of which more than half (around 55 percent or 28 NPPs) are located in the Asia Pacific region (9 in China alone), eight reactors in the CIS (Commonwealth of Independent States) with six in Russia and two in Lithuania. In Europe (including Turkey), a total of eight reactors are under construction.

Worldwide, the peak of construction was in 1968 and 1970 respectively with 37 construction starts. Since then, the number of construction starts has been steadily decreasing to only one construction start in the year 1996 (in China). Since the late 1980s, nearly all new construction starts of reactors have been in the Asia Pacific region (see Figure 2), while nuclear construction nearly stopped in the Western hemisphere.[1] In the U.S., the construction of the two Westinghouse PWRs at the Vogtle site in Georgia constitutes the first construction start since 1978. In the European Union, the last completed construction project was the Gen II reactor Civeaux-II in France, here construction started in 1991 and the reactor started commercial operations in 2002. The only countries currently entering the nuclear sector (in 2018) are Belarus, Turkey, Bangladesh, and the United Arab Emirates.

[1] See Wealer et al. (2018) for an analysis of the worldwide diffusion of reactor technologies.

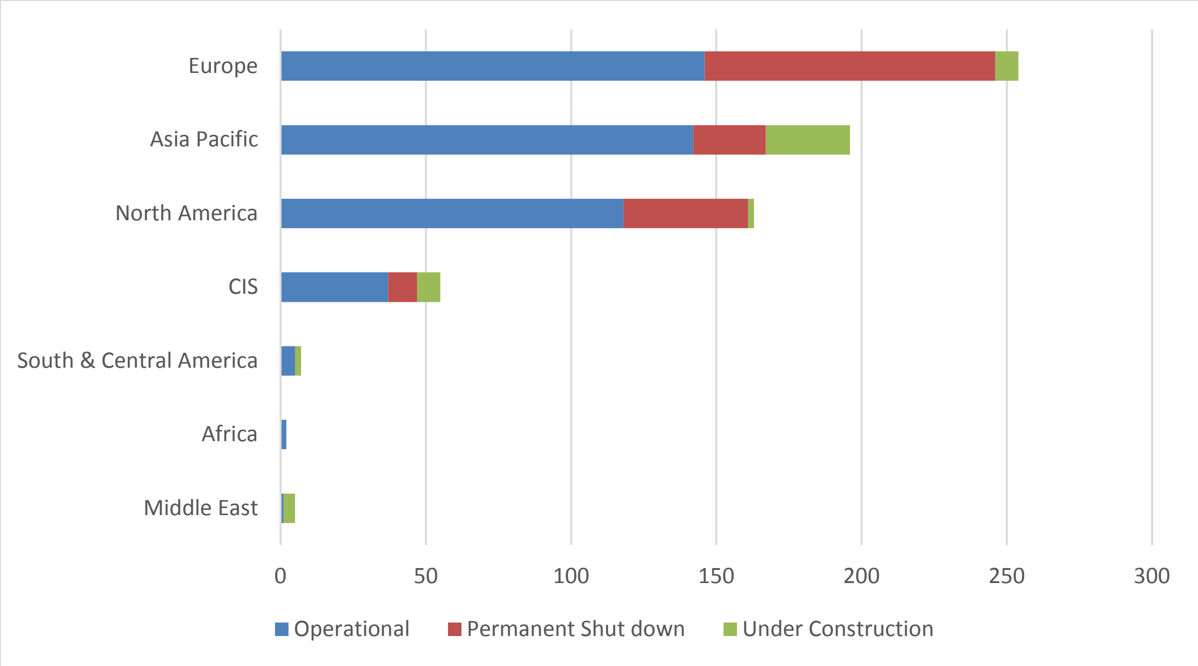

Figure 1: Nuclear power plants (operational, shut down, under construction) by region, as of 30.06.2019.

Source: Data from IAEA PRIS.

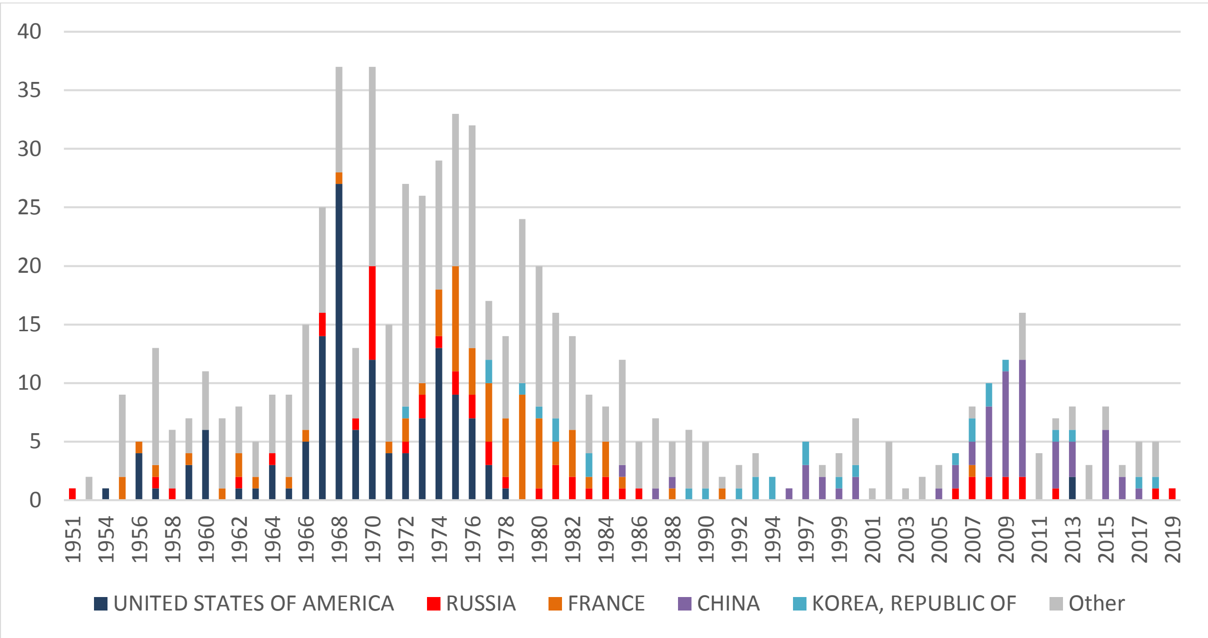

Figure 2: Construction starts, worldwide 1951-2019.

Source: based on Data from IAEA PRIS 2019.

Around two thirds or 68 percent of the 448 reactors are more than 30 years old. The U.S. has the oldest fleet, averaging 38.5 years, followed by Europe (34.6 years) (Figure 3). Considering that these nuclear reactors were designed for 30 to 40 years of operation, they would need to be replaced by new reactors or would need major lifetime extensions. A recent study form the International Energy Agency (IEA) calls, therefore, for supporting nuclear energy with subsidies for both, to extend the lifetimes of the existing reactors and for new technologies (IEA 2019). At a European level, if the share of nuclear power is expected to be 15 percent in 2050 (European Commission 2018), more than 100 new reactors would need to be constructed in the coming years. Considering the technical lifetimes, only 4,080 GW of nuclear capacity would be on the grid (i.e. in Finland, France, and Slovakia) in Europe by 2050 (Wealer et al. 2019).

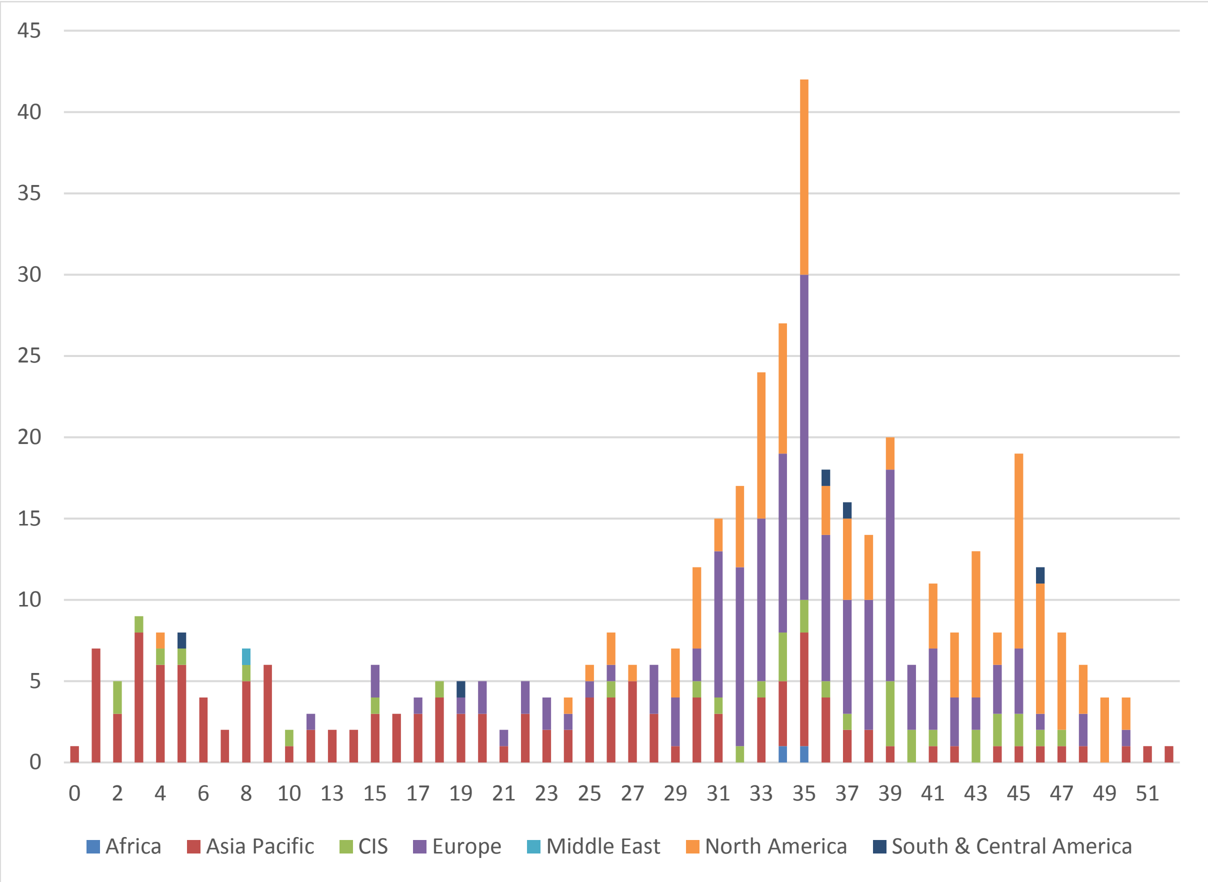

Figure 3: Number of reactors by age worldwide, as of 01.09.2019

Source: Own depiction based on IAEA PRIS Database

2.2 Development of construction costs

When comparing historical construction costs or cost estimates for nuclear new build, the majority of the literature on nuclear power economics as well as the utilities use the concept of overnight construction costs (OCC). OCC represent the costs as if the full expenditure were spent overnight and include the engineering, procurement, and construction cost (EPC) by the vendor; the owner's cost, which are mostly preconstruction expenditures[2] and depend on the EPC contract, i.e. which costs are borne by the owner outside of the EPC contract. One major flaw of the OCC, especially when talking about nuclear power plants, is that they do not take into account the financing cost or construction duration. Construction costs are the major component of the levelized cost are between, 60-80 percent, depending on the cost of capital and the duration of construction (MacKerron 1992; Haas, Thomas, and Ajanovic 2019). It does not make much economic sense to compare reactor costs without including the cost of capital (Koomey, Hultman, and Grubler 2017; Haas, Thomas, and Ajanovic 2019) as nuclear power construction projects are characterized by long construction times, a period where no income is generated. The financing cost consist of the interest to be paid during construction (IDC) but are not limited to the debt part but also to provide an acceptable rate of return to equity investors (D'haeseleer 2013, 38–39). The University of Chicago study (2004) shows that IDC can be as much as 30 percent of the overall expenditure, depending on the construction schedule and duration. In addition, with nuclear reactors being high-risk investments, investors may add a risk premium on the interest charges, which can have a substantial impact on the financing costs (World Nuclear Association 2017, 19).

Reactor cost quotes are in most cases firm-fixed price offers. Vendors can include contingencies in estimates to account for unknown costs that are omitted or unforeseen due to a lack of complete project definition and engineering (i.e. project contingencies) and to compensate of uncertainty in cost estimates caused by performance uncertainties with the development status of a technology (i.e. process contingencies) (NETL 2011, 4–5). Total contingency costs are between 9 and 20 percent (D'haeseleer 2013, 75). The reactor vendor needs to justify these costs to and negotiate them with the buyer as they are

[2] This includes general administration, pre-operation, R&D, spare parts, site selection, acquisition, licensing, public relations, taxes. See D'haeseleer (2013, 37–38) for more details and a compilation of different cited definitions of owner's cost.

charged to the latter whether the contingent events occur or not; depending on how much of the contingency costs actually gets expended, a vendor's profits will vary (University of Chicago 2004, 3–5).

The major part of the literature on historical construction costs deals with the United States of America. In the U.S., the escalation of capital costs was observed early on and has been shown regularly for several decades now (Mooz 1978, 1979; Komanoff 1981; Zimmerman 1982; DOE/EIA 1986; Koomey and Hultman 2007). In the U.S. OCC escalated between 1970 and 1989 from around 800 to 9,500 USD_{2018}/kW (Davis 2012, 53). Koomey and Hultman (2007) converted OCC to total construction costs (TCC) and found that these escalated from around 1,200 to more than 17,000 USD_{2018}/kW. Grubler (2010) reviews the economics of the French nuclear program by analyzing the annual investments expenditures of EDF published for the first time by Girard et al. (2000) and finds, that even under better different institutional settings, the French PWR program exhibited cost escalation, too: units completed after 1990 were 3.5 times more expensive than the first reactors in the 1970s. This triggered the release of the official cost estimates, published by the French national audit agency in 2012 (Cour des Comptes 2012): OCC for the 58 PWRs of around 103 billion USD; with OCC doubling between 1980 and 2000. Escobar Rangel and Lévêque (2015) analyzed the data and confirm that the scaling-up of the French nuclear program did not translate into cost reductions, although using the 2012 data, they found learning effects within a reactor technology type. Koomey, Hultman, and Grubler (2017) express considerable criticism about the data published by Cour des Comptes (2012): an additional 10 billion USD of OCC originating in the inclusion of construction-related engineering and labor costs and pre-operating charges are omitted; further, IDC published by EDF amount to some 23 billion EUR in contrast to CdC's of 13 billion EUR.

Construction costs for other countries than the U.S. and France are more difficult to obtain. A recent survey of construction costs was published by Lovering, Yip, and Nordhaus (2016) and led to a controversial discussion in this journal. The study included historical construction costs for Canada, Germany, Japan, India and Korea as well as costs for early first generation reactors, thus widening the data set beyond the U.S. and France and questioning the generally accepted notion that there is no positive learning curve in nuclear construction projects. In a reply to the publication, Koomey, Hultman, and Grubler (2017) highlight a controversial aspect of the study: the impossible replication of the data used due to the unavailability of the data and the non-independent sources for the costs. For example, the

Korean construction costs came from the state-owned utility, the French costs were based on an outdated survey by Cour des Comptes (2012) (see above).

Barkatullah and Ahmad (2017, 133–134) provide a comprehensive overview of the current financial support schemes by the government. Traditionally, in addition to public sector funds (especially for the rollout of nuclear power reactors),[3] governments may also have equity ownership. Examples are state-owned monopolists like Areva and EDF in France, KEPCO in Korea, or equity ownership in joint venture agreements, e.g. China General Nuclear (CGN) and Electricité de France (EDF) joint venture for the construction of the Taishan EPR in China or EDF/CGN for Hinkley Point C in the U.K. Other forms of government funding mechanism include additional cost recovery rates or surcharges on electricity sales (e.g. Vogtle project in Georgia in the U.S.), use of national funds (e.g. infrastructure funds), creation of a government-run private bank, banks to finance infrastructure, and asset pooling. Support and incentives for nuclear projects can also be provided by the governments in form of loan guarantees (e.g. Vogtle project), guaranteed long-term electricity contractual agreements (e.g. Hinkley Point C), or with export credit agency financing (e.g. the France-Coface loan to Finnish utility TVO for Olkiluto-3 in Finland).

2.3 Gen III/III+ reactors

In 2019, PRIS lists 24 operational Gen III/III+ reactors.[4] Already two decades ago, in 1996, the first Gen III reactor was connected to the grid: the ABWR (advanced boiling water reactor) from GE/Hitachi/Toshiba in Japan, of which four are in operation in total. Another operational Gen III design is the ACPR-1000 in China (Yangjiang-5 and 6). Two APR1400 reactors, a Gen III design by KEPCO, were connected to the grid in 2016 (Shin Kori-3) and in 2019 (Shin Kori-4, although not yet in commercial operation), eight reactors are under construction; four in the United Arab Emirates, where KEPCO is for the first time constructing outside of Korea.

In 2016, the first Gen III+ reactor was connected to the grid in Russia, with no indication on construction costs. The most built Gen III+ reactor is currently the Westinghouse AP1000, for which an escalation of

[3] Pittman (1961, 1566) reports that in the US about 200,000,000 USD were spent annually on the civilian program (e.g. the Power Reactor Demonstration Program in the U.S.).

[4] See Reinberger, Ajanovic, and Haas (2019) for the technological development of the different reactor generations.

capital costs can already be observed in the U.S., where construction costs at the Vogtle site escalated from 2,350 to around 11,000 USD$_{2018}$/kW (Schneider et al. 2019, 126). In 2003, MIT (2003) estimated the OCC for the AP1000 in their "base case"[5] to be around 2,800 USD$_{2018}$/kW (2,000 USD$_{2002}$/kW). Six years later, MIT (2009) updated these costs to 4,800 USD$_{2018}$/kW (4,000 USD$_{2007}$/kW).[6] In 2018, the first AP1000 reactors were successfully connected to the grid in China (Sanmen-1 and 2, and Haiyang-1 and 2) but with no indication on costs.

Another Gen III+ design is the EPR by Framatome (former Areva). In Europe, three EPRs are under construction since 2005 (Olkiluoto-3 in Finland since 2005, Flamanville-3 in France since 2007, and Hinkley Point C since 2018). In 1998, Framatome (then NPI) claimed OCC for the EPR of 2,200 USD$_{2018}$/kW (1,415 USD$_{1998}$/kW). Five years later, in 2003, Finish nuclear utility TVO signed a turnkey fixed-price deal with Framatome (then Areva) for around 3,111-3,422 USD$_{2018}$/kW (2,250-2,475 USD$_{2004}$/kW) (Thomas 2010b, 11); in 2007 costs for the Flamanville EPR were estimated to be around 3,300 USD$_{2018}$/kW (2,590 USD$_{2007}$/kW) (Thomas 2010b, 13). Since then costs have escalated to 12.4 billion EUR or around 8,430 USD$_{2018}$/kW for Flamanville-3, while fueling the reactor is estimated for late 2022,[7] 10 years after planned commissioning date and 15 years after construction start. The costs for Hinkley Point C also increased already, even before construction officially started from 22 billion USD$_{2018}$ (20 billion USD$_{2013}$) or 6,750 USD$_{2018}$/kW to around 27 billion USD$_{2018}$ (25.4 billion USD$_{2015}$) or around 8,300 USD$_{2018}$/kW (See Thomas (2016), Mendelevitch et al. (2018), and Schneider et al. (2019) for more details).

As it is the case with the Westinghouse AP1000, the first EPR was brought online in China. In December 2018, Taishan-1 started commercial operation, followed by the grid connection of the second EPR at the same station in June 2019. Although "western" designed Gen III+ reactors were brought online in China, it seems, that the Chinese market for western technologies has evaporated, with China recently

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[5] These OCC were assumed in their base case, in another case cost improvement of 25 percent were assumed. "*The cost improvements we project are plausible but unproven*" (p. 41).

[6] And even though, 30 percent of "First-of-a-kind" (FOAK) costs were added by the University of Chicago (2004) in their study; construction costs were with 1,500 USD/kW even lower. The study also argued that construction in China would decrease the FOAK costs. In 2011, OCC were updated to 4,210 USD/kW mainly due to the overestimated effects of construction projects in Asia and Europe (the largest contributing factor was in design maturation) - although these costs still represent "FOAK" costs (University of Chicago 2011).

[7] World Nuclear News. 2019. "EDF warns of added costs of Flamanville EPR weld repairs." November, 16, 2019. https://www.world-nuclear-news.org/Articles/EDF-warns-of-added-costs-of-Flamanville-EPR-weld-r.

opting for its own design, the Hualong One reactor (Schneider et al. 2019, 61). In addition, Russia is developing Gen III+ reactor technologies and in 2018, Russia launched the construction of the first VVER-TOI at the Kursk 2 station. Even though the development of Gen III/III+ looks uncertain now (Thomas 2019), we focus on this technology in the paper.

In a recent survey of cost estimates for nuclear power plants, Barkatullah and Ahmad (2017) range OCC for Gen III/III+ reactors between 5,000-7,300 USD_{2018}/kW or 6,100 USD_{2018}/kW on average for an EPR in Western Europe or North America. Sharp and Kuczynski (2016) estimate costs for an AP1000 to be around 6,000 USD_{2018}/kW but with no indication on the cost level, i.e. total investment cost or overnight costs. OECD/NEA (2015, 156) give a detailed overview over OCC as well as total construction costs (i.e. including IDC 5 or 10 percent) for several markets and reactor technologies: 3,382 USD_{2018}/kW for a Gen III+ for the U.S. market, for Europe the OCC range is between 3,681-5,863 USD_{2018}/kW and on average 4,881 USD_{2018}/kW. A study by the U.S. Energy Information Administration (2016) sets OCC to 5,945 USD_{2018}/kW for an AP1000. A study by the IEA and NEA (2015) give estimates around 5,300 USD_{2018}/kW on average for the European market. Figure 4 compiles different construction cost estimates for Gen III/III+ reactors for the US and European market. All these costs are cost estimates, as no Gen III/III+ has started commercial operation or has been connected to the grid, neither in North America nor in Europe.

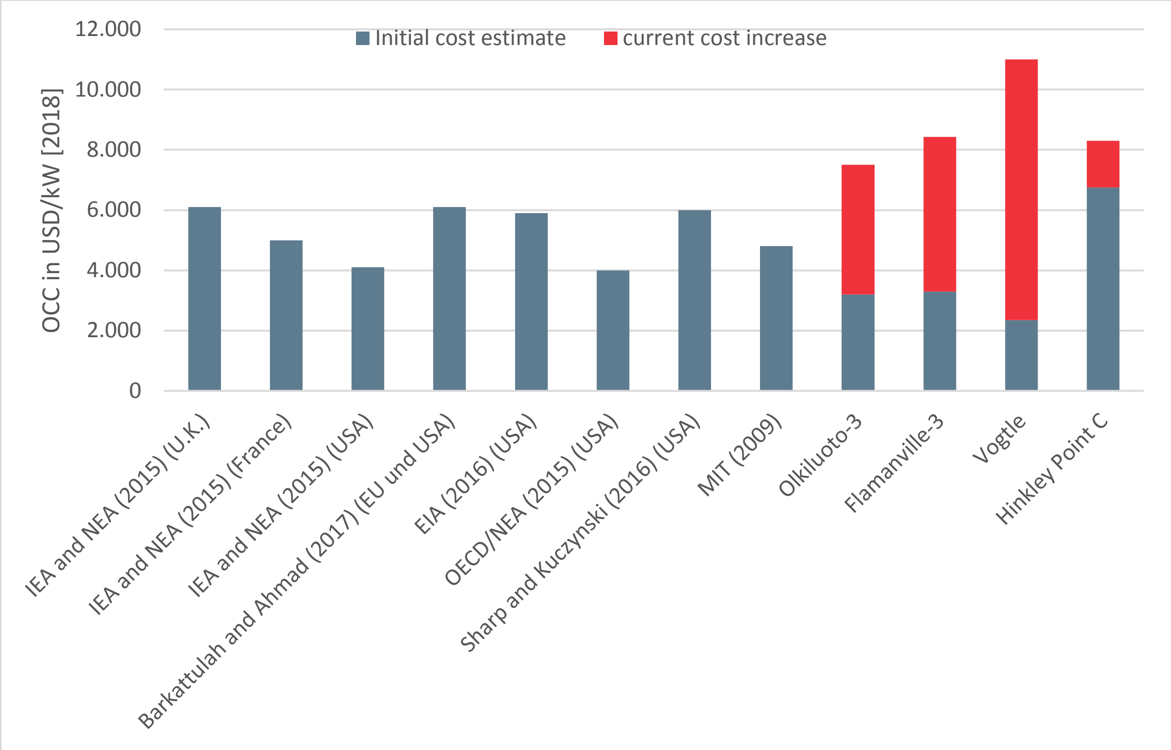

Figure 4: Overnight construction cost estimates for Gen III/III+ reactors in the US and Europe and cost estimates for current construction projects.

Source: Own depiction based on Sharp and Kuczynski (2016), OECD/NEA (2015), DOE/EIA (2016), Barkatullah and Ahmad (2017), IEA and NEA (2015), MIT (2009), and Schneider et al. (2019).[8]

3 The Model

We choose a holistic approach to construction costs and thus include OCC and interest during construction (IDC). In the existing literature Monte Carlo Simulations (MCS) have not been used quiet often although it is a relatively simple and powerful method of analyzing various kinds of systems under uncertainty (Heck, Smith, and Hittinger 2016; Darling et al. 2011; Spinney and Watkins 1996).

To analyze the profitability of an investment in a new nuclear power reactor a private investor may consult the net present value (NPV). This figure compares future revenue streams—dependent on the wholesale price for electricity—to present and future costs. Because both variables are discounted to

[8] Note: Sharp and Kuczynski (2016) do not indicate the cost level, i.e. total construction cost or overnight construction costs.

the present, the NPV indicates the present value of an investment. The higher the NPV, the more profitable the investment is from a business perspective. Equation 1 gives the basic formula for the NPV. R_t represents the revenues, i.e. the difference of income and expenditure in the time period $t \in [0, T]$ years, with $T = T_{con} + T_{op}$ (*construction time* + *operation time*); r is the yearly cost of capital rate. It is assumed that the cost of capital during construction equals the weighted average costs of capital (WACC).

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t}$$

Equation 1: Net Present Value

In this paper, income is solely generated by electricity sales; expenditures comprise fixed and variable operation and maintenance (O&M) costs, fuel costs, and total construction costs (TCC). Following Rothwell (2016), TCC are calculated according to Equation 2; the IDC-factor is estimated by Equation 3: The construction time T_{con} influences IDC exponentially. Figure 5 illustrates Equation 3: For example, the combination of 10-year construction period and WACC of 8 percent leads to an IDC-factor of 0.5067, i.e., one third of total construction costs are IDC.[9]

$$TCC = OCC(1 + idc)$$

Equation 2: Total Construction Costs

$$idc \cong \frac{r}{2} \cdot T_{con} + \frac{r^2}{6} \cdot T_{con}^2$$

Equation 3: idc factor

[9] The IDC may be calculated on a monthly basis, however, in this paper, IDC are approximated annually, e.g., a 8.0 percent annual rate equals a monthly rate of 0.6434030 percent. The inaccuracy employing annual cost of capital in contrast to a monthly resolution results in a difference of only 0.9. percent points for five years.

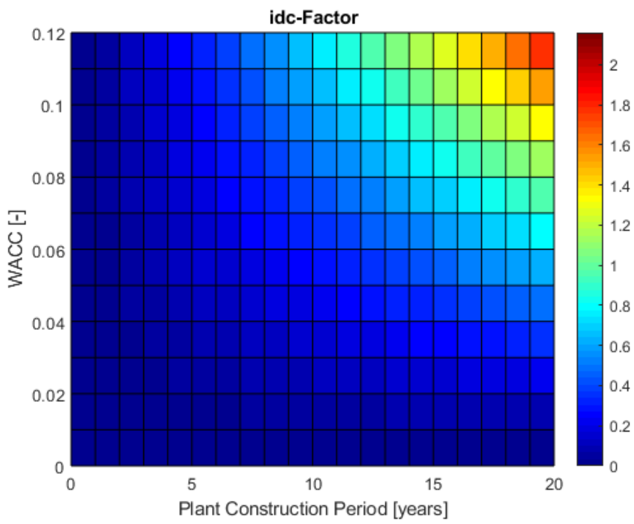

Figure 5: idc-factor as function of plant construction period and WACC.

Source: Own depiction.

Equation 4 yields the levelized cost of electricity (LCOE). The LCOE incorporates all costs related to the technology and puts them in relation to the total power output along its lifetime. For each period $t \in [0, T]$ the costs (TCC_t, $O\&M_t$, $Fuel_t$, $Carbon_t$) and the electricity ($Electricity_t$) are discounted with cost of capital rate *r* (WACC).

$$LCOE = \frac{\sum_{t=0}^{T}(TCC_t + O\&M_t + Fuel_t + Carbon_t) \cdot (1+r)^{-t}}{\sum_{t=0}^{T} Electricity_t \cdot (1+r)^{-t}}$$

Equation 4: Levelized Cost of Electricity

As the future electricity price and capital costs are uncertain values, and the prevailing inconsistency of OCC in the literature, a Monte-Carlo simulation offers insight into the likelihood to achieve a certain NPV and LCOE. Monte-Carlo simulation is a stochastic technique in which a large number of the same experiment (i.e. several thousands to millions) is carried out. For each experiment, different values of the pre-defined variables are chosen from a certain range based on an assumed distribution. In this paper, three variables vary: OCC, the wholesale price of electricity, and the weighted average cost of capital (WACC). Table 1 shows the basic parameter set.

For each experiment the algorithm randomly picks a value from the assumed probability distribution for each variable and applies them to the NPV and LCOE formula. After all n experiments the simulation issues a probability distribution of the NPV and the LCOE based on the random experiments. The results are presented considering a five year and a 15-year plant construction period. Within the graphs, the different model scenarios are coded: ND-5 represents a normally distributed OCC and a 5-year construction period; UD-15 refers to a uniform distributed OCC and 15-year construction period.[10]

4 Data

This section summarizes a host of literature on data for investments into Gen III/III+ reactors in the U.S. and in Europe. Based on the above discussion on costs, we assume overnight construction costs between 4,000 and 9,000 USD_{2018}/kW. For the Monte Carlo Simulation, we assume, for simplification, that OCC are spread continuously over the construction period and range from 4,000 to 9,000 USD_{2018}/kW. The simulation was carried out applying a uniform distribution as well as normal density of the OCC as suggested by Rothwell (2016). The mean value amounts to 4,747 USD_{2018}/kW; the standard derivation is 496 USD_{2018}/kW as depicted in Figure 6.[11]

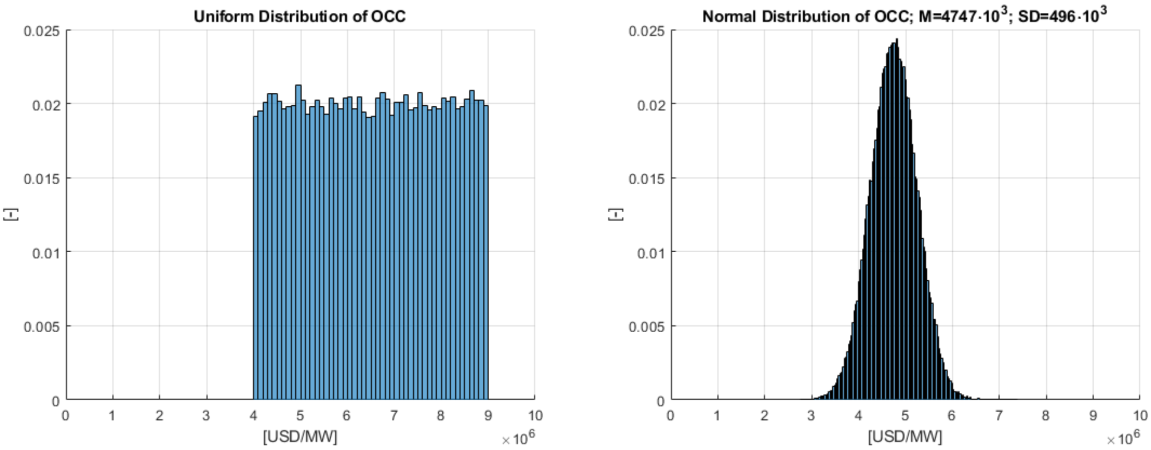

Figure 6: Uniform (left) and normal (right) distribution of OCC.

Source: own depiction, normal distribution based on Rothwell (2016).

[10] Calculations were carried out with MathWorks MATLAB R2018b. Unless stated otherwise, all currency information is in real 2018 U.S. dollar (USD_{2018}).

[11] Mid 2018 values are converted from mid-2013 values (mean=4,400 USD/kW, SDev=460 USD/kW) as applied by Rothwell (2016).

The weighted average cost of capital (WACC) is an indicator commonly used in investment budgeting. It reflects how an investment is financed employing debt and equity capital. The cost of debt r_d and the expected rate of return on equity r_e are set off against the respective shares of debt *d* and equity *e* of the investment. Therefore, the WACC represents the minimum return to meet the interests of shareholders and creditors. For the Monte Carlo Simulation, we assume a range between four and ten percent (Rothwell 2016).

$$WACC = \frac{d}{d+e} \cdot r_d + \frac{e}{d+e} r_e$$

Equation 5: Weighted average cost of capital.

We assume the wholesale price of electricity in the range between 20 and 80 USD_{2018} per megawatt hour (MWh). This is a reflection based on the current situation in the U.S. and in Europe and as conservative estimate of the medium-term price trend. Long-term price forecasts in electricity markets are difficult to make because fundamental aspects such as market design are subject to change. The lower range corresponds to a system with high shares of renewables, the higher range corresponds to a situation where natural gas is the marginal supplier of electricity, and it also includes a CO_2 price. Fixed and variable O&M as well as fuel costs are congruent with Barkatullah and Ahmad (2017). For the Monte Carlo Simulation we use a generic Gen III/III+ reactor with 1,600 MW of capacity to the grid and assume construction duration between five and fifteen years; this corresponds to the average construction period of ten years for 63 reactors completed over the past decade by nine countries (Schneider et al. 2019, 42).

The capacity factor is estimated to be 85%, although there are also nuclear power plant fleets with a higher capacity factor, e.g. 91% in Finland but also with a lower capacity factor, e.g. 73% in the United Kingdom (Joskow and Parsons 2009). We also do not account for a decrease of the capacity factor due to a growing share of renewables that produce at zero marginal costs. Table 1 summarizes the input variables for the Monte Carlo Simulation.[12]

[12] For simplification, we abstract from other parameters that could be taken into account, e.g. the tax regime and depreciation, and additional sales of heat as a co-product of electricity.

Parameter	Distribution	Range
Overnight construction costs (OCC) [USD/kW]	Uniform / normal[13]	4,000-9,000
Wholesale price of electricity [USD/MWh]	Uniform	20-80
Weighted average cost of capital (WACC) [%]	Uniform	4-10
Fixed O&M [USD/MW]	Constant	93,280
Variable O&M [USD/MWh]	Constant	2.14
Fuel [USD/MWh]	Constant	10.11
Plant construction period T_{con} [years]	Constant	5, 15
Plant operation period [years]	Constant	40
Plant capacity to grid [MW]	Constant	1600
Capacity factor	Constant	0.85
Number of experiments n [-]	-	100,000

Table 1: Inputs for Monte-Carlo Simulation.

5 Results

5.1 Base results for different distributions

The results are presented in histograms — for better comparability all histograms have the same scaling — and in Box-Whisker-Plots. The latter show the 25th and 75th percentiles (lower and upper edge of the blue box) and the median (red line in the box). The whiskers indicate the most extreme data points not considering outliers. The outliers are represented by red '+'.

In all four analyzed scenarios, independent of the distribution of the OCC and the construction duration, investing in a nuclear power plant results in significant losses (Figure 7). Assuming a normal distribution of OCC as suggested by Rothwell (2016) results in slightly better values for both, the long and the short construction duration. Although in the "best case", assuming five-year construction and normal distribution, the 95 percentile NPV is still -0.2 billion USD.

[13] Normal density suggested by Rothwell (2016).

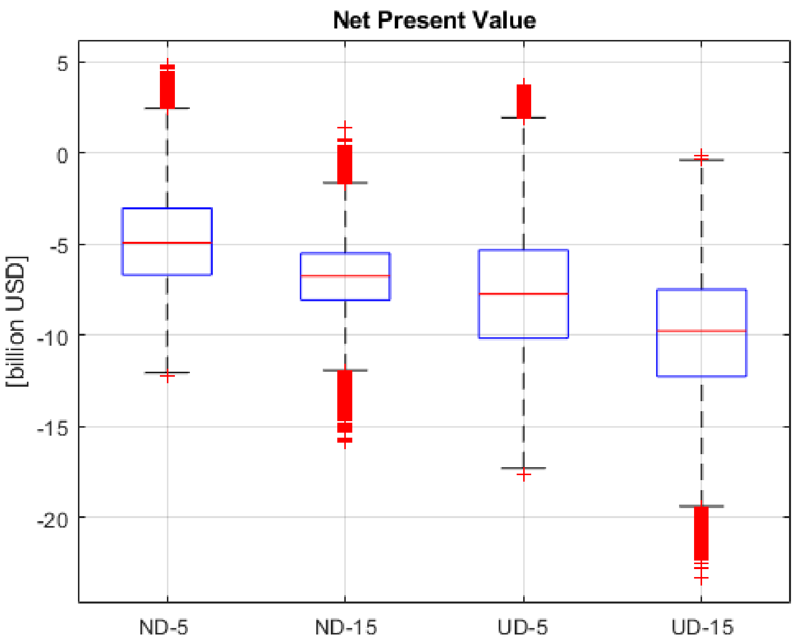

Figure 7: Box-Whisker-Plot of NPV scenarios.

Source: own depiction.

Figure 8 illustrates the distribution of the individual NPVs for each scenario. Assuming a 15-years construction period, as it would for instance be the case, when Olkiluoto-3 is connected to the grid in 2020, the net present value is always negative. Cutting down the construction time to 5 years, the NPV has a low chance to be positive.

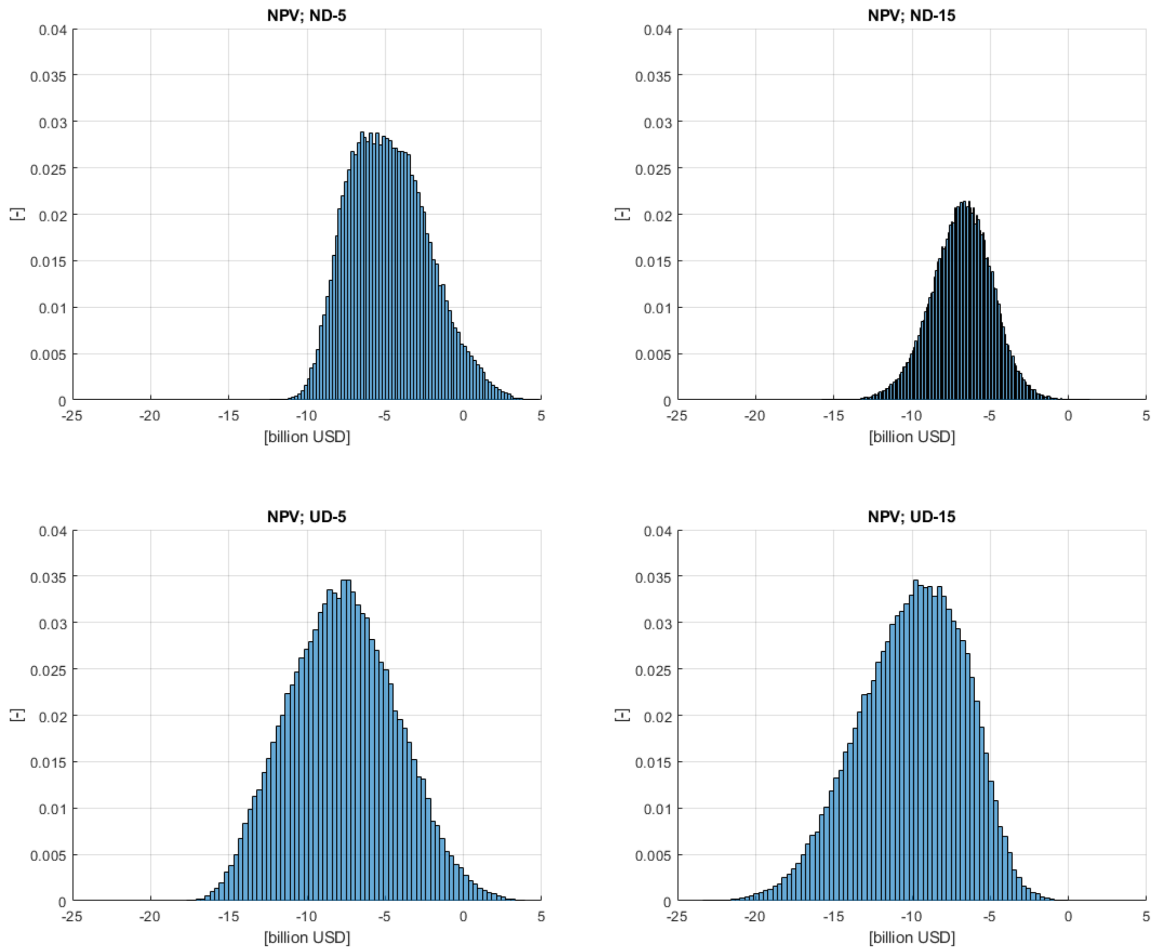

Figure 8: Histogram of NPV for uniform and normal distribution of OCC; 5 (left) and 15 (right) year construction period.

Source: own depiction.

5.2 Levelized cost of electricity (LCOE)

The LCOE metric is defined as the long-term break-even price an investor should receive to cover all costs. In other words, given the power output over the technology's lifetime, the LCOE equals the price of electricity at least required to prevent losses. Figure 9 shows the model results for the distribution of LCOE and a Box-Whisker-Plot of all analyzed scenarios. In the four analyzed scenarios, the mean levelized costs are between around 91 USD_{2018}/MWh and 222 USD_{2018}/MWh (Figure 9). With wider curves and lower peaks, the range of possible outcomes increases, making it more improbable to achieve a certain value. In accordance therewith, the Box-Whisker-Plots show a larger box.

For the scenarios with 15 years of construction the results are more widely distributed most likely due to uncertainties associated with interest during construction. The mean LCOE significantly increases with longer construction periods. In a “best case scenario”, we find the mean LCOE to be around 91 USD2018/MWh, which nearly doubles (factor 1.85) to 169 USD2018/MWh when assuming 15 years of construction instead. Assuming a uniform distribution of OCC, LCOEs are between 116 and 222 USD_{2018}/MWh. Table 2 summarizes all these results.

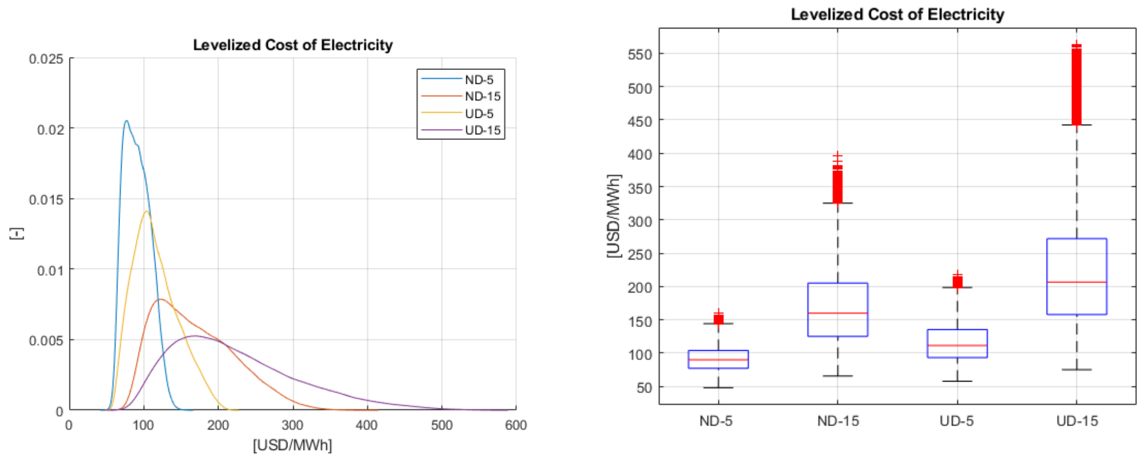

Figure 9: Model results for LCOE scenarios.

Source: own depiction.

	ND-5	ND-15	UD-5	UD-15
Mean NPV [USD]	-4.77 billion	-6.82 billion	-7.71 billion	-9.97 billion
Median NPV [USD]	-4.94 billion	-6.76 billion	-7.74 billion	-9.76 billion
95 percentile NPV [USD]	-0.26 billion	-3.76 billion	-1.99 billion	-4.99 billion
Mean LCOE [USD/MWh]	91.38	168.59	116.01	221.90
Median LCOE [USD/MWh]	89.96	160.03	111.47	206.53
5 percentile LCOE [USD/MWh]	66.42	97.33	73.29	112.42

Table 2: Main results from the Monte-Carlo analysis.

5.3 The importance of capital costs

Assuming five years of construction, the average share of the interest during construction of the total construction costs is around 16 percent. Figure 10 shows a Box-Whisker-Plot of modeled IDC as the share of TCC for all scenarios. Increasing the construction time to 15 years leads to an idc -factor of about 0.72 on average and a share of 41 percent of TCC, ten percent higher than the University of Chicago study (2004) showed. The maximum idc factor equals 1.125 for 15 years construction, making the IDC the main cost driver. Figure 11 shows mean values of OCC, IDC, and TCC as their sum. These results confirm the importance of taking capital costs into account, as argued by Koomey, Hultman, and Grubler (2017) and Haas, Thomas, and Ajanovic (2019).

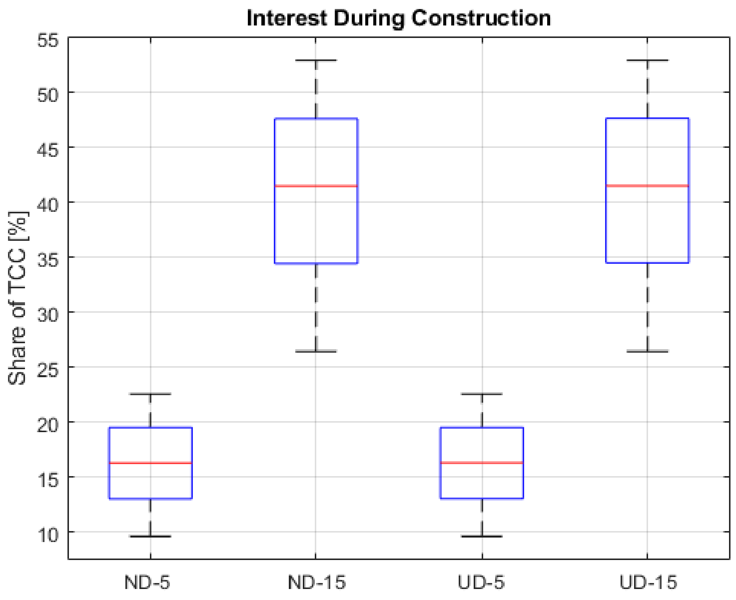

Figure 10: Box-Whisker-Plot of interest during construction (IDC) as share of TTC for all scenarios.

Source: own depiction.

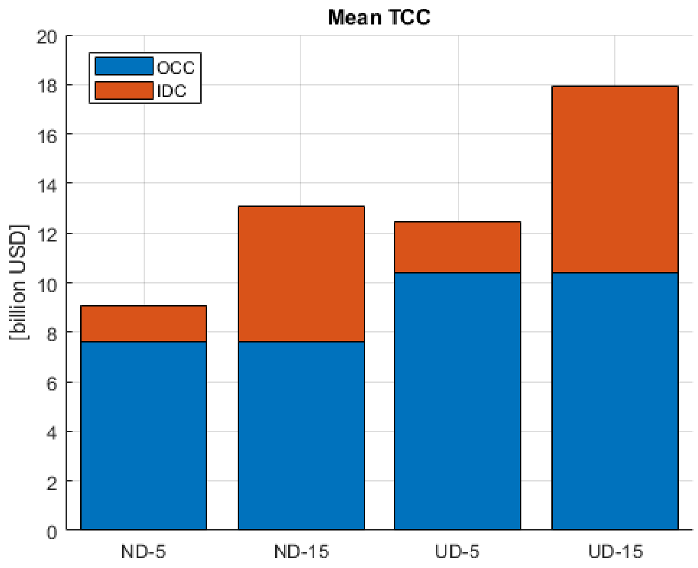

Figure 11: Mean TCC, OCC and IDC for all scenarios.

Source: own depiction.

5.4 Extending reactor lifetimes to 60 years

There is some discussion about the lifetime of the Gen III/III+ reactors. Engineering studies suggest that the lifetime of these new reactors might be 60 years, instead of 40 years as for previous reactor designs, but since the first Gen III reactor has only been online for 20 years, there is no empirical evidence for this claim. In general, regulatory oversight agencies grant license extensions from 40 to 60 years, e.g. in the U.S. for most license demands. In some cases, 80 years of operation are envisioned.[14] On the other hand, longer lifetimes can come with high costs, as increasing maintenance costs and needed safety investments and upgrades lead to higher operating costs.[15] For the sake of argument, we implement a 60 year lifetime in our model. In ND-05, additional 20 years of lifetime result in a marginal increase of the mean NPV from -4.77 billion to -4.52 billion USD_{2018}—an improvement of 0.16 billion USD_{2018}. The median NPV increases from -4.94 billion to -4.74 billion USD_{2018}. For LCOE, the mean LCOE improves from 89.96 to 88.06 USD_{2018}/MWh; the median LCOE from 89.96 to 86.52 USD_{2018}/MWh. Overall, the isolated influence of a 60 year lifetime compared to 40 years is reflected by a marginal improvement of the NPV and LCOE. As can be seen in Figure 12, the distribution of NPV highlights negative values.

[14] IAEA. 2018. "Going Long Term: US Nuclear Power Plants Could Extend Operating Life to 80 Years." November, 15, 2019. https://www.iaea.org/newscenter/news/going-long-term-us-nuclear-power-plants-could-extend-operating-life-to-80-years.

[15] In the U.S., for example, this led to closures of plants before reaching their extended lifetime (e.g. Oyster Creek, Kewaunee) or the call for subsidies to keep the plants running. See Lovins (2013, 2017), and Clemmer et al. (2018) for a current analysis of the situation in the U.S.

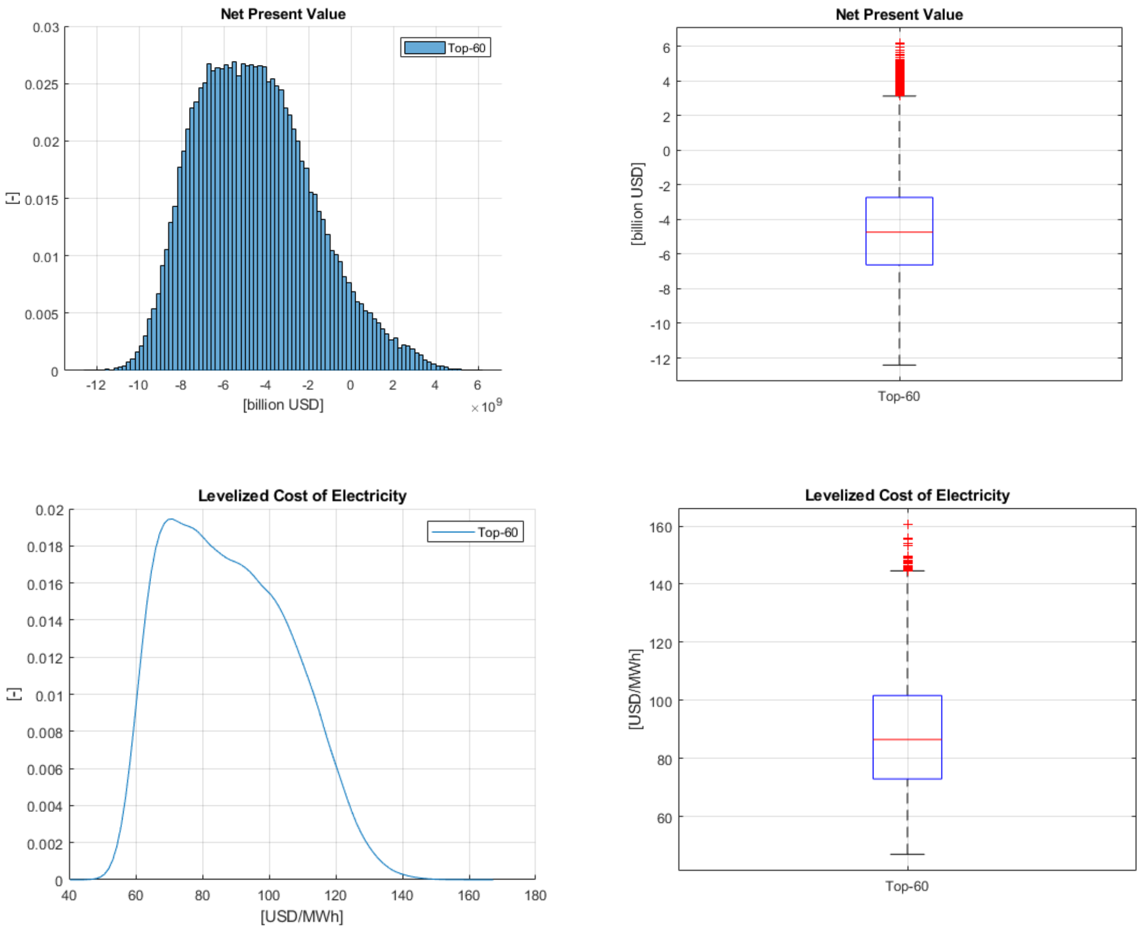

Figure 12: Model results of LCOE and NPV with 60 years lifetime and normal distribution of OCC.

Source: own depiction.

6 Conclusions and Policy Implications

In this paper, we apply Monte-Carlo simulation technique to calculate the net present value of an investment into a new nuclear power plant of the type Gen III/III+. Given the complexity of such investments, and the variability of parameters, the choice of the methodology appears reasonable: Employing a Monte-Carlo Simulation allows for incorporating uncertainty into the calculation of sensitive figures, e.g. for investment decisions or the estimation of possible costs. We carried out several scenarios considering different uncertain parameters, i.e. overnight construction costs, capital costs, and the wholesale price of electricity, as well as the plant construction time to determine the net present value (NPV) and levelized cost of electricity (LCOE).

It is understood that the perspective adopted in this paper is one of a private investor. Thus, the analysis excludes negative externalities, costs for decommissioning, waste management, long-term storage of waste, etc. Costs for decommissioning and waste management have been so far neglected as it was generally assumed, that their impact in the calculations would be small due to the discounting of expenses occurring at the very end of the lifetime. Only in the recent years decommissioning and intermediate storage costs are coming to the forefront (Kunz et al. 2018; Wealer, Seidel, and von Hirschhausen 2019), while costs for high-level waste management are still unknown (The World Nuclear Waste Report 2019). In addition, expenses corresponding to radioactive waste escorting operation are as well not yet part of the simulation. The same applies for liability costs given the risk of accidents. In a second generation model these costs may be incorporated. The impact of the variable capacity factor due to an increased share of renewable energy sources in the market may also be investigated in more detail.

The model yields robust results: Investing into a Gen III/III+ nuclear power plant today is not a profitable business case, but would very likely generate significant losses. The expected NPVs are highly negative in most of the cases, in the range of several billion USD. The model only finds positive values in a very small number of cases. The results also confirm the importance of capital costs and the length of the construction period: Interest during construction times is a major cost driver not to be underestimated. Raising the expected lifetime to 60 years improves the financial results, but it does not invert the negative expected net present value.

The modeling results confirm the dominant stream of the literature about the lack of competitiveness of nuclear power in competitive electricity markets (Davis 2012). Longer lifetimes made possible by new reactor design is no game changer for profitability. Policy debates should take into account capital costs, construction times and the other types of costs mentioned here, rather than base themselves only on overnight cots (OCC). The current trend in the U.S. seems to confirm this result, where nuclear power plants seek public support for operating their plants, whereas there is no willingness-to-invest into new plants.

Next research steps could include further refining the cost estimates, integrating the costs for decommissioning power plants and disposing of the waste, and extending the analysis to regions without competitive electricity markets. Linking the investment model with an electricity market model would allow refining the parameters, but also leading to a better understanding of the price dynamics in a low-carbon environment. Whereas cost data on decommissioning is currently being developed, attributing costs for waste storage to individual nuclear power plants seems to be difficult; an average value might be more pragmatic. Last but not least, we need a better understanding of the mechanisms underlying investment decisions in a state-owned context, such as India or China.

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