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The Rise of Renewable Energy and Fall of Nuclear Power

Competition of Low Carbon Technologies

February 2019

REI – Renewable Energy Institute

Renewable Energy Institute is a non-profit organization which aims to build a sustainable, rich society based on renewable energy. It was established in August 2011, in the aftermath of the Fukushima Daiichi Nuclear Power Plant accident, by its founder Mr. Masayoshi Son, Chairman & CEO of SoftBank Corp., with his own private resources. The Institute is engaged in activities such as; research-based analyses on renewable energy, policy recommendations, building a platform for discussions among stakeholders, and facilitating knowledge exchange and joint action with international and domestic partners.

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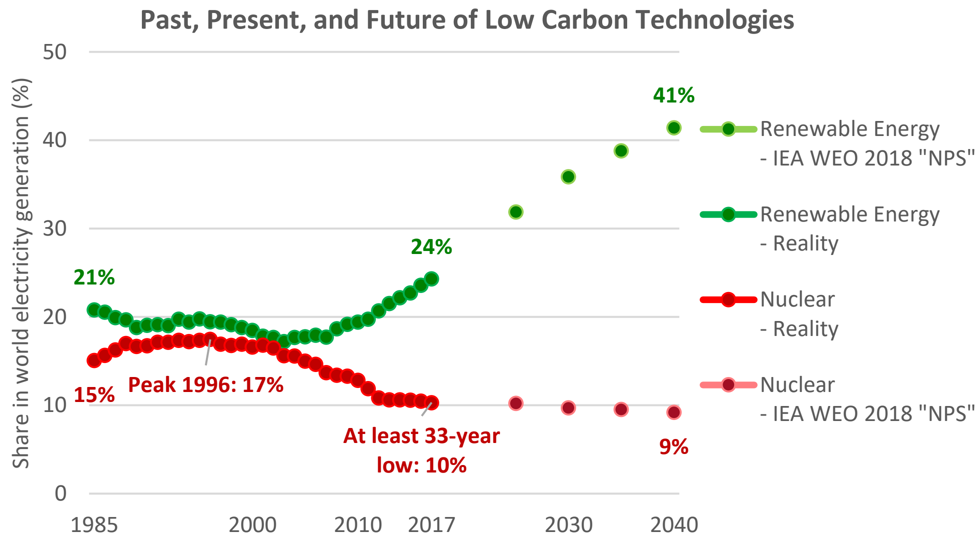
EXECUTIVE SUMMARY

Because of climate change, only low carbon technologies should now be pursued to build a sustainable future electricity mix. So far, nuclear power and renewable energy have been the two key low carbon electricity generation technologies the world has relied on, energy efficiency also playing a critical role in optimizing energy uses. Carbon capture and storage lagging far behind these two technologies in terms of deployment, and still having to demonstrate it can economically and substantially reduce greenhouse gas emissions when fitted to fossil fuel power plants, is out of the equation for now. This report explores what contributions are to be expected from nuclear power and renewable energy only in the years to come, with a focus on nuclear power.

In the past 2-3 decades, global electricity generation significantly increased (about +160%) and the fight against global warming gained strong momentum. At the same time, the share of claimed "cheap" and "clean" nuclear power in the world electricity generation mix endlessly fell – reaching an at least 33-year low of about 10% in 2017 – because of the technology stagnating expansion. Without massive lifetime extensions and deployment of new builds, nuclear power is doomed to an ineluctable decline. The opposite trajectory of renewable energy.



Sources: for actual data; BP, Statistical Review of World Energy 2018 (June 2018), and for projections; International Energy Agency, World Energy Outlook 2018 (November 2018)

Consistent with this analysis, in its latest World Energy Outlook (WEO) 2018, the International Energy Agency's central scenario ("New Policies Scenario" – NPS) forecasts the share of nuclear power to fall further – below 10% in 2040, and that of RE to significantly increase to reach more than 40% at the same date.

While there is a very large socio-political consensus to support energy efficiency and RE as effective means against climate change, expanding or maintaining nuclear power is a much more divisive issue. In many key countries nuclear power is simply not a pillar of the energy transition even when considering it could be regarded as a tool to reduce carbon dioxide emissions.

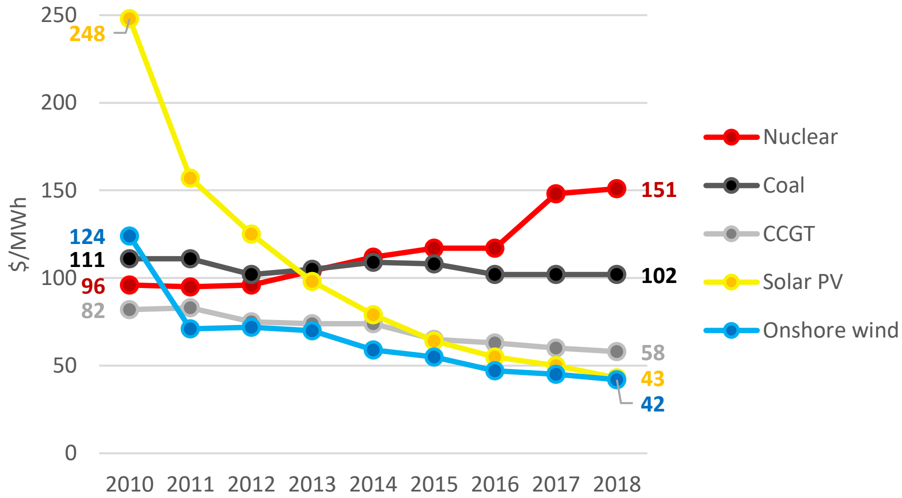
For instance, Germany, Korea, Belgium, and Switzerland are planning to phase out nuclear power, and France – the nuclear superpower – is planning to significantly reduce its reliance on the technology. In the United States, Japan, the United Kingdom, Canada and Sweden, because of economic and technological issues nuclear power is losing ground to the detriment of renewable energy, even if there is no voluntary policy to reduce the importance of the atom. In China, India, the United Arab

Emirates, and Saudi Arabia expansion of nuclear power is and will be negligible compared with that of renewable energy. Only in Russia, not a leader in the fight against climate change, the fate of nuclear power does not seem so gloom – without being much brighter either.

These developments are the results of three industrial overwhelming difficulties nuclear power is confronted with; cost, technology, and waste legacy.

A new economic reality has struck the nuclear industry in the first two decades of the 21st century; nuclear power is often neither cheap nor even cost competitive anymore as it has been continuously claimed for decades by its proponents. Existing plants face a deteriorated economic situation with cost increases due to more stringent safety standards following Fukushima Daiichi nuclear accident in Japan in 2011, and the competition of renewable energy, particularly low costs new wind and solar power. New nuclear power plants are often prohibitively expensive and very challenging to finance, especially in competitive markets.

Unsubsidized Global LCOE of New Electricity by Generating Technology 2010-2018



Source: Lazard, Levelized Cost of Energy Analysis – Version 12.0 (November 2018)

In addition, nuclear power is facing a number of various technological challenges; from successfully deploying current evolutionary generation III reactors (i.e. on time, to budget, and cost competitive), to making significant progresses in innovative generation IV reactors developments, and simply surviving in the 21st century electrical grid that will require more flexibility and less vulnerability to extreme weather events. Under current circumstances, and in the race against time humanity is engaged to prevent climate change, nuclear power is not poised to provide a rapid and significant contribution.

Finally, the end life cycle of nuclear power is marked by two significant technological and financial issues; decommissioning and waste storage, no country has ever come close to fully solve – despite nuclear power already quite long history. As of early 2018, about 170 nuclear reactors had been permanently shut down worldwide, out of which less than 20 had been fully decommissioned, and no disposal facility for high level waste and spent nuclear fuel had started operations.

In conclusion, unless unforeseeable dramatic changes shake the nuclear power industry very quickly, it will certainly play a minor role in the medium to long-term future of electricity generation. And therefore, only be a negligible force to advance the decarbonization of the power sector.

To solve this problem renewable energy will be the major solution.

INTRODUCTION

- Because of climate change only low carbon technologies should now be pursued to build a sustainable future electricity mix. In this regard, this report explores what contributions are to be expected from the existing key low carbon technologies; nuclear power and renewable energy, with a focus on the former. –

While writing this report at the end of 2018, the nuclear renaissance dream of the 2000s seems far, so far.

This broken dream originates in the industry own failures to deliver what it has promised; cheap and clean electricity. At the time the world needs it most.

As a result, following decades of stagnation and fall, nuclear power share in global electricity generation decreased to just 10% in 2017 – an at least 33-year record low.

Based on hard cold facts, this report shows and explains nuclear power irreversible decline by introducing global and key countries developments, and by highlighting the industry overwhelming difficulties; cost, technology, and waste legacy.

Whereas Japan government still demonstrates a strong support for nuclear power, this report aims at recommending another path for the country energy policy. A path in which energy efficiency and renewable energy can lead to a more economic, sustainable, and safer future.

I NUCLEAR POWER ON THE EDGE

1 Global trends, status, and prospects; falling out of favor

In the past 2-3 decades, global electricity generation significantly increased and the fight against climate change gained strong momentum. At the same time, the share of claimed "cheap" and "clean" nuclear power in the world electricity generation mix endlessly fell because of its stagnating expansion. Without massive lifetime extensions and deployment of new builds, nuclear power is doomed to an ineluctable decline. The opposite trajectory of renewable energy.

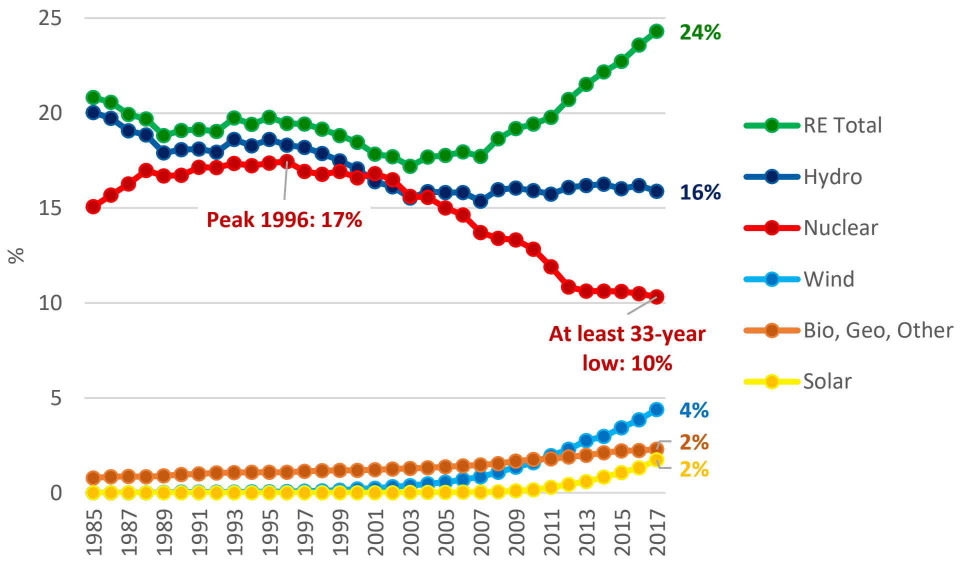
Between 1985 and 2017 world electricity generation increased by about 160%.[1] And for the past 20-25 years since the Earth Summit (1992) and Kyoto Protocol (1997) there has been an ever-growing consciousness of climate change risks, culminating with the Paris Agreement (2015).

Nuclear power which has so often been praised, by its proponents, for its cost-competitiveness and climate friendliness with regard to greenhouse gas (GHG) emissions has yet spectacularly failed at expanding its share in the world electricity generation mix. A contrast particularly striking with renewable energy (RE), which share has been continuously growing since 2007 especially thanks to remarkable progress in wind and solar power deployment.

With 10%, nuclear share in global electricity generation in 2017 fell to an at least 33-year low (Chart 1). That is much lower than its already more than 20-year old peak of 17% in 1996. It is also important to note that nuclear power decline started well before Fukushima Daiichi nuclear accident in 2011.

Nuclear share in global electricity generation in 2017 was 2.4 times less than that of RE, which increased to 24% in 2017. This increase is primarily the result of wind and solar power impressive take-off over the past 10-15 years. Wind and solar power shares reached 4% and 2% in 2017, respectively, from 0% both in 2000.

Chart 1: Shares of Low Carbon Technologies in World Electricity Generation 1985-2017

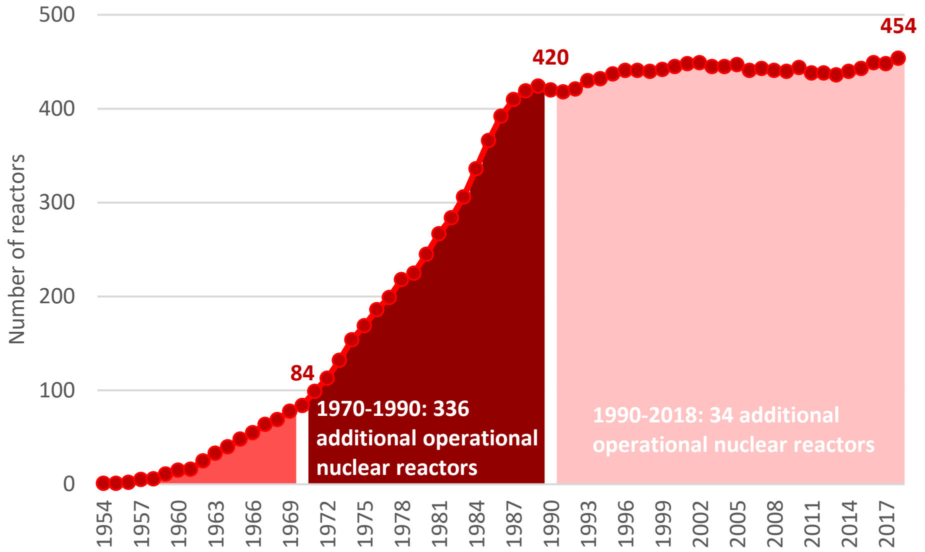


Source: BP, Statistical Review of World Energy 2018 (June 2018)

This long-term trend can be explained as follows; while global electricity generation kept significantly increasing, nuclear power expansion stagnated.

Indeed, whereas the number of operational reactors increased by almost 340 worldwide between 1970 and 1990, this number decreased to just 34 since then – about 10 times less (Chart 2).[a]

Chart 2: World Cumulative Operational Nuclear Reactors 1954-2018 (Dec. 3)



Source: IAEA, Power Reactor Information System (accessed 3 December 2018)

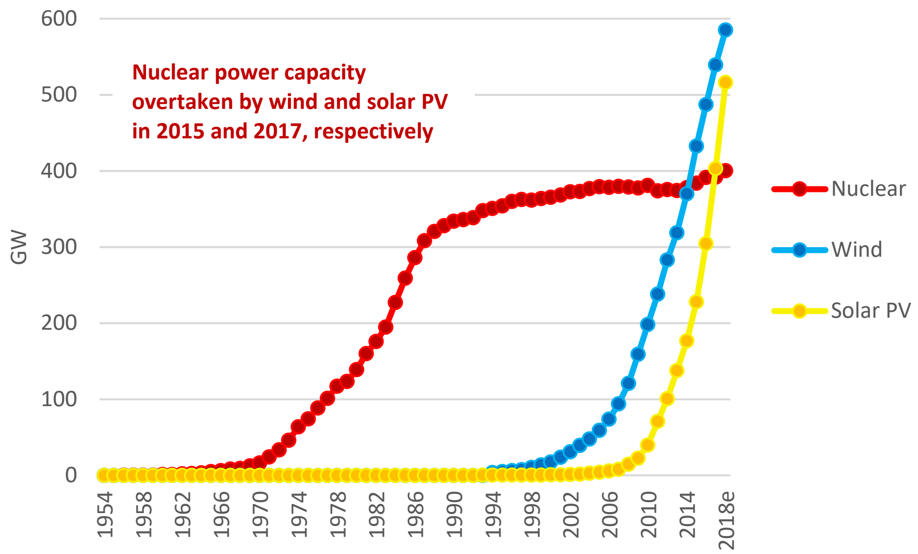
As a result, nuclear power cumulative installed capacity increased marginally "only" +66 gigawatts (GW) since 1990, or 2.4GW/year in this period, reaching about 400GW as of 3 December 2018 (Chart 3 on next page).[b] In comparison, in a much shorter period of time (starting around 2000) very roughly 600GW and 500GW of wind and solar power capacity were added – largely enough to surpass nuclear power.

This demonstrates how relatively simple and distributed technologies can be rolled out very quickly in comparison with very complex and large centralized nuclear power plants, which may be commissioned well after 10 years of construction; e.g. Olkiluoto 3 (Finland), Flamanville 3 (France), Kakrapar 3 and 4 (India), Ohma and Shimane 3 (Japan), or Leningrad II-2 and Novovoronezh II-2 (Russia) to name just a few, but not the worst (construction of Khmelnitski 3 and 4 in Ukraine started in 1986 and 1987, respectively, already more than 30 years ago…).[2] Climate change requiring action to be taken urgently, this confers a certain advantage to wind and solar over nuclear.

Even without considering that nuclear power may be vulnerable to global warming as again demonstrated in the summer of 2018 when in Europe a heatwave forced some reactors to either reduce their output or temporarily shut down because of cooling water related issues.[3]

[a] The scope of this report is limited to civil nuclear power reactors which are those used to generate electricity that is supplied to customers through electricity grids, as opposed to research reactors generally not used for electricity generation.
[b] Unless otherwise noted, all installed capacity data are net.

Chart 3: World Nuclear, Wind, and Solar PV Cumulative Capacity 1954-2018e (Dec. 3)



Sources: for nuclear; IAEA, Power Reactor Information System (accessed 3 December 2018), for wind; GWEC, Global Wind Reports Annual Market Updates, and for solar PV; IEA-PVPS, Trends in Photovoltaic Applications 2018 (December 2018). And 2018 estimates for wind and solar PV; Bloomberg NEF, World Reaches 1,000GW of Wind and Solar, Keeps Going (2 August 2018)

Because of this stagnation, and in combination with Fukushima Daiichi nuclear accident in 2011, and its subsequent consequences in Japan and Germany especially, as well as safety concerns in France, electricity generation from nuclear power was still well below 3,000 terawatt-hours (TWh) in 2017, 6% below its 2006 peak level (Chart 4 on next page).[c]

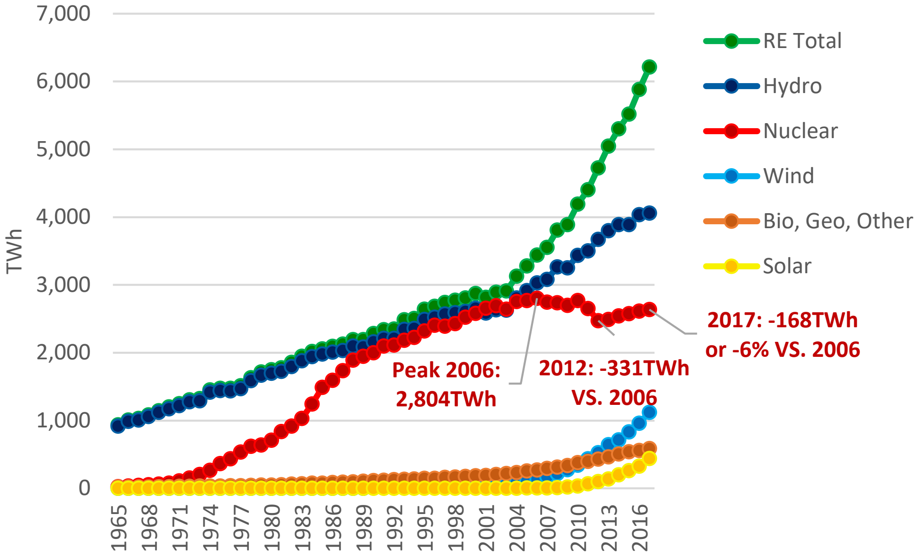
After reaching its lowest level of the 21st century in 2012; 2,472TWh, or -331TWh VS. 2006, electricity generation from nuclear power increased a little bit globally from 2012 to 2017; +163TWh. Essentially the result of nuclear power expansion in China; +151TWh in this period.

The comparison with RE, which has completely eclipsed the 6,000TWh mark in 2017, is particularly painful for nuclear power.

Again, this has been possible mainly thanks to dramatic growth in wind and solar power, which combined have accounted for the majority of new electricity generation from RE between 2006 and 2017. And since 2011, these two technologies combined have filled in more than half of the gap that separated them from nuclear in terms of electricity generation. Just another proof of how fast and efficiently wind and solar can be successfully massively spread.

[c] Unless otherwise noted, all electricity generation data are gross.

Chart 4: World Electricity Generation from Low Carbon Technologies 1965-2017



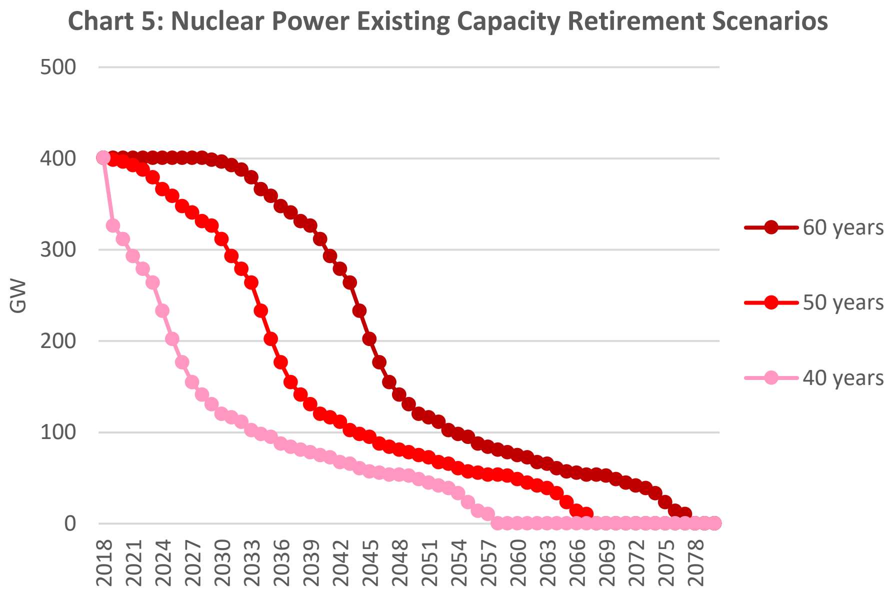
Source: BP, Statistical Review of World Energy 2018 (June 2018)

To avoid marginalization in the world electricity generation mix, nuclear power development trajectory will need a severe shift of direction that seems quite unlikely today.

Indeed, global electricity generation is expected to keep increasing significantly; very roughly from 26,000TWh in 2017 to 40,000TWh in 2040 (according to the International Energy Agency (IEA) latest World Energy Outlook (WEO) 2018 – New Policies Scenario (NPS), its central scenario), or about +57% within the next quarter century.[4]

At the same time, since most reactors have been built in the 1970s-1990s the world nuclear power fleet is relatively old; average of about 30 years (and almost two-thirds of operational reactors have been first grid connected for over 30 years).[5]

Under the assumptions that all existing reactors would be shut down after 40 years of operation and no new reactor would be built, the global nuclear power fleet installed capacity would be drastically reduced by around ¾th or 300GW by the early 2030s (Chart 5 on next page).



Source: REI based on IAEA, [Power Reactor Information System] (accessed 3 December 2018)

These assumptions may be objected on two grounds. First, there are reactors operating over 40 years and for which there are plans to be operated longer. Second, there are currently 54 reactors with a combined installed capacity of approximately 55 GW under construction in the world (as of 3 December 2018). These, however, include several reactors which have been under construction for a very long time and/or may never be commissioned.[6]

Yet, counterarguments to these claims may also be advanced. For instance, a not negligible number of reactors may be shut down well before 40 years of operation because of economic, technical, and political reasons as reality as already demonstrated it in recent years in the United States (e.g. Crystal River 3, San Onofre 2 and 3…) and Germany (e.g. Kruemmel, Philippsburg 1…), notably. And it is possible to show that the current construction pace of 10GW/year (period 2018-2022, assuming all new reactors are commissioned as planned) is well-below the replacement rate needed to just maintain the global fleet at its current level of about 400GW (at a 2040 horizon), with the exception of an extremely unlikely scenario in which all existing reactors would retire after 60 years of operation (Table 1).[7]

Table 1: Nuclear Annual New Build Capacity to Maintain Global Fleet at Current Level (horizon 2040)

	Lifetime scenario		
	40 years	50 years	60 years
New capacity to be added annually (GW)	15	13	4

Source: REI based on IAEA, [Power Reactor Information System] (accessed 3 December 2018)

As of 3 December 2018, no nuclear reactor has ever been operated for over 50 years yet. In addition, a number of reactors have obtained operating license extensions to operate until 60 years, but have already announced their closures well before their licenses expire.[8]

Thus, based on these observations, our conclusion is that the share of nuclear power in electricity generation is probably to further decrease.

This is consistent with most recent projections from the International Atomic Energy Agency (IAEA) and the IEA, two highly respected organizations for their expertise when it comes to nuclear power and energy outlooks.

The IAEA forecasts nuclear power to account for 6-12% of the world electricity production in 2040, against 10.3% in 2017 (Table 2).[9] The higher range would require a very substantial increase of about 250GW in nuclear power installed capacity compared with 2017, an increase of 11GW/year.[10] Considering trends in retirements and additions this is quite ambitious. More precisely this would require new capacity to be added at a 14-25GW/year pace (depending on retirement scenarios), again that is well above the 10GW/year planned for the period 2018-2022.

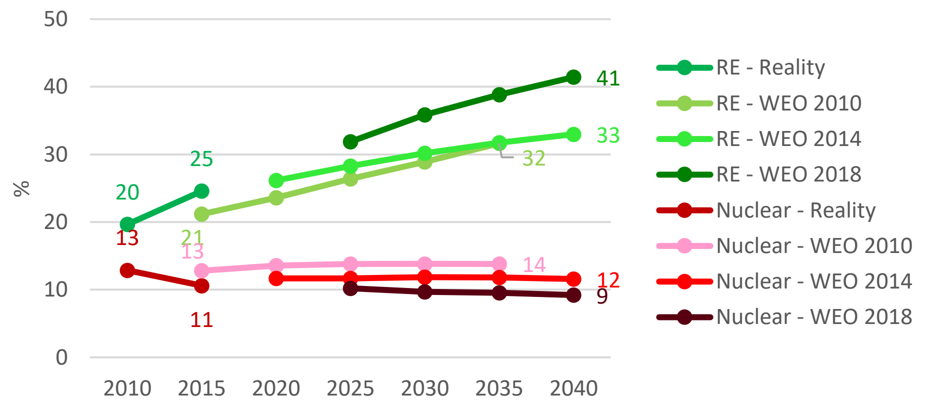
Table 2: IAEA Global Nuclear Power Projections to 2040

	2017	2040	
		Low	High
Nuclear installed capacity (GW)	392	323	641
Nuclear net electricity generation (TWh)	2,503	2,560	5,087
Nuclear share in electricity generation (%)	10.3	6.0	12.0

Source: IAEA, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050 – 2018 Edition (September 2018)

And the IEA forecasts a reduction of nuclear power share in electricity generation in its WEO 2018 – NPS (Chart 6). Indeed, the IEA has not only been continuously revising downward its outlook for nuclear power, it now also envisions its 2040 situation to be worse than it is today.

Chart 6: IEA WEOs – NPS Projections; Nuclear VS. RE Shares in Electricity Generation



Source: IEA, World Energy Outlooks 2010 (November 2010), 2014 (November 2014), and 2018 (November 2018)

And nuclear power will probably be progressively replaced – and quicker than originally expected – by RE which is cost competitive, environmentally friendly, and inherently harmless. For instance, in its latest WEO 2018, the IEA forecasts the share of RE to reach more than 40% in 2040 – 4 times more than that of nuclear; below 10%.

Looking back in the past, it may also be noticed that the IEA in its WEO 2010 provided relatively conservative estimates – compared with reality. Indeed, in 2010, the IEA outlook projected; on the one hand the share of nuclear power to reach 13% in 2015, but this actually declined to 11%, on the other hand that of RE to reach 21% only, but this increased to 25% in reality.

Considering trends, both in terms of actual achievements and forecasts, it is possible that in its next outlooks the IEA will again revise its forecasts downward for nuclear power and upward for RE.

2 Key countries' policies; not a pillar of CO_2 emissions reduction

While there is a very large socio-political consensus to support energy efficiency and RE as effective means against climate change, expanding or maintaining nuclear power is a much more divisive issue. And quite often nuclear power is simply not a pillar of the energy transition even when considering it could be regarded as a tool to reduce carbon dioxide emissions.

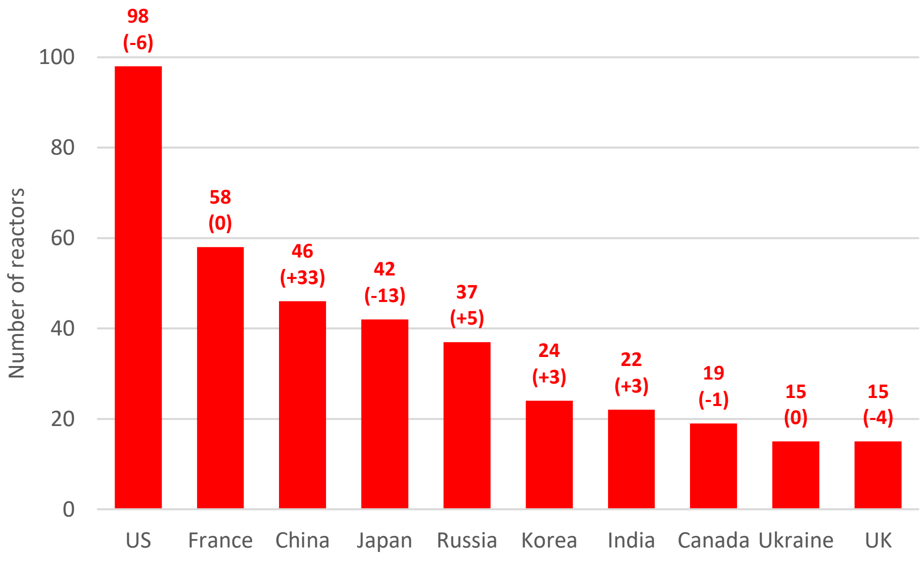
– This section first introduces a general overview of five key indicators at the country level to provide the readers with an important frame of basic knowledge facilitating their understanding of the discussions that unfold; (1) leading countries by number of nuclear reactors, (2) leading countries by nuclear power installed capacity, (3) leading countries by nuclear share in electricity generation, (4) average age of nuclear reactors in selected countries, and (5) nuclear power reactors under construction by country.

Then, key countries are grouped into three categories depending on their stance towards nuclear power; (A) political reduction/phaseout of nuclear power (France, Germany, Korea…), (B) moderate action resulting in nuclear power slow decline (Japan, United Kingdom, United States…), and (C) supporting expansion of nuclear power, but marginally compared with RE (China, India…). –

Someone who would have fallen asleep in the mid-1980s and would wake up today would certainly not notice how much the world has changed in the past 30-35 years only by looking at the leading countries of the nuclear power industry. And for good reason, the historical leaders of yesterday, the United States (US) and France, are still those of today – by far – despite very little or no progress in the past quarter century, and harsher domestic environments in the past decade.

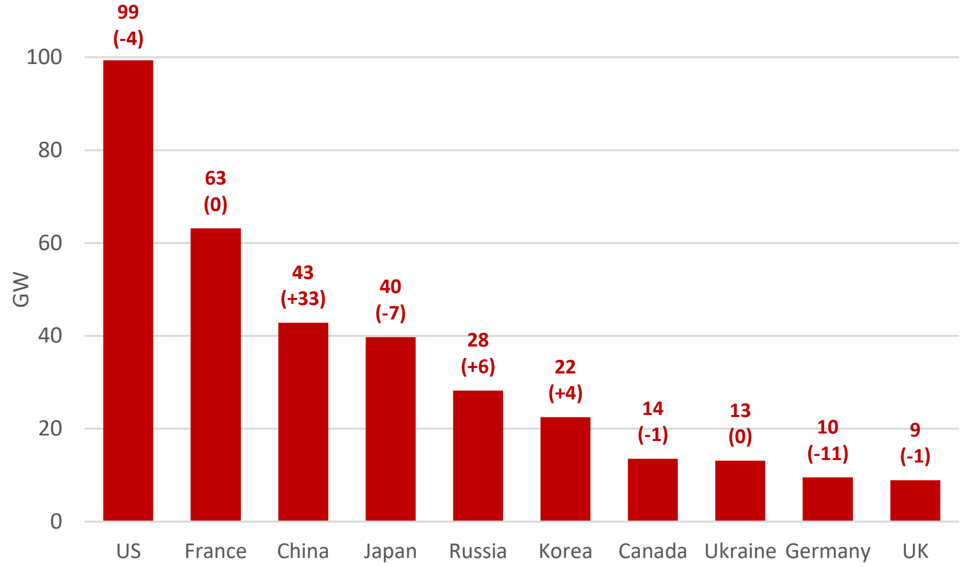
As of 3 December 2018, the US and France were the countries with both the highest number of operational nuclear reactors; 98 and 58, respectively (Chart 7 below), and the most nuclear power installed capacity; 99GW and 63GW, respectively (Chart 8 on next page).

Chart 7: Top-10 Countries, Number of Operational Nuclear Reactors 2018 (Dec. 3)



Note: between brackets is indicated the difference with 2010
Source: IAEA, Power Reactor Information System (accessed 3 December 2018)

Chart 8: Top-10 Countries, Nuclear Power Installed Capacity 2018 (Dec. 3)



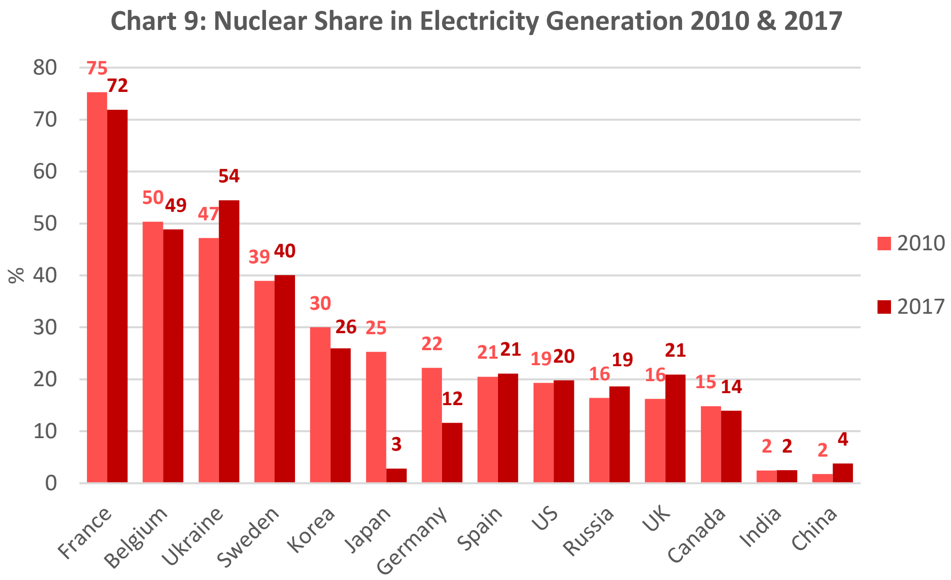
Note: between brackets is indicated the difference with 2010

Source: IAEA, Power Reactor Information System (accessed 3 December 2018)

The most important change in these rankings is China finally overtaking Japan (in 2018) for the last place on the podium of nuclear powers. This results from the combination of China important efforts in scaling up nuclear power; +33 reactors with a total combined capacity of 33GW since 2010, and the aftermath of Fukushima Daiichi nuclear accident in Japan; closures of 13 reactors with a total combined capacity of 7GW in the same period.

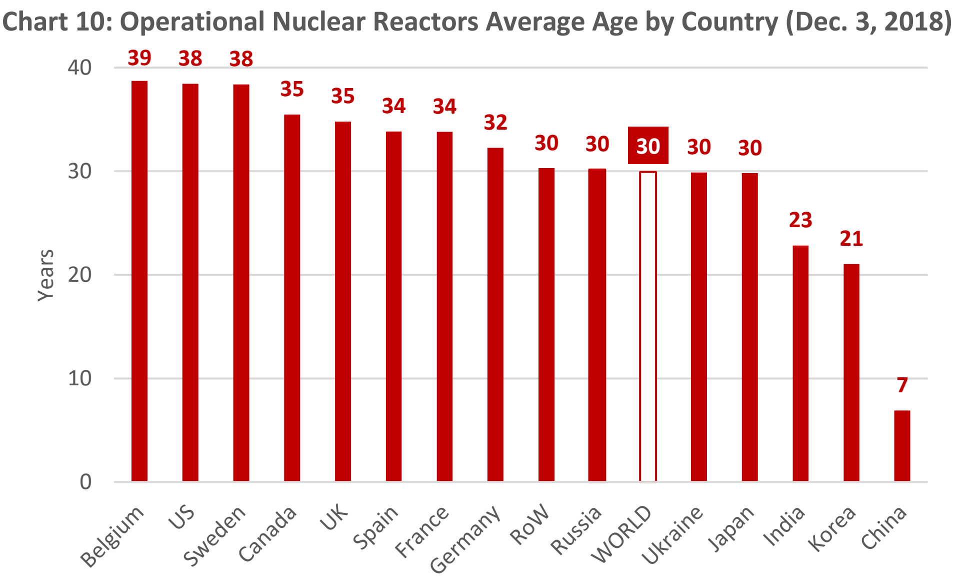
Another important point, somewhat less significant though, is Germany not being a top-10 country anymore in terms of number of nuclear reactors (only 7 operational reactors as of 3 December 2018) with the permanent shutdown of 10 reactors with a total combined capacity of 11GW following the decision of the country to phase out nuclear power in 2011.

As for the share of nuclear power in electricity generation, France, with still more than 70% of its electricity production from nuclear in 2017, remains by far the most reliant country on the atom (Chart 9 on next page). It is followed by relatively smaller economies such as Belgium, Ukraine, and Sweden where nuclear share is relatively high; between 40% and 55%. In major developed economies such as the US, the United Kingdom (UK), Canada, and Germany the share of nuclear power is about 10-20% only. Nuclear power in electricity generation is marginal in all major Asian economies Japan, China – despite its significant progress mentioned above, and India; below 5%, with the exception of Korea 25-30%.



Note: only countries with at least 5 nuclear reactors and 5GW installed capacity are included
Source: BP, Statistical Review of World Energy 2018 (June 2018)

Most of operational nuclear reactors throughout the world are not recent, particularly in Europe, North America, and Japan, where their average age is usually roughly between 30 and 40 years (Chart 10). That is rather the end of their originally planned operating lifetime. Operating license extension may be granted on technical grounds. However, unprofitable nuclear reactors may well be closed before they reach the end of their expected lifetime. Thus, building new reactors or extending the lifetime of existing ones is a pressing difficult question in many countries, which also depends on the cost of other low carbon alternatives. Asian countries such as China, which has a quite new fleet – average age of 7 years, Korea, and India, where reactors are relatively young will have more time to address this issue.

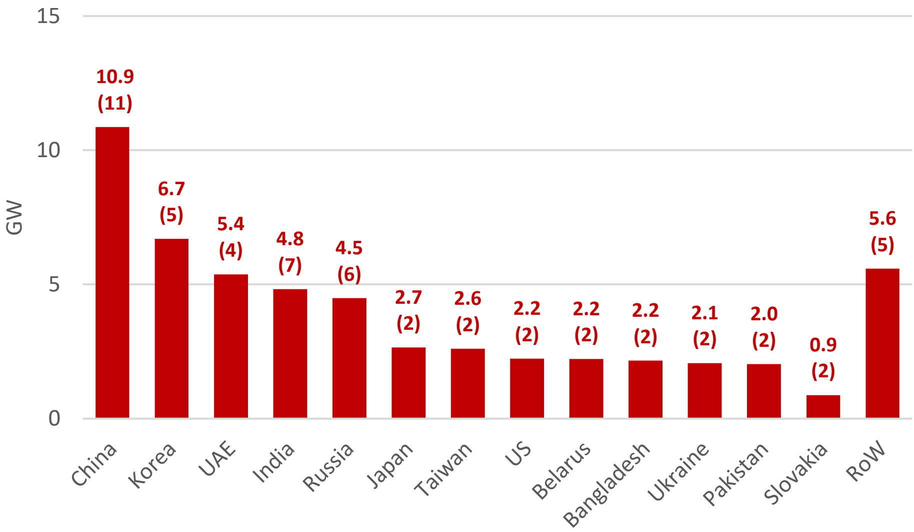


Note: RoW (rest of world) includes all the other countries with an operational nuclear reactor
Source: IAEA, Power Reactor Information System (accessed 3 December 2018)

Analyzing new nuclear reactors under construction also provides meaningful information. As of 3 December 2018, there were 54 reactors under construction worldwide with a total combined capacity of about 55GW. Again, these include a few reactors which have been under construction for a very long time and may never be commissioned. For example, there is no completion date on sight for Lungmen 1 and 2 (1.3GW each) in Taiwan which constructions started in 1999. In addition, new build projects frequently suffer multi-year delays, and cost overruns sometimes amounting to billions of dollars as for examples Flamanville 3 in France and Vogtle 3 and 4 in the US.

In this context, China leads the way with 11 reactors (combined capacity of 11GW) expected to be commissioned by 2021 (Chart 11). Quite behind is India with 7 reactors (5GW), Russia 6 reactors (4GW), Korea 5 reactors (7GW), and the United Arab Emirates (UAE) 4 reactors (5GW).

Chart 11: Nuclear Power Under Construction by Country (Dec. 3, 2018)



Notes: between brackets is indicated the number of reactors under construction. And RoW (rest of world) includes Argentina, Brazil, Finland, France, and Turkey

Source: IAEA, Power Reactor Information System (accessed 3 December 2018)

The UAE, as well as Belarus, Bangladesh, and Turkey are the few new countries to join the nuclear club signaling the lack of appeal of nuclear power to the numerous countries which have never used it. Only 34 countries have ever relied on nuclear power, 3 have already stopped; Italy, Kazakhstan, and Lithuania. At least, 3 countries completely ban nuclear power; Australia, Austria, and Denmark.[11] At least another 2 prohibit the construction of new nuclear reactors and have no reactor in operation – that may be considered as a de facto complete ban of new nuclear power; Ireland (which never had a reactor in operation) and Italy (which has permanently shut down 4 reactors).[12] And some others ban the construction of new reactors and have reactors in operation; Belgium, Germany, and Switzerland.[13]

Very interestingly also is the clear lack of interest of European and North American countries to build new reactors while the situation (aging fleet) rather requires to act. That highlights the fact that lifetime extension and/or other low carbon alternatives are more likely to be pursued instead. This trend can be explained based on economic, socio-political, and technical reasons as different country groups' stories tell.

A) Countries with political reduction/phaseout of nuclear power: Germany, France, Korea, Belgium, and Switzerland

While only a few countries are currently building their first reactors, more countries with a long experience of nuclear power have plans to either phase out this technology (Belgium, Germany, Korea, and Switzerland) or substantially reduce their reliance on it (France) (Table 3).

Table 3: Countries Phasing out or Targeting a Reduction of their Dependence on Nuclear Power

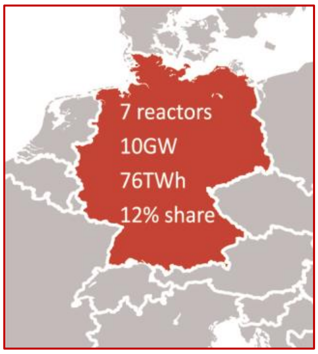
		Nuclear Progresses (2010 → 2017/2018 as of Dec. 3)			
Phase-out	Target year	Number of reactors	Installed capacity (GW)	Electricity generated (TWh)	Share in electricity generation (%)
Germany	2022	17 → 7	20 → 10	141 → 76	22% → 12%
Belgium	2025	7 → 7	6 → 6	48 → 42	50% → 49%
Switzerland	No date (new constructions prohibited)	5 → 5	3 → 3	27 → 20	38% → 32%
Korea	Early 2060s	21 → 24	19 → 22	149 → 148	30% → 26%
Reduction	Target year	Number of reactors	Installed Capacity (GW)	Electricity generated (TWh)	Share in electricity generation (%)
France	50% by 2035	58 → 58	63 → 63	429 → 398	75% → 72%

Sources: created by REI based on; World Nuclear Association, Country Profiles (accessed 3 December 2018) for target years, IAEA, Power Reactor Information System (accessed 3 December 2018) for number of reactors and installed capacity (2018 as of Dec. 3), and BP, Statistical Review of World Energy 2018 (June 2018) for electricity generated and share in electricity generation (2017)

These plans vary in terms of ambitions, but convey a common powerful message; countries are ready to turn their back on nuclear power, for economic and/or socio-political reasons, without shying away from their climate change responsibilities and commitments.

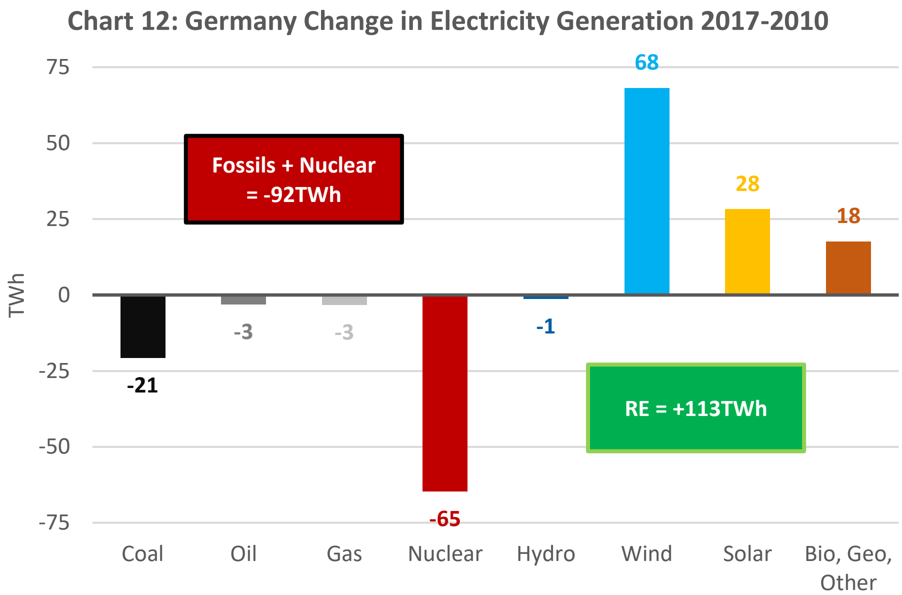
Germany

Germany, that is today the leader of this group of countries in terms of actual achievements and that is so often criticized for its reliance on coal power, has made significant progresses in reducing its reliance on electricity generation from both nuclear and all fossil fuel resources – and especially coal – since 2010 thanks to an impressive deployment of non-hydro renewables (Chart 12 on next page).



Nuclear in Germany 2017/18[d]

[d] Throughout this section country maps for nuclear power are provided. The sources used to support these maps are; the IAEA for the number of reactors and installed capacity (as of Dec. 3, 2018), and BP for electricity generation and share in electricity generation in 2017. All data are based on calendar years.



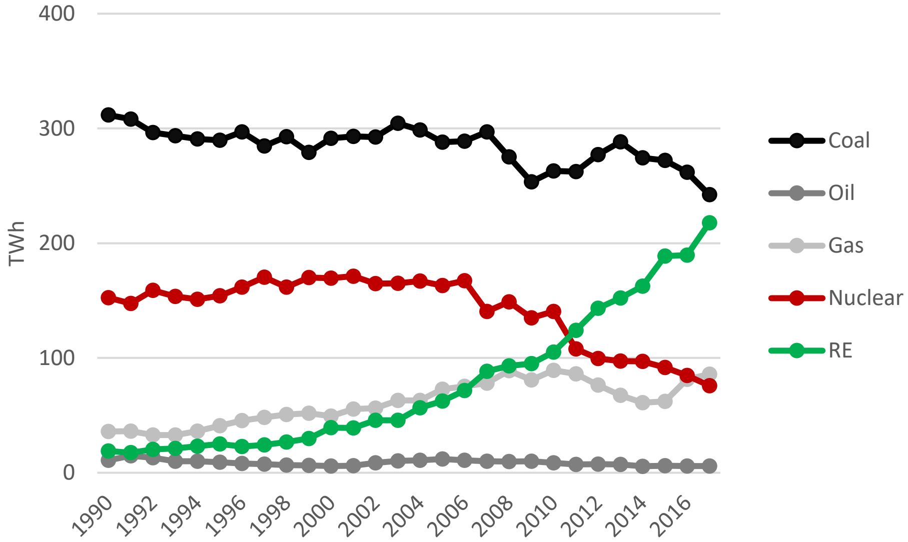
Note: change in other being negligible (<1TWh) it is not included in this chart
Source: BP, Statistical Review of World Energy 2018 (June 2018)

As a result, emission intensity of Germany electricity generation decreased from 558gCO_2/kWh (gram of carbon dioxide per kilowatt-hour) in 2010 to 500gCO_2/kWh in 2017, or -12%.[14] Though this level of emission intensity is still relatively high (for instance, that of the European Union is 314gCO_2/kWh), it must be highlighted that Germany is demonstrating that CO_2 emissions reduction in the power sector is feasible while phasing out nuclear power, and that after nuclear power phaseout is completed, RE further expansion will be at the detriment of fossil power accelerating the decarbonization of the country electricity production.[15]

These remarkable progresses have been made possible thanks to two key factors: the rapid establishment, just within a couple of months after Fukushima Daiichi accident, of a nuclear reactor closures roadmap – an idea that had the time to germinate over decades in Germany with the anti-nuclear movements in the 1970s and an early agreement between policy makers and power companies to limit the lifetime of nuclear power stations to 32 years around 2000 – and aggressive policies to promote RE with supporting mechanisms (FiTs, then auctions) which have delivered capacity and cost reductions.[16] Notably, since 2010, Germany shut down 10 of its 17 nuclear reactors and added 29GW and 25GW of wind and solar power, respectively.[17] And wind and solar power projects in auctions are now commonly competitively procured between $50 per megawatt-hour (/MWh) and $65/MWh, and even, sometimes, without subsidies as demonstrated by offshore wind projects awarded in 2017.[18]

And in 2018, RE may finally overthrow coal as the country main technology for electricity generation. Unthinkable 30 years ago (Chart 13 on next page).

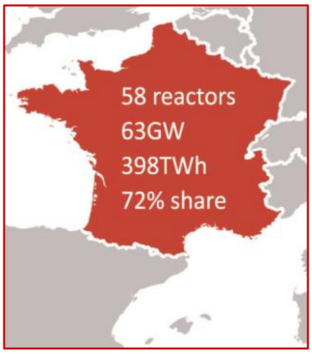
Chart 13: Electricity Generation by Technology in Germany 1990-2017



Note: other being negligible (<30TWh annually throughout the period) it is not included in this chart
Source: BP, Statistical Review of World Energy 2018 (June 2018)

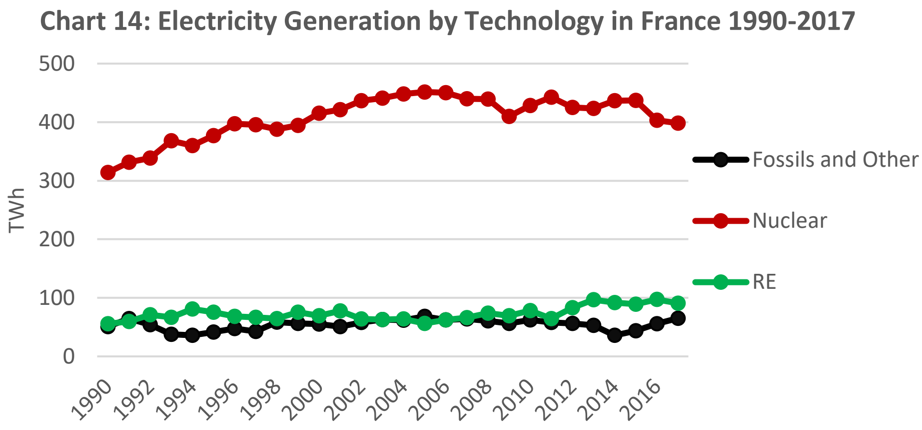
France

The essential ingredients of Germany success have been at least partly – and painfully – lacking in France until now. In particular, the nuclear reactor closures roadmap has still not been completely established yet, 3 years after the adoption of the landmark Law Relative to the Energy Transition for Green Growth (!).[19]



Nuclear in France 2017/18

This critical Law targeted the aggressive reduction of nuclear power share in the country electricity generation mix to 50% by 2025, against 72% in 2017. At constant electricity generation with 2017 level this would mean a further reduction of 121TWh.[20] A similar effort to that of Germany, taking into account that nuclear power suffered a poor year again in France in 2017, as in 2016, plagued with safety concerns and technical troubles. Indeed, in 2016 and 2017, electricity generation from nuclear power was "only" about 400TWh, against roughly 420-445TWh for the period 2010-2015 (Chart 14 on next page).[21]



Source: BP, Statistical Review of World Energy 2018 (June 2018)

The absence of a clear roadmap has created uncertainty, which combined with an existing, but too limited support for RE deployment, as well as some local opposition against RE projects (especially onshore wind), has led to postpone the nuclear power reduction target to 2035 (officially announced in November 2018).

On a more positive note, however, it has also finally been announced that 14 nuclear reactors should close by 2035, starting with Fessenheim 1 and 2 in 2020, and 8 candidate power plants for the 12 other reactor closures have been identified; Blayais, Bugey, Chinon, Cruas, Dampierre, Gravelines, St. Laurent, and Tricastin.[22]

And recent tenders for wind and solar power have demonstrated the cost competitiveness of the two technologies. In 2018, onshore wind auction price was $74/MWh, and that of large-scale (5-17MW) ground mounted solar photovoltaic (solar PV) $59/MWh.[23] This should bring confidence to decision makers that in the pursuit of their ambitious goal, nuclear power can be replaced cost efficiently by other low carbon technologies.

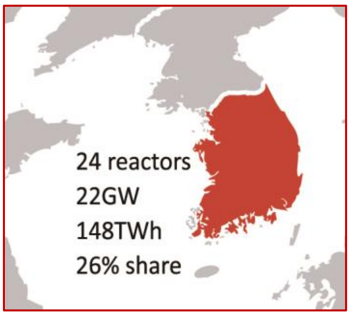
Korea

In terms of ambitions of reduction of electricity generation from nuclear power, Korean phaseout is as ambitious as those of Germany and France; about 150TWh, but in a much longer timeframe. Indeed, while these efforts are taking place now in Germany, and will probably take place in the next two decades in France, Korea is planning to end its reliance on nuclear power in the early 2060s.

This does not mean that Korea is a laggard, but rather that the country faces a quite different situation.

ts nuclear power fleet is more than a decade younger; reactor average age of 21 years, than those of Germany and France; 32 and 34 years, respectively.

In addition, Korea is still building 5 new reactors with a combined capacity of 7GW which should all be commissioned by 2023.[24]



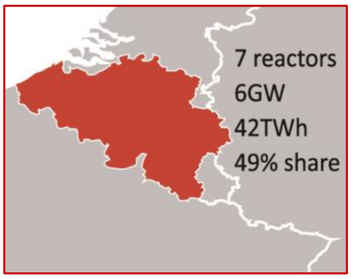
Nuclear in Korea 2017/18

Finally, Korea electricity generation is still growing, and RE have not fully proven their relative cost competitiveness with nuclear power in the country yet (which is a relatively unusual case). For instance, in 2018, the settlement price – the price generators get paid on the market based on cost reviews of the Cost Assessment Committee of Korea Power Exchange – of nuclear power is about \$55/MWh, while those of wind and solar power are around \$90/MWh and \$85/MWh, respectively.[25] Considering these developments, it is logical Korea will need more time to reach its target.

In the medium-term, by 2030, to move forward with its nuclear power phaseout plan Korea will aim at expanding the share of RE in its electricity generation mix to about 20% from roughly 5% currently.[26] Energy policies supporting this effort are a FiT scheme and a renewable portfolio standard.

Belgium

Belgium nuclear power phaseout is also ambitious even if it will require shutting down less reactors (7), with less installed capacity (6GW) and generating less electricity (usually about 40-50TWh a year). That is because nuclear power still accounts for roughly half of the country total electricity generation – one of the highest shares in the world, and the deadline for the permanent closures of all reactors is coming soon; 2025.



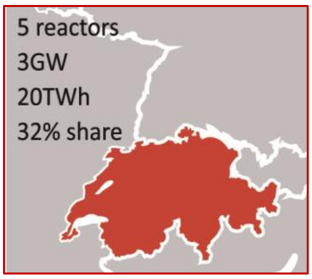
Nuclear in Belgium 2017/18

Belgium will need to significantly ramp up its RE installed capacity quickly if it is to meet its goal in a sustainable way (i.e. without increasing electricity generation from fossil fuels).

So far, reduction in electricity generation from nuclear power (-6TWh) has been more than offset by increase in electricity generation from RE (+9TWh) in the period from 2010 to 2017. However, the road to 0TWh from nuclear remains long; 42TWh, and the country starts to run out of time (only 8 years).

Part of the solution may come from offshore wind power. Belgium, by adding 165 megawatts (MW) of offshore wind power capacity in 2017, got closer to have 1 GW of offshore wind power cumulative installed capacity. Further reduction in cost will be necessary though; about \$115-150/MWh in 2018-H2, which is relatively higher than in other countries.[27]

Switzerland



Nuclear in Switzerland 2017/18

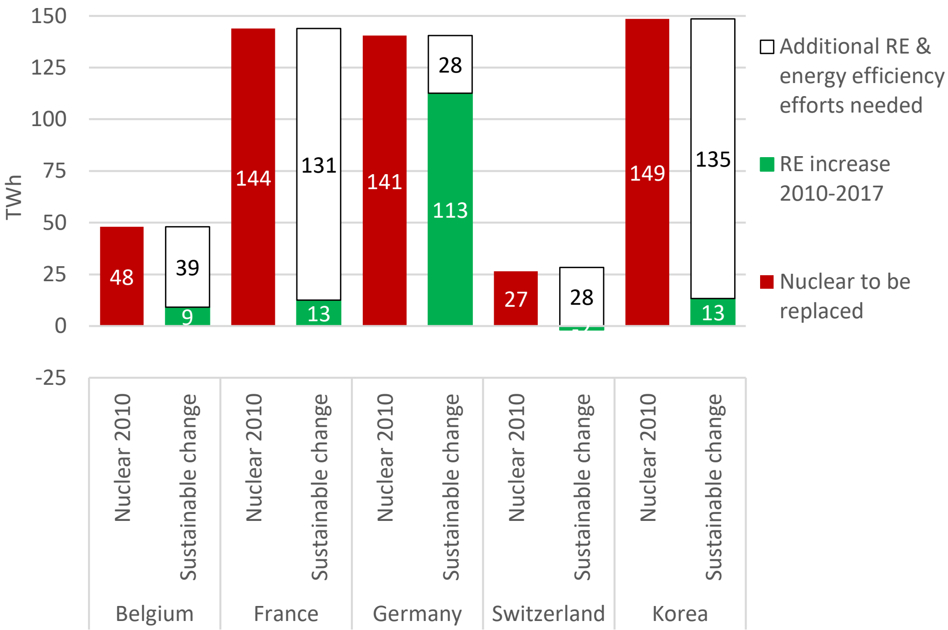
Finally, Switzerland, which is the country of this group with the lowest number of nuclear reactors (5), nuclear power installed capacity (3GW) and generated "only" 20TWh from nuclear power in 2017 (still almost one-third of the country total electricity production), appears to be the least advanced in its phaseout progresses.

Advances are limited to the announced shutdown of the Muehleberg reactor in 2019 as well as a new legislation prohibiting the construction of new nuclear power plants, and pushing for energy efficiency and expansion of non-hydro RE.[28]

There are no limits on nuclear reactor operating lifetime in Switzerland. The country most recent reactor, Leibstadt, has been connected to the grid in 1984.[29] Assuming it will operate for 50 or 60 years, Switzerland nuclear power phaseout may happen in 2034 or 2044.

Chart 15 below summarizes what remains to be done for all these countries to reach their goals of reducing or phasing out electricity generation from nuclear power in a sustainable way.

Chart 15: The Path to Replace Nuclear Power Without Increasing CO_2 Emissions



Note: for France the amount of electricity generated from nuclear power to be replaced is calculated based on the country total electricity generation and nuclear electricity generation in 2010; 569TWh and 429TWh, respectively. The nuclear reduction target being 50% of the country total electricity generation, nuclear electricity generation should decrease to 285TWh, 144TWh less than in 2010

Source: BP, Statistical Review of World Energy 2018 (June 2018)

It may also be mentioned here that in Taiwan a referendum in November 2018 reversed a previous policy of phasing out nuclear power by 2025.[30] Yet, after the closures of 2 reactors (Chinshan 1 and 2) in October 2018, Taiwan now only has 4 operational reactors with a total combined capacity of 4GW.[31] In addition, Taiwan has an ambitious target of 5.5GW offshore wind power capacity by 2025, and has been successful in tendering 1.7GW of this capacity at \$73-84/MWh in 2018.[32]

B) Countries with moderate action resulting in nuclear power slow decline: US, Japan, Canada, UK, and Sweden

In recent years, some other key countries have seen their nuclear power plant fleet shrinking, but without any real political push. And this trend may well persist because alternative lower cost carbon technologies are available, or will become soon. This is the case of Canada, Japan, Sweden, the UK, and the US (Table 4 on next page).

Table 4: Countries with Moderate Action Resulting in Nuclear Power Slow Decline

	Nuclear Progresses (2010 → 2017/2018 as of Dec. 3)			
Country	Number of reactors	Installed capacity (GW)	Electricity generated (TWh)	Share in electricity generation (%)
US	104 → 98	103 → 99	849 → 847	19% → 20%
Japan	55 → 42	47 → 40	292 → 29	25% → 3%
Canada	20 → 19	14 → 14	90 → 97	15% → 14%
UK	19 → 15	10 → 9	62 → 70	16% → 21%
Sweden	10 → 8	10 → 9	58 → 66	39% → 40%

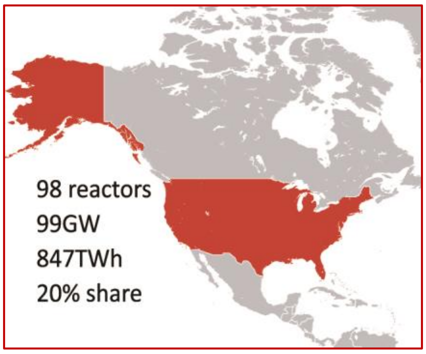
Notes: electricity generated may increase despite less installed capacity thanks to higher capacity factors. The share of nuclear power in electricity generation depends on electricity generated from nuclear power and total electricity generation

Sources: created by REI based on; IAEA, Power Reactor Information System (accessed 3 December 2018) for number of reactors and installed capacity (2018 as of Dec. 3), and BP, Statistical Review of World Energy 2018 (June 2018) for electricity generated and share in electricity generation (2017)

United States

In the US, the country with the largest nuclear power fleet; still 98 reactors with a total combined capacity of about 99GW, nuclear power is facing great economic difficulties, in competitive markets particularly.

In June 2017, an analysis by Bloomberg NEF showed that 34 out of the 61 nuclear power plants (operating 99 reactors), in the US were losing money with losses totaling almost $3 billion annually because they were outcompeted by cheaper gas and RE.[33]



Nuclear in the US 2017/18

In this context, unprofitable nuclear power reactors are closing across the country.[34] 7 nuclear reactors (total combined capacity; more than 5GW) shut down since 2013. At least 12 reactors (total combined capacity; over 11GW) have announced early retirement plans by 2025. Another 10 (total combined capacity; about 10GW) would have closed if not rescued by States subsidies in Illinois (Clinton 1 and Quad Cities 1 and 2), New Jersey (Hope Creek 1 and Salem 1 and 2), and New York (Fitzpatrick, Ginna, and Nine Mile Point 1 and 2).[35] And a study by the Union of Concerned Scientists published in November 2018, forecasts that an additional 13 reactors (total combined capacity; more than 12GW) will be unprofitable in the period 2018-2022 possibly making the lists of early retirement plans and rescued reactors even longer.[36]

Almost all these closures or announced closures come nearly a decade or more before scheduled license expirations of these reactors (after 40 years of operation, or 60 years when license for an additional 20 years of operation has been granted), i.e. even though they could technically operate for decades (Table 5 on next page).

Table 5: US Nuclear Power Reactors Announced Closures for Economic Reasons Since 2013

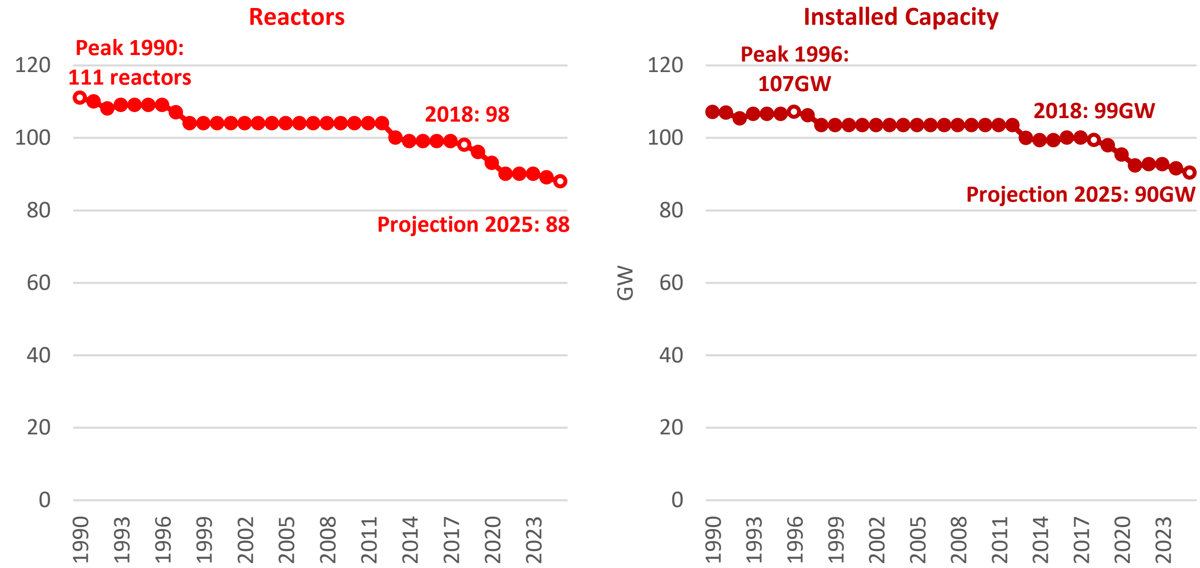
Reactor name (State)	Closure year	Scheduled license expiration year	Net capacity (MW)
Crystal River 3 (Florida)	2013	2016	860
Kewaunee (Wisconsin)	2013	2033	566
San Onofre 2 and 3 (California)	2013	2022	2,150
Vermont Yankee (Vermont)	2014	2032	605
Fort Calhoun 1 (Nebraska)	2016	2033	482
Oyster Creek (New Jersey)	2018	2029	619
Reactor name (State)	**Planned closure year**	**Scheduled license expiration year**	**Net capacity (MW)**
Pilgrim 1 (Massachusetts)	2019	2032	677
Three Mile Island 1 (Pennsylvania)	2019	2034	819
Davis Besse 1 (Ohio)	2020	2037	894
Duane Arnold 1 (Iowa)	2020	2034	601
Beaver Valley 1 and 2 (Pennsylvania)	2021	2036 & 2047	1,826
Perry 1 (Ohio)	2021	2026	1,256
Indian Point 2 and 3 (New York)	2020 & 2021	Under review	2,060
Palisades (Michigan)	2022	2031	805
Diablo Canyon 1 and 2 (California)	2024 & 2025	2024 & 2025	2,256

Sources: IAEA, Country Statistics: United States of America, US Nuclear Regulatory Commission, Status of Initial License Renewal Applications and Industry Initiatives, and Power Generating Companies, Pilgrim, Three Mile Island, Davis-Besse, Duane Arnold, Beaver Valley, Perry, Indian Point, Palisades, and Diablo Canyon (all accessed 18 September 2018, except IAEA; 3 December 2018)

At the same time, only a few new reactors have been recently commissioned or are under construction. In 2016, Watt Bar 2 (Tennessee), which construction started in 1973, was connected to the grid. The first reactor to be connected to the country grid in 20 years.[37] And the expansion of Vogtle (Georgia) nuclear power plant is currently the only project moving forward with the construction of 2 new reactors (3 and 4, capacity of 1.1GW each). Reactor 3 could start in 2021, and reactor 4 in 2022 unless further delays postpone again the beginnings of their operations, which were originally planned for 2019 and 2020, respectively.[38]

If all these developments take place as planned and no new closures are announced, the US nuclear reactor fleet will be reduced to 88 reactors and 90GW by 2025, a roughly 15-20% decrease compared with its 1990s peaks of 111 reactors (1990) and 107GW (1996) (Chart 16 on next page).

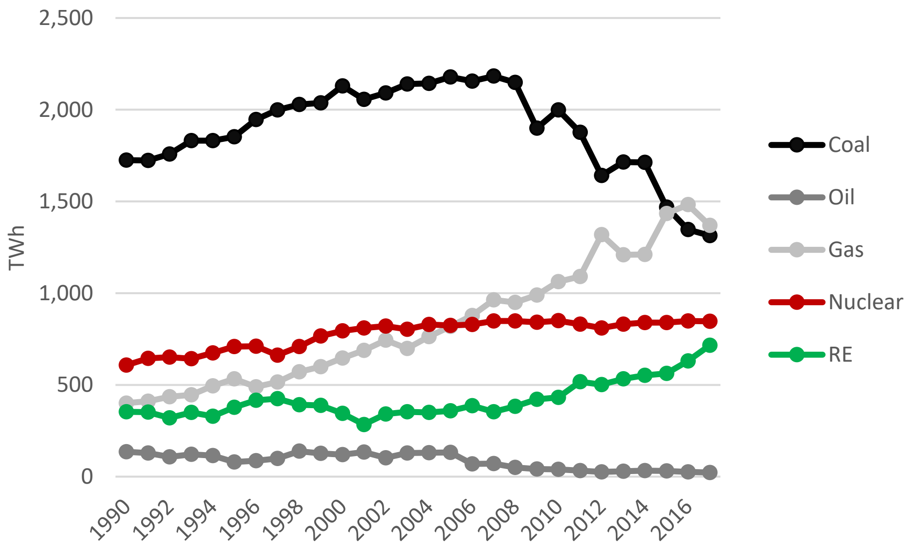
Chart 16: Nuclear Power Decline in the United States 1990-2025



Source: REI based on IAEA, [Power Reactor Information System](#) (accessed 3 December 2018) and information made available throughout this section

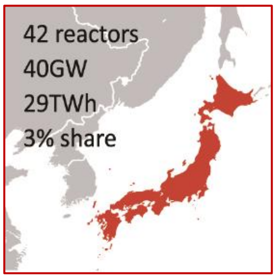
Regarding CO_2 emissions, reduction of nuclear power from its 1990s peaks has not resulted in an increase of emissions countrywide. In 2017, CO_2 emissions in the electric power sector with 1,744 million tons of CO_2 were even 25% below their level in 2000.[39] That is mainly because of fuel switching from coal to gas, RE deployment and energy efficiency improvements (Chart 17).[40]

Chart 17: Electricity Generation by Technology in the United States 1990-2017



Note: other being negligible (<20TWh annually throughout the period) it is not included in this chart
Source: BP, [Statistical Review of World Energy 2018](#) (June 2018)

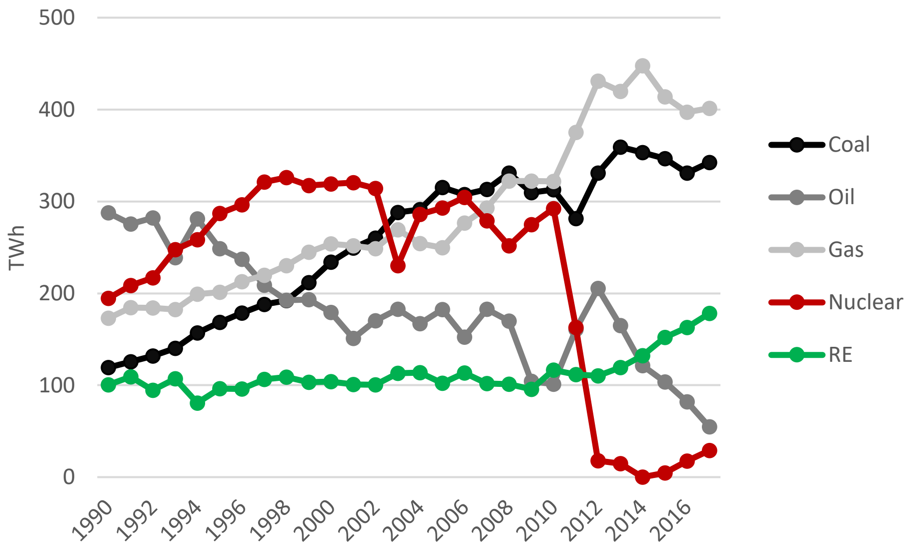
Japan



Nuclear in Japan 2017/18

In Japan, in the decade prior to Fukushima Daiichi nuclear accident in March 2011, electricity generation from nuclear power was usually around 300TWh (Chart 18), and accounted for 27% of the country total electricity generation in average in this period.[41] Following the accident, output from nuclear power significantly decreased and its share accordingly fell, to 3% in 2017, because of a number of key issues plaguing nuclear power; difficulties in restarting nuclear reactors, more stringent safety standards, fierce local opposition, and economic and technical troubles having led to the permanent shutdown of 13 reactors with a total combined capacity of more than 7GW.[42]

Chart 18: Electricity Generation by Technology in Japan 1990-2017



Note: other being negligible (<15TWh annually throughout the period) it is not included in this chart
Source: BP, Statistical Review of World Energy 2018 (June 2018)

As a result, only 9 reactors with a total combined capacity of almost 9GW had been authorized to restart operations as of the beginning of December 2018 (Table 6).

Table 6: Nuclear Reactors Authorized to Restart Operations in Japan (Early December, 2018)

Reactor name	Net capacity (MW)	First grid connection (year)	Electric Power Company
Genkai 3 and 4	2,254	1993 & 1996	Kyushu
Ohi 3 and 4	2,254	1991 & 1992	Kansai
Sendai 1 and 2	1,692	1983 & 1985	Kyushu
Takahama 3 and 4	1,660	1984 both	Kansai
Ikata 3	846	1994	Shikoku

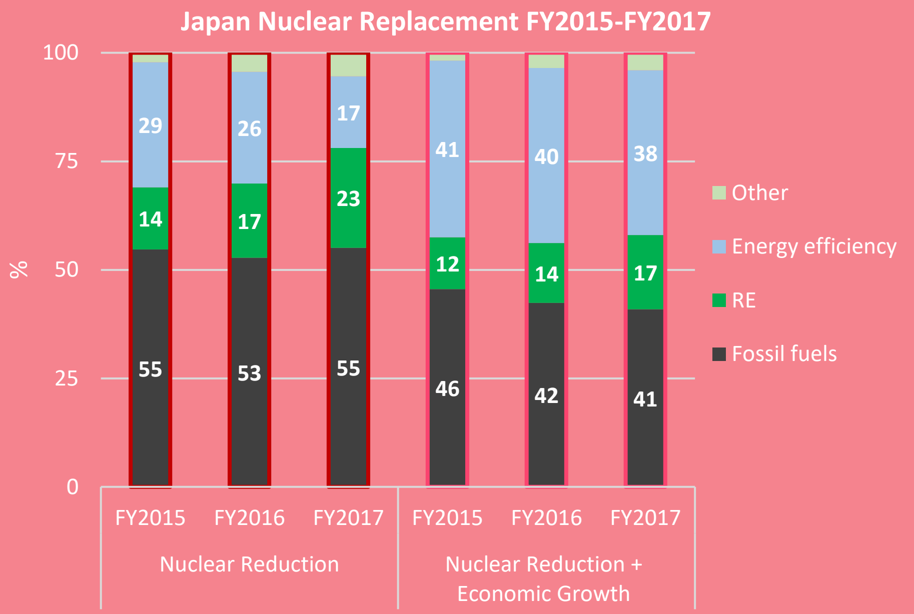
Sources: IAEA, Country Statistics: Japan, and World Nuclear Association, Nuclear Power in Japan – updated November 2018 (both accessed 3 December 2018)

Taking 2010 as a baseline year, this has left a gap of up to roughly 290TWh (in 2014, when there was no electricity generated from nuclear power at all) to be filled in by electricity generated from other technologies and/or electricity consumption reduction.[43] #1 JAPAN TOPICS below describes how RE expansion and energy efficiency (including energy savings) have replaced 40-55% of nuclear power electricity generation in the past 3 fiscal years.

#1 JAPAN TOPICS: 7 years after Fukushima Daiichi accident, Japan halfway in replacing nuclear

At the end of fiscal year (FY) 2017 ending on 31 March 2018, electricity generation from nuclear power reached 33TWh in Japan. The highest level since FY2011, but still 255TWh less, or almost -90%, than in FY2010, the year at the end of which Fukushima Daiichi nuclear accident happened.[44]

In the past 7 years, large-scale deployment of RE, essentially solar PV, following the introduction of a feed-in tariff (FiT) scheme in July 2012, and progress in energy efficiency have enabled to meet 40-43% of the reduction in electricity generation from nuclear power in the period from FY2015 to FY2017. This range even increases to 53-55% when taking economic growth into account:

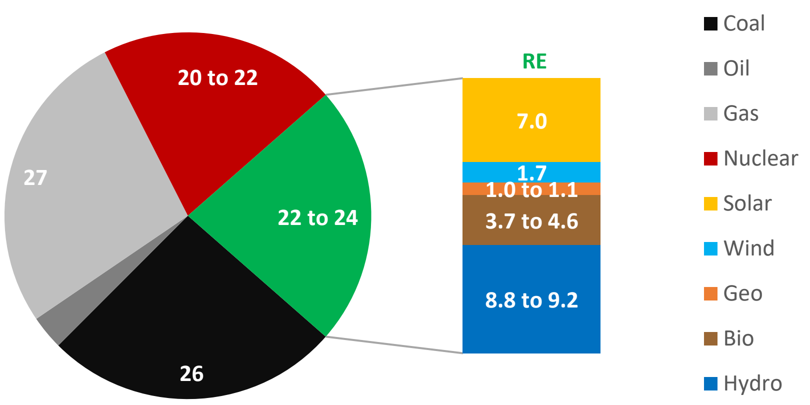


Sources: created by REI, based on IEA, [World Energy Statistics 2018] (September 2018) for electricity generation data, and Government of Japan, Cabinet Office, Economic and Social Research Institute, [National Accounts for 2017] (accessed 22 January 2019) for economic growth data

These achievements make Japan roughly halfway on its path towards becoming a nuclear-free society.

Yet, these developments, negative for nuclear power, encouraging for RE and energy efficiency, have surprisingly still not convinced the Japanese government to be more realistic and adopt a more moderate nuclear power target for FY2030, and pursue more aggressive goals for other more successful low carbon technologies. Indeed, as it currently stands, based on its Long-term Energy Supply and Demand Outlook, Japan ambitiously targets nuclear power share to reach 20-22% in FY2030 from only 3% in FY2017 and, less ambitiously – considering current dynamics, that of RE to increase to 22-24% from 16% in FY2017 (the remaining being fossil fuels) (Chart 19 on next page).[45]

Chart 19: Japan Planned Electricity Generation Mix in FY2030 (%)



Source: Japan Ministry of Economy, Trade and Industry, Long-term Energy Supply and Demand Outlook (July 2015)

And this actually overoptimistic nuclear power target, which seems already out of reach as demonstrated in #2 JAPAN TOPICS below, is likely to put Japan climate change target at risk.

#2 JAPAN TOPICS: The Long-term Energy Supply and Demand Outlook, unrealistic for nuclear power

Japan Long-term Energy Supply and Demand Outlook of 2015, confirmed in its latest Strategic Energy Plan in 2018, targets nuclear power to account for 20-22% of the country total electricity generation of 1,065TWh in FY2030.[46] That is to say, electricity generation from nuclear power is expected to amount to 217-232TWh in FY2030.

Assuming a capacity factor of 70% (slightly higher than that of the nuclear power fleet in Japan in FY2010; 67.2%), generating 217-232TWh would require about 35-38GW of gross nuclear power installed capacity in FY2030.[47]

As of early December 2018, according to the IAEA, Japan still had 42 existing reactors with a total combined capacity of 40GW.

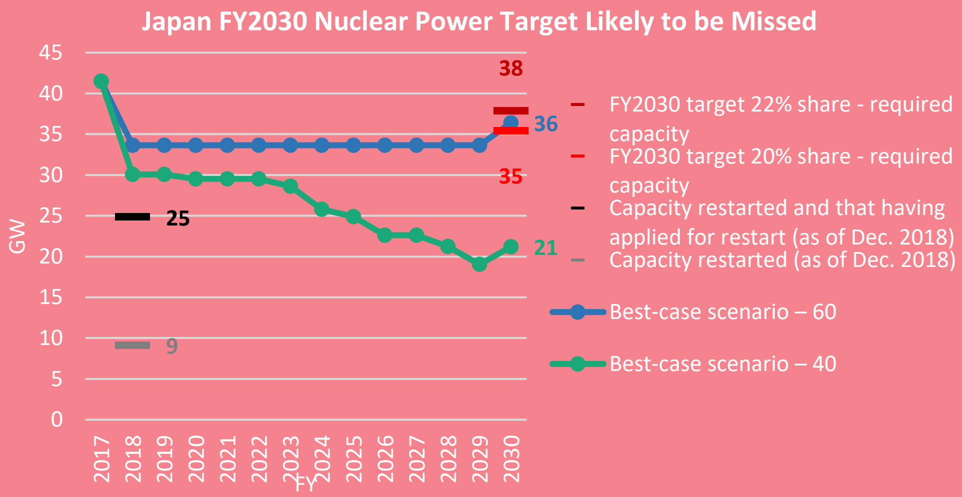
As a matter of fact, however, because of Fukushima Daiichi nuclear accident and its subsequent consequences on nuclear power social acceptance, political support, safety, and economics, only 9 reactors with a combined capacity of almost 9GW have been authorized to restart until now. An additional 16 reactors with a combined capacity of about 15GW have applied for restart.[48]

And still out of the 42 existing reactors, 8 reactors with a total combined capacity of approximately 8GW have either actually already been shut down; Ikata 2, Ohi 1 and 2, and Onagawa 1, or announced plans to permanently shut down Fukushima Daini 1, 2, 3, and 4 (likely shutdown).[49]

In addition, Japan has 2 reactors under construction Shimane 3 (1.3GW) and Ohma (1.3GW) for which commissioning dates are unknown.[50] The new Higashidori reactor project led by Tokyo Electric Power Company (TEPCO) which construction started in January 2011 and was halted because of the Great East Japan Earthquake which triggered a tsunami and accident at Fukushima Daiichi nuclear power plant, is now indefinitely deferred.[51] It is not recognized as "under construction" by the IAEA because the first major placing of concrete for the base mat of the reactor building has not been made.[52]

And reactors may be allowed to operate for a period of 40 years (default limit), or a maximum of 60 years if a lifetime extension is granted.[53] So far, only a few reactors have been granted the right to operate until 60 years; Mihama 3, Takahama 1 and 2, and Tokai 2.[54]

By designing scenarios assuming the full restart of all the remaining 34 existing reactors (i.e. considering the closures with immediate effect (from the end of FY2018) of the 8 reactors having either actually already closed or announced permanent shutdowns plans), the start of the 2 reactors under construction for FY2030, and setting the lifetimes of reactors at 40 years ("Best-case scenario – 40") and 60 years ("Best-case scenario – 60"), respectively, the extreme requirements to meet Japan FY2030 nuclear power target clearly appear:



Note: calculations in this chart are based on gross installed capacity

Sources: *REI based on IAEA, Power Reactor Information System (accessed 3 December 2018) and information made available throughout this section*

Only if all existing reactors are restarted and lifetime extensions to 60 years are granted, and operations effectively carried out up to 60 years, Japan can meet its FY2030 nuclear power target.

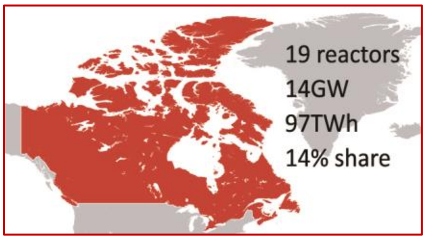
Based on observed developments aforementioned, it seems highly unlikely to expect a full nuclear restart, and many lifetime extensions beyond 40 years to be granted.

The only remaining options would then either be to; build additional new reactors – for which there is currently no active plans, and/or reach significantly higher capacity factors.[55] These are equally improbable. As a result, it may be advanced that Japan Long-term Energy and Supply and Demand Outlook is unrealistic for nuclear power.

Thus, the real question now is not; if Japan will miss its nuclear power target, but by how much. Consequently, this should signal Japanese policy makers to revise upward the country target of 22-24% for RE in electricity generation in FY2030, and implement ambitious policies to successfully stimulate RE further expansion and pursue additional energy efficiency gains.[56] Otherwise, Japan may rely more on imported expensive dirty fossil fuels to fill in the gap left by nuclear anticipated underachievement, jeopardizing the country climate change target; 26% reduction of GHG emissions by FY2030 compared with FY2013.[57]

Canada

In Canada, nuclear power is also in decline. Canada is best known for being the world's second largest electricity producer from hydropower; almost 400TWh in 2017, 57% of the country electricity generation.[58] Its nuclear fleet is limited to 19 reactors with a total combined capacity of 14GW and accounting for 14% of the country electricity generation in 2017. Thus, in Canada, a country blessed with a significant hydropower potential, nuclear power has never been the main low carbon technology. And its contribution in this field will probably become even smaller in the next decades.

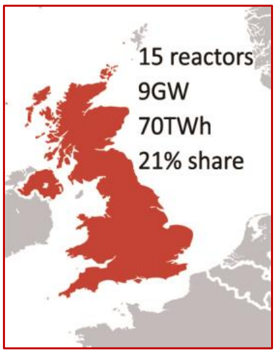


Nuclear in Canada 2017/18

There is currently no reactor under construction in Canada. And plans to build new ones have been either deferred or lapsed.[59] Only costly refurbishment and lifetime extensions are being pursued.[60] These will maintain some nuclear reactors operational for a longer period, but not indefinitely. For instance, it has been decided that the 6 reactors (total combined capacity of more than 3GW) at the Pickering nuclear power plant will be shut down by 2024, joining 6 other reactors already closed and still not decommissioned.[61]

In addition, Canada is phasing out coal power; still accounting for 11% of the country electricity generation.[62] And wind power further expansion (12GW installed capacity and 5% of electricity generation in 2017) will certainly help filling the nuclear and coal gaps by providing more cost competitive low carbon electricity.[63] In Alberta in 2017, an auction for 600MW of wind power capacity delivered a record weighted average price of $29/MWh.[64]

United Kingdom



Nuclear in the UK 2017/18

On the other side of the Atlantic Ocean, the UK is at a crossroad. The UK has almost already reached its very ambitious goal of phasing out coal power by 2025; coal accounted for only 7% of electricity generation in 2017, against 65% in 1990.[65] A great achievement that has been made possible essentially thanks to fuel switching from coal to gas, expansion of RE, and gains in energy efficiency. To further decarbonize its power sector, as required to meet its 2050 emission reduction target; at least -80% GHG compared with 1990, the UK will now need to reduce electricity generation from gas.

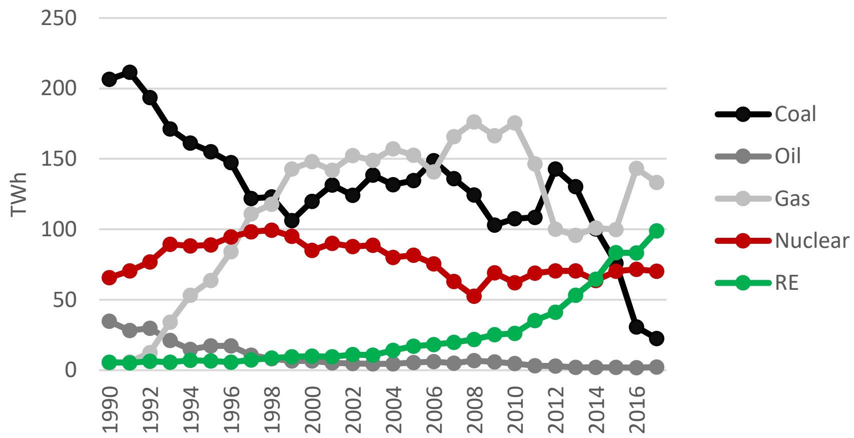
Beyond energy efficiency, that should always be pursued, this leaves the door open for a competition between nuclear and RE. A contest, which result may already be relatively easy to guess today.

Since 1995 – a year marked by the new last grid connection of a nuclear reactor in the UK to date (Sizewell B), the number of operational nuclear reactors and installed capacity in the UK decreased from 35 to 15 and from 12GW to 9GW.[66]

And over the past two decades, pronounced interest in multiple new nuclear reactor projects (Hinkley Point C-1 and 2, Sizewell C-1 and 2, Wylfa Newydd 1 and 2 – suspended, Oldbury B-1 and 2 – suspended, Moorside 1, 2, and 3 – cancelled, and Bradwell B-1 and 2), by the successive governments, has demonstrated why new builds should rather stay at the stage of projects than actually being constructed.[67] This comes down again to the economics. The strike price for Hinkley Point C (construction of reactor 1 started on 11 December 2018) is around $115-120/MWh for 35 years (for delivery in 2026/2027).[68] And that targeted for Wylfa Newydd – project halted by Hitachi in January 2019 because of economic issues – up to about $100/MWh also for 35 years (for delivery in 2025).[69] These are uncompetitive.

In the meantime, RE has shown that it can be efficiently deployed on a large-scale – RE electricity generation eclipsed nuclear electricity generation in the UK in 2014 (Chart 20), and is now quite cost competitive. For instance, in 2017, auctions for over 3GW of offshore wind capacity delivered prices around $100/MWh for delivery in 2021/2022 and significantly dropped to $75/MWh for delivery in 2022/2023.[70]

Chart 20: Electricity Generation by Technology in the United Kingdom 1990-2017



Note: other being negligible (<10TWh annually throughout the period) it is not included in this chart
Source: BP, [Statistical Review of World Energy 2018] (June 2018)

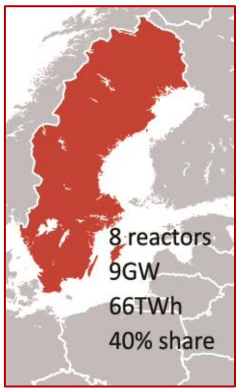
Thus, if competition there is, it would rather be between existing and aging nuclear (reactors average age of 35 years already as of 3 December 2018) and RE. Again, reactor lifetime extensions beyond 40 years are being sought, but these are only temporary solutions.[71]

Sweden

Still in Europe, in Sweden, nuclear power future seems even more compromised. There are currently 8 operational nuclear reactors with a total combined capacity of 9GW in Sweden.[72]

These reactors are among the oldest in the world; average age of 38 years.

In 2017, nuclear power accounted for 40% of the country electricity generation. A share that should reach 0% by 2040 since Sweden is targeting to generate 100% of its electricity from RE by 2040. As surprising as it may seem, Sweden is not officially directly phasing out nuclear power though.[73]



Nuclear in Sweden 2017/18

Of the 8 existing operational reactors in Sweden, 2 are scheduled for shutdown (Ringhals 2 in 2019 and Ringhals 1 in 2020) without replacement, and the remaining 6 are targeting lifetime extensions up to 60 years into the early 2040s.[74] This would roughly coincide with the 2040 100% RE target.

Economics, may however, decide their fate before this date. With abundant cheap hydro and wind power accounting for approximately 55% and 9% of electricity generation, respectively, in the Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden), nuclear has already become an endangered species, which survival in Sweden owes a lot to the relief of a capacity tax on nuclear power production which phaseout started in 2017 (to be phased out gradually over two years).[75]

C) Countries supporting expansion of nuclear power, but marginally compared with RE: China, India, UAE, and Saudi Arabia

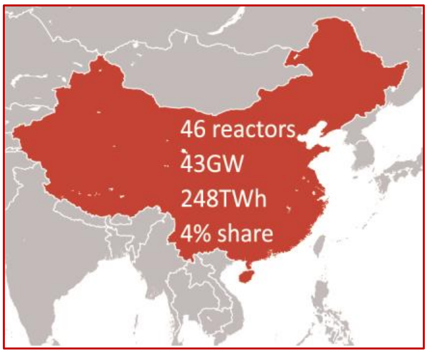
Nuclear power is declining in many places, but not everywhere. In a few major economies such as China and India it is even expanding (Table 7). However, when compared with RE, deployment of nuclear power in these countries appear to be somewhat minor.

Table 7: Countries Supporting Expansion of Nuclear power, but Marginally Compared with RE

	Nuclear Progresses (2010 → 2017/2018 as of Dec. 3)			
Country	Number of reactors	Installed capacity (GW)	Electricity generated (TWh)	Share in electricity generation (%)
China	13 → 46	10 → 43	74 → 248	2% → 4%
India	19 → 22	4 → 6	23 → 37	2% → 2%

Sources: created by REI based on; IAEA, Power Reactor Information System (accessed 3 December 2018) for number of reactors and installed capacity (2018 as of Dec. 3), and BP, Statistical Review of World Energy 2018 (June 2018) for electricity generated and share in electricity generation (2017)

China



Nuclear in China 2017/18

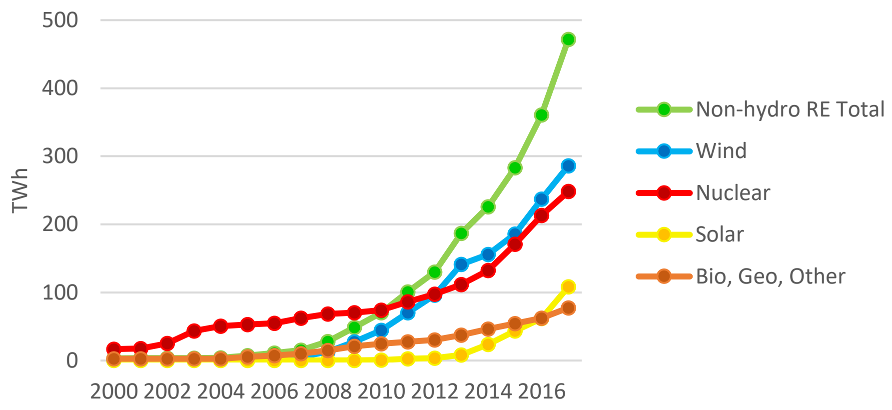
China has been the world's major growth engine for nuclear power in the past decade. It added what some may describe an "impressive" 33 nuclear reactors with a total combined capacity of 33GW since 2010. Empirically, a very similar expansion to that of France in the 1980s, i.e. same as that of a much smaller economy a while ago.[76] And despite all these efforts, China will even fall short of its official target of 58 GW by 2020, that is itself less than half of the most ambitious previously reported, at the beginning of the 2010 decade, goal of 120GW.[77] Indeed, if all the 10 reactors, with a total combined capacity of almost 10GW, planned to be commissioned by 2020 are delivered on time, China installed capacity will reach less than 53GW by 2020, more than 5GW less than its target.[78]

While nuclear ambitions have been scaled back down, those for RE have instead been exceeded. This may be best illustrated by the exceptional growth of solar power. At the end of 2016, the National Energy Administration and the National Development Reform Commission of China released the country 13th Five-Year Plan for the Power Sector that notably set a target of 110GW of solar power capacity by 2020.[79] At that time China had a little less than 80GW solar power capacity installed.[80] Then, in 2017 alone, China added 53GW of solar capacity, well enough to smash its 2020 target.[81]

However, among RE technologies, with the exception of hydropower which generated 1,156TWh – by very far the largest amount in the world – accounting for about 18% of China total electricity generation in 2017, that is not solar power, but wind power which has made the greatest strides so far.

In 2013, wind power overtook nuclear power in terms of electricity generation and has maintained its leadership as the first non-hydro low carbon technologies in China since then (Chart 21). This lead even extended to a record +38TWh differential in favor of wind over nuclear in 2017.

Chart 21: China Electricity Generation from Non-Hydro Low Carbon Technologies 2000-2017

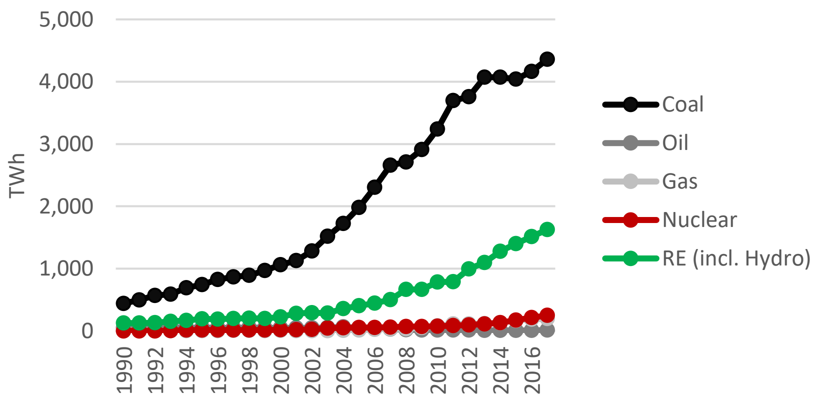


Source: BP, Statistical Review of World Energy 2018 (June 2018)

In addition, there is currently only one reactor expected to be commissioned after 2020; Tianwan 6 with a capacity of 1GW, which start is planned for 2021.[82] And no new construction has been started since December 2016, 2 years(!).[83] Plans for further expansion of nuclear power certainly exist, but it is unclear which projects will actually be built.[84]

These trends clearly show that whereas RE is to play a key role in China power sector decarbonization – a huge task with coal power still being the main technology for electricity generation by far (Chart 22), nuclear is to stay behind in the shadow.

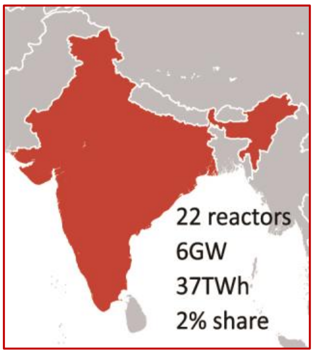
Chart 22: Electricity Generation by Technology in China 1990-2017



Note: other being negligible (<50TWh annually throughout the period) it is not included in this chart
Source: BP, Statistical Review of World Energy 2018 (June 2018)

India

India is another perfect example of a country expanding in nuclear power and even more in RE.



Nuclear in India 2017/18

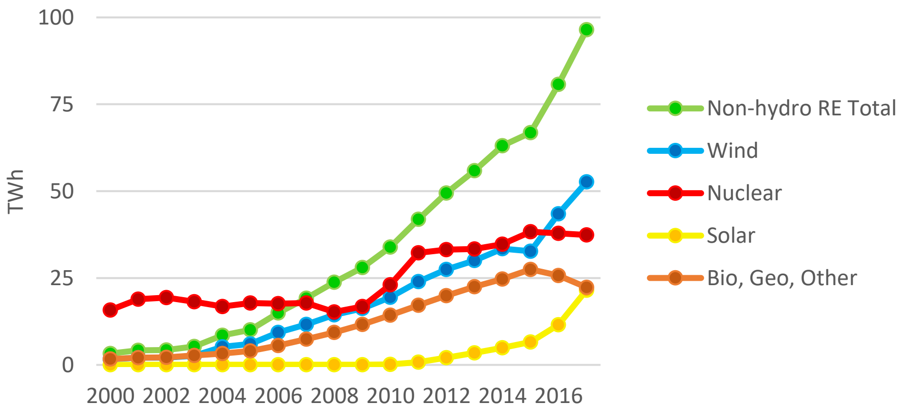
Since 2010, India only added 3 operational reactors to its fleet, resulting in a 2GW increase of its cumulative nuclear power capacity. If all the 7 reactors currently under construction with a capacity of 5GW are built as planned and no shutdowns occur, India will have 29 operational reactors and 11GW nuclear power capacity by 2026.[85] This may be seen as an optimistic projection since 5 reactors with a combined capacity of almost 1GW are already over 35 years old (as of 3 December 2018).[86]

In 2018, India revised down by almost 3 times its nuclear power target, from 63GW by 2032 to 22GW by 2031 (gross) due to slow implementation of new projects that may be related to difficulties such as lacks of funding, reliable supply chain that can handle huge increase in orders, and trained workforce to build and operate the plants at the planned level of activity.[87] Still, that would require roughly a doubling of the possible existing fleet in 2026.

On the other hand, for example, the solar 2022 target has been significantly revised upward from 20GW to 100GW in 2015.[88] Supported by multiple successful auctions and dramatic cost reductions in solar PV modules, dramatic growth in solar capacity at quite competitive costs unfolded. Indeed, India cumulative solar power capacity reached more than 24GW at the end of September 2018, against only about 3GW at the end of 2014.[89] And solar power projects are now commonly competitively procured in the range of $40-50/MWh in India.[90]

With significant progresses in wind power deployment also taking place, RE electricity generation excluding hydropower (136TWh in 2017) is, as in China, also completely surpassing that from nuclear power in India (Chart 23).

Chart 23: India Electricity Generation from Low Carbon Technologies 2000-2017



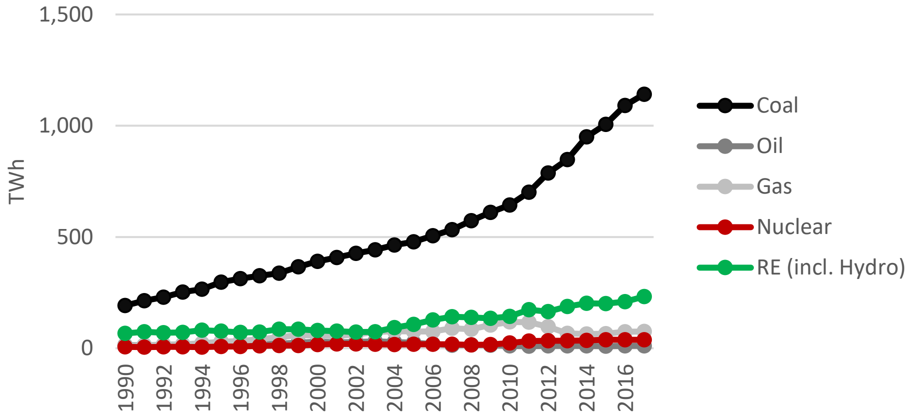
Source: BP, Statistical Review of World Energy 2018 (June 2018)

And with continuous significant growth in RE, particularly solar and wind, the gap with nuclear power will just keep growing.

This demonstrates how RE dominates the race against nuclear in rapidly growing economies where the need for cheap clean and rapidly scalable power is critical.

That is the reason why, as in China, not nuclear, but RE will be key to decarbonize India power sector. Again, this task will be huge, coal power being very dominant – in 2017, coal with more than 1,100TWh generated (Chart 24), accounted for more than 75% of the country total electricity generation.

Chart 24: Electricity Generation by Technology in India 1990-2017



Note: other being negligible (<1TWh annually throughout the period) it is not included in this chart
Source: BP, Statistical Review of World Energy 2018 (June 2018)

These developments in China and India are also observable in other countries such as the UAE or Saudi Arabia. Indeed, these two countries have shown their interest in developing nuclear power, but again RE, and particularly solar, has a clear economic advantage over the atom. In the past 2-3 years, solar has even demonstrated that it can be cost competitive with electricity generation from domestic gas productions – traditionally the cheapest solution for electricity generation in the region.

United Arab Emirates

The UAE, blessed with good oil & gas and excellent solar resources, has started construction of its first 4 nuclear reactors (Barakah 1, 2, 3, and 4) with a total combined capacity of more than 5GW in 2012-2015 and expects to have them all commissioned by 2021.[91] The levelized cost of electricity (LCOE) of nuclear power is estimated to be approximately $80-100/MWh in the UAE.[92] That is uncompetitive with solar PV and just competitive with concentrating solar thermal power (CSP), a promising technology in desertic areas, which costs are going down.

Indeed, in the UAE, solar PV LCOE is estimated to be between $40/MWh and $60/MWh, and may even be as low as $20-30/MWh as suggested by auctions in 2016.[93] And CSP LCOE may be competitive with auction result showing price of $73/MWh in 2017 for a 700MW project including systems providing up to 15 hours of storage (a combination of a tower and a field of troughs collecting heat and storing that heat in molten salt).[94] That is quite encouraging for a technology which installed capacity was less than 5GW worldwide at the end of 2017, and is now poised for further growth.[95]

With an electricity generation that is still increasing and an energy policy that aims at diversifying away from fossil fuels and being respectful of the environment, it is unsurprising that on strong economic grounds the UAE is targeting to significantly expand in RE, and thus especially solar, to the detriment of nuclear power.[96] Indeed, to reach its goals, the UAE Energy Strategy 2050 targets a 44% share of electricity from RE against only 6% for nuclear – which would not require any new reactor to be built.[97]

Saudi Arabia

Sharing some similarities with the UAE in terms of geographical location and natural resources endowment, Saudi Arabia also has nuclear power ambitions. These have not materialized yet though. Indeed, while the country targets to have about 18GW of nuclear power capacity by 2040 (originally by 2032), it does not have any reactor under construction.[98]

Whether this will be realized is quite uncertain, but what is not is solar power immediate and already proven cost competitiveness for which Saudi Arabia also has ambitious targets (25GW for CSP and 16GW for solar PV by 2040).[99] As a matter of fact, an auction in Saudi Arabia in 2017 delivered solar power at an impressive price of $23/MWh.[100] Unbeatable for nuclear power, and almost unbeatable even for electricity generation from domestic gas production.

This demonstrates again that the straightforward way to meet growing electricity needs cost efficiently, quickly, and environmentally is RE not nuclear power.

Russia

Nuclear in Russia 2017/18

Russia could not be included in any of the categories (A), (B), or (C) because it provides a quite unique country case. Russia is a historical player of the nuclear power industry with poor ambitions in the fight against climate change – for instance, it has still not ratified the Paris Agreement, and has no significant plan for domestic expansion of either nuclear or RE.[101]

There are currently 37 operational nuclear reactors with a total installed capacity of 28GW in Russia (as of 3 December 2018). Nuclear power consistently accounts for roughly 15-20% of the country electricity generation since 2000.[102] Russia is now building 6 reactors with a combined capacity of less than 5GW. If a governmental decree of 2016 advancing new reactor constructions is realized, and anticipated closures take place, total installed capacity of nuclear power in Russia could reach about 30GW by 2030, a slight increase – not a sign of a very dynamic domestic market.[103]

More dynamic is the country strategy to export nuclear power technologies. Until now, Russian company ROSATOM has been relatively successful in selling and starting constructions of its VVER-1200 – the first ever generation III+ reactor connected to the grid (Novovoronezh II-1 in Russia in 2016) – in foreign countries including Bangladesh, Belarus, and Turkey.[104]

And as for RE, Russia has the very modest ambition to increase the share of RE (excluding large hydro) from below 1% currently to 2.5% by 2024.[105]

In conclusion, it appears that key countries – with the exception of Russia – having embraced nuclear power until now, or planning to do so, do not support nuclear power as a major actor in the further decarbonization of the power sector. And as its contribution becomes increasingly minor, civil nuclear may eventually be essentially linked to interest in problematic military use of the technology.

II INDUSTRIAL OVERWHELMING DIFFICULTIES

1 Cost; not cheap and getting more expensive

A new economic reality has struck the nuclear industry in the first two decades of the 21st century; nuclear power is often neither cheap nor even cost competitive anymore as it has been continuously claimed for decades by its proponents.

A) Existing plants

Costs of existing and new build nuclear power plants are quite different, with the former being much more cost competitive than the latter. That is because older plants have been constructed under completely different and much more favorable conditions. For instance, with strong political support, in regulated markets, and with less stringent safety standards that is to say facing lower financial risks and lower costs. Older plants have also had the time to recover their initial investments costs. Yet, this is not preventing these plants to see their economics deteriorate in particular where competition is now taking place and enhancement in safety has been required following Fukushima Daiichi nuclear accident.

The US, France, and Japan, three of the four largest nuclear superpowers, are good examples of this new reality. Though stories are not completely the same.

China is not covered here because the country nuclear power plant fleet is much younger; average age of 7 years against about 30 years or more for the US, France, and Japan, making the comparison of existing plants with these three latter countries inappropriate.

<u>United States</u>

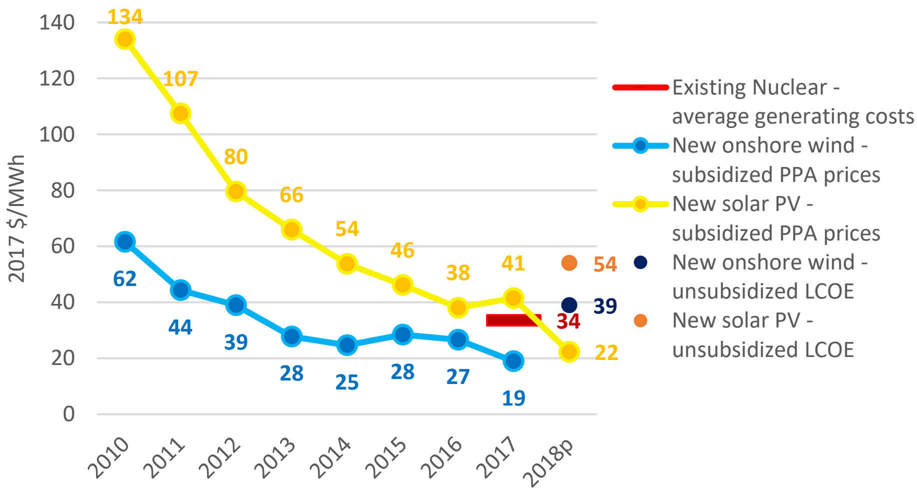
In the US, where it costs an average of $34/MWh to run an existing amortized nuclear power unit, the majority of 34 out of 61 plants (consisting of 99 reactors), were out of the money in 2017 because they were getting paid $20-30/MWh only for the electricity they generate.[106] The situation was particularly tough for reactors selling electricity into competitive markets.

It may be useful here to briefly explain that existing reactors after a few decades of operations have in general already paid for the relatively high capital cost of their construction, and the capital investment is thus amortized. Depreciation periods for nuclear power reactor is 15 years in the US, 50 years in France (initially 30 years until 2003), and 15 years in Japan.[107] These are usually shorter than operating lifetimes which are now often targeted around 40-60 years. Once a reactor is amortized, its production cost is equal to its operating expenses, essentially; operation and maintenance (O&M) and fuel and waste costs, which are relatively low. Amortized production costs are therefore quite different from LCOE, which estimate electricity generation costs of power plants over their entire operating lifetime (and thus and most importantly their initial construction costs).

In 2016, costs associated with safety upgrades following Fukushima Daiichi nuclear accident were estimated in a S&P Global Platts review, a major provider of energy and commodities information, to more than $4 billion for the entire US fleet through 2020, or $40 million per reactor.[108] These were relatively low in comparison with France; about $5 billion or $80 million per reactor, and Japan; $25-30 billion or about $640 million per reactor (this differs from the $530 million per reactor according to the Power Generation Cost Analysis Working Group set up by Japan Ministry of Economy, Trade and Industry (METI) in 2015).[109] These additional costs are certainly negatively impacting nuclear power economics in the US. However, the main issue for nuclear power in the US is the economic competition from other technologies, particularly cheap gas and RE which lower wholesale prices reducing nuclear power margin.[110]

In the US in 2017, most recent power purchase agreements (PPAs), still subsidized and competing with existing nuclear power, were around $20/MWh or even below for onshore wind (LCOE of about $40/MWh in 2018 excluding subsidies such as the production tax credit), and below $40/MWh – and even as low as $20/MWh in a few cases – for solar PV (LCOE of about $55/MWh in 2018 excluding subsidies such as the investment tax credit). This is either roughly the same or cheaper than nuclear power (Chart 25). And as wind and solar costs keep declining, pressure will further accentuate on nuclear power.[111] Thus a situation that is already complicated for nuclear may well just exacerbate and soon become untenable. In the period 2013-2025, 19 reactors with a total combined capacity of more than 16GW are expected to permanently shut down on economic grounds. And another 10 with a total combined capacity of about 10GW have recently been rescued by States subsidies.

Chart 25: New Onshore Wind and Solar PV Putting Heavy Stress on Existing Nuclear Power in the US



Sources: existing nuclear; Nuclear Energy Institute, Nuclear Costs in Context (October 2018), new onshore wind – subsidized PPA prices; U.S. Department of Energy, Wind Technologies Market Report 2017 (August 2018), new solar PV – subsidized PPA prices; Lawrence Berkeley National Laboratory, Utility-Scale Solar: Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States – 2018 Edition (September 2018), and new onshore wind and solar PV unsubsidized LCOE from Bloomberg NEF, Levelized Cost of Electricity (accessed 5 December 2018)

France

The situation in France is somewhat different, but cost competitiveness of existing nuclear is also deteriorating while that of RE keeps improving.

Because France is phasing out coal power, does not have access to cheap gas, RE is the only alternative to nuclear for electricity generation.

Until the beginning of the 2010 decade there was no real economic competition between nuclear power and RE in France.

Existing amortized nuclear power in France costs about $50/MWh (based on ARENH "Regulated Access to Incumbent Nuclear Electricity" of €42/MWh). And non-amortized costs, or LCOE, of existing nuclear power may have increased from $64/MWh in 2010 to $81/MWh in 2017 due to a significant increase in maintenance investments, including implementation of stricter safety standards following Fukushima Daiichi nuclear accident.[e]

In comparison, unsubsidized LCOE for new onshore wind decreased from more than $100/MWh in 2014-H2 to a little below $70/MWh in 2018-H2. And that for new solar PV from more than $150/MWh to below $60/MWh in the same period. These are the results of technological improvements as well as successful implementation of energy policies such as FiTs and auctions.

Table 8 below summarizes these cost comparisons between existing nuclear power and new RE in France.

Table 8: Summary – Cost Comparisons; Existing Nuclear VS. New RE in France in the 2010 Decade

Technology	Estimate	2018 $/MWh
Existing nuclear	Amortized – ARENH for the year 2018	48
	Non-amortized Cour des Comptes (2012) for the year 2010	64
	Non-amortized own estimate (2018) for the year 2017	81
New onshore wind	Bloomberg NEF for 2014-H2	101
	Bloomberg NEF for 2018-H2	67
New solar PV	Bloomberg NEF for 2014-H2	157
	Bloomberg NEF for 2018-H2	59

Note: non-amortized estimates are provided to give readers indications about the cost of nuclear power including all costs throughout its entire lifetime to enable comparisons with other technologies on the same ground (whether existing or new). In reality, however, competition takes place between existing amortized nuclear and new RE

Sources: existing nuclear; amortized-ARENH from Commission de Régulation de l'Énergie, ARENH (accessed 28 September 2018), non-amortized Cour des Comptes from Cour des Comptes, The Costs of the Nuclear Power Sector (January 2012), non-amortized own estimate from Cour des Comptes, Annual Public Report 2016 – Tome 1, Observations (February 2016) (in French) and Réseau de Transport d'Électricité, Annual Electricity Report 2017 (February 2018), and new onshore wind and solar PV from Bloomberg NEF, Levelized Cost of Electricity (accessed 5 December 2018)

New onshore wind and solar PV at $67/MWh and $59/MWh, respectively, have not undercut existing amortized nuclear power at $48/MWh in France yet. However, they have clearly gotten much closer to being cost competitive with nuclear power in a quite short period of time. And as RE costs keep decreasing and more capacity are deployed, this trend may be accelerated with close to zero marginal cost wind and solar also pushing back nuclear power in the merit order reducing the capacity factor of nuclear power plants, increasing the cost of these latter ones. Cost parity between nuclear and RE in France may thus only be a matter of a few years.

Japan

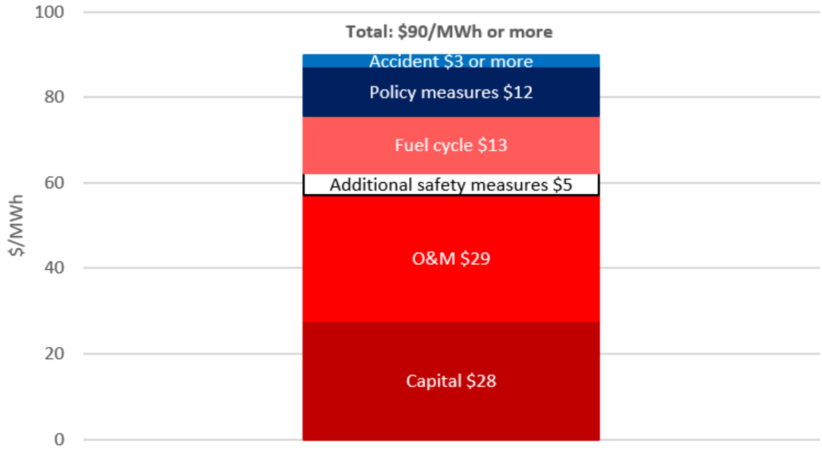
In Japan, prior to Fukushima Daiichi nuclear accident, cost of existing amortized nuclear power was estimated at about $55/MWh.[112] Higher than in the US, somewhat comparable with France. This was competitive compared with fossil alternatives and much cheaper than RE – with the exception of large hydropower.[113]

[e] The LCOE of $81/MWh in 2017 is an own estimate based on the assumptions that the production cost of nuclear power estimated by the Cour des Comptes in 2016 for the year 2014 has not changed since then, and that net electricity generation from nuclear power was 379TWh in France in 2017 according to French transport system operator Réseau de Transport d'Électricité data.

Since the accident happened, more stringent safety standards have been advanced in the country (#3 JAPAN TOPICS on page 44), resulting in costly necessary investments for safety upgrades.

In 2015, METI estimated the cost of these additional safety measures to be apparently relatively negligible +$5/MWh (Chart 26).

Chart 26: Nuclear Power Electricity Generation Cost Structure Japan 2014



Notes: main assumptions include; installed capacity of 1.2GW, capacity factor of 70%, discount rate of 3%, operation lifetime of 40 years, construction costs of about $3,300/kW, decommissioning costs of about $640 million, and costs of Fukushima Daiichi nuclear accident at about $110 billion acknowledging these may increase in the future hence the mention "or more" (these latter costs have been re-estimated to approximately $190 billion in 2016)

Source: METI, Report on Analysis of Generation Costs, Etc. for Subcommittee on Long-term Energy Supply-demand Outlook (May 2015)

Yet, these extra costs amounting to at least several hundred millions of dollars per reactor have been sufficient to provoke the permanent closures of 11 reactors with a total combined capacity of more than 6GW between 2015 and 2018 (Table 9).[114] This clearly demonstrates how the costs of safety upgrades may have a very powerful impact on nuclear power plants operators' decisions to seek authorizations for restarts.

Table 9: Nuclear Reactors Permanently Shut Down in Japan after Fukushima Daiichi Accident

Reactor name	Net capacity (MW)	First grid connection (year)	Permanent shutdown (year)	Electric Power Company
Ohi 1 and 2	2,240	1977 & 1978	2018 both	Kansai
Ikata 1 and 2	1,076	1977 & 1981	2016 & 2018	Shikoku
Mihama 1 and 2	790	1970 & 1972	2015 both	Kansai
Genkai 1	529	1975	2015	Kyushu
Onagawa 1	498	1983	2018	Tohoku
Shimane 1	439	1973	2015	Chugoku
Tsuruga 1	340	1969	2015	Japan Atomic Power Company
Monju	246	1995	2017	Japan Atomic Energy Agency

Sources: IAEA, Country Statistics: Japan, World Nuclear Association, Nuclear Power in Japan – updated November 2018 (both accessed 6 December 2018), and Mycle Schneider, The World Nuclear Industry Status Report 2018 (September 2018)

In the meantime, as everywhere else in the world, deployment of wind and solar power in Japan has come with significant cost reductions in recent years. For instance, onshore wind LCOE decreased from about $190/MWh in 2014-H2 to about $115/MWh in 2018-H2, and that of solar PV collapsed from roughly $310/MWh to $125/MWh, also, in the same period.[115]

Though these LCOE may still be relatively high compared with global standards and maybe above the cost of existing nuclear, there are reasons to be optimistic. In the case of wind, deployment has been quite limited even after Fukushima Daiichi accident; less than 1GW increase in cumulative installed capacity between 2010 and 2017, and there is room for growth and potential economies of scale.[116] In the case of solar, generous FiTs have enabled a massive expansion in terms of installed capacity; +45GW between 2010 and 2017.[117] As the pipeline of relatively expensive solar projects diminishes, and more aggressive policies will be pursued (auctions) cost of solar PV should further decrease.

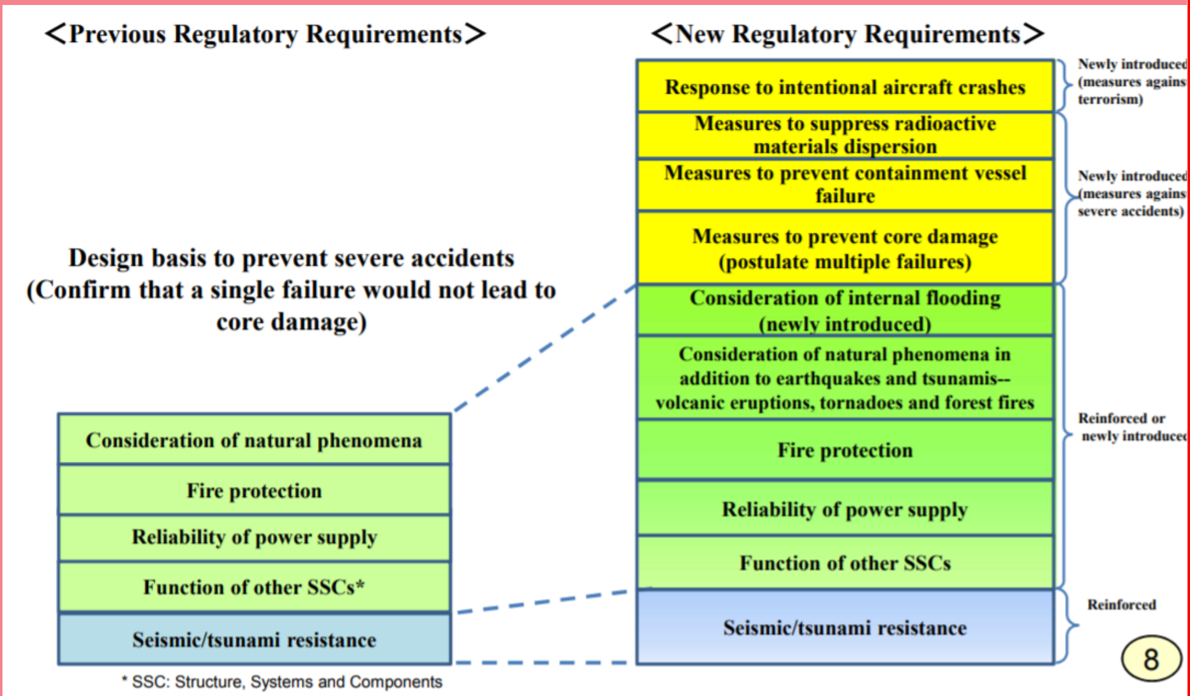
In addition, progress of the electricity system reform in Japan should also benefit RE further cost reductions by making power system operations in the country fairer. By 2020, the regional vertically integrated electric power companies should be unbundled, resulting in their grid segments (transmission & distribution) becoming independent from generation and supply interests. This will probably prevent discrimination against RE when it comes to grid connection limitations and curtailments, lowering these risks and their associated costs should benefit RE competitiveness.

#3 JAPAN TOPICS: New more stringent safety standards for nuclear power plants in Japan

Following Fukushima Daiichi nuclear power plant accident in March 2011, Japan introduced significant reforms for much safer operations with stricter safety requirements by the new Nuclear Regulation Authority.[118]

In particular, the new regulatory requirements tighten measures to prevent or deal with severe accidents and acts of terrorism. New requirements against severe accidents are measures to prevent core damage and containment vessel failure, and measures to suppress radioactive materials dispersion:

Comparison between Previous and New Regulatory Requirements



Source: Nuclear Regulation Authority of Japan, New Regulatory Requirements for Light-Water Nuclear Power Plants – Outline – (August 2013)

Lauded as the "world's toughest nuclear safety standards" by Japanese regulators – without demonstrable evidence, these standards may still be considered insufficiently rigorous to eliminate any chance of a serious disaster.[119]

At the beginning of December 2018, on the one hand 9 nuclear reactors met these new more stringent safety standards and had been authorized to restart operations, on the other hand another 18 reactors, including Ohma and Shimane 3 under construction, had applied for safety reviews.[120]

On the other hand, 11 reactors decided to close to avoid investing at least several hundred millions of dollars (per reactor) to be allowed to restart. This is notably the case of Ohi 1 and 2.[121]

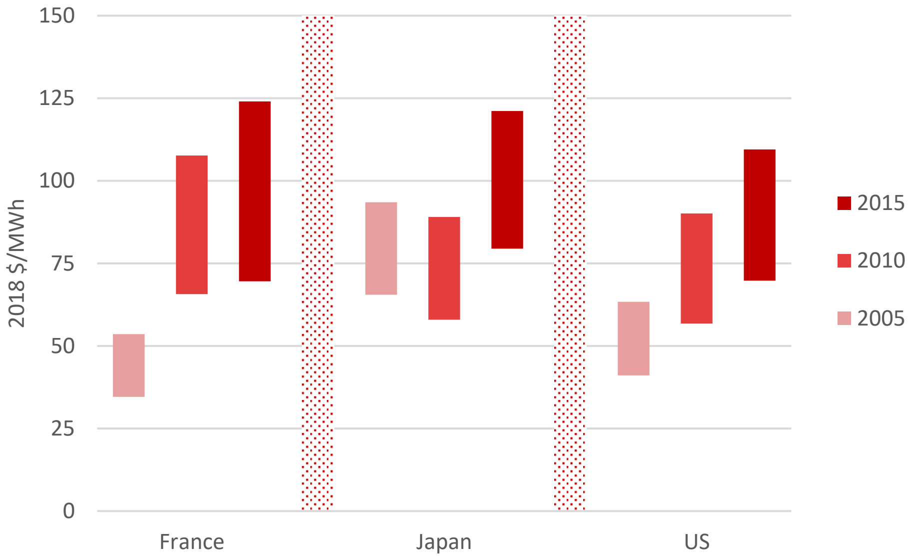
B) New plants

Though there may still be economic competition between existing nuclear power and new RE depending on places, we can almost talk of a "game over" when it comes to compare new nuclear power with new RE, with the latter having basically completely eclipsed the former on a cost-basis almost everywhere in the world.

New reactor designs, more stringent safety standards, less favorable economic, financial and political frameworks, as well as more competitive power markets have all contributed to weaken nuclear economics and make the constructions of new projects more expensive.

Every 5 years the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA) publish a joint report entitled "Projected Costs of Generating Electricity." Over the last 3 editions of this report, estimated LCOE of new nuclear power soared in key nuclear power countries; France, Japan, and the US (Chart 27).

Chart 27: New Nuclear Power Soaring LCOE

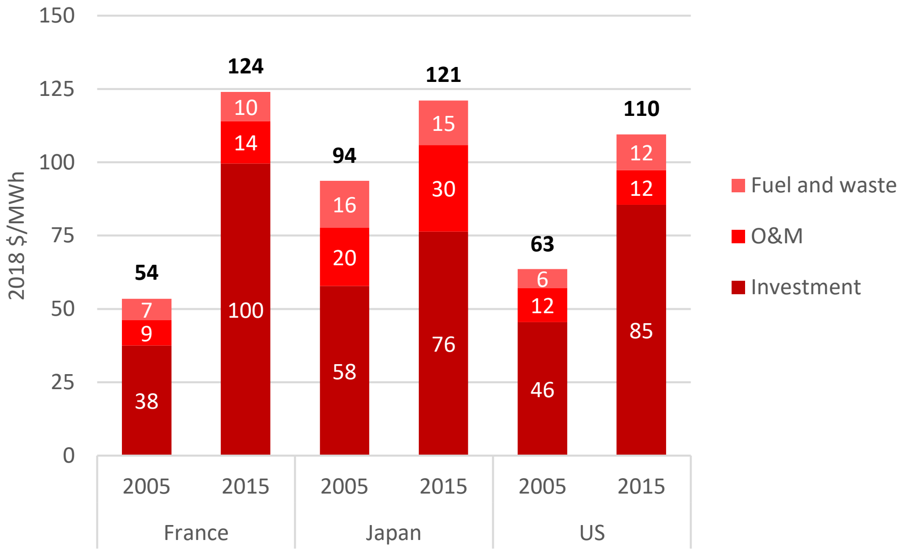


Note: cost ranges for discount rates of 5% (minimum) and 10% (maximum)
Source: IEA/NEA, [Projected Costs of Generating Electricity 2015] (September 2015)

Back in 2005, the IEA/NEA estimated the LCOE of new nuclear power in France in the range of $35-55/MWh. A decade later, to $70-125/MWh – a doubling. In the case of Japan, LCOE of new nuclear power increased from $65-95/MWh in 2005 to $80-120/MWh in 2015, a 20-30% increase. Finally, in the US, as in France, estimated LCOE of new nuclear power roughly doubled in this 10-year period from about $40-65/MWh to $70-110/MWh.

These massive cost increases between the 2005 and 2015 estimates are largely the result of an explosion of investment costs (essentially construction costs); from about +$20/MWh (more than +30%) in Japan to roughly +$40/MWh (about +90%) in the US, and over +$60/MWh (almost +170%) in France, which account for the very large majority of nuclear power electricity generation costs; roughly 60-80% (Chart 28 on next page).

Chart 28: Evolution of Nuclear Power Electricity Generation Cost Structure 2005-2015 Estimates



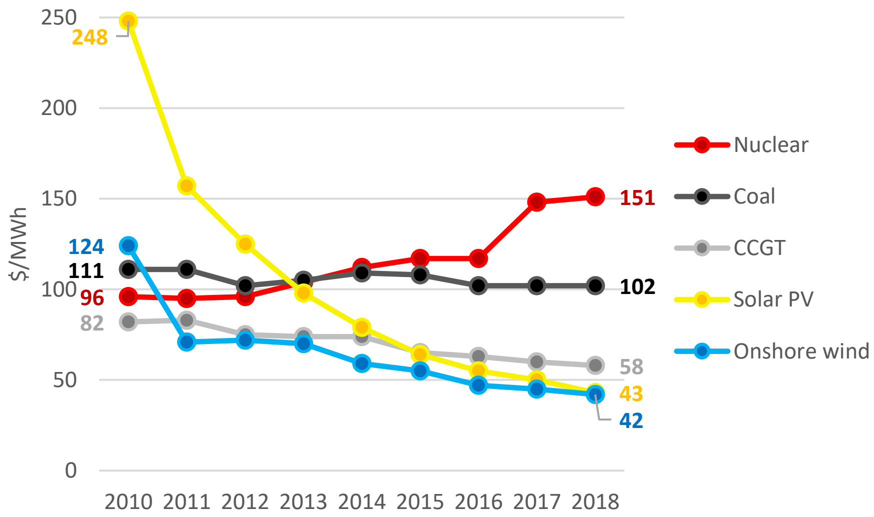
Notes: discount rate of 10%. Investment costs include construction costs, refurbishment and decommissioning costs, and interest during construction

Sources: IEA/NEA, Projected Costs of Generating Electricity 2005 (March 2005), and IEA/NEA, Projected Costs of Generating Electricity 2015 (September 2015)

To a lesser extent, increases in O&M costs of roughly +$10/MWh (about +50%) in Japan and +$5/MWh (+65%) France, as well as an increase in fuel and waste costs of approximately +$6/MWh in the US (+90%) also contributed to make the cost of generating electricity from nuclear power higher.

These significant cost increases of nuclear power happened at the same time with the significant expansion of onshore wind and solar PV, which costs have dramatically decreased to the extent that, according to Lazard – the world's leading financial advisory and asset management firm, globally recognized for its expertise in assessing LCOE of electricity generating technologies – they have now become not only the cheapest new low carbon technologies, but also the most economic new technologies to generate electricity (Chart 29).

Chart 29: Unsubsidized Global LCOE of New Electricity by Generating Technology 2010-2018



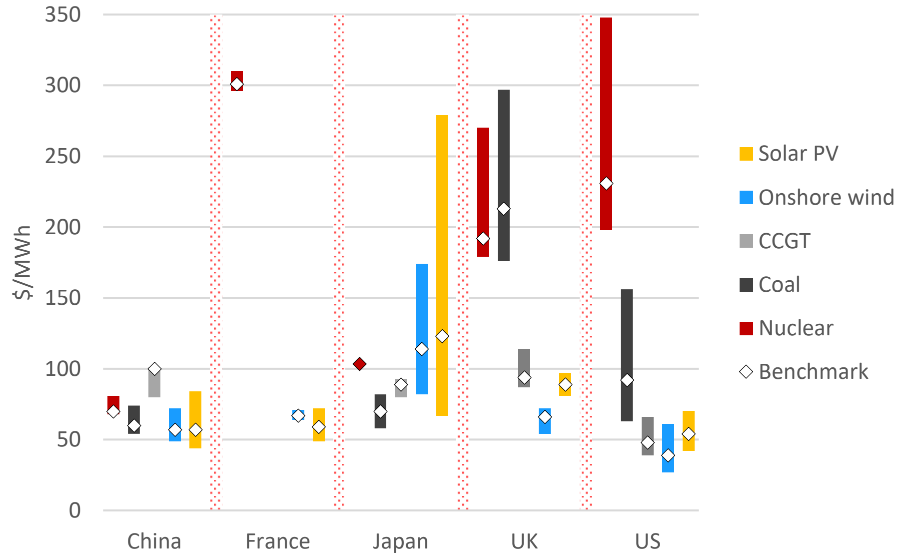
Note: costs of decommissioning and waste disposal not included

Source: Lazard, Levelized Cost of Energy Analysis – Version 12.0 (November 2018)

In the world in 2018, at about $40/MWh for both onshore wind solar PV, LCOE of these two RE technologies were 25-30% lower than that of new combined cycle gas turbines (CCGT) at almost $60/MWh, roughly 60% lower than that of new coal at more than $100/MWh, and 70-75% lower than that of new nuclear power at more than $150/MWh(!).

Of course, LCOE of generating technologies vary across countries, yet the story remains the same; new nuclear power is very often not competitive with new other technologies, particularly onshore wind and solar PV (Chart 30).

Chart 30: Unsubsidized LCOE of New Electricity by Generating Technology in Key Countries 2018-H2



Note: costs of decommissioning and waste disposal not included

Sources: Bloomberg NEF, Levelized Cost of Electricity (accessed 26 November 2018), except for Japan – nuclear from METI, Report on Analysis of Generation Costs, Etc. for Subcommittee on Long-term Energy Supply-demand Outlook (May 2015)

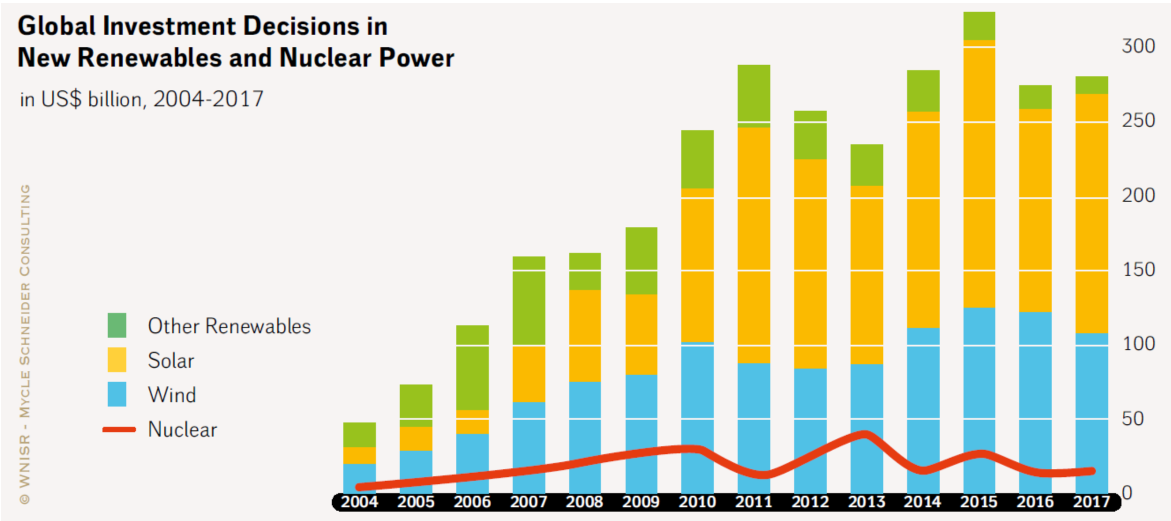
According to Bloomberg NEF, the global authority on economic data on energy investments, among key countries, new nuclear power is only cost competitive in China at roughly $70-80/MWh. It is completely out of the economic equation in France (about $300/MWh), the UK (in the range $180-270/MWh), and the US (approximately $200-350/MWh) because of assumptions of very high capital expenditures – in line with real facts.

Nuclear power might still be able to survive in Japan granted the estimate by the Power Generation Cost Analysis Working Group set up by METI in 2015 is still relevant. This is an open since in its estimate the Working Group assumed the cost of the Fukushima Daiichi nuclear accident at about $110 billion, from which it derived the cost of a nuclear accident at around $80 billion for a 1.2GW reactor, i.e. a downward adjustment based on power generation output scale, among others.[122] In 2016, however, the Japanese government revised its own estimate for the cost of the Fukushima Daiichi nuclear accident; initially estimated at roughly $100 billion in 2013, this was significantly increased to about $190 billion – nearly a doubling, and 75% more than the starting point used by the Working Group.[123] In addition, estimated decommissioning and waste management costs are highly uncertain. Also, the Working Group's estimate uses construction costs of nuclear power plants, which have now been first grid connected about 10-15 years ago with conservative designs.[124]

Construction costs of new nuclear power plants are also an extremely complicated financial challenge for investors (including very large power companies) today. With very high upfront costs amounting to billions of dollars, risks of long delays and important cost overruns, in a sector going through major transformations, new nuclear power projects are very often simply too risky without government support.

According to the World Nuclear Industry Status Report 2018, and Global Trends in Renewable Energy Investment 2018 report, global investments in new nuclear has never reached $50 billion annually since 2004 at least, whereas investment in new RE power – excluding large hydropower – has always been well above $200 billion annually since 2010, and even as high as $323 billion in 2015. Lower investments in 2016 and 2017 are attributable to substantial cost reductions in wind and solar technologies, notably (Chart 31).

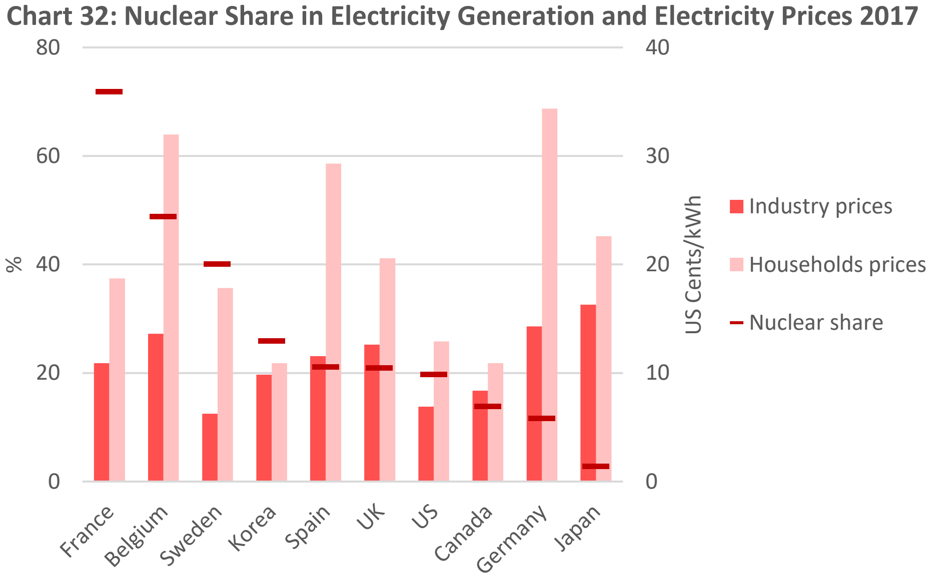
Chart 31: Global Investment Decisions in Nuclear and RE Power 2004-2017



Sources: Mycle Schneider, [The World Nuclear Industry Status Report 2018](#) (September 2018), and Frankfurt School-UNEP Centre/Bloomberg NEF, [Global Trends in Renewable Energy Investment 2018](#) (June 2018)

It comes thus without surprise that the nuclear industry rather pursues reactors lifetime extensions than new builds. This can save nuclear power in short-term to medium-term, but the more distant future of the technology appears particularly gloom.

In addition, a high share of nuclear power in a country electricity generation mix is not synonym of low electricity prices for electricity consumers as sometimes believed (Chart 32 on next page).



Sources: BP, [Statistical Review of World Energy 2018](#) (June 2018), and IEA, [Energy Prices and Taxes – Third Quarter 2018](#) (October 2018)

For instance, the share of nuclear power in France and the UK were 72% and 21% in 2017, respectively, and the prices for electricity were quite similar in these countries around 12 US cents/kWh for industry and 20 US cents/kWh for households. In the US and Canada, the share of nuclear power in electricity generation was much lower than in France and below that in the UK; in the range 15-20%, and these two countries had lower electricity prices both for industry and households than France and the UK.

This can be explained by a number of factors; electricity generation mix, which depends on availability of natural resources, economics of different technologies, political choice, transmission and distribution costs, competitive or regulated supply of electricity to customers, as well as national fiscal orientations (taxes and subsidies).

Nuclear economics are thus far from being brilliant, and these could be even worse if the technology was held fully responsible in case of accidents.

C) Nuclear power limited liabilities

Operators of nuclear power plants are liable for any damage caused by their nuclear related activities, regardless of fault. They therefore subscribe insurances for third-party liability, which is a requirement in most countries.[125]

However, third-party liability is limited so that beyond limits covered by insurances countries can accept responsibility as insurer of last resort.[126] And these limits are always set way too low; below $15 billion, with regard to the real costs of a severe accident as demonstrated by Fukushima Daiichi nuclear accident; about $70 billion in compensation to ex-residents and to businesses for commercial damages only, i.e. excluding the also enormous costs of decommissioning the wrecked reactors ($70 billion) and treating & storing contaminated soil ($50 billion) (Table 10 on next page).[127]

Table 10: Maximum Nuclear Power Operators' Liability Amount for a Nuclear Incident

Country	Maximum operator's liability amount ($ billion)	Maximum financial security limit to cover operator's liability amount ($ billion, unless otherwise noted)
Belgium	1.4	1.4
Canada	0.8	0.8
China	0.0	0.0
France	0.8	0.8
Germany	unlimited	2.8
India	0.2	0.2
Japan	unlimited	1.1
Korea	0.4	0.4
Russia	unlimited	recommended amount is $5 million
Sweden	0.4	0.5
Switzerland	unlimited	1.0
United Kingdom	0.2	0.2
United States	14.1	14.1

Notes: a nuclear incident is defined as "any occurrence or succession of occurrences having the same origin which causes (nuclear) damage […]." by the Paris Convention on Third Party Liability in the field of Nuclear Energy (July 1960). And for Canada only, liability is phased in over 4 years starting at $0.5 billion from 1 January 2017, and increased each year until it reaches $0.8 billion or a higher amount set by regulation

Source: NEA, Nuclear Operators' Third-Party Liability Amounts and Financial Security Limits (November 2018)

Nuclear power operators' liabilities may be supplemented with public funds and/or international funds (established under either the Brussels Supplementary Convention of 1963 or the Convention on Supplementary Compensation for Nuclear Damage of 1997). These are, however, not available in all countries using nuclear power, and once again quite negligible; a few billions of dollars maximum, considering the cost of a severe accident.[128]

Not accounting nuclear power fully responsible for the significant harm it can cause on human beings and the environment may be seen as a failure to internalize a negative externality, which makes nuclear power cost artificially lower than it really is. In other words, a form of subsidy.

Solving all these cost issues is the first prerequisite for nuclear power to survive in the 21st century.

2 Technology; a very challenging crossroad

Nuclear power is facing a number of various technological challenges; from successfully deploying current evolutionary generation III reactors (i.e. on time, to budget, and cost competitive), to making significant progresses in innovative generation IV reactors developments, and simply surviving in the 21st century electrical grid that will require more flexibility and less vulnerability to extreme weather events. Under current circumstances, and in the race against time humanity is engaged to prevent climate change, nuclear power is not poised to provide a rapid and significant contribution.

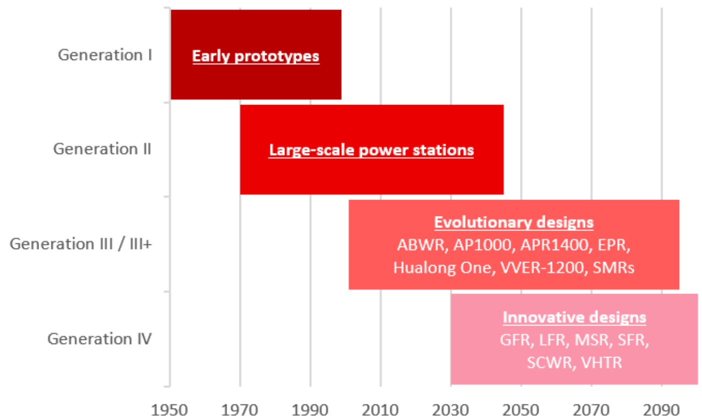
A) No optimism for new generations of nuclear reactors

The bulk of today nuclear power plant fleet is constituted by generation II-type reactors which started to be deployed in the 1970s.[129] A few new generation III / III+ reactors, based on evolutionary designs with improvements in safety systems (especially the use of passive rather than active systems) and thermal efficiency, have been commissioned in the period from 1995 to 2018 (note: generation III+ reactors offer further improvements in safety over generation III including greater attention paid to developing resistance to external sources of danger notably, but otherwise the characterization of designs as generation III or III+ is based on chronology rather than design features).[130]

Generations I, II and III / III+ reactors rely on nuclear fission as the source of heat (i.e. fission splits a larger atom into 2 or more smaller ones releasing energy) and usually use water as both coolant and moderator, to slow neutrons (e.g. pressurized water reactor (PWR), and boiling water reactor (BWR)).[131]

Small modular reactors (SMRs), and more innovative designs generation IV reactors that would make use of fuel much more efficiently and minimize radioactive waste production – most of them are fast neutron reactors (i.e. there is no neutron moderator); e.g. gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), supercritical water-cooled reactor (SCWR), and very high temperature reactor (VHTR) – which coolant is gas, also rely on nuclear fission and are not expected to be either significantly deployed by 2030 (SMRs) or commercially deployed before 2030 (generation IV reactors) (Chart 33).[f]

Chart 33: Evolution of Fission Reactor Technology



Source: created by REI based on; Generation IV International Forum, [Evolution Reactor Technology](#) (accessed 9 October 2018)

[f] A fast neutron reactor designed to produce more plutonium than the uranium and plutonium it consumes is called a fast breeder reactor.

So far, only a few generation III / III+ reactors have been grid connected. They, however, now account for the majority of reactors under construction. Simpler generation III reactors usually face shorter construction times, lesser delays, and may be less expensive than generation III+ reactors (Table 11).

Table 11: Examples of Generation III (Dec. 3, 2018)

Vendor	Country	Design	Type	Net Capacity (MW)	# of operational reactors	# of reactors under construction	First grid connection (year)	Construction time range (years)	Delay range (years)	Approximate cost range ($/kW)
GE Hitachi-Toshiba	US/ Japan	ABWR	BWR	1,100-1,400	4 (Japan)	4 (2 in Japan and 2 in Taiwan)	1996	3-?*	0-?*	2,500-3,000*
KHNP	Korea	APR1400	PWR	1,300-1,500	1 (Korea)	9 (5 in Korea and 4 in UAE)	2016	5-10	0-6	2,000-4,000
CNNC-CGN	China	Hualong One	PWR	About 1,000	0	6 (4 in China and 2 in Pakistan)	n/a	4-6	0	2,500-4,500

*Based on projects commissioned before Fukushima Daiichi nuclear accident. All projects under construction are now delayed, face more stringent safety standards with associated costs in Japan, and may never be commissioned in Taiwan.
Sources: created by REI based on; World Nuclear Association, Country Profiles, IAEA, Power Reactor Information System (both accessed 3 December 2018), Mycle Schneider, The World Nuclear Industry Status Report 2018 (September 2018), and information made available throughout this section

GE Hitachi-Toshiba pioneered generation III reactors with American/Japanese based technologies ABWR deployed for the first time in Japan in 1996; Kashiwazaki Kariwa 6 and 7. In the 2000s, another two ABWRs were connected to the Japanese electrical grid; Hamaoka 5 in 2004 and Shika 2 in 2005. All these 4 reactors were constructed in a short period of time of around 3-4 years and at competitive costs, but prior to the establishment of stricter safety standards introduced after the Fukushima Daiichi nuclear accident.[132] Projects under construction face a quite uncertain future. In Japan, the reactors Ohma and Shimane 3 will have to overcome domestic obstacles in terms of more stringent safety standards, economics, and social acceptance, in order to start operation. And in Taiwan, it is extremely unlikely that reactors Lungmen 1 and 2, which constructions started in 1999 and are deferred, will ever be commissioned. In the short-term, the only realistic hope that remained to export the ABWR design was the controversial – due to its high cost; over $20 billion for two reactors (combined capacity of around 2.9GW) – Wylfa Newydd project in the UK that has been frozen by Hitachi in January 2019 because of economic difficulties.[133]

This leaves the door open to competitors such as the APR1400 of Korean KHNP and Hualong One of Chinese CNNC-CGN.

In 2016, after 8 years of construction (including 3 years of delay) the first APR1400 reactor was connected to the electrical grid; Shin-Kori 3 in Korea. Another 5 projects are under construction in Korea; Shin-Kori 4 (delayed by 6 years, if commissioned in 2019 as now planned), 5, and 6, and Shin-Hanul 1 and 2. In the UAE, 4 APR1400 reactor projects are also under construction; Barakah 1, 2, 3, and 4 with a total combined capacity of more than 5GW and a total cost of $20 billion. The four Barakah reactors, which constructions started between 2012 and 2015, are now expected to be operational in 2020 and 2021, against between 2017 and 2020 initially, all reactors are behind schedule from 1 year to 3 years.

There is no Hualong One reactor in operation yet, but 6 are under constructions; Fangchenggang 3 and 4 and Fuqing 5 and 6 in China, and Kanupp 2 and 3 in Pakistan. All these reactors have started construction quite recently, in 2015 and 2016, and it is too early to conclude whether or not they will be delivered on time and at their initially targeted costs.

In the case of generation III+ reactors – the most advanced designs, projects are plagued with long construction times; from 5 to 14 years (usually at least 8 years) often because of multi-year delays (up to 10 years!), and higher costs; around $7,500-11,000/kW for the most expensive designs being built in France or the US – roughly 2 to 5 times the costs of generation II reactors in these two countries – due to significant cost overruns (Table 12).[134]

Table 12: Examples of Generation III+ Nuclear Reactor Technologies (Dec. 3, 2018)

Vendor	Country	Design	Type	Net Capacity (MW)	# of operational reactors	# of reactors under construction	First grid connection (year)	Construction time range (year)	Delay range (year)	Approximate cost range ($/kW)
AREVA (& EDF)	France	EPR	PWR	1,600-1,700	1 (China)	3 (1 China, 1 Finland, and 1 France)	2018	9-14	4-10	3,500-7,500
ROSATOM	Russia	VVER-1200	PWR	1,000-1,200	2 (Russia)	8 (2 Bangladesh, 2 Belarus, 3 Russia, and, and 1 Turkey)	2016	5-12	0-5	2,500-5,500
Westinghouse	US	AP1000	PWR	1.100-1,200	4 (China)	2 in US	2018	8-9	2-4	3,000-11,000

Note: The EPR Hinkley Point C-1, which constructed started in the UK on 11 December 2018 is not included in this table
Sources: created by REI based on; World Nuclear Association, Country Profiles, IAEA, Power Reactor Information System (both accessed 3 December 2018), Mycle Schneider, The World Nuclear Industry Status Report 2018 (September 2018), and information made available throughout this section

Among the generation III+ reactors, two designs have particularly caught the general public's attention the French EPR of AREVA (& EDF) and the American AP1000 of Westinghouse.

Of the 4 EPR projects which started construction between 2005 and 2010 only one has finally been connected to the grid after 9 years of construction; Taishan 1 in China in June 2018. The three others; Taishan 2 in China, Olkiluoto 3 in Finland, and Flamanville 3 in France, may be first grid connected before 2020 (at the earliest in 2019). All projects have faced long delays; 4 to 10 years, and significant cost overruns. The latter is particularly true for the Finnish and French projects. In the case of Olkiluoto 3; from $3.6 billion initially to $9.6 billion, and in the case of Flamanville 3 from $3.7 billion to $12.4. Roughly a tripling in both cases(!).[135] On 11 December 2018, construction of a fifth EPR started in the UK; Hinkley Point C-1.[136] A sixth EPR project is expected to start construction in the UK in 2020; Hinkley Point C-2.[137] These two reactors (combined capacity of 3.3GW) are planned to be connected to the grid by 2026 and 2027, respectively, at a total cost of about $25 billion.[138]

AP1000 projects have also met great difficulties to be delivered especially in the US. As of early December 2018, there were 6 AP1000 ongoing reactor projects; 4 had been commissioned and connected to the grid (Haiyang 1 and 2 and Sanmen 1 and 2, all in China in 2018), and 2 were still under construction (Vogtle 3 and 4 in the US). All these projects construction times are long; about 8-9 years, including delays of 2 to 4 years. Also, they were/are all over budget. In particular, the combined costs of reactors Vogtle 3 and 4 have skyrocketed to more than $27 billion from the initial cost estimate of $14 billion – almost a doubling.[139] Significant delays and cost overruns sealed the fate of two (other) AP1000 reactor projects in the US, VC Summer 2 and 3, which have been cancelled in 2017 after 4 years of construction and billions of dollars spent.[140]

Costs overruns of Russian ROSATOM VVER-1200 reactor projects are less documented. In Russia, however, it is known that all reactors with this design, either already connected to the grid (Leningrad II-1 and Novovoronezh II-1) or still under construction (Baltic 1, Leningrad II-2, and Novovoronezh II-2), have been/are in the majority of cases at least 4 years behind originally expected commissioning schedule. Compared with other generation III+ reactors, VVER-1200 appear relatively less expensive for now. Progresses in the construction of reactors Rooppur 1 and 2 in Bangladesh, Belarusian 1 and 2 in Belarus, and Akkuyu 1 in Turkey, which constructions have started more recently – between 2013 and 2018, will demonstrate whether or not this design can be built on time and to budget.

Compared with these large-scale designs, SMRs come with the promises that smaller reactors could be operated flexibly and be more cost competitive, with regard to their lower upfront costs.

Until now, only a few SMR designs have progressed towards construction as well as completion.[141] One of these projects is the Shidao Bay 1 (or Shidaowan 1) HTR-PM being built in China. It is a demonstration plant, with twin reactor modules driving a single 200MW steam turbine.[142] Construction started in 2012 with the goal of starting operations in 2017.[143] As of early December 2018, the plant was still not commissioned.[144] More problematic, at almost $90/MWh it is about 40% more expensive that the average $63/MWh standard tariff for new nuclear power plants in China.[145]

In the US, NuScale is leading the development of SMRs. It is targeting an initial operational date of 2026 and a LCOE of $65/MWh – 20% and 70% more than solar PV and onshore wind, respectively, unsubsidized LCOE in the US in 2018.[146]

Elsewhere in the world, progresses related to the development of SMRs have been limited and not encouraging with delays and cost overruns due to project management issues such as floating reactors Akademik Lomonosov 1 and 2 in Russia, still under construction according to the IAEA as of 3 December 2018).

SMRs are thus not only very far from being massively deployed in a near future, but also will find it very difficult to find markets with these high levels of costs. At this point, it therefore appears extremely unlikely that SMRs will play any significant role in the future of electricity generation.

B) Flexibility of nuclear reactors

With the significant deployment of cheap variable wind and solar power on the supply side, operations of the 21st century electrical grid will require a lot more flexibility than in the past, when outputs of conventional power plants were essentially adjusted to balance variations in electricity demand.

Because of its particular technical features, nuclear power plants are not the most flexible options of the power system, especially in terms of short-term load following capabilities. For instance, whereas it usually takes from 2 hours to 2 days to start-up a nuclear power plant with a maximum ramp rate (i.e. the speed with which a power plant can modulate its power for capacity) of only 1-5% per minute (/min), it takes only 10 to 20 minutes to start-up an open cycle gas turbine (OCGT) which maximum ramp rate is 20%/min. Also, nuclear power is the least capable type of power plants to provide very quick change in output only up to 5% in 30 seconds against 20-30% for an OCGT (Table 13).

Table 13: Comparison of the Load Following Ability of Dispatchable Power Plants

Type of power plant	Start-up time	Max. change in 30 sec.	Max. ramp rate (%/min.)
OCGT	10-20 min	20-30%	20%/min
CCGT	30-60 min	10-20%	5-10%/min
Coal	1-10 hours	5-10%	1-5%/min
Nuclear	2 hours – 2 days	up to 5%	1-5%/min

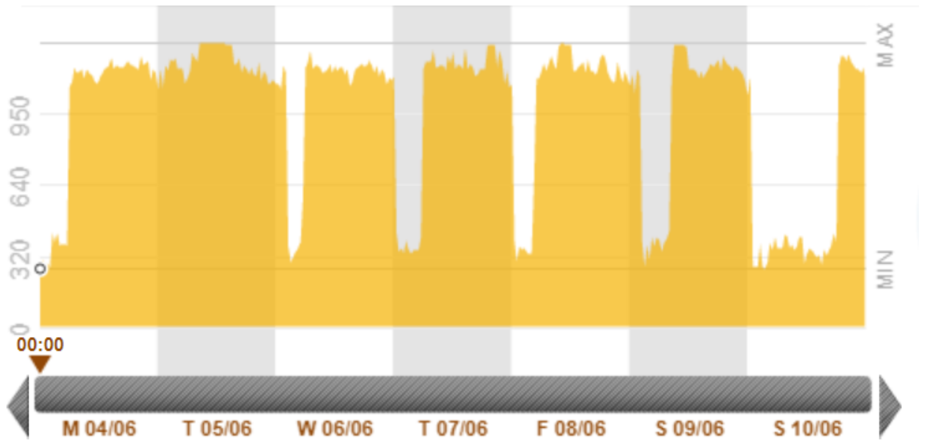
Source: NEA, Nuclear Energy and Renewables, System Effects on Low-carbon Electricity Systems (November 2012)

However, nuclear reactor can be operated at a power level as low as 25% of their rated capacity.[147]

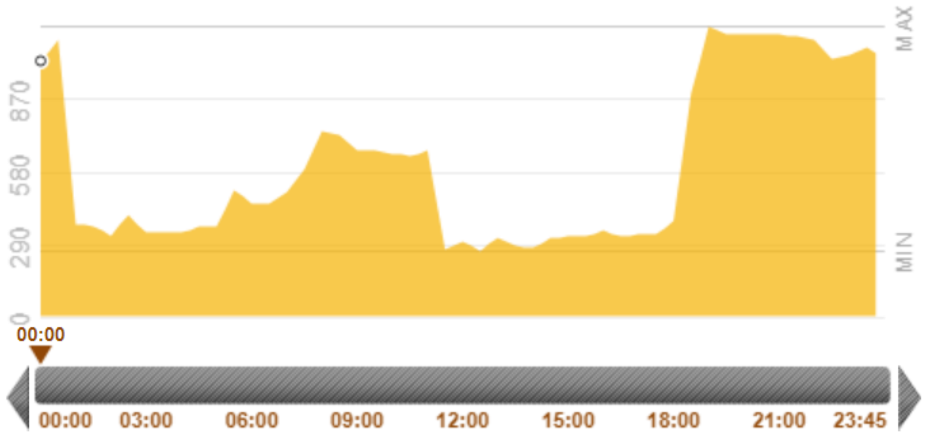
Chart 34 below provides illustrative examples of a nuclear reactor being flexibly operated; Golfech 1 in France, a generation II reactor PWR-type connected to the grid for the first time in 1990 and with a net capacity of 1,310MW.[148]

Chart 34: Flexible Operations of Nuclear Reactor Golfech 1 in France

Weekly Basis: Monday 4 – Sunday 10 June 2018



Daily Basis: Sunday 5 August 2018



Source: Réseau de Transport d'Électricité, eCO2mix: Consumption, Generation and Inter-Regional Flows – Occitanie (accessed 12 October 2018)

Operations of Golfech 1 show that either on a weekly (4-10 June 2018) or a daily basis (5 August 2018), it is possible to adjust the power output of a nuclear reactor depending on system needs.

On a weekly basis, it can be observed that Golfech 1 output is usually ramped down during the night – from around midnight when electricity consumption significantly decreases because people go to sleep and commercial facilities close, and then is ramped up in the early hours of the morning at about 5-6AM when electricity demand significantly increases because of the restart of daily economic activities. On Sunday, output remains low throughout the day; approximately 300-400MW – roughly 25-30% of the reactor net capacity, except in the evening from 6:30PM when electricity consumption for lightning purposes increases (some factories may also be preparing for the full restart of production from Monday morning).

On a daily basis, Golfech 1 reactor may also be ramped up and down more than once and at different levels of output. After the steep ramp down at the beginning of the night from more than 1,100MW at 0:30AM to below 400MW at 1AM (about -730MW in 30 minutes), a first significant ramp up can be observed from 6:30AM to 8AM; from 450MW to 740MW (+290MW in 1 hour and 30 minutes). Then from 11AM to 11:30AM output of the reactor is decreased from about 660MW to 270MW (approximately -390MW in 30 minutes). And finally, later in the day, output is ramped up again from 6PM to 7PM from below 400MW to almost 1,200MW (about +770MW in 1 hour).

Nevertheless, this type of example should also be counterbalanced with the possibility that unsuccessful attempts of flexibly operating a nuclear reactor may cause a serious accident. For instance, it is considered that because of excessive ramping the fuel rods of the Brokdorf reactor in Germany were damaged in 2017.[149]

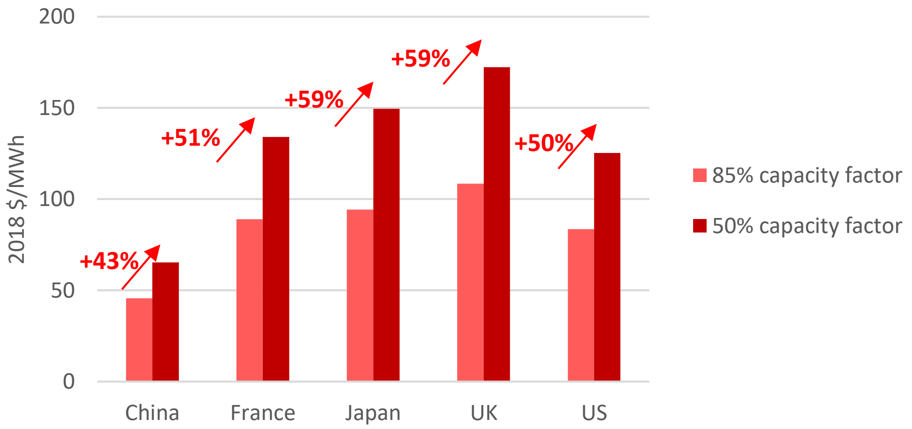
On technical grounds, nuclear power therefore does not appear as an ideal solution to move forward with the grid integration of RE.

Equally importantly, flexible operations of nuclear power plants reduce their capacity factors further deteriorating their already weakened economics.

Historically, with their relatively low fuel and marginals costs nuclear power plants have generally dominated the economic dispatch competition. With the arrival of even lower marginal costs technologies – wind and solar power, which marginal costs are close to zero – nuclear power has been relegated to second place or below. That is a major issue for nuclear power, which thus does not only have to deal with potential technical flexibility issues, but also economic ones. This is, however, not the case in Japan because of irrelevant uneconomic power plant dispatch rules (#4 JAPAN TOPICS on next page).

Operating less hours under harsher conditions would make capital cost intensive nuclear power LCOE between 40% and 60% more expensive (estimates for new plants), excluding potential additional costs due to excessive wear and tear (Chart 35).

Chart 35: Nuclear Power LCOE Very Negatively Affected by Lower Capacity Factor (for new plants commissioned from 2020)



Note: discount rate of 7%

Source: IEA/NEA, Projected Costs of Generating Electricity 2015 (September 2015)

Indeed, according to the IEA/NEA, the LCOE of a nuclear reactor that would operate with a capacity factor of only 50% instead of 85% (slightly higher than the maximum capacity factor of the global nuclear power fleet in the past 20 years; 83% in 2002), would be much higher. For instance; $65/MWh at 50% VS. $46/MWh at 85% in China (+43%), $134/MWh at 50% VS. $89/MWh at 85% in France (+51%), $150/MWh at 50% VS. $94/MWh at 85% in Japan (+59%), $172/MWh at 50% VS. $108/MWh at 85% in the UK (+59%), and $125/MWh at 50% VS. $84/MWh at 85% in the US (+50%).

Thus, current nuclear technologies are unlikely to survive the flexibility challenge they will increasingly frequently be confronted with.

Based on this analysis, and also considering that new reactors, and particularly generation III+ reactors, are prohibitively expensive SMRs have started to be developed.

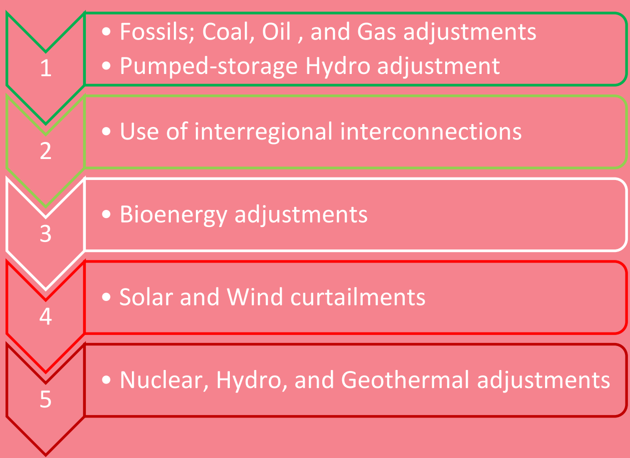
#4 JAPAN TOPICS: The irrelevant dispatch of nuclear power plants in Japan

When it comes to natural energy resources Japan is RE rich with large and various hydro, bioenergy, geothermal, wind, and solar potentials. And with the exception of bioenergy, technologies based on these resources do not need fuels and operate with close to zero marginal costs.

At the same time, Japan has relatively scarce domestic uranium resources and therefore relies on overseas uranium supply.[150] In addition, generating electricity from nuclear power generates dangerous radioactive waste which safe management and storage requires extra costs. According to congruent estimates from the Power Generation Cost Analysis Working Group set up by METI and the IEA/NEA, these fuel and waste costs amount to about $15/MWh in Japan.

On economic, energy security, environmental, and safety grounds, it is thus a no-brainer that all RE – with the exception of bioenergy – should get priority dispatch over nuclear power. Yet, this is incomprehensibly still not the case in Japan, where nuclear power is irrelevantly granted dispatch priority over wind and solar because it is considered more difficult to adjust output from nuclear reactors:

Priority Dispatch Rule of Power Plants in Japan



Source: REI based on Japan Agency for Natural Resources and Energy, Curtailment of renewable energy, introducing more renewable energy - 7 September 2018 (accessed 19 October 2018) (in Japanese)

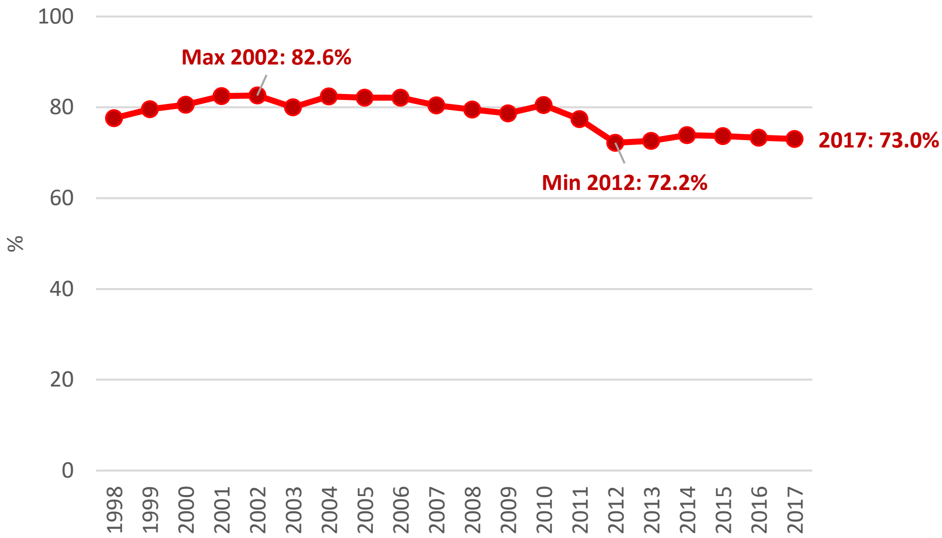
It would certainly be in the country's best interest to abolish this inefficient rule as soon as possible.

C) Reliability of nuclear reactors

Nuclear proponents often like to insist on this technology reliability as opposed to the variability of RE such as wind and solar to hint at some presumed inherent superiority of nuclear power over RE. Overall, it is not discussable that nuclear power has higher capacity factor than RE; e.g. 74% for nuclear power, 26% for wind, and 13% for solar PV in OECD (Organization for Economic Co-operation and Development) countries in 2016.[151] However, this should not hide a number of significant reliability and fragility issues nuclear power is particularly confronted with. These relate to the fact that nuclear power plants are inherently large-scale facilities where critical activities are concentrated (e.g. operation of reactors, fuel logistic) requiring safety guards, and which operations may affect the whole power system.

First, it is interesting to observe the evolution of the global fleet of nuclear reactors capacity factor which demonstrated a decreasing trend over the past 20 years (Chart 36).

Chart 36: Nuclear Power Global Capacity Factor – Weighted Average 1998-2017



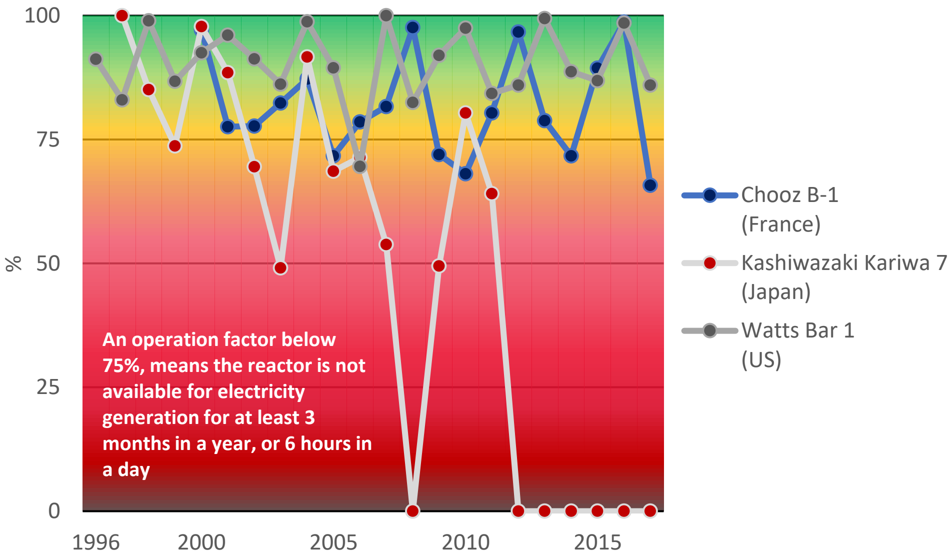
Source: IAEA, Load Factor Trend (accessed 15 October 2018)

From 1998 to 2011 nuclear power capacity factor was consistently around 80%, ranging roughly between 77% and 83%, with a peak of 82.6% in 2002. Since 2012, this capacity factor fell to 72-74%, mainly because of the consequences of Fukushima nuclear accident in Japan.

Though such level of capacity factor is still relatively high compared with other technologies, it may be said that a capacity factor of 75% is somehow (assuming that reactors are generating electricity at their maximum capacity all the time they are in operation) the equivalent of a 3-month period of unavailability over a year, or 6 hours over a day. In other words, nuclear power is quite far from generating electricity at full power 24/7 as so often wrongly claimed.

Another relevant indicator to assess the reliability of a nuclear power reactor is its operation factor. The operation factor of a reactor is defined by the IAEA as "the ratio of the number of hours the unit was on-line to the total number of hours in the reference period, expressed as a percentage."[152] Compared with capacity factor, operation factor does not take into account performances, only reactor hourly availability – regardless of available capacity and actual production. Operation factor may vary greatly over time for a given reactor, as well as among different reactors (Chart 37 on next page).

Chart 37: Examples of Nuclear Power Reactors Operation Factors 1996-2017



Source: IAEA, Power Reactor Information System (accessed 15 October 2018)

For instance, Chooz B-1 in France, Kashiwazaki Kariwa 7 in Japan, and Watts Bar 1 in the US, which have all been connected to the electrical grid for the first time in 1996 (all data are not available from 1996), have shown various levels of operation factors on an annual basis each, and in comparison to each other.

Watts Bar 1 has demonstrated relatively good operation factors; always over 80% (sometimes close to 100%) in the period 1996-2017, with the exception of 2006 when the reactor operation factor was just below 70%.

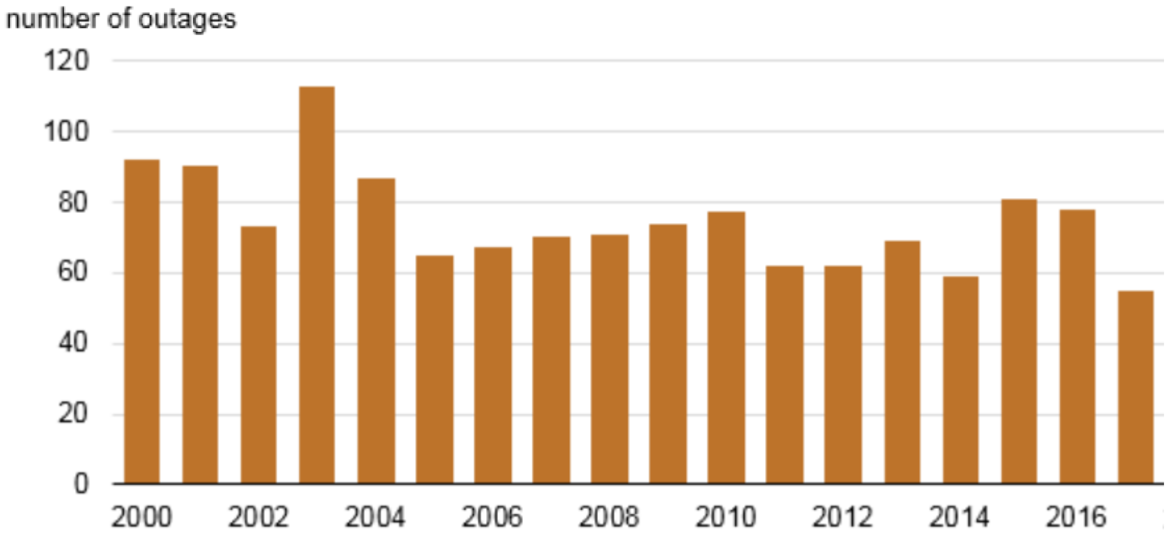
In comparison, since 2000, Chooz B-1 operation factor has been 9 years over 80% and 9 years below 80%, with a record low 66% in 2017, meaning the reactor could not provide electricity for more than a third of the year – or 4 months.

Finally, Kashiwazaki Kariwa 7 track record has been particularly poor – even before Fukushima Daiichi nuclear accident which has undeniably negatively impacted its operations since then. After a perfect start with a 100% operation factor in 1997, the reactor operation factor has varied a lot; between 0% and 98% in the period from 1998 to 2011. In addition, of the terrible year 2008 when the reactor was offline all year following an earthquake in 2007, 2003 (because of the discovery in 2002 of deliberate falsifications of data related to safety issues), and 2007 & 2009 (also related to the 2007 earthquake) were quite chaotic years with the reactor unavailable for electricity generation for roughly 6 months.

Operation factors of nuclear power plants are affected by planned and unplanned outages. Planned outages take place for refueling (usually during between 30 and 50 days in the US for the period 1998-2018 for example) and those associated with major maintenance, tests and inspections. Unplanned outages may be related to various unexpected issues such as surprising equipment failures, operational errors, external environmental events (earthquake, hurricane, heat waves…), or political decisions. In the following, political decisions impacting operation factors of nuclear power plants will not be addressed since these are not directly related to technological features of reactors, which is the core of this section.

Unplanned outages are part of nuclear reactors typical operations. Therefore, electrical grids always have to be ready to sustain possible unexpected sudden losses of very large amount of power. For instance, in the US, grid operators had to manage at least 55 unplanned outages every year since 2000, and even more than 110 in 2003 (Chart 38).

Chart 38: Total Unplanned Outages in the US 2000-2017



Source: U.S. Energy Information Administration, U.S. nuclear plant outages increased in September after remaining low during summer – 15 October 2018 (accessed 19 October 2018)

To illustrate more concretely how unpredictable unplanned outages affect availability of nuclear power plants, a nuclear power plant has been selected; Cattenom in France. This plant consists of 4 generation II reactors PWR-type with a total combined capacity of 5.2GW (1.3GW for each reactor) connected to the grid between 1986 and 1991.

Table 14 on next page lists all unplanned outages which occurred at Cattenom nuclear power plant in 2017 only. Brief descriptions of the outage characteristics are also provided.

Table 14: Unplanned Outages at Cattenom Nuclear Power Plant in 2017

Outage number	Outage start	Outage end	Duration (days approx.)	Max. lost power (MW)	Cause
Reactor 1 (1,300 MW)					
#1	19 May 5:50PM	6 July 3:00AM	47	1,300	failure
#2	6 July 5:30AM	6 July 8:00PM	1	260	failure
#3	15 July 1:41PM	15 July 1:44PM	0	810	failure
#4	16 July 6:00AM	16 July 6:30PM	1	1,300	failure
#5	22 Sep. 6:45AM	22 Sep. 7:00PM	1	110	failure
#6	11 Oct. 2:00AM	11 Oct. 2:15AM	0	200	failure
#7	19 Oct. 4:10PM	19 Oct. 7:40PM	0	918	strike
Total (7)	*n/a*	*n/a*	*49*	*1,300*	*failure (6)/ strike (1)*
Reactor 2 (1,300 MW)					
#1	18 May 0:45AM	18 May 2:45AM	0	900	failure
#2	10 June 2:00PM	10 June 3:15PM	0	580	failure
#3	10 Sep. 9:45AM	10 Sep. noon	0	850	failure
#4	27 Sep. midnight	27 Sep. 7:00PM	1	610	failure
Total (4)	*n/a*	*n/a*	*1*	*900*	*failure (4)*
Reactor 3 (1,300 MW)					
#1	29 May 7:15AM	31 May 11:00PM	3	1,300	failure
#2	6 June 1:10AM	6 June 11:00PM	1	1,300	failure
#3	7 June 7:00AM	7 June 9:40AM	0	1,280	failure
Total (3)	*n/a*	*n/a*	*4*	*1,300*	*failure (3)*
Reactor 4 (1,300 MW)					
#1	20 Sep. 5:00AM	23 Sep. 2:00AM	3	785	ramp up by steps
#2	23 Sep. 3:35PM	26 Sep. 10:00AM	3	340	ramp up by steps
#3	29 Oct. 5:55AM	29 Oct. 9:15AM	0	1,000	failure
Total (3)	*n/a*	*n/a*	*6*	*1,000*	*ramp up by steps (2)/failure (1)*
TOTAL PLANT (17)	**n/a**	**n/a**	**60**	**2,600**	**Failure (14)/ ramp up by steps (2)/ strike (1)**

Source: Réseau de Transport d'Électricité, Unavailability of Generation Resources (accessed 15 October 2018)

In 2017, Cattenom nuclear power plant had to deal with 17 unplanned outages, essentially due to unexpected failures. These outages totaled about 60 days for the 4 reactors, out of which 49 days for reactor 1 only, especially because of an important failure that lasted from 19 May to 6 July. Twice, lost power due to these surprising failures amounted to 2.6GW from 29 May to 31 May and on 6 June.

These observations confirm that unplanned outages are not only common, but also with a potential significant impact on power system operations. Indeed, solving the sudden loss of one nuclear reactor or more with a gigawatt or more of installed capacity is certainly more challenging than managing the forecasted fluctuations in electricity generation from distributed wind and solar power. Issues related to the integration of large centralized nuclear power plants are too often overlooked both from technical and economic perspectives.

When discussing nuclear power plants reliability, it is also necessary to address their vulnerability to natural risks including earthquakes, tsunamis, and extreme climate & weather events, the latter becoming more frequent and stronger as global warming intensifies.

Beyond Fukushima Daiichi nuclear accident, Japan is quite familiar with the negative impact earthquakes and/or tsunamis can have on regular nuclear power plants operations. For instance, in

2004, 2005, 2007, 2009, and 2011 nuclear reactors in Japan shut down automatically due to ground acceleration exceeding their trip settings.[153]

In addition, nuclear power plants operations are affected by various climate & weather events such as heat waves, hurricanes, and winter storm for examples.

In Europe, vulnerability of nuclear power plants to heat waves is well-known. In the summer of 2018, some plants had to reduce reactor outputs (e.g. at Loviisa in Finland, Tricastin in France, Brokdorf in Germany, Forsmark in Sweden, and Muehleberg in Switzerland…) or temporary shut down reactors (e.g. Bugey 2 and 3, Fessenheim 2, and St. Alban 1 in France, and Ringhals 2 in Sweden) because water temperatures were too high for reactor cooling.[154] This already happened in 2003, 2006, and 2015.[155]

In the case of the St. Alban 1, during the most intense part of the summer 2018 heat wave – from 29 July to 8 August, the reactor was completely stopped 3 times for a total period of time of more than 7 days, including almost 5 consecutive days between 3 August and 8 August (Table 15).

Table 15: St. Alban 1 Nuclear Reactor Temporary Shutdowns because of Summer 2018 Heat Wave (29 July to 8 August)

Temporary shutdown	Shutdown start	Shutdown end	Duration (hours/days)
#1	29 July 4:00AM	30 July 6:30PM	38.50/1.6
#2	1 August 2:15PM	2 August 1:30PM	23.25/1.0
#3	3 August noon	8 August 5:00AM	113.00/4.7
Total (3)	n/a	n/a	174.75/7.3

Source: Réseau de Transport d'Électricité, Unavailability of Generation Resources (accessed 25 October 2018)

In the US, reactor 3 at Turkey Point nuclear power plant in Florida was temporary shut down when hurricane Irma struck in 2017, and the two reactors at Brunswick (1 and 2) nuclear power plant in North Carolina when hurricane Florence made landfall in 2018.[156]

Winter storms, can also affect nuclear power plants operations as demonstrated by winter storms Juno in 2015 and Grayson in 2018, which both led to temporary closures of Pilgrim 1 nuclear reactor in Massachusetts.[157]

And with global warming intensifying, not only may extreme climate & weather events get worse, sea-level rise may also prove problematic with increasing risks of serious flooding. Across the world, this issue could threaten at least 100 nuclear power stations built on coastlines (because they need large amount of cooling water from the sea) and just a few meters above sea level, making them vulnerable to flooding caused by accelerating sea-level rise and more frequent storm surges, in addition of possible tsunamis.[158]

Finally, reliability of nuclear power plants may be affected by various security risks due to their strategical importance as large-scale dangerous infrastructures providing critical energy services. These may range from cyberattacks to terrorisms with potential dramatic consequences beyond the electrical grid. Efforts, in these fields are pursued, but neither information technologies nor armed forces protections are flawless.

3 Decommissioning and spent fuel & radioactive waste disposal; little progress

The end life cycle of nuclear power is marked by two significant technological and financial issues; decommissioning and waste storage, no country has ever come close to fully solve – despite nuclear power already quite long history. As of early 2018, about 170 nuclear reactors had been permanently shut down worldwide, out of which less than 20 had been fully decommissioned, and no disposal facility for high level waste and spent nuclear fuel had started operations.

A) Decommissioning[g]

The decommissioning of a nuclear power plant is a very complicated process both from technical and financial perspectives. This issue is only about to significantly intensify as a lot of plants built in the 1970s and 1980s will reach the end of their lifetime in the two coming decades.

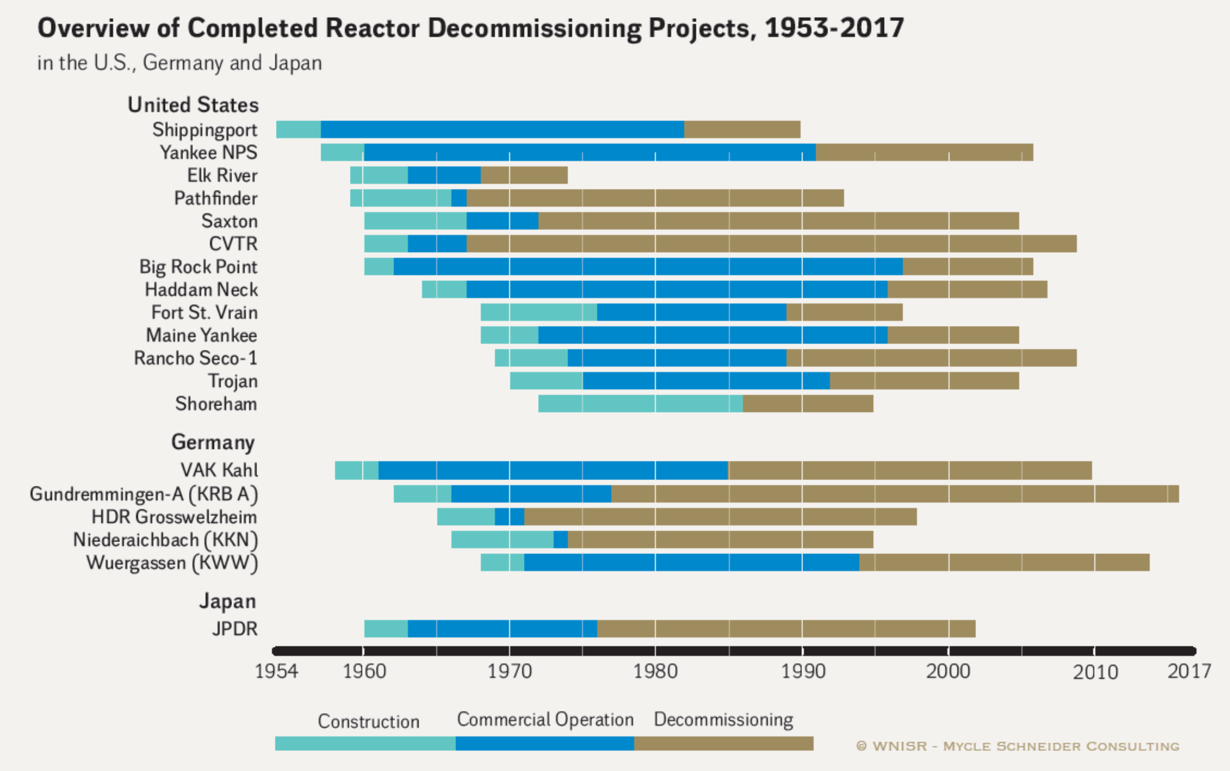
According to The World Nuclear Industry Status Report 2018, at the end of the first half of 2018, about 170 nuclear power reactors with a total combined capacity of roughly 70GW were permanently shut down across the world, out of which only 19 with a total combined capacity of about 6GW had been fully decommissioned (first quarter of 2018). Of these 19 reactors, only 10 had been returned to greenfield sites. Because of its complexity, decommissioning is usually a lengthy process; almost 20 years in average. It is also costly; from a few hundred millions to a few billions of dollars per reactor.

After years or decades of hard work, only 3 countries have completed the decommissioning of nuclear reactors; the US (13), Germany (5), and Japan (1). Often, the periods of time these countries needed to decommission these reactors were much longer than the combined periods of time to construct and operate the reactors in question (e.g. CVTR, Pathfinder, and Saxton in the US, Gundremmingen A, HDR Grosswelzheim, and Niederaichbach in Germany and JPDR in Japan) (Chart 39 on next page).

In addition, it is important to note that decommissioning periods may vary greatly; from 6 years for the Elk River reactor and up to 42 years for the CVTR (Carolinas-Virginia Tube Reactor) both in the US.

[g] This subsection on decommissioning benefits greatly from all the work carried out by Mycle Schneider and his team in the framework of The World Nuclear Industry Status Report 2018 (September 2018), in which a dedicated "*Decommissioning Status Report*" provides up-to-date, numerous and valuable information and data on the matter of decommissioning (for more information see pages 134-151 of the report in question). Unless otherwise noted, all information in this subsection comes from the aforementioned report.

Chart 39: Nuclear Reactors Fully Decommissioned (as of the end of 2017)



Sources: Mycle Schneider, The World Nuclear Industry Status Report 2018 (September 2018), and IAEA, Power Reactor Information System 2018

These decommissioning projects were relatively easy; largely generation I small early prototype or demonstration reactors with a low power output (usually below 200MW) and operated for periods of time in the majority of cases not exceeding 20 years, resulting in smaller radiological inventories.[159] Yet, decommissioning of most of the generation I reactors has not even started fully.

In terms of actual implementation of decommissioning (limited to the technological aspect), the process can generally be divided into 3 main stages; the warm-up-stage, the hot-zone stage, and ease-off-stage for the processes of defueling, deconstruction, and dismantling – some of which may take place in different stages.

The warm-up-stage includes dismantling of systems that are not necessarily needed for the decommissioning process, dismantling of higher contaminated system parts (e.g. steam generators, and parts of the primary cooling-circuit), defueling, and the installation of the logistic in the hot zone.

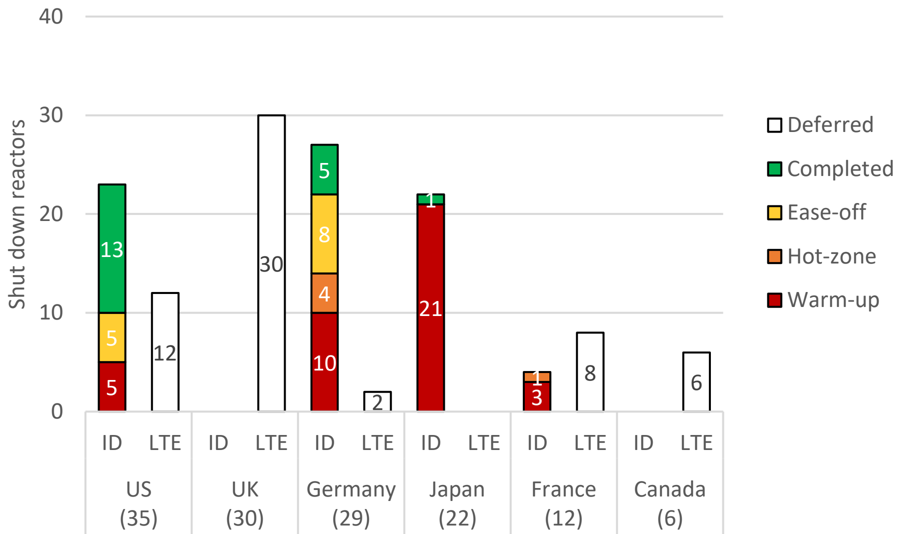
The hot-zone-stage is related to the dismantling of highly contaminated or activated parts (e.g. the reactor pressure vessel and its internals, and the biological shield).

The ease-off-stage deals with the removal of operating systems, the decontamination of the buildings, and the demolition of these latter ones for the release of the reactor site as a greenfield available for unrestricted use. In some countries (in the US for example), the release as a brownfield – the buildings can be further used for nuclear related or other activities – is allowed.

There are two strategies for nuclear reactors decommissioning; immediate dismantling (ID) and long-term enclosure (LTE), also called “safe storage,” that consists in deferring decommissioning to benefit from radioactive decay. ID presents a number of advantages over LTE, among which; skilled and experienced operating staff can perform the decommissioning process, a clear line of responsibilities is drawn, and it is more likely that the provisions set aside for the decommissioning work match the necessary amount.

Chart 40 below summarizes the decommissioning status of permanently shut down nuclear reactors in 6 selected countries; the US, the UK, Germany, Japan, France, and Canada in the first half of 2018.

Chart 40: Decommissioning Status of Permanently Shut Down Nuclear Reactors in Selected Countries



Notes: for each country the total number of reactors permanently shut down is indicated between brackets. For Japan shut down reactors do not include Fukushima Daini 1, 2, 3, and 4 for which a permanent closure is likely, but the decommissioning process has not started yet. This approach defers from that of the report used as a source. As an update, nuclear reactors Oyster Creek in the US and Onagawa 1 in Japan permanently shut down after the publication of the report used as a source have been included in the chart above

Source: Mycle Schneider, The World Nuclear Industry Status Report 2018 (September 2018)

United States

The US is the most advanced country in decommissioning nuclear reactors with 13 (out of which 6 have been returned to greenfield sites) of its 35 permanently shut down reactors being now fully decommissioned. Decommissioning work is currently ongoing at 10 other reactors; 5 are in the warm-up-stage (Fort Calhoun 1, Oyster Creek, San Onofre 2 and 3, and Vermont Yankee), and 5 in the hot-zone-stage (Humboldt Bay, LaCross, San Onofre 1, and Zion 1 and 2). More, 12 reactors, are in LTE, which is limited to 60 years in the US.

Decommissioning of the 13 reactors fully decommissioned took 14 years in average. In most cases, the process even lasted less than 10 years, which is quite short by international comparison. One important reason is that in most cases the pressure vessel was removed and transported intact for disposal, while the internals were segmented under water or in air and dry stored on-site as wastes along with spent nuclear fuel awaiting a federal repository. In some cases, this was also done for other large components such as the steam generators. This reduces decommissioning time and costs. In the case of the Trojan reactor, both the pressure vessel and internal structures were removed intact and shipped together with the steam generators to the Hanford site, a decommissioned nuclear production complex operated by the US federal government, in the State of Washington (northwest of the US). Finally, another particularity of the US decommissioning policy is the possible use of explosives to demolish the concrete buildings.

In addition to these developments, it is important to keep in mind that more than half (7) of the fully decommissioned reactors have not returned to greenfield sites yet because they are still storing spent fuel on-site (dry storage) notably. This demonstrates the critical need for disposal facilities for high level waste and spent nuclear fuel.

United Kingdom

Progresses in the UK are extremely slow; no reactor has ever been decommissioned despite 30 permanent shutdowns. That is because the strategy is to seal and store the biological shield, the pressure vessel, the external pressure circuit, and steam generators while the actual dismantling will start only 85 years (LTE term) after the initial shutdown – which is quite controversial. Indeed, even after this very long period of time the larger amount of the reactor wastes will still not be suitable for disposal as low-level waste and the reduction in decommissioning costs with the increase in deferral time is largely offset by the increased costs of preparing and managing the LTE of the reactors.

Germany

In Germany, 29 nuclear reactors have been permanently shut down, out of which 5 have been fully decommissioned and 3 have been returned to greenfield sites. Decommissioning activities are quite dynamic with 10 reactors in the warm-up-stage, 4 in the hot-zone-stage, and 8 in the ease-off-stage, against only 2 in LTE. Among the key issues to move forward with these active plans are the insufficient numbers of transport and storage casks being produced to defuel the reactors.

Japan

Of the 22 nuclear reactors permanently shut down in Japan, only 1 has been fully decommissioned in 1996 and released as a greenfield in 2002; the JPDR (Japan Power Demonstration Reactor), a small research reactor of 12MW.[160] All the other reactors (21) are in the warm-up-stage of their decommissioning. Decommissioning periods for these reactors are expected to be well over 20 years. Tokai 1, which decommissioning is ongoing since 2001 should be fully decommissioned by 2025. Fugen ATR and Hamaoka 1 and 2 started their decommissioning process in the late 2000s and are expected to be decommissioned around 2035. Between approximately 2040 and 2060 another 11 reactors should be fully decommissioned.[161] There is no completion date for Fukushima Daiichi reactors 1, 2, 3, 4, 5, and 6. A long rocky road is ahead especially as the country lacks experience in decommissioning so far.

France

In France, 12 reactors have been permanently shut down and none fully decommissioned. The majority of shut down reactors are in LTE (8), 3 are in the warm-up-stage, and only 1 in the hot-zone-stage; Chooz A. This reactor should be the first French reactor to be decommissioned, between 2020 and 2025.[162] Super-Phenix may follow by 2030.[163] The decommissioning of all other reactors are at least two decades away.[164]

Canada

As in the UK, all permanently shut down nuclear reactors (6) in Canada are in LTE, with close to no progress at all.

Overall, it is thus clear that the decommissioning of nuclear reactors represents a long-term complex technological challenge. Beyond that, its financing related issues also offer complicated and long-lasting headaches for the industry.

Costs of decommissioning nuclear reactors amount to at least a few hundred millions to a few billions of dollars per reactor. Table 16 below provides examples of decommissioning costs of fully decommissioned reactors in the US and Germany.

Table 16: Examples of Decommissioning Costs of Nuclear Reactors in the US and Germany

Country	Reactor name	Type	Net capacity (MW)	Approximate total decommissioning costs (2018 $ million)	Approximate decommissioning costs per installed capacity (2018 $/kW)
Germany	Gundremmingen A	BWR	237	2,590	10,930 (expected)
	Wuergassen	BWR	640	1,180	1,840
United States	Haddam Neck	PWR	560	900	1,610
	Maine Yankee	PWR	860	550	640
	Trojan	PWR	1,095	330	300

Sources: decommissioning costs for Germany from Deutsches Institut für Wirtschaftsforschung, Status and Prospects of the Decommissioning of Nuclear Power Plants in Germany (November 2015) (in German), decommissioning costs for the US from NEA, Costs of Decommissioning Nuclear Power Plants (April 2016), and type and installed capacity from IAEA, Power Reactor Information System (accessed 6 November 2018)

The cost of Gundremmingen A decommissioning is particularly high. Though no clear statement justifying this fact could have been found, it may be due to the serious incident which caused a partial crack in a primary safety valve and the contamination of components, notably, resulting in the plant early closure in 1977, and – possibly – ultimately a more complex decommissioning process.[165]

Securing the necessary financing for decommissioning related expenses is critical. There are different approaches from a country to another, but the risks are the same in all countries; insufficient or unavailable financial resources, underperformance of the funds, possible bankruptcy of the operator, and underestimation of future costs.

To hedge against these risks 4 types of approaches have been advanced until now; the public budget, the external segregated fund, the internal non-segregated fund, and the internal segregated fund.

In the case of the public budget, State authorities take over the responsibility and with that the accumulation of financial resources via taxes. For example; the Nuclear Decommissioning Authority in the UK for already permanently shut down reactors, or the German government for the former German Democratic Republic nuclear reactors.

In the case of the external segregated fund, operators pay their financial obligation into a publicly controlled and managed fund. Private or state-owned external, independent bodies manage the funds. There can be centralized funds for the whole industry, or decentralized funds for each operator; e.g. most of the utilities in the US, and in the UK for the operational nuclear plants (the Nuclear Liabilities Fund).

In the case of the internal non-segregated fund, operators of nuclear facilities are obliged to form and manage funds autonomously. Operators manage the financial resources, which are held within their own accounts as reserves. For example; Germany.

In the case of the internal segregated fund, operators feed a self-administrated fund, which is separated from the other businesses. This approach has been taken in Canada, France, and Japan.

As demonstrated by reality, there is no silver bullet; no approach guarantees that sufficient financing will be secured to cover significant decommissioning costs.

In the US, the large majority of utilities collect decommissioning money from customers through rates that are then placed in nuclear decommissioning trust funds (the remaining operators must provide financial assurance through either prepayment or parent-company guarantee). In 2016, the specific costs to decommission a nuclear reactor were around $700/kW for public power utilities and $850/kW for investor-owned utilities. And there is an increasing risk that the money in the nuclear decommissioning trust funds will not be sufficient especially because of a significant number of early nuclear reactor closures due to deteriorating economic conditions. This issue is particularly problematic because in most cases the nuclear decommissioning trust funds are built up year by year over the expected lifetime of reactors.

Concerns related to decommissioning financing are also shared in France and Japan, particularly.

In France, current decommissioning cost estimates for Électricité de France (EDF)'s shut down nuclear power plants are around $7.4 billion, while the Group has only provisioned $3.9 billion.[166] In addition, for its operational fleet (i.e. the country entire nuclear reactor fleet), EDF expects decommissioning costs of around $370/kW – quite low by international standards.[167]

In Japan, the Power Generation Cost Analysis Working Group set up by METI in 2015 estimated the cost of a nuclear reactor decommissioning to amount to some $640 million, or about $530/kW.[168] This is higher than the estimate in France, and relatively lower than costs observed in the US – with the big and probably decisive differences that the US does not prohibit the removal and consequent burial of large-scale parts such as the pressure vessel, and is much more experienced in decommissioning. Another issue related to the decommissioning of nuclear reactors in Japan is that power companies are permitted to temporarily divert decommissioning funds for other business purposes, risking that the funds are not available anymore when needed. This issue already arose when Japan Atomic Power Company decided to use its decommissioning fund to cover construction costs of Tsuruga reactors 3 and 4, which have later been abandoned.

Thus, decommissioning of reactors is certainly a quite difficult problem from both technological and financial points of views for the nuclear power industry. Yet, issues with radioactive waste storage are even worse.

B) Spent fuel & radioactive waste disposal

Nuclear power plants generate significant quantities of spent fuel and radioactive waste. Disposal of spent fuel and high-level waste is especially problematic, again both on technological (extremely complex) and financial (long-term and very costly; at least billions of dollars) grounds. Public acceptance is also a major issue. After about 65 years of civil nuclear use no disposal facility for spent fuel and high-level waste has started operations.

Spent nuclear fuel

Since the fuel burned in a nuclear reactor emits large amounts of heat and radiation, it is necessary to cool it in a fuel pool for several years after its removal from the reactor. Currently, two methods are used for handling spent nuclear fuels (SNF) after cooling. It is either directly disposed as waste (“once-through”), or applying a chemical treatment it is “reprocessed,” plutonium is removed from SNF, mixed with uranium and used as mixed oxide (MOX) fuel. China, France, Russia, the UK… are conducting reprocessing of some amounts of SNF, but the UK has decided to stop reprocessing. In Japan alone, there is no option for direct disposal of SNF, and the country has a policy of reprocessing all SNF.

Nuclear power uses heat obtained from nuclear fission energy of uranium for electricity generation. Natural uranium ore, which is used as fuel for nuclear reactor, is constituted primarily of 99.3% of uranium-238 with 0.7% uranium-235. In order to use it for electricity generation, it is necessary to concentrate uranium-235 which is easily fissile, and nuclear fuel has raised the proportion of uranium-235 to about 3-5% (incidentally, atomic bombs increase concentration by more than 90%).

In order to cause nuclear fission, neutrons are bombarded in the nucleus of uranium-235. At this time, the atomic nucleus divides and releases enormous energy, and at the same time a few neutrons pop out. That neutron hits another nucleus and causes nuclear fission, and neutrons pop out – so chain a series of fission reactions.

When operating a nuclear reactor, it is most important to maintain a sustained controlled nuclear reaction. So as not to runway, e.g. water is used to decelerate the movement of neutrons, control rods are moved in and out between fuel to absorb neutrons, and the reaction is kept sustained.

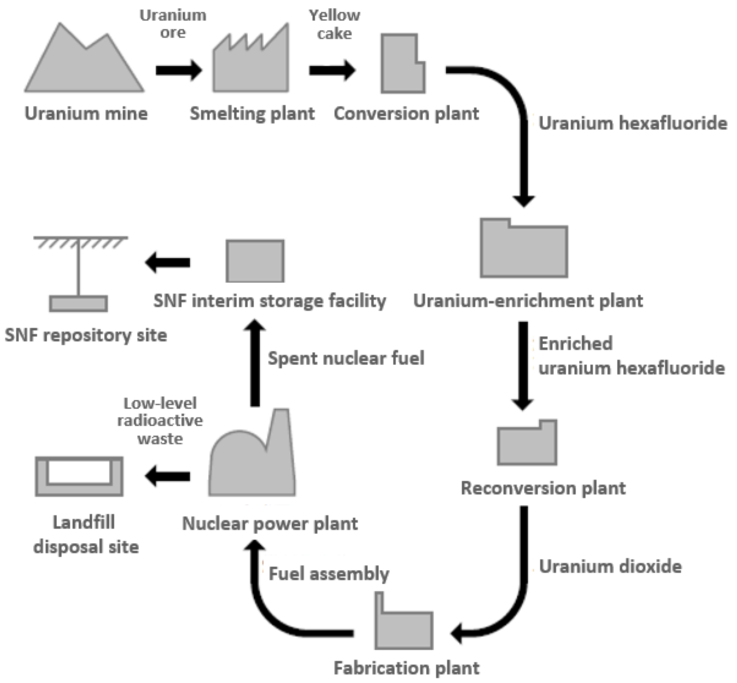
In the process of nuclear fission, various fission products (radioactive materials) are produced. Mainly, there are nuclides such as cesium-134, cesium-137, iodine-131, strontium-90. Since they are generated in a very unstable state, they collapse while emitting intense radiation and stabilize over a long period of time. In addition, uranium-238 absorbs neutrons and turns into plutonium-239 which is prone to nuclear fission.

After burning nuclear fuel in the nuclear reactor for a certain period of time, there are 3% to 4% of fission products, 1% of uranium-235 and plutonium-239, trace amounts of transuranic elements, and 95% of uranium-238 remain in the fuel rods.

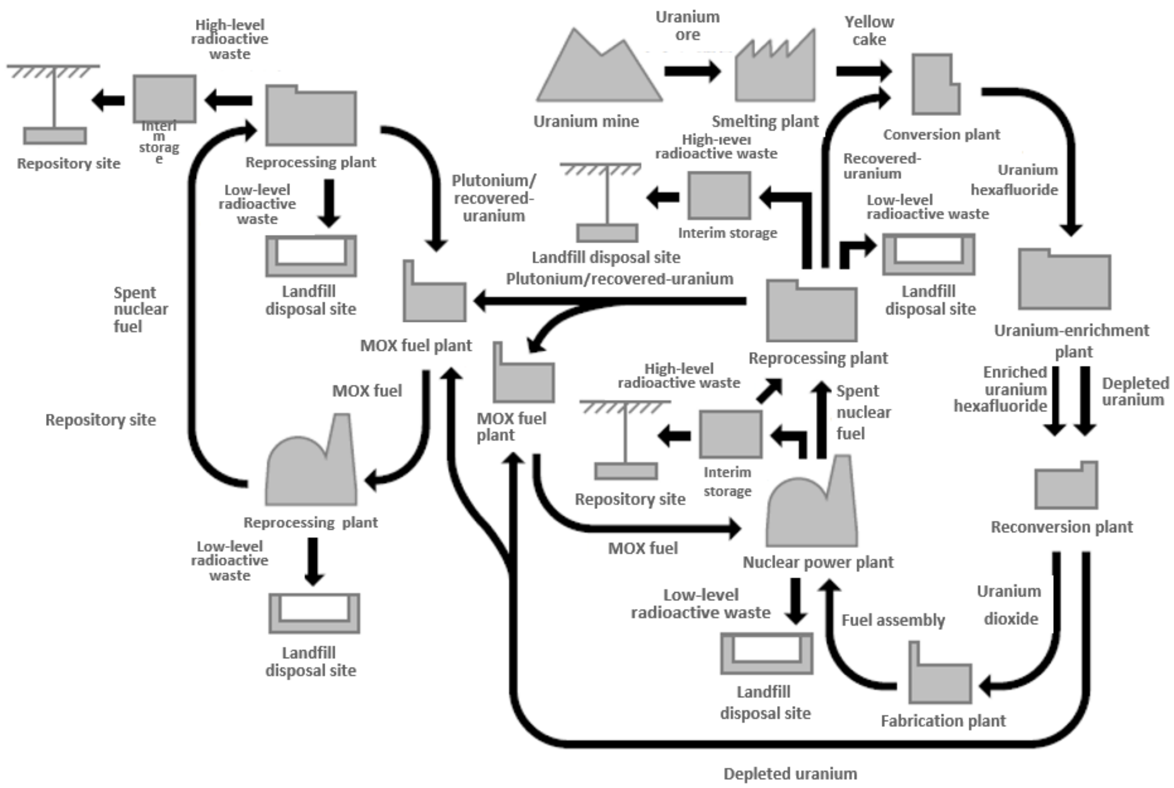
The nuclear fuel cycle is the flow of nuclear material, which is the whole course including the mining of natural uranium and the final disposal of SNF (Chart 41 on next page). In general, the phase from uranium mining to electricity generation is called "upstream" or "front end," and disposal of SNF and radioactive waste is called “downstream" or "back end."

Chart 41: Flow of Nuclear Fuel Cycle

Nuclear Fuel Cycle 1: Once Through Case



Nuclear Fuel Cycle 2: Reprocessing Case



Source: Citizens' Nuclear Information Center

Reprocessing adds a new reprocessing cycle to the general light water reactor cycle. It is a process of taking out plutonium from SNF, with melting the fuel and releases fission products and reprocessed uranium which was confined in the fuel rods. In each process of reprocessing, various radioactive substances are discharged, and in particular, highly radioactive liquid waste remains. This high level radioactive liquid waste must be solidified with glass and finally disposed as waste (high level vitrified waste).

There are four commercial reprocessing facilities in the world. La Hague in France (for commercial and nuclear weapons) and Mayak in Russia (was mainly developed for nuclear weapons) are in operation. There are also two in the UK, but Sellafield THORP was closed in 2018 and Magnox is scheduled to close in 2020. The US used to conduct commercial reprocessing in the past, but the program is currently stopped as the technology leads to nuclear proliferation.

In Japan, construction of a reprocessing facility has been underway since 1993, in Rokkasho. However, the start of formal operation has been postponed for 23 times, and according to the latest schedule it is expected to start operation in 2021. If it is realized, it would be the first case that non-nuclear state would own the world's largest commercial reprocessing facility. The total project cost is estimated to be almost $130 billion yen by the latest outlook of the operation company.

The original objective of reprocessing is not to use plutonium as MOX which burns the extracted plutonium in a light water reactor, but to use it in a "fast breeder reactor" which produces plutonium more efficiently. SNF from the breeder reactor will further reprocess, take out plutonium, and continue the cycle. Research and development has been advanced in many countries, but due to technical and economic aspects as well as safety issues, commercial development projects have not been put into practical use.

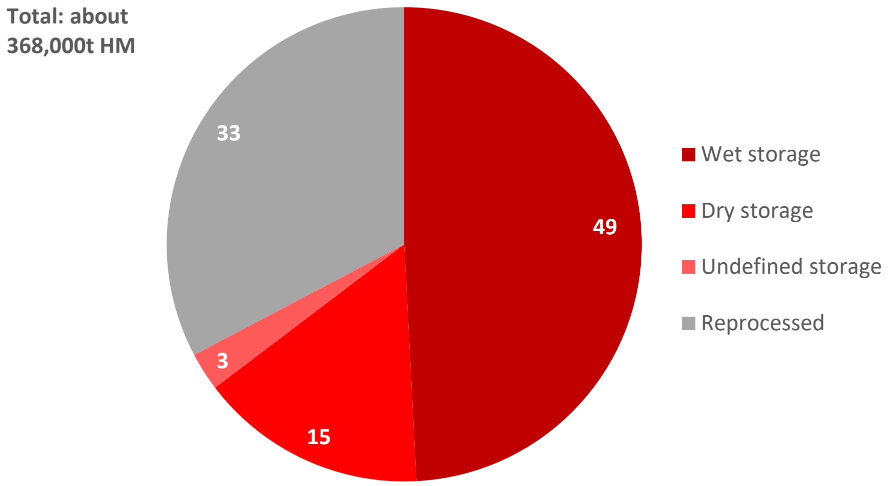
Plutonium extracted from SNF (reactor grade plutonium) can also be diverted to nuclear weapons. In countries where reprocessing has been conducted, such as the UK and the US, how to dispose plutonium taken out is a big challenge. The amount of plutonium around the world which separated from SNF exceeds that of military plutonium separated from nuclear arsenal.

Only France 's MELOX is under operation as a manufacturing facility that processes MOX fuel. In the UK there was also the Sellafield MOX, but it was closed in 2011 following the Fukushima Daiichi accident. In any case, MOX fuels must be disposed as spent "MOX" fuel after burned in nuclear reactors.

Many countries in the world are shifting from reprocessing policy to direct disposal of SNF as waste. Even in which case, SNF needs to be strictly managed as highly radioactive waste for a long period of time. After being taken out from a nuclear reactor, the fuel is stored for cooling in a storage pool at the reactor site for several years. After 50 years of interim storage, transferred to a deep place and eventually disposed.

There are two types of interim storage methods, wet type and dry type. Wet type is to keep SNF in the water storage pool. Dry type is to store in a container that can be cooled using an inert gas such as air or nitrogen. Regardless of which method is used, if the nuclear power plant continues to operate, the storage capacity will increase. In the past 60 years from 1954 to 2013, a total of about 370,000 metric tons of heavy metal (t HM) of SNF was discharged from nuclear power plants around the world (excluding India and Pakistan). At the end of 2013, two-thirds are in storage, most of it is wet type storage (Chart 42 on next page). The remaining third was reprocessed. SNF that has been stored or reprocessed must be disposed of as final radioactive waste.

Chart 42: Spent Fuel Discharged from Nuclear Power Plants Worldwide 1954-2013 (%)



Source: IAEA, Status and Trends in Spent Fuel and Radioactive Waste Management (January 2018)

There are various kinds of radioactive waste, and the level of radiation is also different. IAEA classifies waste in order of high radioactivity; high-level waste (HLW, including SNF), intermediate-level waste (ILW), low-level waste (LLW), very low-level waste (VLLW), very short-lived waste (VSLW), and exempt waste (EW).[169]

However, some countries have different standards. For example, in Japan, SNF is not classified as waste. Only "high-level vitrified waste" that solidified the reprocessed liquid waste is classified as HLW, and high radiation level waste including control rods is as classified as LLW (no "ILW" in the classification).

The way to dispose of waste depends on the radioactivity level. HLW should be kept in a deep stable underground layer. In contrast, LLW can be stored at disposal facilities near the surface of the earth. However, even LLW must be kept in isolation for at least several decades.

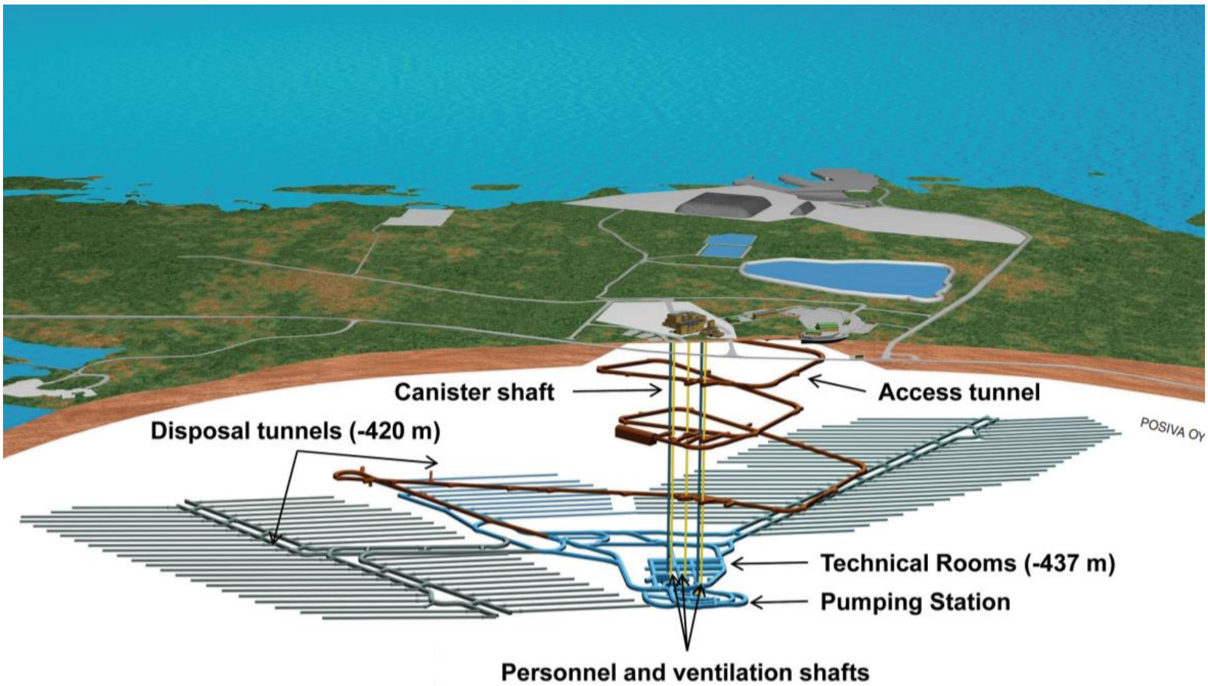
Since the number of nuclear power plants to be decommissioned will increase, it is necessary to dispose disassembled removed equipment as a large amount as radioactive waste. It is a very important challenge for each country to ensure sufficient disposal facilities. In addition, the operation of other final disposal facility for SNF and HLW is the biggest issue for nuclear operation.

Deep geological repositories

Following storage, spent fuel and HLW are to be disposed of in deep geological repositories at depths of several hundred meters or more in suitable geological formations. In theory, these repositories, if properly sited and constructed, should provide passive, multibarrier isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations should provide the very long-term stability typical of stable geological environments. At depths of several hundred meters, in a tectonically stable region, processes that could disrupt disposal facilities are so slow that the deep rock and groundwater systems should remain practically unchanged over hundreds of thousands or even millions of years.[170]

In reality, despite research undertaken for several decades, there is still no deep geological repository in operation anywhere in the world.[171] Only in a few countries significant progress has been made. Finland, France, and Sweden are now close to the construction and implementation of their own deep geological repository. Finland has granted construction license of a geological repository "Onkalo" in 2015 (Chart 43). Commissioning is expected in the 2020s. In France, the beginning of the pilot industrial phase of the facility Cigéo (Centre industriel de stockage géologique – industrial center for geological disposal) is planned for 2026.[172] And in Sweden a construction license application has been submitted, but some technical hurdles remain to be cleared about corrosion phenomena possibly damaging copper canisters in a way that could affect long-term safety notably.[173] In many other countries, plans for such projects are progressing slowly.

Chart 43: Onkalo, Finland Deep Geological Repository Underground Research Facility Illustration



Source: GeoFoorumi (Geological Survey of Finland Contact Magazine), Underground Test Laboratory (March 2010)

In the US, the Yucca Mountain site in the State of Nevada has been selected already more than 30 years ago, and despite $15 billion spent the project is currently on hold because of local political opposition.[174] In Germany, exploration work at Gorleben has been suspended due to technical issues and local opposition. A site has to be determined by 2031, with commissioning expected around 2050 (Gorleben is still an option).[175] Like in Germany, no site has been selected in Japan yet.

Beyond major technological and financial (developed from the next paragraph) difficulties geological repository projects are confronted with, social acceptance is also problematic. Populations understandably often do not want to live in environments which may be contaminated durably by leakages of dangerous radioactive materials.

Financial liabilities

Waste producers are usually responsible for the financing of all activities related to the management and disposal of spent fuel and radioactive waste. Funds are established while nuclear power plants are productive and earning money to cover the costs of radioactive waste generated during operations and/or from decommissioning. Funding systems are widely based on the "polluter-pays-principle."

One of the important issues, is that many of these costs appear long after nuclear power plants permanent shutdowns, i.e. when the source of income has dried up because plants are not generating electricity anymore. Arrangements to ensure long-term funding are thus necessary.

Another issue is when the original owner or operator no longer exists, this is a problem for old plants especially. In these cases, States often become responsible for the funding, and there is a competition among funding priorities.

In many countries, a special fund has been established to cover the costs of spent fuel and radioactive waste management and disposal. In some cases, these funds also include decommissioning costs (e.g. Finland and Sweden).

As for decommissioning, whether the funds established will be sufficient to cover the enormous and quite uncertain costs of spent fuel and radioactive waste management and disposal is an open question.

In the US, it is estimated that the cost of a repository for commercial spent fuel and HLW could be between about $27 billion and $91 billion.[176] In France, the estimated cost of the Cigéo project for long-lived ILW and HLW disposal is estimated at approximately $28 billion.[177] In Japan, the total costs for disposing HLW and a part of LLW is estimated at around $34 billion.[178] In Germany, the fund for nuclear waste amounts to $27 billion and if it turns out to be insufficient taxpayers will foot the bill – an infringement of the "polluter-pays-principle."[179] And in Finland, the cost of constructing and operating Onkalo for 100 years is estimated at $4 billion.[180]

Beyond uncertainty regarding costs of managing and disposing spent fuel and radioactive waste, there is again the risk of not securing enough money from electricity generation from nuclear power plants, particularly in very competitive power markets. For instance, as of the end of June 2018, EDF estimated the cost of waste removal and conditioning, and of long-term radioactive waste management in France to $35 billion, out of which only $11 billion – less than a third – had been provisioned.[181] As close to zero marginal cost, cost competitive RE keeps being deployed in well-interconnected Europe, this may prove an increasingly difficult task for the French power company. And in Japan, the issue may be even more severe – if not impossible – for power companies, which are not authorized to restart their nuclear power plants in a power market that has become more competitive, and are already liable for enormous waste costs of around $30 billion (excluding spent fuel reprocessing) for which they had only provisioned $9 billion in FY2017, very roughly just a third.[182]

Because of a variety of technical and sociopolitical reasons, many countries face delays in their expensive programs for spent fuel and HLW disposal. This has resulted in the need for more and longer storage of these harmful byproducts of electricity generation from nuclear power until disposal facilities are available. The length of the storage period could be many decades, and new storage facilities have to be built.

CONCLUSION

In the race against the clock the world is engaged in fighting climate change, renewable energy and nuclear are the two main options to decarbonize the power sector.

Globally, while the rise of cost competitive, decentralized, relatively simple and fast to deploy renewable energy is unstoppable, the marked decline of nuclear power is all the more striking.

Among key countries; Germany has already turned its back on nuclear power, and France is planning to substantially reduce its reliance on it. In the United States, many nuclear reactors are closing on economic grounds. In Japan, following Fukushima Daiichi nuclear accident restarting reactors is costly and unpopular. And in China, the world engine of nuclear power growth in recent years, the technology remains marginal in the country electricity generation mix. In all these countries, renewable energy is clearly leading the energy transition.

At the sunset of the 2010s, the fate of nuclear power is on the line. The combination of deteriorated economics, a myriad of inherent inappropriate technical characteristics for the 21st century electrical grid, and quasi-insolvable problems for the disposal of spent fuel and high-level radioactive waste are at the heart of nuclear power overwhelming difficulties.

Unless unforeseeable dramatic changes shake the nuclear power industry very quickly, it is certainly doomed to play a minor role in the medium to long-term future of electricity generation. And therefore, only be a negligible force to advance the decarbonization of the power sector.

To solve this problem renewable energy will be the major solution.

Appendix: List of Abbreviations

ARENH: Regulated Access to Incumbent Nuclear Electricity
BWR: boiling water reactor
Cigéo: Centre industriel de stockage géologique
CSP: concentrating solar thermal power
EDF: Électricité de France
EW: exempt waste
FiT: feed-in tariff
FY: fiscal year
gCO_2/kWh: gram of carbon dioxide per kilowatt-hour
GFR: gas-cooled fast reactor
GHG: greenhouse gas
GW: gigawatt
GWEC: Global Wind Energy Council
HLW: high-level waste
IAEA: International Atomic Energy Agency
ID: immediate dismantling
IEA: International Energy Agency
ILW: intermediate-level waste
LCOE: levelized cost of electricity
LFR: lead-cooled fast reactor
LLW: low-level waste
LTE: long-term enclosure
METI: Ministry of Economy, Trade and Industry
MOX: mixed oxide
MSR: molten salt reactor
MW: megawatt
MWh: megawatt-hour
NEA: Nuclear Energy Agency
NPS: New Policies Scenario
OCGT: open cycle gas turbine
OECD: Organization for Economic Co-operation and Development
O&M: operation and maintenance
PPA: power purchase agreement
PWR: pressurized water reactor
REI: Renewable Energy Institute
SCWR: supercritical water-cooled reactor
SFR: sodium-cooled fast reactor
SMR: small modular reactor
Solar PV: solar photovoltaic
TEPCO: Tokyo Electric Power Company
TWh: terawatt-hour
VHTR: very high temperature reactor
VLLW: very low-level waste
VSLW: very short-lived waste
WEO: World Energy Outlook

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