"The Energy Transition"

What is the role of nuclear technology in a world of growing alternative power and digital innovation?

Antonio VAYÁ SOLER
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OECD-NEA (ex-Framatome)

Executive Summary

The energy transition is a whole new paradigm that is disrupting the world's economy in a way never seen before. In the near future, the resulting energy system will certainly be 4D: decarbonized, decentralized, digitalized and deregulated.

Guided by technology agnosticism and strategic diagnosis principles, nuclear power technology is analyzed in detail in the present report to highlight its potential to succeed in the 4D energy scenario.

The role of nuclear energy in decarbonized economy is undeniable. In fact, nuclear power is the only dispatchable (non-intermittent) low-carbon technology for electricity generation ready to be deployed massively. The IEA's 2DS projections show that nuclear power is one of the major contributors, up to 15%, in GHG emissions savings. Despite these benefits, nuclear development is not on track to meet 2DS targets. This situation is mainly due to the high upfront costs of this technology and current difficulties in western countries to deliver new nuclear projects on time and on budget.

Huge investments in variable renewable energy (VRE) resources are also needed to decarbonize the electricity generation system. VRE development will lead to a progressive decentralization of the energy system in order satisfy the increasing appetite for self-consumption. Nevertheless, VRE has one main drawback: intermittency. In the short term, nuclear power will be the capacity backbone assuring grid flexibility and stability. The presence of big nuclear power plants could be, however, restricted in the long term. In this case, Small Modular Reactors (SMRs) emerged as a competitive solution in an energy scenario with a high penetration of VRE and distributed electricity generation.

Digitalization is a huge opportunity to increase the global competitiveness of nuclear technology. On the one hand, it facilitates the development of smart grids, which are beneficial for baseload nuclear. On the other hand, it will reshape the entire nuclear industry. Different digital levers like *System Engineering*, *Building Information Management* and *Product Lifecycle Management* can be harmoniously combined with *Knowledge Management* practices to reduce construction costs and increase millennials retention. Though, this transformation will take some time (at least 10 years) given the organizational/cultural changes at stake. This revolution will also be noticed in the value side of nuclear industry. New revenue streams will appear and enhanced modes of stakeholder/ecosystem interaction will be possible. For instance, utilities and their revisited business models, could take advantage of technologies like the blockchain. This technology and its unique capabilities for cost-effective and transparent traceability, may unleash and monetize the true value of nuclear power. Cybersecurity of nuclear power plant could also be reinforced with blockchain solutions.

Driven by economies of scale and learning effects, VRE is becoming more competitive than new nuclear builds. Furthermore, the high fixed cost structure of nuclear technology is not suitable for deregulated market conditions. SMRs are again an alternative to increase competitiveness in uncertain economic environments. Improved competitiveness is also possible in both cost/value sides through standardization, new policies, digitalization and innovative financing modes. The final objective is to lower financial risk which is one of the main cost driver alongside construction costs.

If the digital transformation of the nuclear industry is finally a success, delivering new nuclear projects on time and on budget could become a reality. Consequently, the atmosphere of distrust between nuclear stakeholders will gradually vanish. Building trust around nuclear power will reduce risk, increasing its competitiveness and attracting more funding for new projects. This virtuous cycle would boost nuclear development, clear the pathway to meet 2DS targets, and build a more sustainable energy system for all of humanity.

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Content

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1 Introduction

During the 21st Conference of the Parties of the UNFCC[1] held in Paris in December 2015, 195 countries signed up to respond to the global climate change threat. An ambitious goal was set: to keep global temperature rise well below 2ºC above pre-industrial levels. This diplomatic success known as "The Paris Agreement" forged the way towards a low-carbon economy. Since then, most developed and developing countries are undertaking major endeavors to assure this transition.

In parallel, a new ecological conscience is starting to emerge everywhere as people realize that their habits have an impact in the global carbon footprint. Thanks to the falling costs of digital devices and renewable energy, prosumers[2] are increasingly taking the lead. Consequently, utilities are forced to adapt their business models to cope with a more decentralized energy system that is changing at an astonishing speed.

By 2040, the global energy mix will be the most diversified the world would has ever seen[3]. What is the role of nuclear power in this whole new energy paradigm called "The Energy Transition"?

2 Methodological framework

The methodological framework used to answer to this question is based on two main pillars: technology agnosticism and strategic diagnosis.

Technology agnosticism provides an unbiased vision of the use of different technologies to solve the problem of the energy transition. There's no silver bullet and each technology has the same chance to succeed. A neutral assessment of the performance of each technology is then carried out using strategic diagnosis principles.

First, an external analysis is done in order to define the most likely energy scenario in which different technologies may be forced to compete. The main tools for accurate external analysis are Energy scenario method[4] and PESTEL[5]. Second, an internal analysis allows to evaluate strengths and weaknesses of each technology.

Finally, both analyses are matched[6] to show up the potential of nuclear power in the energy transition paradigm as well as to identify the main opportunities to succeed in the selected energy scenario.

3 Energy scenario definition

As discussed in the previous section, strategic diagnosis begins with an external analysis. Energy scenario methodology[4] is utilized to this purpose.

During the *OECD Forum 2017*, Isabelle Kocher[7] explained what the energy industry will look like in the coming years. According to her: "the technological energy revolution is a 3D world: decarbonisation, decentralization and digitalization". In only one sentence, Engie's CEO seamlessly captured the most likely energy scenario to come.

Three main sources have been extensively analyzed in this report[8,9,10] to confirm her vision. However, the 3D scenario does not explain, for instance, why in Europe onshore wind can be as competitive as existing nuclear[10] (see §4.4 and **Exhibit 4**) or the impact of low gas prices in the American nuclear fleet[11]. In reality, the 3D scenario does not capture current liberalized market conditions. That is why an enlarged version of Kocher's scenario is proposed in this report:

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[1] United Nations Framework Convention on Climate Change
[2] Energy consumers who have the choice to buy electricity from a retailer or to produce at least part of it and sell the surplus.
[3] https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html
[4] http://ceepr.mit.edu/files/papers/2016-007.pdf
[5] PESTEL is the acronym for Political, Economic, Social, Technological, Ecological and Legal. This tool captures the importance of macro-environmental factors when talking about future energy trends (e.g. regulatory frameworks, public acceptance, millennials retention, etc.).
[6] https://en.wikipedia.org/wiki/SWOT_analysis
[7] Engie's CEO.
[8] https://www.iea.org/newsroom/energysnapshots/
[9] https://www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf
[10] https://www.capgemini.com/fr-fr/wp-content/uploads/sites/2/2017/11/wemo2017-vst27-web1.pdf
[11] Since October 2012, US nuclear plant owners have closed or announced closure of 14 reactors due to Henry hub gas prices are at historic lows. FirstEnergy Solutions has recently filed for Chapter 11 bankruptcy reorganisation which evidences the critical situation some nuclear owners are facing.

the 4D scenario, where the fourth "D" stands for deregulated[12] market conditions. As PESTEL analysis[5] indicates, this renewed scenario is subjected to two main assumptions: regulatory and policy frameworks might not evolve in the coming years alongside the absence of major nuclear accident.

4 The 4D scenario and nuclear power

The previous section was devoted to the external analysis and led to the definition of the most likely energy scenario for nuclear technology: the 4D scenario. To demonstrate the true potential of nuclear power in this scenario, a complementary internal analysis is needed (see §2).

4.1 Decarbonisation and nuclear power

There is scientific consensus that, in order for the world to meet Paris Agreement targets, global annual greenhouse gas (GHG) emissions (where CO_2 accounts for 90% of these emissions) will need to be reduced by at least 50% from today's levels by 2050. The International Energy Agency (IEA) has transformed this target into the so-called 2ºC Scenario or 2DS (see §7.1).

The energy sector is responsible for about 70% of total GHG emissions. From this 70%, 40% of the emissions come from the power generation sector. Consequently, around 30% of total GHG emissions are due to electricity production. This sector is hence capturing most of the governments' attention as it has the greatest chance to succeed in the short/medium term[13].

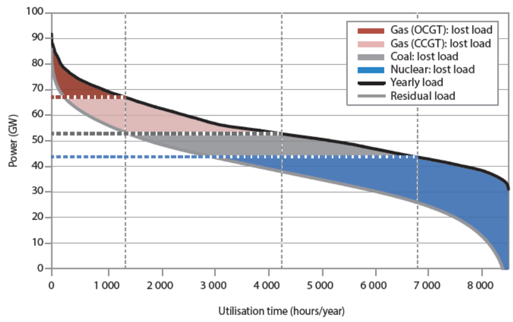

Exhibit 1: Compressing effect after VRE introduction

4.1.1 Potential of nuclear energy in the 2DS

The potential of different technologies to decarbonize the power generation system can be assessed using the carbon footprint concept[14]. According to the IPCC (see **Table 2**), nuclear power is among the technologies with the lowest carbon footprint with 12 gCO_2eq/kWh.

Other technologies like wind power and solar PV have significant potential but they are inherently interment (see §4.2). Hydropower and geothermal are low-carbon dispatchable resources but their massive deployment is limited. The only remaining technology for massive dispatchable low-carbon electricity is nuclear. Further, its carbon footprint is one of the lowest. The potential of nuclear energy to decarbonize the power generation system is undeniable.

The IEA's 2DS projections show that nuclear power is one of the major contributors (up to 15%) in GHG emissions savings over the period of 2012-2050 alongside energy efficiency (25%), wind (15%) and solar (14%). With a current large base of generation, nuclear power could represent the single most important low-carbon electricity generating technology[13].

4.1.2 Projected nuclear development in the 2DS vs. current development

In the 2DS, nuclear capacity should increase from 390 GW in 2012 to 930 GW by 2050 (a factor of 2.4)[13]. This would require annual grid connections rates around 12 GW/year in the present decade, rising to well above 20 GW/year in the following decade[15]. These grid connection rates are technically possible as they have already been observed during the 80's with rates ranging from 15 GW/year to 30 GW/year. Nevertheless, current connections are far below these projections (in 2017 only 3 construction starts and 3.3 GW connected to the grid[16]). New nuclear capacity deployment

[12] Energy market is regulated in some way (subsidies, price premiums for some technologies, etc.) depending on the country policy framework. For the purpose of this report, the term "deregulated" represents current liberalized market conditions observed in the most modern economies.

[13] https://www.oecd-nea.org/ndd/pubs/2015/7208-climate-change-2015.pdf

[14] The carbon footprint is the total amount of CO_2 emitted over the full life cycle of a product or process from extraction of raw materials to decommissioning. It is classically expressed as gCO_2/kWh.

[15] https://www.iaea.org/NuclearPower/Downloadable/Meetings/2014/2015-02-03-02-06/D2_S3_OECDNEA_Paillere.pdf

[16] https://www.iaea.org/pris/

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needs to accelerate in order not to jeopardize 2DS commitments and for that, improved competitiveness of existing nuclear and especially new nuclear is necessary.

In fact, one of the main hurdles for current nuclear development is the incapability of the nuclear industry (mainly in western countries) to deliver nuclear power plants (NPP) on time and on budget. The technology roadmap proposed by the Nuclear Energy Agency (NEA)[15] stands out the responsibility of the nuclear industry to improve constructability, reduce cost and hence increase global competitiveness of nuclear technology. As it will be discussed later in this report, digitalization is the main lever for nuclear industry to achieve this objective (see §4.3.1).

4.2 Decentralization and nuclear power

VRE has a main drawback: intermittency. A massive VRE deployment may have short and long term effects (see **Exhibit 1** and **Exhibit 2**) that are not negligible and depend strongly on the power system capabilities to adapt. The process of increasing the share of VRE while assuring the balance of the grid in a cost-effective way, is commonly known as VRE integration.

The IEA has identified four phases in VRE integration[17]. Each phase is also a step forward towards decentralization and should be supported by performant solutions capable to guarantee increased flexibility and stability of the grid: interconnections development, dispatchable back-up capacity, energy storage and enhanced demand response through smart grids development.

Massive energy storage with batteries could be the final solution for VRE integration but they are still prohibitively expensive[18]. The added flexibility to the grid induced by batteries it may be limited in the short term. The energy transition cannot wait the high costs of batteries to fall. Nuclear has an active role to play during these four phases and can certainly find its place in a distributed power generation system.

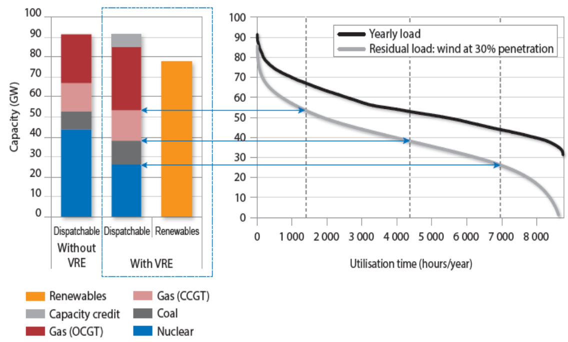

Exhibit 2: Re-optimization of the energy mix after VRE introduction

4.2.1 Short term situation[19]

The only low-carbon dispatchable technology with large potential for massive deployment is nuclear. Low-carbon central facilities like big NPP[20] are the backbone supporting energy transition as they provide capacity when needed increasing the overall reliability of the system. New services for the grid could emerge in the near future and nuclear energy can take advantage of them to increase its profitability (see §4.4).

Another issue that NPP should deal with is the compressing effect of the load curves (see **Exhibit 1**). In the short term, the power system has no time no adapt. VRE priority of electricity injection reduces capacity factors of existing generators. The resulting residual load curve[21] seen by dispatchable technologies is shifted to a lower level. Despite the financial impacts of this effect, NPP can technically cope with load variations through load-following. Extensive experience in load-following has been accumulated in countries like France and Germany. NPP and VRE can therefore cohabite together in the energy transition with nuclear technology assuring (to some extent) the flexibility and stability demanded by the grid.

4.2.2 Long term situation[19]

In the long term, as the system has more time to adapt, investments and disinvestment will be used to optimize the energy mix (lowest production cost). The energy mix may shift from a high fixed cost structure to a more flexible and variable one which is the optimal solution to cope with the intermittency of wind and solar power. Under these conditions,

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[17] https://www.iea.org/newsroom/energysnapshots/share-of-vre-generation.html
[18] According to Capgemini's World Energy Observatory 2017 report, lithium-ion (Li-ion) battery pack were $300/kWh in 2016.
[19] https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf
[20] Power output greater than 1000 MWe.
[21] Residual power = Power demand – VRE generation.

high shares of VRE could accelerate nuclear power phase-out (see **Exhibit 2**). However, digitalization is making grids smarter and this could have two different consequences for nuclear energy.

Smoothing load curves

Through enhanced demand response, smart grids are able to change load profiles to reestablish a continuous demand for longer periods of time. This leads to a reduction of compressing effects, higher capacity factors and hence increased profitability for baseload nuclear. Smart grids are also more flexible allowing the integration of nuclear power with high shares of VRE in a harmonious and cost-effective way.

Restricted access to large NPP

Smart grids will also enable decentralized energy generation from smaller units where demand/supply balancing is performed on a more local scale restricting the demand for larger NPP. These conditions of energy production require more intensive load-following modes that are less attractive economically and even not technically possible for some current NPP concepts.

Small modular reactors (SMRs) are more suitable for smart decentralized communities thanks to their reduced size and improved capabilities to load follow mainly based in a multi-module approach[22]. Critics to SMRs point at the danger of spreading radioactive material more widely, increasing proliferation risks.

4.3 Digitalization and nuclear power

Digitalization is a huge opportunity to increase global competitiveness of nuclear technology. On the one hand, it will accelerate development of smart grids and thus release the associated benefits for baseload nuclear (see §4.2.2). On the other hand, it will reshape the entire nuclear industry. Digital transformation is the occasion for nuclear organizations to rethink their current processes not only to seek for costs savings but also to find new revenue streams. It's a completely new corporate mind-set of how organizations can create value.

4.3.1 Cost approach

On February 2016, NEI published "*Delivering the Nuclear Promise"* and set the challenging target of 30% reduction of nuclear generating cost by 2018[23].

The feasibility to achieve this objective with digital solutions is assessed in the present report. The cost definition considered is the Levelised Cost of Energy (LCOE)[24].

Table 1 summarizes the main cost drivers with the highest potential for reduction using current industrial digital solutions. They have been obtained from a detailed nuclear cost breakdown after the analysis of different sources[19,25,26,27] (see **Table 3**). The reference case considered is the French LCOE for new nuclear for a weighted average cost of capital (WACC) of 7%[26] (see **Exhibit 3**). Three blocks of actions have been identified. The related digital solutions that can be mobilized will be discussed later in this section. The potential gains have been set by engineering judgement. They don't take into account learning effects which will be analyzed in detail in section §4.4. With all these assumptions, final potential LCOE savings through digitalization account for 26%. This value is aligned with NEI's predictions though, to be effective, more than two years will be necessary given the organizational/cultural changes at stake (see Block 3 analysis).

Block 1: Construction costs reduction for new nuclear

Construction costs are one of the most important cost drivers as they represent almost 60% of total investment costs[27]. To accelerate nuclear development, this cost item should be tackled in priority (see NEA's technology roadmap[15]). The

[22] https://ecee.colorado.edu/~ecen5009/Resources/Nuclear/Ingersoll2015.pdf
[23] http://www.bhienergy.com/assets/Delivering-the-Nuclear-Promise.pdf
[24] https://en.wikipedia.org/wiki/Cost_of_electricity_by_source
[25] https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf
[26] https://www.connaissancedesenergies.org/sites/default/files/pdf-pt-vue/cour_des_comptes_rapport_cout_production_electricite_nucleaire.pdf
[27] http://www.sfen.org/sites/default/files/public/atoms/files/les_couts_de_production_du_nouveau_nucleaire_francais.pdf

main digital levers for construction costs reduction are: *System Engineering* (SE), *Building Information Management* (BIM) and *Product Lifecycle Management* (PLM) (see §7.4 for further information).

The combination of these solutions enhances modular design, shop fabrication and parallel construction resulting in lower work densities, improved on-site access and hence overall labor cost compression. Supply chain integration also enables the application of *Just in Time* principles reducing the risk of stock obsolescence. The cost impact of site-specific rework is likely to rise as complexity of nuclear designs increases (see §7.3). Previous digital levers can certainly keep these costs under control (see also §4.4). IDC depend mainly on project's risk and lead-time. Reduced construction time induced by digitalization will certainly have a positive impact in IDC and thus in global investment costs. Risks issues will be addressed in detail in §4.4.1. Augmented reality tools can also improve overall on-site work efficiency.

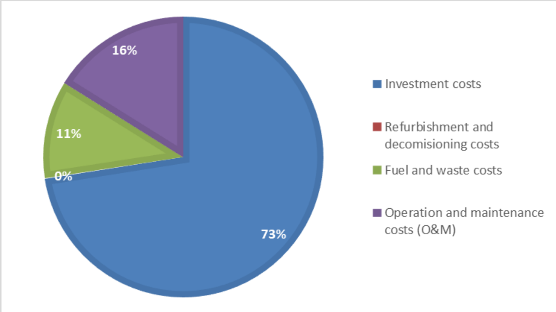

Exhibit 3: French LCOE (WACC=7%)

Block 2: O&M costs reduction for existing nuclear

Operational and maintenance (O&M) activities only represent 16% of total production costs. But its reduction is the only way of increasing the competitiveness of the current nuclear fleet which is already amortized. The main digital levers identified are Internet of Things (coupled to data analytics solutions) and digitals twins. These solutions may lead to significant costs reductions thanks to improved preventive maintenance[28]. Additive manufacturing could also reduce repair cost of complex components. The first additive manufactured component has been already installed in Krško plant by Siemens[29]. Finally, augmented and virtual reality could also improve the on-site operations efficiency.

Block 3: Effective 30% cost reduction target and beyond

In order to meet the 30% nuclear generation costs reduction target, deeper organizational/cultural changes are needed. The first big change addresses the way knowledge is managed in nuclear organizations.

Nuclear industry, as a knowledge-intensive activity, has already taken advantage of *Knowledge Management* (KM) principles. They have been classically used on expert knowledge elicitation. Using Pareto's rule, this might represent only 20% of the total knowledge capital of a firm. Current KM practices are unable to capture and spread the remaining 80% of good practices managed tacitly by different teams. Nuclear organizations should embrace the knowledge economy paradigm[30] (see §7.5) based on digital platforms and communities of practice (CoPs) where knowledge is managed collectively. According to John P. Kotter, traditional hierarchies can cohabite with network-like structures like CoPs rendering the whole organization more flexible and adaptable[31]. To reach this organizational optimum without compromising the safety culture, adaptive approaches based on "*test and learn*" principles could be used[32].

The second big change is about how to combine all these digital levers to effectively yield the expected benefits. In reality, a new digital tool alone does not guarantee better performance. Digital levers must be considered with the process that comes along. Some processes can be automated, another streamlined but with process reengineering[33], the perfect marriage between technology and processes is possible to take performance to the next level. For instance, the digital levers discussed in Block 1 could be harmoniously combined with KM practices to assure the digital continuity of the data. SE, BIM and PLM cascade the data from systems to subsystems, from engineers to subcontractors throughout the entire lifecycle while assuring accessibility and perfect traceability of all modifications. Then, KM, is the bottom-up process picking up lessons learned from the field (design, construction site, etc.) to create a digital learning environment.

If this organizational/cultural shift is carried out with success extra cost savings are even possible. Nuclear could reach a sustained competitive advantage that did not have before[34]. However, the "human" dimension in digitalization should

[28] https://analysis.nuclearenergyinsider.com/ge-hitachi-expands-exelon-analytics-learnings-us-nuclear-fleet
[29] http://www.world-nuclear-news.org/NN-Siemens-prints-part-for-Krsko-plant-0903174.html
[30] https://en.wikipedia.org/wiki/Knowledge_economy
[31] https://hbr.org/2012/11/accelerate
[32] Build-Measure-Learn feedback loop. See: https://en.wikipedia.org/wiki/Lean_startup
[33] https://en.wikipedia.org/wiki/Business_process_reengineering
[34] See VRIO analysis: https://en.wikipedia.org/wiki/VRIO

not be neglected. Two thirds of digital transformation fail[35]. Change management principles and a longer time-frame (at least 10 years) should be taken into account to reduce overall risks. Human-centered approaches like *Design Thinking*[36] could be used to improve users (engineers, on-site workers, etc.) experience and diminish change resistance.

Further cost reductions are possible if financial risk is lowered (see §4.4).

Table 1: Main cost drivers with the highest potential for reduction with digital solutions

		Effective weight (%LCOE)	Gain (%)	Savings (%LCOE)
Block 1 Construction costs	Labour costs[37]	17.2%	30.0%	5.2%
	Indirect costs[38]	12.3%	30.0%	3.7%
	Interests during construction (IDC)	14.6%	20.0%	2.9%
Block 2 O&M costs	Staff	6.4%	20.0%	1.3%
	Consumables	3.2%	50.0%	1.6%
	Repair costs	2.4%	50.0%	1.2%
Block 3	KM initiatives and process reengineering			10.0%
				26%

4.3.2 Value approach

Delivering the nuclear promise is also a matter of value. When talking about value, the first word that comes out is innovation. Innovation is everything that creates value for the final customer, from technological evolutions to new processes and business models. The Innovation Radar[39] provides 12 different ways organizations, including nuclear industry, can innovate. Multiples opportunities are thus offered for vendors, safety authorities and utilities.

Vendor's perspective

Innovation in the nuclear industry has been classically of technical nature. Over the past years vendors have proposed more advanced designs to meet new safety standards in a more cost-effective way. Bringing these models to the market is a long process as nuclear knowledge creation takes time and needs to be validated by safety authorities. In addition, vendors are usually big companies that are specialized in productivity and not in creativity. On the contrary, startups are adept at dealing with the turbulent process of disruptive innovation.

Using open innovation, vendors increase the porosity of their borders to interact with their technological ecosystem formed by SMEs and startups[40]. New ideas are then brought in to accelerate the time-to-market of new designs or to consolidate decommissioning best practices. Vendors' interactions could also include utilities and safety authorities. The whole process can be streamlined with roadmapping[41] techniques and digitally enabled with platforms.

On the other hand, non-technical innovation cycle is much shorter. Vendors have a wide range of market value capturing options[42] at their disposal, such as: monetizing digital data[43] or intellectual property[44]; new customer relationships and services through platforms[45], etc. Digitalization is at the core of most of these innovations.

Safety authorities' perspective

Safety authorities' digital transformation is ongoing[46]. Applying open innovation principles would facilitate collaboration between different safety authorities and stakeholders leading to a harmonization of licensing regimes[47].

[35] https://www.consultancy.uk/news/2656/two-thirds-of-digital-transformation-projects-fail
[36] https://www.ideo.com/post/design-thinking-in-harvard-business-review
[37] Direct recurring cost computed as the number of commodity units x unit installation rate (hr/unit) x unit labor (cost/hr).
[38] These costs regroup design, project management and licensing cost. See also §7.3.
[39] https://www.researchgate.net/publication/3228477_The_Twelve_Different_Ways_for_Companies_to_Innovate
[40] http://www.westinghousenuclear.com/welink
[41] https://cemi.com.au/sites/all/publications/Lichtenthaler%202008.pdf
[42] Yield management principles: https://www.researchgate.net/publication/265509435_Capture_More_Value_Innovation
[43] Selling 3D mock-ups and digital twins.
[44] Open innovation also means bringing ideas out in exchange for money.
[45] For instance, a community where operators are invited to talk about improvements, on-site modifications of a given technology, etc.
[46] http://www.world-nuclear-news.org/RS-US-regulator-highlights-transformation-goals-2103187.html
[47] http://world-nuclear.org/harmony

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Utilities' perspective

Utilities can also take full advantage of open innovation principles discussed previously. Nevertheless, current market trends (see §3) are pushing utilities to change their business models in priority. Driven by digitalization, utilities are progressively leaving integrated asset-based logic for less integrated more service-oriented logic[48]. Current restructuring (RWE, EDF, etc.)[49] is a clear signal of what is going to come: from prosumers, passing through smart grids to the blockchain revolution[9].

The blockchain

This digital ledger has unique capabilities that could help utilities with nuclear assets to deliver more value (see §7.6).

It's hence possible to imagine prosumers with ecological conviction buying a differentiated nuclear MWh at a premium price as it has been produced safely in low-carbon conditions. Blockchain might enable MWh differentiation through improved asset management[50] and cost-effective certification of origin[51]; all these sources of value captured in digital blocks and transferred using cutting-edge algorithms. Carbon trading could also be enhanced[52] resulting in extra revenues for utilities with nuclear assets.

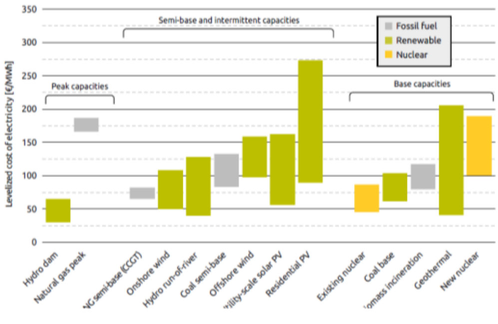

Exhibit 4: LCOE of different technologies in Europe starting production in 2016-2017

Furthermore, blockchain could help to gain public acceptance and fight fake news with a public surveillance of assets' state.

Previous statements are only future projections based current trends. This technology has still in front of it many hurdles to overcome: scalability and high energy consumption, capability to deal with additional layers of transaction and, the most important of all, many legal and regulatory issues[9].

4.3.3 Cybersecurity

Some cyber-attacks to NPP have already been reported[53]. These cyber-security concerns could prevent nuclear operators from introducing new technologies needed to reduce O&M costs (see §4.3.1). Owing to their distributed nature, blockchains provide no 'hackable' entrance or a central point of failure. This increases security when compared with present database-driven transactional structures[54]. Connecting the data analytics solutions of several NPP with a blockchain could improve their overall cyber defense.

4.4 Deregulation and nuclear power

Long term operation of NPP in Europe is still interesting from a financial point of view[55] bearing that LCOE is lower than 50€/MWh (see **Exhibit 4**). New nuclear, though, suffers from competition from VRE. Economies of scale[56] and learning effects underpinned by massive deployment and political support explain the cost reduction of VRE. These effects are obviously applicable to nuclear energy but they need further assessment.

Learning effects for nuclear power are quite special. In fact, they are a typical example of Simpson's paradox[57]. Locally, for a given design, learning effects are positive. However, globally, construction costs increase with time leading to

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48 https://www.pwc.com/gx/en/utilities/publications/assets/pwc-future-utility-business-models.pdf
49 https://www.reuters.com/article/edf-nuclear-restructuring/france-weighs-edf-restructuring
50 Start-up Grid Singularity is using blockchain to collect energy generation and equipment performance data.
51 Volts Markets in US uses blockchain to track Renewable Energy Certificates (RECs).
52 https://powerledger.io/media/Power-Ledger-Whitepaper-v8.pdf
53 https://analysis.nuclearenergyinsider.com/nuclear-cyber-security-research-sharpens-digital-upgrade-valuations
54 https://www.infosecurity-magazine.com/next-gen-infosec/blockchain-cybersecurity/
55 http://s538600174.onlinehome.fr/nugenia/wp-content/uploads/2014/02/7054-long-term-operation-npps3.pdf
56 Market trends show that on-shore and off-shore turbines are getting bigger leading to a lower investment per energy unit.
57 Simpson's paradox is a phenomenon in probability and statistics, in which a trend appears in several different groups of data but disappears or reverses when these groups are combined.

negative learning effects (see **Exhibit 5**)[27,58]. This exhibit also shows a diseconomies of scale effect which is aligned with the results of other studies[59,60] (see §7.7 for further information).

It is important to remember that nuclear is a high fixed costs technology (see **Exhibit 3**). It needs long-term visibility and high capacity factors to be performant; if not, profitability is quickly undermined. Deregulated market conditions are more unpredictable by nature. Variable cost structures perform better in these conditions as they have less inertia to follow the pace set by the market.

In order to improve the financial performance of nuclear power, some solutions are proposed hereafter following the cost/value dichotomy used in section §4.3.

4.4.1 Cost approach

Good conditions for nuclear development

Economies of scale and learning effects could offset the upwards pressure on cost of regulatory changes under certain conditions. These conditions are presented in the *pipeline* model (see §7.8) where cost reduction is mainly driven by the standardization of the nuclear fleet.

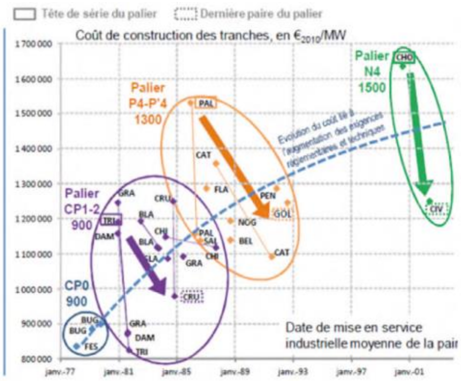

Exhibit 5: Construction costs of French's nuclear fleet

Digitalization

As discussed in §4.3.1, a digital tool combining SE, BIM and PLM supported by KM practices may release positive learning effects while keeping complexity under control. The recent success of South Korea on the Barakah[61] project is mainly due to the use of BIM 4D solutions[62].

SMRs potential

Thanks to their more variable cost structure, SMRs are more suitable for liberalized market conditions with high penetration of VRE. In a long term optimal energy mix, they are suitable for replacing coal plants[63,65]. The enhanced modularity of this technology allows factory manufacturing, which reduces lead-times and thus investment costs drastically[64]. Due to their limited power output, FOAK SMRs will certainly have higher construction costs per MW than bigger reactors (absence of economies of scale). However, their potential for developing positive learning rates is greater (volume effects and surveilled factory environment). With sufficient time, SMRs could become cheaper than big reactors[60, 65] (see §7.9). In addition, SMRs have the advantages of much smaller upfront cost and increased financing flexibility. These characteristics, together with shorter lead-times, result in reduced financial risks making such reactors more attractive for private funding[66].

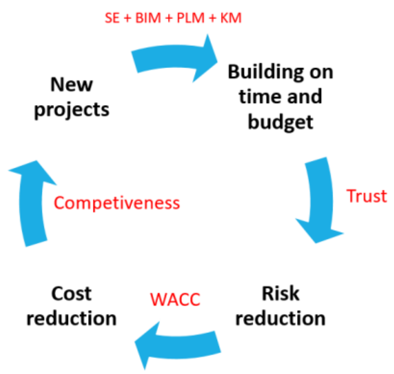

Exhibit 6: Virtuous cycle for nuclear development

Risk and financing issues

Nuclear power is a capital-intensive activity. Consequently, WACC has a huge impact on the LCOE of this technology. For instance, in France, shifting from a WACC of 7% to 3% leads to a LCOE reduction of 40%[19] (greater than the

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58 https://crawford.anu.edu.au/publication/nuclear-power-learning-and-deployment-rates
59 Cantor R., Hewlett J. *The economics of nuclear power: Further evidence on learning, economies of scale and regulatory effects*.
60 https://arxiv.org/ftp/arxiv/papers/1802/1802.07312.pdf
61 http://www.world-nuclear-news.org/NN-Barakah-1-construction-formally-complete-2603187.html
62 https://www.iaea.org/NuclearPower/Downloads/Technology/Experience-APR1400-Construction-(Seo).pdf
63 https://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf
64 The 1-3-8 rule from shipyards: the same task in a factory is 3 times longer in a pre-assembly plant and 8 times longer in the ship.
65 https://policyexchange.org.uk/wp-content/uploads/2018/01/Small-Modular-Reactors-1.pdf
66 https://www.oecd-nea.org/ndd/pubs/2012/7056-system-effects.pdf

foreseen cost reduction through digitalisation presented in **Table 1**). Financial risk (alongside construction costs) is one of the main drivers for costs reduction. De-risking nuclear is possible in two ways:

First, building new reactors on time and on budget. This situation would build trust and trigger positive dynamics for nuclear development (see **Exhibit 6**). Second, exploring alternative financing models like public-private partnerships[67] or pouring low risk equity from institutional investors (pension funds) in a SPE[68,69].

4.4.2 Value approach

Policy issues

As discussed in §4.2, massive VRE deployment should be accompanied by enhanced grid flexibility and stability to assure that final customer is served at all times. Under these conditions, new grid services could emerge pushing governments to intervene the market in different ways. For example, the US has some experience with capacity markets, ZECs[70] and proposed recently the "Grid Resiliency Pricing Rule"[71]. The UK government chose the "Contract for Difference" option for HPC project. Europe is also working on a new version of its Emission Trading System for efficient carbon pricing signal[72]. These political actions will create new revenue streams and some utilities with capacity attributes, like nuclear, could take advantage of them.

5 The Spark: Millennials and nuclear power

Technology improvement is driven by every day people's work and growing knowledge. In the near future, these people will certainly be millennials generation (the *Spark*) which will account for 75% of the current workforce by 2025[73]. In the nuclear sector, this generation will take even a more central role as the age pyramid is shifted to the right[74].

Millennials, alike to any other of its predecessors, are more dynamic. Around 66% of millennials are going to leave their currents jobs in less than 4 years[75]. This trend is not really encouraging for a long-term knowledge-intensive sector like nuclear energy. The KM initiatives discussed in §4.3.1 could help nuclear organizations to cope with high turnover rates. Nevertheless, these initiatives take some time. Millennials retention is therefore critical in the short term[76].

Millennials are looking for the benefits associated to the knowledge economy paradigm. This new paradigm is already present in GAFA[77]. To succeed in the digital transformation, the nuclear industry should mirror technical solutions from aeronautics and automotive industry and organizational solutions from GAFA. This will lead not only to increased knowledge capitalization but also to a greater millennial retention.

6 Conclusion: The virtuous cycle for nuclear development

Despite the important role of nuclear energy to play in the 4D scenario, its development is still slow. Some western countries are experiencing cost overruns in new builds. This creates an atmosphere of distrust among stakeholders (regulators, investors, etc.) pushing back nuclear development even more. Digital transformation of the nuclear industry could reverse this trend. Several levers are proposed in this report resulting in significant cost reductions and potential for millennial retention. A virtuous cycle could then be triggered (see **Exhibit 6**): building on time and on budget will reestablish trust between stakeholders; de-risking this technology will lead to further cost reductions; resulting increased competitiveness will, in turn, attract more funding for new projects. This virtuous cycle would clear the pathway to meet 2DS targets and build a more sustainable energy system for all of humanity.

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[67] https://analysis.nuclearenergyinsider.com/uk-considers-public-finance-new-reactor-saudi-arabia-pick-first-reactor-developer-2019
[68] http://www.world-nuclear-news.org/C-EDF-Energy-expects-20-cost-saving-for-Sizewell-C-18011801.html
[69] Special purpose entity: https://www.investopedia.com/terms/s/spv.asp
[70] Zero Emission Certificates: http://www.world-nuclear-news.org/NP-New-Jersey-passes-ZEC-legislation-1304187.html
[71] http://www.powermag.com/ferc-rejects-does-proposed-controversial-grid-resiliency-rule/
[72] http://www.world-nuclear-news.org/EE-Reformed-EU-Emissions-Trading-System-approved-2802184.html
[73] https://www.forbes.com/sites/workday/2016/05/05/workforce-2020-what-you-need-to-know-now/#6825eaa12d63
[74] Most of the current workforce will retire in the coming years.
[75] https://www2.deloitte.com/content/dam/Deloitte/global/Documents/About-Deloitte/gx-millenial-survey-2016-exec-summary.pdf
[76] Assuming HPC project will take 8 years and using previous data, in the worst scenario, only 0.75*0.66 = 50% of the workforce at beginning of the project will be available to begin another one. 50% of the validated learning might vanish.
[77] Google, Apple, Facebook and Amazon.

"The Energy Transition"

What is the role of nuclear technology in a world of growing alternative power and digital innovation?

7 Appendices

7.1 IEA scenarios[78]

The 2ºC Scenario (2DS): in this scenario there is at least a 50% chance to reduce GHG emissions by almost 60% by 2050.

The 6ºC Scenario (6DS): this scenario describes the possible consequences of extending current trends. In the absence of efforts to stabilize GHG emissions, the average global temperature increase could reach almost 5.5ºC in the long term.

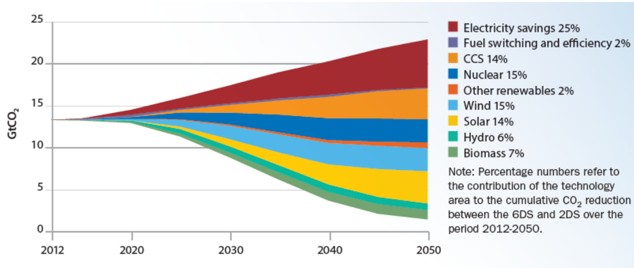

Exhibit 7: CO2 emissions reduction from 6DS to 2DS

7.2 Carbon footprint of selected electricity sources

Table 2: Life cycle carbon footprint of selected energy sources expressed in gCO2/kWh [79]

Technology	Min	Median	Max	Technology	Min	Median	Max
Wind Onshore	7.0	11	56	CCS – Coal – oxyfuel	100	160	200
Wind Offshore	8.0	12	35	CCS – Gas – combined cycle	94	170	340
Nuclear	3.7	12	110	CCS – Coal – IGCC	170	200	230
Ocean (Tidal and wave)	5.6	17	28	CCS – Coal – PC	190	220	250
Hydropower	1.0	24	2200	Biomass – Dedicated	130	230	420
Concentrated solar power	8.8	27	63	Gas – combined cycle	410	490	650
Geothermal	6.0	38	79	Biomass – Cofiring with coal	620	740	890
Solar PV – rooftop	26	41	60	Coal – PC	740	820	910
Solar PV – Utility scale	18	48	180				

7.3 Nuclear cost in detail

Table 3: Nuclear costs breakdown

French LCOE for new nuclear – WACC = 7%		
Costs	**Relative weight (%)**	**Effective weight (%LCOE)**
1. Investment	73	
1.1. Overnight	80	58.4
1.1.1. Base construction	70	40.9
1.1.1.1. Direct	70	28.6
1.1.1.1.1. Labour	60	17.2
1.1.1.1.2. Raw materials and equipment	40	11.4
1.1.1.2. Indirect	30	12.3
1.1.2. Contingency 1.1.3. Owner's	30	17,5
1.2. Financial ~ IDC=f (lead time, WACC)	20	14.6
2. Operational and maintenance (O&M)	16	
2.1. Staff	40	6.4
2.2. Consumables	20	3.2
2.3. Repair	15	2.4
3. Fuel and Waste	11	
4. Refurbishment and decommissioning	< 1	

[78] https://www.iea.org/publications/scenariosandprojections/
[79] https://en.wikipedia.org/wiki/Life-cycle_greenhouse-gas_emissions_of_energy_sources

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Nuclear costs can also be classified in:

Recurring costs: specific-site rework activities, procurement, construction, verification & validation, commissioning, etc.

Non-recurring costs: engineering, design, project management, licensing, etc.

Non-recurring costs are incurred for First Of A Kind reactors (FOAKs) and then amortized for NthOAKs. It may exist, however, recurring specific site rework activities. Recurring cost can be progressively compressed for NthOAKs thanks to learning effects.

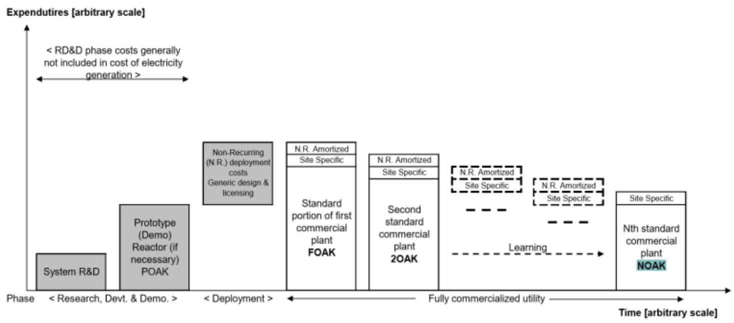

Exhibit 8: Learning effects from FOAKs to NOAKs

7.4 Main digital levers for construction costs reduction

Systems engineering

This discipline emerged as an effective way to manage complexity and change in products. Its main output is a detailed product architecture which facilitates design-to-cost activities and "right the first time" on-site tasks realization.

Building Information Management

This tool provides a virtual environment based on a unified 3D digital mock-up which can be shared with all stakeholders of the project. BIM is at the heart of solutions like Delmia[80]

Product Lifecycle Management

Based on SE and BIM referential, a PLM solution integrates all project data and assures its traceability throughout all the life cycle of the product. In addition, it creates a collaborative virtual environment accessible to all subcontractors increasing supply chain integration.

7.5 Knowledge economy vs. industrial economy

Industrial economy	Knowledge economy
An asset reduces its value when shared	An asset increases its value when shared
Short term assets acquisition	Long term assets acquisition
Factory	Platform
Bureaucratic	Network-like
Rule management	Flow orchestration
Productivity	Contribution
Effort	Learning
Boss	Leader

7.6 What is the blockchain?

The blockchain could be described as the internet of value (in comparison to the internet of information commonly known as the Web). Value can be captured and sent from peer to peer transparently through a digital ledger consisting of enchained blocks. Thirds parties are bypassed cutting costs, speeding up processes and increasing global system flexibility. Recent utility experience[81] have already proven blockchain's 2.0 capabilities to exchange MWh with smart

[80] https://www.youtube.com/watch?v=X8l2DYOSUZY
[81] https://www.endesa.com/-endesa-and-gas-natural-fenosa-complete-first-blockchain-energy-trade-transaction

contracts. What will blockchain 3.0 look like is difficult to predict. Using Web.3.0 trends, blockchain 3.0 might developed smart contract concept further to create decentralized units that rely on their own laws and operate with high degree of autonomy.

7.7 The reasons behind negative learning effects and diseconomies of scale for nuclear

The costs escalation observed in nuclear builds is mainly due to frequent regulatory changes motivated by nuclear accidents. Nuclear reactors are not simple replicates from their predecessors. They are more complex with increasing number of components and, sometimes, they include "too deep" design modifications. As complexity grows, a little modification in one system is likely to induce huge impacts in another system. The weight of recurring specific-site rework activities for NOAKs becomes thus bigger. This phenomenon may be exacerbated for a given design in foreign markets by the lack of harmonization of regulatory frames between countries. In addition, median construction times have also been rising in most countries[82]. This results in higher IDC which prevail over the positive effect of increased power outputs. The final investment per MW installed is thus greater leading to diseconomies of scale.

7.8 The *pipeline* model

This model is inspired by the principles of set-based design[83]. Three main stages have been identified:

Stage 1: Different designs cohabite in the same field. Diversification of designs reduces risk if one design does not meet regulatory requirements. Internal competition between designs helps to bring costs down.

Stage 2: Only the more technologically robust and competitive designs continue.

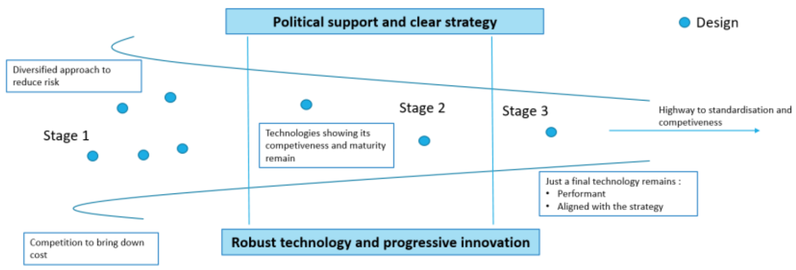

Exhibit 9: The pipeline model

Stage 3: Finally, only one or two designs remain to be built "massively" to improve competitiveness further thanks to standardization. One architect-engineer (AE) firm[84] should be in charge of the massive deployment in order to increase the accumulated experience from every project.

During all this process, government's support and clear strategy are needed. Innovation must be introduced progressively in order to manage complexity efficiently.

7.9 SMRs vs. big reactors learning effects[65]

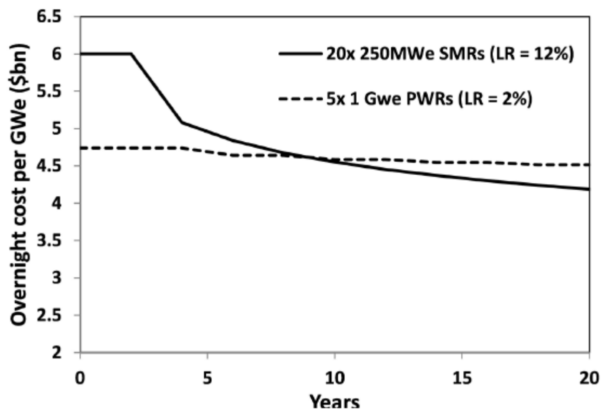

Exhibit 10: SMRs vs big reactors learning effects

[82] https://www-pub.iaea.org/MTCD/Publications/PDF/RDS_2-36_web.pdf
[83] https://www.scaledagileframework.com/set-based-design/
[84] One of the reasons behind American nuclear cost escalation is the absence of AE model.