Cost Estimates and Economics of Nuclear Power Plant Newbuild: Literature Survey and Some Modeling Analysis

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Introduction

The perspectives of nuclear power deployment in the long-term depend very much on the development of costs, in relation to other low-carbon options, and the economics of investments into new capacities. While there is a consensus in the literature that nuclear power is not competitive under regular market economy, competitive conditions[1], at least two issues need to be considered going forward. First, the evolution of future technologies, and second, the treatment of "costs" in other, non-market institutional contexts, such as indigenous suppliers or "home suppliers" or the new (heavily subsidized) export models of countries like China or Russia. The objective of this paper is to provide insights into the economics of nuclear power for electricity generation by considering the perspective of a private (or public) investor.

Status Quo: Reactor Vendors in Financial Troubles and Tainted Technologies

Gen I and Gen II reactors were mainly constructed by integrated home suppliers (Thomas 2010). Table 1 shows, that this is still the case for the majority of the current newbuild projects: in China by majority-owned Chinese companies, in Korea by the state-owned KEPCO, or in Russia by state-owned Rosatom. Near-term future deployment in the "West" currently consists of the EPR or the AP1000. But, especially the EPR could never meet its high expectations and today all three construction projects are well behind schedule and well over their initial cost estimate. In the U.S, no Gen III/III+ has finished construction too

A popular financing policy tool for exporting reactor technology is the concept of "nuclear diplomacy", where the reactor technology is practically given away for free. The strategy consists of delivering the needed capital too, i.e. in form of low-interest

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See footnotes at end of text.

Country	Construction capacity in MW (NPP	Technologies	Generation	Supplier
Argentina	25 (1)	Carem25	SMR	Argentina
Belarus	2,218 (2)	VVER V-491	Gen III+ (2)	Atomstroyexport
China	19,500 (19)	ACPR-1000, HPR-1000, HTR-PM, VVER V-428M, AP-1000, EPR	Gen III (13), Gen III+ (6)	China, cooperation with Toshiba, Areva, and Atomstroyexport
Finland	1,600 (1)	EPR	Gen III+	Framatome
France	1,600 (1)	EPR	Gen III+	Framatome
India	3,907 (6)	PHWR-700, VVER-1000,	Gen II (4), Prototype FBR	Indian, Atomstroyexport Gen III (1), Other (1)
Japan	2,650 (2)	ABWR		Hitachi-GE
Pakistan	2,028 (2)	ACP-1000		China
Russia	4,359 (7)	VVER V-320, VVER V-392 M, VVER V-491, KLT-40S	Gen II (1), Gen III+ (4), Other (2)	Russia
Slovakia	880 (2)	VVER V-213	Gen III+	Atomstroyexport
South Korea	5,360 (5)	APR-14000	Gen III	KEPCO (South Korea)
United Arab Emirates	5,380 (4)	APR-14000	Gen III	KEPCO (South Korea)
USA	2,234 (2)	AP1000	Gen III+	Westinghouse
	51,741 (54)			

Table 1: NPP construction projects in 2017 by country, reactor design, and supplier, worldwide
Source: Own depiction based on Wealer et al. (2018, 32) and inspired by Thomas (2010).

loans; this is extensively done by Russia (Hirschhausen 2017) and China (Thomas 2017). As the interest during construction can be as much as 30% of the overall expenditures, financing costs can be a major barrier for investment. To overcome this, grace periods are often introduced, e.g. Russia offered Bangladesh for the Rooppur NPP a 10-years grace period for the around 12 billion low interest loan.[2]

Due to low construction orders since the 1970s the traditional reactor vendors are in serious financial troubles and own production lines were closed. In 2017, Westinghouse filed for Chapter 11 bankruptcy protection in the US and was sold by Toshiba; Areva was bailed out by the French state (5 billion € capital increase), split up, and the reactor division was sold to EDF; while Hitachi never exported a reactor and its ABWR has been proven as unreliable.[3] Applying a conventional economic perspective, such as proposed by Rothwell (2016), to decompose overnight construction costs (OCC) into indirect and direct costs and the latter into different technical components helps identifying cost positions, which have the most impact on total construction cost. The cost breakdown for a Gen III/III$^+$ shows that the reactor equipment has with 40% the highest impact.[4] It is therefore instructive to have closer look on the supply chain, especially for reactor pressure vessels, which is the most constrained.[5] Here, the major player is Japan Steel Works (JSW) with a market share of 80%. Already in 2009, Westinghouse was constrained as some parts for the AP1000 could only be delivered by JSW. The second major player is Areva-owned Le Creusot in France, which is currently being investigated due to irregularities in quality-control documentation and manufacturing defects of forged pieces produced for the EPR as well as the operational reactors, leading to multiple shutdowns in 2016.

The Perspectives for Nuclear Newbuild

Overnight construction cost (OCC) estimates for Gen III/III$^+$

Not only historical OCC show escalation but estimates too: The MIT (2009) study updated its OCC from 2,000 US$/kW to around 4,000 US$/kW, as did the University of Chicago (2011) study. A recent survey by Barkatullah and Ahmad (2017) finds OCC to be (on average) 6,100 US$/kW for an EPR. Sharp and Kuczynski (2016) estimate OCC for the AP1000 to be around 6,000 US$/kW. Figure 1 compiles different construction cost estimates for Gen III/III$^+$ reactors for the US and European market as well as the current cost estimates for the European and US construction projects.[6]

As always all these cost figures omit costs for decommissioning and waste disposal. As of today, only a few reactors have been decommissioned and actual decommissioning costs are scarce. In the U.S., where the most NPPs were completely decommissioned costs show a high variance, from 280-1,500 US$/kW (excluding waste disposal). In Germany, current decommissioning cost estimates are around 1,250 €/kW, if one includes interim storage and final disposal of radioactive wastes this amounts to 2,000 €/kW.[7]

Future reactor technologies: Gen IV and SMR[8]

As large NPPs face increasing construction cost and construction time, SMRs are presented as a possible solution but no SMR has ever been operated and current projects suffer from serious delays, both in construction and reactor design. A necessary condition to export a standardized SMR across borders is to have common licensing and regulations in different countries. Since standardization is key for manufacturing SMRs, regulations have to be harmonized. Regarding the diversity of institutions, Sainati et al. (2015) consider that “it is difficult to make significant progress in this direction in the short-medium term”. Multiplying SMRs around the globe can thus only happen if a common regulatory framework is designed. At the moment, the economic viability of SMRs is not clear, and they are no option any private investor would seek (Hirschhausen 2017).

Gen IV reactors are considered to be revolutionary but looking closer at the researched Gen IV reactors, one remarks that they are only partly based on fundamentally different technological concepts, e.g., HTRs have been around for at least half a decade and have been proven unsuccessful, the concepts of FBRs and thorium reactors even since the 1950s. As only a few prototype reactors are under construction (e.g., a lead-cooled fast reactor in Russia), future cost estimates are very uncertain. At the moment, deployment for commercial construction seems far from certain; many experts believe that Gen IV reactor types are unlikely to be readily available and competitive anytime soon due to even higher capital costs than Gen III$^+$ reactors.

Monte-Carlo analysis of investment NPV and nuclear LCOE

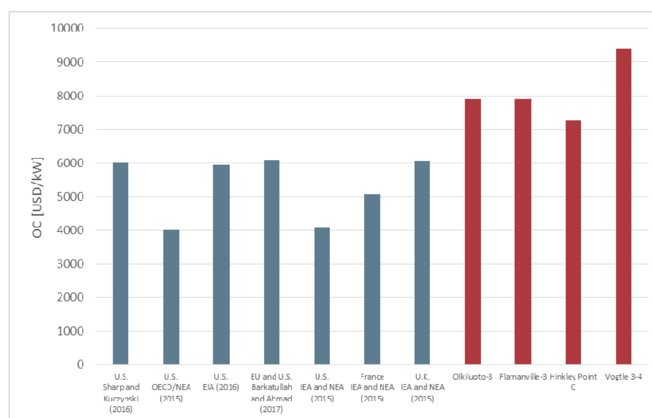

Figure 1: Current overnight construction cost estimates for Gen III/III$^+$ reactors in the US and Europe and cost estimates for current construction projects

Source: Own depiction.

	Nuclear	Coal	Nat. Gas
Baseline (2016) (no CO_2-price)	11.0	5.1	5.0
CO_2-price: 25 €/t	11.0	6.3	5.7
CO_2-price: 100 €/t	11.0	10.0	7.9

Table 2: Levelized costs of conventional electricity (€cents/kWh) Source: own calculations.

Based on the analysis of the levelized cost for electricity generation Davis (2012) concludes, that nuclear power is not competitive compared to natural gas- and coal-fueled electricity generation. This kind of analysis has been conducted in 2016 by DIW Berlin, using a similar methodology, but in a European context. The calculation shows, that nuclear power remains uncompetitive, even when the CO2-price is set to 100€/t CO2 (See Table 2).[9] The investment cost for nuclear power plants have been adjusted to take into account the development since 2013 and are set to 7,500 €/kW[10], and the fuel prices reflect the current situation. An availability of 80% (~7,000 full load hours), and a calculation horizon of 50 years have been anticipated

As neither the LCOE concept nor OCC incorporate any information on the electricity price, we check for profitability for a potential investor by employing a Monte-Carlo analysis of the net present value with the main input parameters wholesale electricity price (30 to 50 €/MWh), investment cost (4,500 to 7,500 €/kWh), debt capital interest rate (5% to 10%), and equity capital interest rate (2% to 10%). The analysis shows that even substantial variations of the main input parameters do not change the overall conclusions: With an average Monte Carlo NPV of around -7.2 bn €, the profitability is very negative. To make investments reach a NPV of 0€ a retail price over more than 90€/MWh would be needed. Considering the falling electricity prices due to a rising share of renewables, this seems to confirm that nuclear power is not competitive under regular competitive conditions.

Conclusion: Nuclear Power is Not Competitive

We find that investment costs for NPPs have significantly increased in the western hemisphere over the last decades and no learning effects could be seen. Current OCC are estimated to be above 6,000 €/kW but they have to be regarded critically; this also applies for decommissioning costs. The breakdown of costs into different systems allowed us to identify some system costs, which are more sensible to future increases. The supply chain for the reactor pressure vessel is the most constrained. In addition, the traditional reactor vendors are in financial troubles with tainted technologies - not one Gen III/III+ has been successfully connected to the grid in the "West". In fact, Post-Fukushima (2011) is characterized by the implosion of nuclear power in Western capitalist market economies, and many of the newbuild projects were abandoned. This leaves the development of nuclear power to "other", non-market systems, where countries hang on to nuclear development, for political, military-strategic, or other reasons, mainly the nuclear superpowers China and Russia. If Russia and China are able to provide the role of a global supplier needs to be seen, but both countries provide a strong government backed package including financing as a policy tool ("nuclear diplomacy"). Although, it is unclear how long Russia is able to sustain this practice, given the macroeconomic weakness of the country (Hirschhausen 2017). When comparing the LCOE of nuclear power plants to other renewable and fossil technologies, competitiveness is far from being in sight, even with a CO2-price of 100€/t, there is no profitable investment to be expected where nuclear becomes competitive.

Footnotes

[1] The recent Data Documentation 93 by the DIW Berlin analyzed the worldwide diffusion of NPPs and concluded that none of the 674 reactors analysed in the text, has been developed based on what is generally considered "economic" grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system. See Wealer, et al. (2018).

[2] See Schneider, et al. (2017).

[3] See Thomas, Steve. 2017. "Corporate Policies of the World's Reactor Vendors." presented at the 21st REFORM Group Meeting, Salzburg.

[4] Cost breakdown: structures & improvements (20%), reactor equipment (40%), turbine generator equipment (25%), cooling system and miscellaneous equipment system (15%), and electrical equipment (10%) (Rothwell 2016).

[5] As they require heavy forging presses of about 14-15,000 tonnes capacity and need to accept hot steel ingots of 500-600 tonnes. See World Nuclear Association. 2016. The World Nuclear Supply Chain: Outlook 2035.

[6] The current cost estimates for the European and US construction projects are drawn from the World Nuclear Status Report 2017 (See Schneider et al. 2017).

[7] See Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft. 2015. Gutachtliche Stellungnahme Zur Bewertung Der Rückstellungen Im Kernenergiebereich. Berlin.

[8] See Wealer et al. (2018) for more details.

[9] The basis for the cost estimation can be found in the DIW Data Documentation 68. See Schröder et al. (2013) "Current and Prospective Costs of Electricity Generation until 2050" DIW Berlin, Data Documentation 68.

[10] 6,000 €/kW + 1,500 €/kW for decommissioning and storage.

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PhD Dinner and Networking Event

By Fabian Moisl, IAEE Student Council Representative

On Sunday evening after the Welcome Reception students and young professionals were invited to meet at the Ni Hao Restaurant in the Groningen city center and enjoy a broad variety of Asian cuisine and drinks.

Student Representative on Council, Fabian Moisl, welcomed the delegates and pointed out all the services IAEE provides for its members: reduced conference fees, access to IAEE's publication (e.g. The Energy Journal and EEEP) and educational programs like summer schools and PhD seminars are just some popular examples.

Furthermore, the fact that motivated students are more than welcome to engage in IAEE by joining a student chapter or creating a new one if none exists at their home university was stressed once more.

Dual Plenary Session 3: Future of Natural Gas Markets

Summarized by Ekaterina Dukhanina, PhD Student, CERNA, Mines ParisTech and Phuong Minh Khuong, PhD candidate, Energy Economics Chair, Karlsruhe Institute of Technology

This dual plenary session was chaired by Machiel Mulder, Professor at the University of Groningen, The Netherlands. Prof. Mulder was joined by Hill Huntington, Executive Director Energy Modelling Forum, Stanford University, USA; Knut Einar Rosendahl, Professor of Environmental and Resource Economics, Norwegian University of Life Sciences, Norway and Ying Fan (Beihang University): Director of Beihang Center for Energy and Environmental Policy Research, Beijing, China.

The session "Future of Natural gas markets" attracted many academic researchers and professionals interested in perspectives on the role of natural gas in the transition of energy markets. After an introduction by Machiel Mulder, Hill Huntington, an Executive director Energy Modelling Forum, Stanford University, provided insights into the US natural gas industry. He pointed out a huge potential of shale natural gas development in the US and highlighted its future trends: with reduced and currently attractive prices, the gas displaces coal for power generation, brings broader fuel competition, and boosts US geopolitical power. However, given its continuing increase, gas will unlikely becomes long-term climate savior since it can endanger groundwater and could cause earthquakes if over-exploitation. In addition, uncertainty of future gas prices might have strong impact for the next decade the shale gas will continue to transform North American markets and exports will become more competitive.

Talking about the future of Russian gas exports to the European market, Knut Einar Rosendahl, Professor of Environmental and Resource Economics, Norwegian University of Life Sciences, Norway, presented the future of Russian gas exports to the European market. Prof. Rosedahl concluded that it is unlikely to have a golden age for the gas in Europe and Russia has other options for its gas (Asian markets and LNG). New pipelines from Russia to the Europe would rather have strategic or geopolitical, than economic interest.

Ying Fan, Director of Beihang Center for Energy and Environmental Policy Research, Beijing, China, provided insights into Chinese gas markets: increasing gas demand in China will be satisfied by new pipelines and LNG. However, the reform of gas pricing system in China and the speed of development of the renewables leave some uncertainties about the future of natural gas in this country.