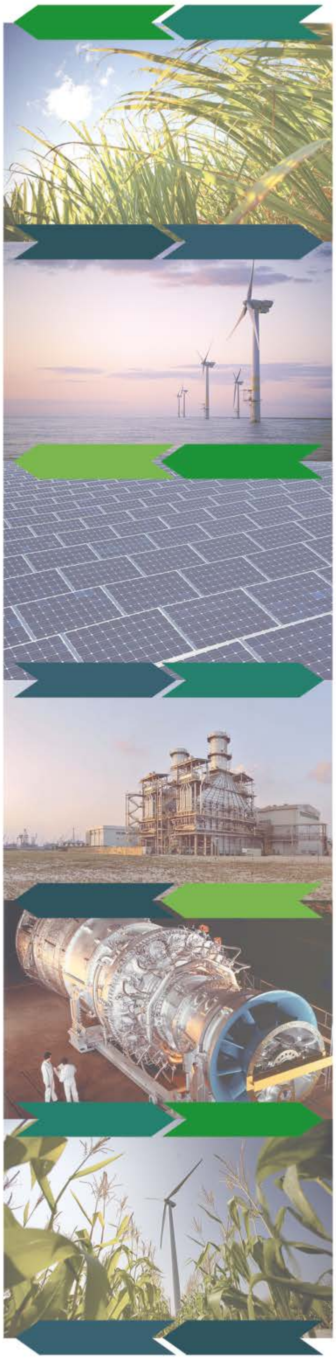
NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



Issue Paper on

Case study 7.5: Perspectives for nuclear power

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Abstract

By the means of a comprehensive literature review, we conduct a technology assessment of nuclear power plants (NPP) with a focus on cost estimates, parameters affecting the economic competitiveness of NPP's as well as prospective developments. The assessment aims at providing up-to-date information as input for the modelling of energy transition pathways in the framework of SET-Nav as well as of other EU modelling projects.

Technical concepts and trends such as lifetime extensions, small modular reactors and generation IV designs are discussed. The analysis highlights the possible albeit uneconomic interaction of NPPs with intermittent electricity generators in energy systems with high shares of renewables. Keeping the geographic focus on the EU, the case study further discusses and quantifies costs including overnight-, financing, O&M, fuel and waste storage costs. While the analysis of the cost structure and of levelized cost of electricity for NPP's hints at a limited competitiveness of NPPs on the short and medium term, due to its static nature and sensitivity to the underlying assumptions it does not provide a clear-cut recommended action.

Moreover, we agree with literature reports stating that the future development of nuclear power may not solely depend on economic considerations. Keeping the 'nuclear option' open – even accepting its limited current competitiveness – to be a distinct choice for certain countries such as France and the UK.

Therefore, we suggest taking NPP capacities as an exogenous input factor for the modelling of transition pathways.

1 Introduction

Nuclear power is one of the most controversial technologies for electricity generation, in particular in the EU. From a strictly technological perspective, nuclear power constitutes a method of generating electricity by harvesting the thermal energy released during the controlled fission of atoms.

Opponents refuse it because of the risk of a nuclear accident and the proliferation of nuclear weapons, the involvement of radioactive and thus toxic materials, and the lack of a reliable solution for the long-term disposal of spent nuclear fuel. On the other side, proponents often consider it to be a sustainable[1], carbon-free source of electric energy and in consequence as an indispensable option for climate protection.

While acknowledging the lack of an obvious panacea, energy economists express diverging views on whether nuclear power should – from a purely economic position - be part of the technological solution basket to address the global energy challenge. Or as Kessides (2010) puts it, the fundamental problem underlying the debate on the potential role of nuclear power in meeting the future global energy needs relates to the persistent lack of consensus on what will be the costs of new nuclear generating plants. Partly, the continuing controversy is due to the large risks and uncertainties related to the cost elements of nuclear power. Cost overruns and significant schedule delays - as currently observed in Finland's European Pressurized Reactor (EPR) in Olkiluoto or the French EPR in Flamanville - are contributing to concerns about nuclear power being far too complex and costly. This raises new questions about the viability of new nuclear plants, especially in deregulated electricity markets.

The uncertainty about the economic competitiveness and thus the future role of nuclear power is mirrored in energy scenarios such as presented in the impact assessment accompanying the new legislative package "Clean energy for all Europeans" (European Commission, 2016). The Reference Scenario as of 2016 was as well the two core policy scenarios EUCO27 and EUCO30 [2] project a virtually constant albeit slightly decreasing share of nuclear power in electricity supply at EU level. The share, currently at around 25% (ref. Figure 1), would decrease to 18.1%, 21.7% and 23.2% respectively in 2050. Taking into account an increasing total electricity demand in Europe (European Commission, 2017; IAEA, 2017a), that implies the construction of a considerable amount of newly built reactors to replace retiring capacities.

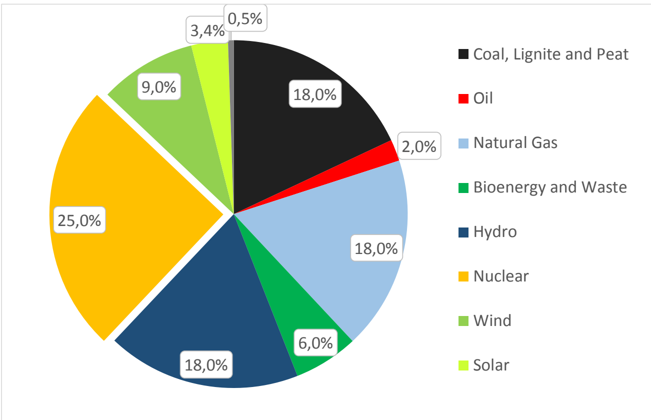

Figure 1: Electricity production in the EU in 2016 (IAEA, 2017)

Contrasting to the EC scenarios, Figure 2 depicts the International Atomic Energy Agency's most recent estimates on Europe's nuclear power capacities for the period up to 2050.

[1] in the sense of supply security and resource efficiency

[2] The Reference Scenario is a projection of the current set of policies coupled with market trends. In contrast, EUCO 27 and EUCO30 model the achievement of the 2030 climate and energy targets as agreed by the European Council in 2014 (the former with a 27%, the latter with a 30% energy efficiency target)

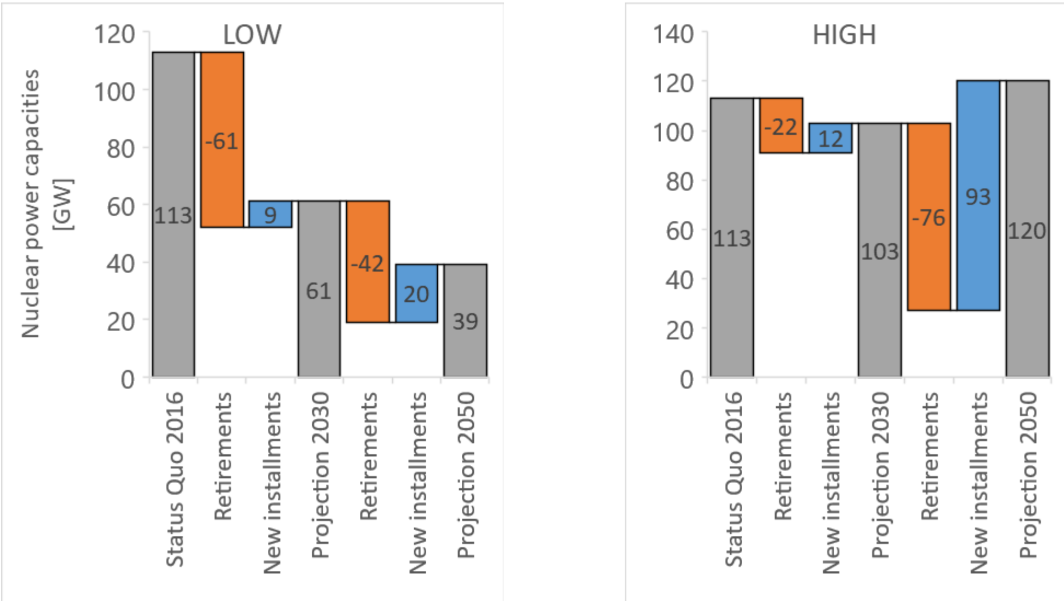

Figure 2: Nuclear power capacities projections in Europe (IAEA, 2017a)[3]

In the HIGH case which corresponds to a beneficial development of framework conditions for nuclear power, retirements are mostly delayed into the period beyond 2030 by life extension measures and the nuclear electrical generating capacity is projected to remain essentially at the level of today.

The LOW case represents IAEA's reference scenario and assumes that current market, technology and resource trends continue and that there are few additional changes in explicit laws, policies and regulations affecting nuclear power. Existing capacities phase out progressively over the upcoming years and are only partially offset by new installations. The share of nuclear electricity will thus decrease from 24.9% in 2016 to 14.8% by 2030 and to 8.2% by 2050. It is particularly noteworthy at this point that IAEA's and the EC's 'continuation of current policies and trends' scenarios diverge that significantly with respect to the future role of nuclear power.

The aim of this case study, therefore, is to conduct a comprehensive technology assessment of nuclear power with a focus on cost estimates and developments. This assessment shall, in turn, lead to an improved representation of nuclear power in SET-NAV's and European modelling of energy transition pathways.

The main methodology to increase our knowledge stock on nuclear power will be desktop research. We screen the relevant literature including peer-reviewed journals, scientific assessments, as well as IAEA reports. The information contained in these reports is consolidated and analysed according to the following guiding categories:

- Costs by reactor design type: Installed costs on new nuclear capacity now and in the future, drivers of these costs, expected fuel cost development and influencing factors.
- System integration: How flexible is nuclear power in a system with a high share of volatile electricity generation?

[3] Not included are here nuclear capacities from EU members from Eastern Europe. In 2016, these amount to 6GW.

- Political framework: How does regulation influence the prospects for nuclear power (relevant developments include e.g. EC State aid guidelines/Hinckley Point, CFD´s in the UK, "Moratorium" in Germany)?

The findings are discussed and reflected with experts within the consortium in order to evaluate the future prospects of nuclear power generation in the EU.

2 Technological concepts

Taxonomies of nuclear power commonly revolve around the choice of the neutron spectrum (fast spectrum and thermal spectrum), the moderator (water and graphite) and the coolant (water, gas, liquid metal, and sodium)

Table 1: Nuclear power plant types 2015 (Adapted from World Nuclear Association, 2016)

Reactor Type	*Number*	*Proportion of Total (%)*	*Neutron spectrum*	*Common Fuel*	*Moderator*
Pressurized water reactor	283	64.0	Thermal	Enriched uranium 235	Light water
Boiling water reactor	78	17.6			
Pressurized heavy water reactor	49	11.1		Natural uranium 235	Heavy water
Others	32	7.3			
Total	442	100			

Water cooled reactors constitute the large majority of civil nuclear power plants. Of currently 442 operating reactors, 96 per-cent are water-cooled. The light water reactor (LWRs) is the most common reactor design worldwide and is divided into two types: Pressurized Water Reactors (PWRs) which produce steam for the turbine in separate steam generators and Boiling Water Reactors (BWRs) which use the steam produced inside the reactor core directly in the steam turbine. All LWRs require fuel that is enriched in the fissile isotope, U-235. Due to the lack of a separate cooling circuit disconnected from the reactor core, the BWR constitutes a simpler design and thus requires lower capital costs. However, it leads to wear at the steam turbine. Heavy Water Reactors (HWRs) use enriched water, i.e. water where 99 % of hydrogen prevails in form of the heavy hydrogen isotope deuterium. Heavy water`- used as a moderator improves the overall neutron economy, allowing for fuel that does not require enrichment.

In Europe, there are currently 129 nuclear power reactors in 14 EU Member States in operation. They have a total capacity of 120 GW and an average age close to 30 years. Half of the EU's nuclear electricity is produced in only one country – France. Again the large majority of currently operating plants are PWRs, with France, Germany, Czech Republic, Netherlands and Belgium, Slovenia operating them exclusively. Sweden is the only European country having more than one BWR in operation. The United Kingdom mostly relies on its own developed advanced gas cooled.

For the further classification of costs, we rely on the segmentation into four generations following its historical development (Locatelli, Mancini, & Todeschini, 2013). However, it must be stated that due to its ubiquity and limited data availability for other designs only costs for pressured water reactors are assessed.

- First generation 1950-1970: Early prototypes of several different designs

- II generation (1970-1995): Commercial plants currently still in operation. (PWR)
- III/III+ (1995) evolution of generation II LWR
- IV Generation (2030+) designs called revolutionary because of their discontinuity with gen III NPPs

2.1 GEN II Long-Term Operation Programmes

As the current European power plant fleet consisting mainly GEN II reactors is reaching the end of its originally intended lifetime, Long Term Operation Programmes gain in importance. Long Term Operation (LTO) programmes designate the extension of the lifetime of nuclear power plants beyond what has been originally licenced. LTOs usually entail comprehensive and capital-intensive safety upgrades as well as the replacement of wearing parts. LTOs are granted for an additional operating time of ten years. In nuclear power reactors, neutron irradiation, high temperatures, and extreme pressures lead to high requirements on the used material. Factors that affect the economics of LTO include replacement of obsolete equipment, safety upgrades to current standards, and the ageing of irreplaceable components such as the reactor pressure vessel or the containment building (OECD, 2012). In Europe, LTOs have to be approved by a national regulatory agency in order to comply with the EU Safety Directive. Existing GEN II PWRs plants were generally licensed with a commercial lifetime of 30 to 40 years. As can be seen in Table 1 LTOs might – assuming regulatory approval and economic competitiveness – considerable extend the lifetime of the European nuclear power plants. The economics of LTOs are assessed in 4.1. Without anticipating 4.1, it can be stated that LTOs dispose of a high perceived economic attractiveness of nuclear power plants. Extending the operation of a depreciated power plant with low variable costs appears to be a no regret option. However, there are several risks and uncertainties that can influence the utilities' decision to extend the operational lifetime of NPPs such as public acceptance, changes in national policies or security, technological risks, and financial risks (OECD, 2012).

2.2 GEN III/III+

As Breeze (2017) states in his comprehensive book on "Nuclear Power", third-generation reactors comprise a group of water-cooled reactors that are based on the main branch of second-generation water-cooled reactor design, the PWR, the pressurized heavy water reactor (PHWR), and the BWR. One of the key design improvements in third-generation reactors is the use of passive safety features such that if a reactor goes out of control, naturally driven processes will shut it down. Other changes are aimed at improving the fuel technology and increasing the overall thermal efficiency of nuclear plants which is low compared to fossil fuel plants.

Another feature of third-generation designs, at least for the European market, is the ability to adapt its output in function of changes in residual load (ref. section 3).

The small modular reactor (SMR) is a specific branch of GEN III PWR that gains particular attention in the literature. The motivation behind SMRs is twofold: Due to its small size of 25-300 MW, it is supposed to be better suited for the deployment in developing countries whose power grids may not support power plants with a standard unit sizes of 1 or 1.6 GW (Kessides, 2010). In addition, capital requirements for the construction of this kind of NPPs are less pronounced and thus less challenging for investors.

Moreover, proponents of this design expect to achieve significant economies of scale through the serial production of small modular, factory-built integral pressurized water reactors. The avoidance of intensive on-site engineering and construction activities shall further improve the competitiveness of this design. von Hirschhausen (2017) reports on a study carried out by the University of Cambridge which proclaims levelized costs of electricity in the order of 65 €/MWh[4].However, this scenario presupposes the construction of 300-500 reactors and thus is discarded as a probable development by the author.

2.3 GEN IV

The catchword of Generation IV nuclear power reactors comprises a multitude of reactor designs currently being researched for commercial applications. The development of these designs is coordinated by the Generation IV International Forum (GIF). The research in novel reactor designs is motivated by a variety of goals including improved safety, sustainability, efficiency, as well as costs and thus leads to several considerably different concepts. However, the most developed Gen IV reactor design, the sodium fast reactor, has received the greatest share of funding over the years, relating mainly to the development of a sustainable closed fuel cycle for the reactors (Baschwitz, Mathonnière, Gabriel, Devezeaux de Lavergne, & Pincé, 2017). A closed fuel cycle implies that exhausted fuel is reprocessed to provide new fuel and thus reduces the volume and longevity of toxic waste generated by the plant. The new fuel generation is generated thanks to the fast neutron spectrum which converts fertile material into fissile material, increasing the efficiency of usage of the nuclear fuel by a factor of 50 (Locatelli et al., 2013).

2.4 Outlook: Nuclear Fusion.

While the discussion about nuclear power is commonly centred on the generation of electricity through the means of nuclear fission, there is another nuclear technology based on the fusion of hydrogen atoms. Significant research and development activities (such as ITER) are currently ongoing in the nuclear fusion branch. Although nuclear fusion promises to provide humankind with sustainable electric energy for millenniums, technological as well as economic issues persist. Whether it will play a role in our future energy system remains uncertain as of today.

3 Flexibility and system integration of nuclear power

Due to their high upfront cost and low variable costs, nuclear power plants were historically designed as base-load power plants intended to mostly operate at nominal capacity. However, two developments lead to significantly increased flexibility requirements for the operating modes of nuclear power reactors.

- In several countries, the share of nuclear power in the gross final electricity generation has become that large that the utility operators had to implement manoeuvrability capabilities to adapt to load variations on all time scales. A prime example is surely France, but in the European Union also Belgium and Slovakia present shares of over 50%. In consequence, the NPPs have to contribute ensuring the balance between supply and demand.
- In addition, the large-scale deployment of intermittent renewable electricity sources (i.e. wind and photovoltaic) significantly decrease the need for baseload capacity and incentivise for load following operating modes. Germany serves as an example where the feed-in of near-zero marginal cost renewable electricity leads to merit order effects on the spot markets (Sensfuß,

[4] All monetary values in this case study are expressed in €2010.

Ragwitz, & Genoese, 2008) and even negative prices (Nicolosi, 2010). As a result, load-following capabilities became important to avoid losses during phases of low spot prices.

As transition pathways towards carbon-free energy systems generally comprise important increases in the deployment of intermittent renewables, requirements for the existing NPPs and newly built plants in terms of flexibility will continue to increase (Cany et al., 2016). To assess the future role of nuclear power in our future energy system and in particular a potential complementarity between renewable electricity sources and nuclear power, energy system modelling should include a precise representation of the manoeuvring capabilities of NPPs. Several questions might arise here: Which technical restrictions apply to the up or down ramping of NPPs? Does the flexible operation have an impact on the lifetime or cost of the plants, components or fuel?

Elements of response can be found in Lokhov (2011); NEA (2011) and Pouret & Nuttall (2007). Table 2 depicts the main flexibility parameters for a novel GEN III+ European Pressurized Reactor[5].

Table 2:[6] EPR flexibility parameters: Adapted from (Lokhov, 2011; Pouret & Nuttall, 2007)

Grid Demand	Power range	Variation rate	Time scale
Load follow	Between 60% and 100%	5% /min	> 15min
	Between 25% and 60%	2.5% /min	
Spinning reserve	± 10%: between 60 and 100%	2% /min	15 min
Frequency control	± 3%	1% /min	30s

It turns out that nuclear power plants can contribute to the frequency control, the spinning reserve, as well as follow a variable load programme. The primary frequency control allows remote short-term adjustments of electricity production up to 30 seconds according to demand usually by varying the torque of the steam turbine. Secondary control acts on the scale of seconds to several minutes. Power output regulation in the load following regime is achieved using neutron-absorbing control rods. Its variation rate is limited due to negative void reactivity coefficients and the effect of xenon poisoning. Exceptions in case of emergency load variations are, however, possible. The parameters for load following in Table 2 are valid during 90% of the fuel cycle, meaning that for the remaining 10% of the cycle the variation rates are reduced. Since most of the nuclear power plants implemented in Europe dispose of load following capabilities, the overall impact of the load-following on the acceleration of ageing of large equipment components is assumed to be limited (NEA, 2011). However, there is some influence of the load-following on the ageing of some operational components, and thus one can expect an increase in the maintenance costs. The high difference in operating and maintenance cost between French and US power plants as observed in Boccard, (2014) can likely be – among other reasons – attributed to the load following regime in France. It should be noted at this point that the British advanced gas-cooled reactors (AGR) are not adapted for load-following. Given their already advanced age, upgrades in this direction can confidently be disregarded - even if hypothetically technically possible.

It can thus be summarised that the majority of the current GEN II PWR, as well as all Generation III and III+, are technically capable of flexible operation modes. However, that does not answer the question whether nuclear power should play the role of load following power plants in our future energy system.

[5] For ramping and load following parameters of other French PWR, please refer to the accompanied parameter data set or (NEA, 2011)

[6] All % values relate to nominal Power

4 Historic, current and prospective costs of nuclear power

Civil nuclear power reactors, used for the generation of electricity, are facilities that can be characterized by their high construction and relatively low operating costs. Due to their enormous size and technical complexity, most components must be specially designed and constructed, often with few potential suppliers worldwide. These components are then assembled on site and structures are constructed to house the assembled components. All stages of design, construction, assembly and testing require highly-skilled, highly-specialized engineers and differences in reactor design and site-specific factors have historically meant that there was little scope for spreading design and production costs across multiple projects (Davis, 2011).

In consequence, the retrospective evaluation of the economic viability of historic NPPs is always a difficult process involving several subjective assumptions. Heated discussions, as well as back and forth within the scientific community, are thus commonplace (Gilbert, Sovacool, Johnstone, & Stirling, 2017; Koomey, Hultman, & Grubler, 2017; Lovering, Nordhaus, & Yip, 2017; Lovering, Yip, & Nordhaus, 2016). Without anticipation of the following review, it shall be pointed out, that the 'true costs of nuclear power plants' can never be reported. Instead, any statements merely represent a more or less consistent approach. Far more than for any other electricity generation method, the costs depend on factors subject to significant uncertainties (Kessides, 2010).

The costs of nuclear power depend on four major components.

- **Capital or construction costs**—includes the costs of the direct engineering, procurement, and construction (EPC) services that the vendors and the architect-engineer team are contracted to provide, as well as the indirect owner's costs, which include land, site preparation, project management, training, contingencies, and commissioning costs. Added to this are the financial charges occurring during the construction period. If one omits these latter parts of the capital costs, it results in the so-called overnight costs, i.e. the costs that occur in the hypothetical case that the NPPs was constructed in a single day. It is subject to debate whether total capital costs or the construction costs are the appropriate measures to analyse historic costs developments of NPPs. One could argue that capital costs give a complete picture, as they incorporate effects of financing conditions but also construction time delays while overnight cost provides a picture less dependent of the external framework and more intrinsic to the technology itself. We will report values for both.
- **Operations and maintenance (O&M)**—relate to administration, management, support and upkeep of a power station (labour, material and supplies, capital upgrades and additions, spares, insurance, security, planned maintenance and contractor services, licensing and regulatory fees, and corporate overhead costs).
- **Fuel costs**—reflect the cost of fuel (uranium, plutonium, thorium, MOX) for the power station
- **Back-end costs**—are those related to the decommissioning and dismantling of nuclear facilities at the end of their operating life and the long-term management and disposal of radioactive waste.

As rule of thumb, capital costs represent about 60% of the total levelised cost, operations & maintenance around 20% and fuel together with back-end costs amount to slightly less than 20%. In the subsections 4.1-4.4, we aim at providing quantifications for the said components and at shedding light on the main drivers leading to changes and thus uncertainties in regards to the total costs. By calculating the net present value of the costs components and dividing their sum by the total amount of generated electricity during the lifetime of the power plant, one obtains the levelized costs of electricity (LCOE). It can be interpreted as the minimum average amount of revenues that a utility must generate over its lifetime in order to break even. The LCOE allows a first economic assessment of the cost competitiveness of different generation technologies, which is presented in 4.1.

Von Hirschhausen (2017) affirms that the cost competitiveness of nuclear power has to be discussed on both the long- and short timescale. Indeed, the scientific debate usually centres on the question, whether a carbon-free energy system requires newly built NPPs (ex.: Brook et al., 2014; Cany et al., 2016; Suna & Resch, 2016). However, while nuclear power plants actually have low variable cost, in light of the mature age of the European nuclear power plants and the increasing feed-in of RES, its short-term competitiveness cannot be taken as granted per se. In response, sections 4.2 and 4.1 tackle this issue.

Finally, this chapter addresses a topic worth highlighting in the context of nuclear power economics: Its positive and negative externalities.

4.1 Capital and construction costs

Construction costs constitute the largest factor in the overall cost of electricity from nuclear power. Due to its size, its use of highly specialised components and materials (reactor vessel, control rods, fuel bundles, particular concretes (Bamonte & Gambarova, 2013)), the requirement of highly specialized engineering as well as on-site construction and assembly, the construction of such plants is a complex process. In addition, the number of potential suppliers for these products and services is currently limited (Davis, 2011). Typically construction durations of around 5 years can be assumed, but much longer construction periods were reported for the more recent American and European reactors (Berthélemy & Escobar Rangel, 2015). Long construction durations are particularly impactful as the substantial financial investment in preparation and construction has to be provided before the plant generates any revenues, which are subject to discounting.

In consequence, the economic competitiveness of nuclear power depends – to a large degree – on the construction costs and the speed of build (Kessides, 2010). While capital costs present a ‘more complete’ picture as they incorporate financing conditions and lead time delays, overnight construction costs are said to better represent the intrinsic costs of the chosen nuclear power plant design. Whether the former or the latter is the more appropriate metric for comparison is under discussion (Lovering et al., 2017).

Table 3 shows capital and overnights costs recently reported for western nuclear power plants from several sources. Boccard (2014) accumulated capital cost data based on the most recent French court of Audit Report and provides a comprehensive cost assessment of the cost of the French nuclear power plant park as well as estimates for the new Gen III+ European Pressurized reactor in Flamanville. Davis (2011) reports from two high impact studies, i.e. the MIT 2009 ‘Update of the MIT 2003 Future of Nuclear Power’ and the U.S. Department of Energy (DOE) 2010 ‘Updated Capital Cost Estimates for Electricity Generation Plants’ study. While their credibility is beyond dispute, Davis states that both studies were completed prior to Fukushima Daiichi nuclear disaster and thus do not incorporate any cost increases due to recent elevated regulatory scrutiny. Finally, Locatelli et al (2013) report from a multitude of sources including the EIA’s annual energy outlook 2011.

Table 3: Reported capital and overnight costs of GEN II/III NPPs

Generation	**GEN III/III+**			**FR GEN II**	**US GEN II**
Author	Boccard (2014)	Davis (2012)	Locatelli (2013)	Boccard (2014)	
Capital costs [€/kW]	5300	3200-4000	1900-3750	1524	2556
Type	Capital costs	Overnight construction costs	Overnight construction costs	Capital costs	Capital costs

As for second-generation NPPs, the high difference in capital costs between reactors build in France and those built in the US is particularly striking: While the French ones were constructed for capital costs of roughly 1500 €/kW, the American counterparts were in average 70% more costly. This is even more peculiar considering that the chosen reactor designs were highly comparable: The first 48 reactors built in France were licenced American Westinghouse reactors. They were built in a short timeframe during the 1980s and displayed according to Boccard (2014) an great overall cost stability with a limited 1.4% yearly growth rate. A stable political framework in France and the reliance on tested and standardized designs can be seen as the main factor enabling such low capital costs.

It must be stated explicitly at this point that these low costs relate to outdated reactor designs that nowadays would not be approved anymore by western regulatory agencies. In fact, increases in construction costs can to a large extent be related to increased complexity due to increased safety requirements (Locatelli et al., 2013). Davis (2012) and Locatelli (2013) estimate construction costs between 1900 and 4000 €/kW for GEN III reactor types with average values exceeding the 'optimal' French costs by more than a factor two.

As for the GEN III+ reactors, the public debate is currently dominated by recurrent news on cost escalations and lead-time delays of the ongoing EPR projects in Flamanville, Olkiluoto and Hinkley Point. Costs and construction time at the first two locates increased by more than two times (Locatelli et al., 2013). Projected total capital costs for those European Pressurized reactors are now exceeding 5000 €/kW. Multitudes of reasons are put forward to retrace the origin of these substantial costs overruns. Proponents of nuclear power emphasise first-of-a-kind issues, i.e. the high learning costs of building the first unit of yet untested innovative technology and the knowledge and competence loss of the involved architect and engineering companies due to the long period without the ongoing construction of new NPPs. This argumentation line implies that NPPs dispose of significant cost reduction potentials due to learning effects and eventually become competitive assuming that one overcomes the high up-front costs for this not yet mature technology. On the other side, the cost overruns are not considered as actual 'overruns' but instead mainly attributed to poor forecasting resulting in overly optimistic cost estimates. Currently observed costs would reflect the increased security requirements post-Fukushima, as well as hidden development cost previously buried into the state's accounts, are now exposed thanks to the greater transparency requirements of public works construction (Kessides, 2010). In turn, they could be seen as a good proxy for future costs.

The discussion cannot be resolved at this point. While any attempts at determining learning curves with actual predictive value have so far turned out to be fruitless, negative learning effects due to ever-increasing security requirements and complexity increments as claimed by (Grubler, 2010; Koomey et al., 2017) based on analysis of historical cost data, cannot be extrapolated indefinitely into the future. Significant costs reductions through standardization and full-scale deployment of nuclear power can – albeit highly unlikely in the current political framework – not be ruled out with certainty.

As for GEN IV reactors, at this point no reliably construction cost forecast can be found in the literature. However, construction costs for GEN III+ reactors can be seen as lower bound for most GEN IV OCC due to their intrinsic increased complexity caused by the closed fuel cycle. (Locatelli et al., 2013).

While much research has been carried out in determining the construction and capital costs of built nuclear power plants and in elucidating the reasons behind historic cost developments and divergences, for the current and future generation estimates for construction cost, remain the subject of high degrees of uncertainty.

4.2 Financing costs

High overnight construction cost, coupled with long lead times make the financing costs a crucial parameter for assessing the economic competitiveness of nuclear power and a substantial part of total project costs. Assuming levelized costs of electricity as the metric of choice for the evaluation, all future revenues generated through the sale of electricity are depreciated by a real discount rate. This discount rate comprises the risk-free interest rate as well a premium reflecting the risk of the project. NPPs are susceptible to a high number of technological but mainly regulatory risk factors that lead to appropriated discount rates well above the risk-free rate. However historically, constructors of NPPs – mainly state-owned electric utilities – benefited from simplified access to funds through loan guarantees. The choice of the discount rate thus significantly impacts the profitability of NPPs, yet turns out not to be a trivial one. Table 4 displays the impact of two different rates on the cost structure.

Table 4: Exemplary cost structures in function of the discount rate (NEA, 2011)

	5% real discount rate	10% real discount rate
Capital costs	58.6%	75.6%
Operation and maintenance	25.2%	14.9%
Fuel costs	16.0%	9.5%
Back end costs	0.3%	0.0%

It turns out that already slight changes in the discount rate lead to substantial shifts in the cost structure. This particularly impacts the capital costs, which in this example increase from 60% to 75% of total projects costs when the discount rate is increased by 5pp. It is lucid, that higher discount rates directly relate to higher capital costs, and thus imply a higher share of capital costs in the. In addition cost incurring in the future, such as the back-end-costs but also fuel costs are depreciated more heavily and thus are less determining for economic viability considerations.

In the literature discount rates between 4.5% and 10% can be found (Boccard, 2014; Koomey et al., 2017; NEA, 2011).

4.3 Operation, maintenance and fuel costs

In comparison to the capital cost, expenses for operation and maintenance and fuel procurement are much less subject to uncertainty and present a much greater cost stability over time. (Boccard, 2014) estimates fuel costs at a value of 7.1-7.3 €/MWh and O&M costs at 19.3 €/MWh (US GEN II)-28.5 €/MWh (French GEN II). The author relates the higher O&M costs in France to inefficiencies of the monopolistic electricity provider EDG but one could also argue that they partly stem from higher wear due to intensive load following (ref. section 3).

Nevertheless, costs for O&M and fuel procurement can much more confidently be extrapolated from historic GEN II onto GEN III/III+.

4.4 Back end costs.

Back end costs primarily relate to those expenditures necessary for the dismantling of the retired power plant as well as the safe long-term deposit of radioactive nuclear wastes. Dismantling a nuclear power plant is a complex process that spreads out over several decades. And while the final disposal of low and intermedium level wastes is established a practice, the disposal of high-level radioactive wastes is an in deep geological repositories is a much more complicated and especially controversial undertaking. Consequently, providing reliable estimates for back-end costs is a complicated exercise, necessarily based on many assumptions. Table 5 shows cost estimates for the dismantling and the disposal of nuclear wastes.

Table 5: Back-end costs of French NPPs according to (Boccard, 2014)

Back-end	**€/kW**
Dismantling	321
Waste	463
Total	784

Interestingly the nominal value of these costs in comparison to the original capital costs is substantial, i.e. in the case of French GEN II reactors, it reaches nearly 50%. However, as the name implies, these costs mainly occur at the end the lifetime of the NPP and thus are particularly impacted by the discounting rate. As regards the economic viability of nuclear power, the back end costs therefore only have minimal influence.

4.5 LCOE of nuclear power

In order to enable cost comparisons of different generating technologies, one can fall back to the levelized costs of electricity (LCOE). LCOE serves as a tool for the economic assessment of the average total cost to build, operate and decommission a power plant over its lifetime divided by the total energy output of the asset over that lifetime. In the case of nuclear power, the total costs comprise capital, O&M, fuel, back-end and if taken into consideration the external costs. The LCOE can also be regarded as the average minimum cost at which electricity must be sold in order to break-even over the lifetime of the project. Table 6 displays reported LCOE of GEN II and GEN III/III+ NPPs.

Table 6: Reported LCOE of GEN II/III NPPs

Generation	**GEN III/III+**			**FR GEN II**	**US GEN II**
Author	Boccard (2014)	Davis (2012)	Locatelli (2013)	Boccard (2014)	
LCOE [€/MWh]	76-117	79	42-95	59-83	65

As for second generation plants, it strikes that although the construction cost for the US reactors was significantly higher than their French counterparts, the final levelized costs are much closer to another. (Boccard, 2014) explains that the benefits reaped through standardization of the plant fleet, the stable regulatory framework and licencing of a fully developed technology were mainly offset by higher operating costs (ref subsection 4.3) as well as a much lower capacity factor (78% vs. 90%). Concerning the overall competitiveness, NPPs LCOE is at best as low as the observed spot market prices and thus historically fall flat in comparison to other generation facilities.

Reports for levelized cost of electricity for GEN III reactors display a much greater variety, with values reaching from 42€/MWh – 117€/MWh. To set these costs in relation, we compare them to The terms of the power purchase agreement for the reactors planned for Hinkley Point C announced in October 2013. This agreement in the form of a contract for the difference would cover 35 years at a predetermined, index-linked price, the so-called 'strike price' amounting to 111 €/MWh.

to inflation (Thomas, 2016). Taking into account a return on investment of 10% for the construction and operating company EDF that would result in levelized costs for Hinckley point C of roughly 100€/MWh. That lies well within the error margin of the values from Table 6. It must be stated clearly at this point that even considering that costs for Hinkley Point C are inflated due to First-of-a-Kind issues, under the current framework nuclear is not competitive with either coal or natural gas. In particular natural gas with reported LCOE of 45-50/MWh (Davis, 2011), has turned out to be the more economic companion of renewable energy sources, also at high shares of intermittent RES and high carbon tax values. (Cany et al., 2016; Suna & Resch, 2016).

However, although the LCOE comparisons in the literature present a clear picture, a conclusion that from a merely economic perspective the role of nuclear power in the future energy system is limited would still be premature. In particular in energy systems mainly based on renewables and very high greenhouse gas emission reductions, the externalities of renewable energy sources in form of integration costs become significant (Hirth, Ueckerdt, & Edenhofer, 2015) and the requirements for flexibility measures considerable. (Cany et al., 2016) therefore suggest a system mainly based on nuclear power generators where the power modulation is achieved by coupling to hydrogen production facilities and increased cogeneration of heat and power (Leurent et al., 2017). Although such a development appears highly improbable, a decisive answer on these questions can only be provided with assessment approaches taking into account dynamic effects and uncertainties.

4.6 Costs of system integration in an electricity system with high shares of RES

In this subsection, we intend to elaborate on the interplay between renewable energy sources and nuclear power. As laid down in section 3, all modern GEN III reactors dispose of the necessary tools to modulate to a large extent their power in function of the grid requirements. This becomes increasingly important when the share of intermittent electricity increases in the system. As regards the GEN II reactors, the same applies to most pressurised water reactors in use in Europe. From an economic perspective, two factors oppose this technical feasibility:

Increased wear: Load-following and frequency control imply numerous and demanding manoeuvres, which increases the constraints on core equipment. In consequence, costs arise from the maintenance and the lifetime issues related to increased wear (NEA, 2011). In addition, the authors report a study from EDF claiming that operating NPPs at their maximum load reduces the unscheduled outage coefficient and thus overall performance. However direct causality could not be established and quantifications for the costs related to increased O&M due to load following could not be found in the literature. In consequence, neglecting this element in the overall cost considerations is the most practical approach.

Decreased capacity factor: The economic consequences of load-following are mainly related to the reduction of the capacity factor(Cany et al., 2016; Kessides, 2010; NEA, 2011). Renewable energy sources with near zero marginal costs shift the merit order towards lowerr costs and thus sometimes pushes nuclear power out of the capacity pool that needs to be dispatched. Expressed differently, they increase the slope of the residual load curve and thus significantly reduce the amount of required baseload. Existing NPPs are in turn forced to proceed with load following to avoid negative contribution margins. The associated reduction of the capacity factor is particularly threatening for the economic viability of capex intensive power plants such as NPPs. (Cany et al., 2016) evaluate scenarios assessing the impact of increasing shares of wind power on the French nuclear. They find that wind and solar penetration of 15-50% lead to revenues losses in the order 12-48%. However, the authors add that effective losses are expected to be even greater because the integration of near-zero marginal cost renewables reduces the electricity wholesale market price. Decreasing capacity factors clearly put into question the economic viability of NPPs, the full extent, however, has once again to be examined through energy system modelling.

4.7 Economics of Long Term Operation programmes

As shown in Figure 2 without any life extensions through long-term operation programmes, the European nuclear capacity would thus fall dramatically until 2030, especially if the construction of new nuclear power plants (NPPs) is also slowed down as a result of the Fukushima Daiichi disaster
Assuming that from a safety perspective, a nuclear power plant is eligible for a long-term operation programme, (NEA, 2011) estimates the capital costs to amount to 500-840 €/KW corresponding to LCOE 23-54 €/MWh. These investments to enable the lifetime extensions already comprise a 10% supplement in order to adopt the required safety feature modification post-Fukushima.

It is noteworthy, that while LTOs generally are considered as profitable, the economic viability of LTOs is by far not necessarily guaranteed at current spot market prices of around 35[7] €/MWh.

4.8 Cost estimates for negative externalities of nuclear power

The comparison of the levelized cost of electricity for different generation states which technology is the most competitive from a purely business perspective and thus indicates into which technology private investors favour. However, this consideration omits positive and negative externalities allocated to the society as a whole but which are not borne by the private investors. Incorporating these externalities in the economic analysis allows drawing a more precise picture about which technology should be build taking total welfare as the decisive criterion.

In the case of nuclear power, estimating these externalities is a complex process. The most recent and comprehensive assessment of negative externalities is provided by (Rabl & Rabl, 2013) who also served as the project coordinator of the cutting edge series "External Costs of Energy" launched by the European Commission. In their article, the authors estimate the costs, resulting from the normal operation of the plant, the nuclear waste and from a possible nuclear accident. They found costs amounting to 2.5 ¬ 32 €/MWh with a most probable estimate of 7.9 €/MWh. In any case, the costs are well below those of conventional generation technologies and roughly similar to those caused by renewables.

[7] Again expressed in €2010.

5 The role of state support for the future development of nuclear power in Europe

The previous sections have illustrated that on the short and medium, private investments into nuclear power plant generation are improbable, given its current low economic competitiveness compared to other generating technologies. With the exception being investments into the lifetime extensions (ref. subsection 4.1). On the long-term, while the economic viability of system based on large shares of nuclear power can ultimately not be ruled out, ongoing high upfront costs and uncertainties regarding actual cost reduction potentials, spot market and CO2 prices oppose such a development. Nuclear power, as of today, can be considered as a non-mature technology, which requires state support if its future role shall be stabilized or even expanding.

Considering also that also historically NPPs did at best break-even over their lifetime (ref subsection 4.5) it has to be inquired for civil nuclear power why it continues to play a prominent role in future energy systems, such as projected by the European Commission and others. (von Hirschhausen, 2017) comprehensively explore this question and relate the ongoing reliance on the phenomenon of 'economies of scale'. In consequence, even without direct economic viability in the civil electricity generation sector, nuclear power would make sense for those countries able to exploit to a large degree 'possible 'economies of scope'

Without a doubt, reliance on civil nuclear power entails benefits that are not directly incorporated in the economic assessment:

- Environmental benefits:—reduced GHG emissions to be gained from adding nuclear rather than coal- or gas-fired generating capacity.
- Fuel mix diversification: nuclear power can serve as a hedge against uncertain fossil fuel and carbon price development. Considering volatile fossil fuel prices and significant uncertainties underlying the future price of carbon, non-fossil technologies have an ''option value'' (Rabl & Rabl, 2013).
- 'Benefits of scope': Keeping civil nuclear power would reduce costs in the complementary military branch and uphold attractiveness of the nuclear sector for highly qualified personnel. In addition, synergies with the nuclear fusion branch appear conceivable.

As a result, states might be willing to continue to support civil nuclear power, even while acknowledging its limited economy. This may be especially valid for countries such as France or the United Kingdom that keep the nuclear strike capacities. In their cases providing the means to lift the issue of high upfront cost and of the large market, uncertainties seem critical to keep civil nuclear power in the liberalized electricity markets of today and tomorrow. State support in form of feed-in premiums or similar version has been central to developing recent EPR projects such Hinkley Point C, and Olkiluoto (IAEA, 2017b).

6 Conclusions

This case study assesses the perspectives for nuclear power with a focus on cost estimates. Total project costs for nuclear power plants mainly are mainly determined by the construction and financing costs and only to a lesser extent on operations and maintenance, fuel, and back-end costs. Significant nuclear power specific technological, regulatory and market risks and uncertainties lead to wide range of cost estimates, particularly for the newest GEN III reactor types.

Financing issues related to high up-front costs, as well as recent developments in the power markets such as the decline of natural gas prices but primarily the large-scale deployment of renewable energy sources challenge the economic viability of nuclear power in our liberalized energy markets. While technically possible in most cases, a flexible operation of the NPPs to complement the feed-in of intermittent renewables is undesirable from an economic perspective. Market-based expansion of nuclear power plants is thus not to be expected, with the exception of long-term operating programs that may stabilize the share of nuclear power during the upcoming decade.

Certain Member States of the EU might, however, continue to rely on nuclear power for reasons beyond the merely economic viability. We thus agree with the proposition of von Hirschhausen (2017) to exclude the deployment and dispatch of new nuclear power plants out of the modelling process and to rely on exogenously set capacity assumptions.

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