Is this the end of the line for Light Water Reactor technology or can China and Russia save the day?

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The Public Services International Research Unit (PSIRU) investigates the impact of privatisation and liberalisation on public services, with a specific focus on water, energy, waste management, health and social care sectors. Other research topics include the function and structure of public services, the strategies of multinational companies and influence of international finance institutions on public services. PSIRU is based in the Business Faculty, University of Greenwich, London, UK. Researchers: Prof. Steve Thomas, Dr. Jane Lethbridge (Director), Dr. Emanuele Lobina, Prof. David Hall, Dr. Jeff Powell, Sandra Van Niekerk, Dr. Yuliya Yurchenko

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1. Introduction

The promises made for a new generation of Light Water Reactor (LWR) technologies, so-called Generation III+, in the late 1990s led countries like the USA and the UK to launch new nuclear power programmes. The basis for these programmes was that these new designs would not only be cheaper than other low-carbon sources but would be competitive with fossil-fuel generation. Twenty years on, many of these promises have been proven false and the reactor programmes of the USA and the UK are in total disarray. However, Russia has built up an impressive export order book, larger than the export order books of all the other vendors put together, while China has started building reactors in China in large numbers and is now targeting the export market. Both Russia and China have developed their own designs that they claim achieve the same safety standards as Gen III+ designs. This has led some to suggest that Russia and China could largely take over the world market for reactors sustaining a strong world market for new reactors.

In this article, we look at the claims made for Gen III+ designs and review actual experience against these claims. For experience of construction of these designs we draw on Thomas (2015). This article reviewed construction experience with the three designs then under construction, cataloguing all the reported construction problems, and the cost and time over-runs. We then examine the status of the nuclear industries in China and Russia, identifying strengths and weaknesses and assessing whether they have the capability to sustain a strong world market for reactors. This section draws on Thomas (2016) for China and Thomas (2017) for Russia.

2. Light Water Reactor technology and Gen III+

There are two basic designs of reactors[1] cooled and moderated by ordinary water[2], Light Water Reactors (LWRs): Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs). These two designs have increasingly dominated the stock of commercial operating power reactors. In April 2017, the IAEA PRIS data base showed 449 commercially operating power reactors and of these, 290 were PWRs and 78 were BWRs. LWRs have their origins in the reactors used for submarine propulsion.[3] Some authors[4] have claimed that it was this advantage and the fact they were being offered by the two dominant heavy electrical companies, GE and Westinghouse, which allowed them to dominate the market rather than any superiority over the large number of alternative reactor designs using different coolants and moderators. By the mid-70s and before the 1978 Three Mile Island (TMI) accident, problems of cost were becoming serious and Bupp & Derian (1978) in their influential book 'Light Water: How the nuclear dream dissolved' talked about the 'extravagance of prophesy' particularly on costs, that had led to the collapse of reactor ordering in the USA.[5] Reactor orders continued in Europe after TMI into the 1980s, notably in France, almost all for LWRs.

[1] For an account of reactor technology see…
[2] 49 reactors in service use water with a heavy isotope of hydrogen, deuterium, so-called heavy water
[3] http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx (Accessed April 4, 2017
[4]
[5] No reactor order not subsequently cancelled was placed in the USA from 1974-2013 and more than 100 reactor orders, some almost complete, were cancelled.

However, by the time of the Chernobyl disaster in 1986, there were strong signs very few more orders would be placed in the short- to medium-term.

Costs increased dramatically and the Three Mile Island and Chernobyl accidents made it clear that serious nuclear accidents were not just a theoretical possibility that would never happen. For the decade following Chernobyl there were few orders worldwide. The cost of power from nuclear reactors was clearly far higher than power from coal or gas; financiers were reluctant to lend money for nuclear construction because of its poor record of being built to time and cost; and the opening up of electricity to competition meant utilities were less able to pass high costs on to consumers.

The future for nuclear power looked bleak and as what now appears a last resort attempt to save the industry, a new generation of reactors evolved from existing LWRs was promoted.[6] The publicity was designed to show that these new designs addressed all the issues that were seen as being behind the collapse of ordering: cost; safety; and financeability. Thoroughgoing standardisation was expected to be a feature that would contribute to meeting all these objectives. In the USA and the UK the governments tried to reinforce this process by introducing systems of comprehensive reactor design review that would approve a standardised design for construction at any site for a period of 10 (UK) or 15 years (USA).

2.1. Cost

In the late 1990s, the cheapest form of generation was generally gas-fired plants, occasionally coal for plants near cheap deposits of coal. To be economic, nuclear therefore had to match the generating cost of gas and this meant nuclear construction costs could be no more than $1000/kW and this was the cost forecast for Gen III+ reactors. Whether this forecast was based on a realistic and detailed estimate of construction costs or whether it was adopted simply because that was the cost needed is a moot point. However, in retrospect, this forecast is scarcely less 'extravagant' than the 'power too cheap to meter' claim made more than 40 years previously.[7] Standardisation, a feature that was expected to bring benefits in terms of safety and financeability was also expected to be an important feature.

2.2. Safety

There was no specific claim on safety across all designs other than that the new designs would be significantly safer than existing ones. For example, Westinghouse claimed the core damage frequency for its AP1000 would be 5 x 10^{-7} (5 in 10 million years) 1 per cent of the frequency for 'current' plants and less than one thousandth of the requirements of the US Nuclear Regulatory Committee (NRC).[8] One of the ways to achieve this was use of 'passive safety' under which, in an accident situation, there would be much less reliance on engineered safety systems such as

[6] A more radical set of new designs using coolants and moderators other than light water known as Generation IV was also talked about these are acknowledged to be decades away from commercial deployment.
[7] Lewis Strauss
[8] https://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-4-8-ANRT-WS/2_USA_UK_AP1000_Westinghouse_Pfister.pdf (Accessed April 3, 2017)

emergency core cooling systems, rather the plant would be kept in a safe condition by natural processes such as natural convection.

For some designs there was also the addition of 'core-catchers', whereby if there was a core meltdown, the core would be 'caught' and prevented from entering the environment. Following the 9/11 attack in 2001, there was also a requirement to design containment buildings so that they could survive an impact by a large aircraft.

2.3. Financeability

The issue here was that even if new reactors were forecast to be cost competitive, financiers would be reluctant to lend money for reactor construction because of the poor record of reactors being built to time and cost. The main strategy was to make reactors simpler so that they were easier to build. Greater simplicity could be achieved, it was argued, by re-evaluating all the safety systems that had been progressively added to reactors in response to accidents and experience in general rationalising them to achieve at least the same level of safety but with a much simpler design. The use of passive safety was also expected to simplify the design.

Another element in the strategy to reduce cost and time over-runs was the use of modularisation. Reactors were largely an on-site activity with most of the work taking place at the site rather than in factories. It was argued that site work is notoriously difficult to control and if much of the construction could be shifted to factories with on-site work restricted much more to just assembling modules, the risk of cost and time over-runs would be dramatically reduced. Construction time was predicted to be four years or less.

2.4. Design review

In 1992, the US NRC introduced a system of Design Certification[9] that would represent a comprehensive review of the design that would mean the design could be built, subject only to local issues, for a period of 15 years, renewable for 10-15 years. The rationale for this process was that under the previous methods, the design would be given approval in principle before construction but the details of the design would be reviewed during construction. This was aid to have caused delays in construction when resolving design issues led to a slow-down in the construction process. The first designs to complete this process were the Combustion Engineering System 80+ and the GE ABWR in 1997 and the Westinghouse AP600 in 1999. These designs were never ordered and their approval has now expired. The Westinghouse AP1000 started its review in 2002 and was given approval in 2006 but Westinghouse submitted a series of design changes and the final design was given approval only in 2011 with the 2006 approval superseded. Four reactors of this design began construction in 2013/14. The ESBWR started the process in 2005 and was given design certification in 2014 but no orders for reactors of this design are in prospect. The Areva EPR began its review in 2007 but in 2015, Areva applied to suspend the progress because of the absence of customers. The KEPCO APR1400 only began its review in 2014. Toshiba and GE-Hitachi separately applied for Design Certification renewal for their versions of the ABWR (see below for details) but Toshiba withdrew

[9] https://www.nrc.gov/reactors/new-reactors/design-cert.html (Accessed April 4, 2017)

the request in 2016 with little progress apparently having been made. The GE-Hitachi renewal is still in progress also with little apparent progress.

The UK introduced a design review, known as Generic Design Assessment (GDA) in 2007.[10] The EPR began the process in 2007 and was given a Design Acceptance Confirmation (DAC) in 2012. The Westinghouse AP1000 began its review in 2007 but in 2011, it paused the process because of lack of customers, restarting it in 2014 with completion in 2017. The Hitachi-GE ABWR began its review in 2013 and is expected to complete it by the end of 2017. The CGN Hualong One (see below) started its review in 2017. The ESBWR started its review in 2007 but was withdrawn only a year later.

A detailed critique of the generic review process is not carried out here but there are serious issues raised. In some cases design features are not specified in detail and are only resolved later when there is a potential customer. This clearly means vendors reduce the money they spend on specifying the design in detail till they have a customer. For some elements of the design where technology is moving rapidly, for example, IT systems it would make no sense to freeze the design and not take account of technical progress in these areas. As a result, only a small part of the design of the version of the AP1000 that received regulatory approval in 2006 was specified in full detail and the design amendments were largely the result of US customers being found. So in practice the difference between generic review and review on a site by site basis, as is still the case in jurisdictions other than the UK and the USA, may be much less than at first sight.

Safety regulation is in all cases under national jurisdiction and regulators from different countries impose different design requirements. For example, in 2009, the French, Finnish and UK regulators jointly expressed concerns about redundancy in the Instrumentation & Control (I&C) systems. However, the solution to this problem was different for each of the countries and for the UK, the design will only be specified at the construction phase. While many countries will look to the analysis of experienced, and open regulatory regimes such as that of the USA, they may well still impose their own design requirements so the standard design will tend to apply to only one country. While the system has been in existence for 25 years it has been little tested in practice with only one design, the AP1000 in the USA actually being built in the country it was certified. Whether a design certified more than a decade previously would still be close enough to the state of the art to be credible remains to be seen.

3. The Designs and experience with them

There are four designs claimed to be Gen III+ that have are under construction although by April 2017, only one reactor was actually in service: the Westinghouse AP1000 (eight under construction), the Areva EPR (four under construction), the Rosatom AES-2006 (one in service and five under construction and China's Hualong One marketed by both CNNC and CGN (see Table 1). [11] The ABWR design supplied by GE, Toshiba and Hitachi has been built in a 1980s version of the design (four in service and four under construction). The design was updated in the 1990s for the US market but not ordered and is being updated again for the UK market but not expected to be ordered before about

[10] http://www.onr.org.uk/new-reactors/assessment.htm (Accessed April 4, 2017)
[11] A review of Gen III+ designs https://aris.iaea.org/Publications/IAEA_WRC_Booklet.pdf Accessed April 4, 2017

2020. The KEPCO APR1400 was based on a design licensed from US Combustion Engineering and approved by the US Nuclear Regulatory Commission (NRC) in 1997 but never ordered. The Korean version (one in service and seven under construction) does not meet Gen III+ standards but is being upgraded and is under review by the NRC. The GE ESBWR was approved by the NRC in 2014 but has no realistic order prospects.

There CAP1400 is a design developed in China by SPI based on the AP1000 but scaled up to about 1400MW. Construction had not started on reactors of this design by April 2017. In 2010, Rosatom announced a new design, WWER-TOI that would be cheaper and quicker to build than the AES-2006 with the expectation that orders for this design would be placed from 2011 onwards. However, by 2017, no firm orders for this design had been placed. Other designs exist but are not under active review by a regulatory body and have little prospect of winning orders in the short-term.

The lack of a precise definition of the characteristics of reactors that can legitimately be termed Gen III+ means there is a significant diversity between the designs that their vendors claim to meet Gen III+ standards. The World Nuclear Association stated that: 'Generation III (and III+) are the advanced reactors discussed in this paper, though the distinction from Generation II is arbitrary.'[12] In simple terms, it appears the designs can be divided into radical new designs and those developed from existing designs. The former category, which includes AP1000 and ESBWR rely much more on passive safety and modularisation. The latter includes EPR, AES-2006, ABWR and APR1400 and given that additions will have been made to their predecessors such as core-catchers, it seems implausible that these designs could be simpler than their predecessors.

3.1. AP1000

The Advanced Passive 1000 (AP1000) was developed from the AP600 which received US Design Certification in 1999 but was not marketed because it was judge to be uneconomic. The AP1000 was submitted for review in 2002 when the process was forecast by Westinghouse to be a short one because the AP1000 represented only a scaled up AP600 and Design Certification was initially given in 2006. The following year, Toshiba bought the Westinghouse nuclear business from the British government for US$5.4bn.[13] Design modifications followed and it was not until 2011 that final Certification was given. By then construction had already (in 2009-10) started on two pairs of AP1000s in China (see Table 2) at the Haiyang and Sanmen sites and these appeared to be based on the design certified in the USA in 2006. A new Chinese company, State Nuclear Power Technology Corporation (SNPTC), later renamed State Power Investment Corporation (SPI) was set up in 2007 to participate in the construction of the imported AP1000s with a view to transferring the technology to SPI so that the AP1000 would form the basis for China's home market. It appears that hopes that costs would be reduced by this were not fully realised and SPI scaled up the AP1000 to form the CAP1400. Construction on two pairs of reactors in the USA, Summer and Vogtle, started in 2013. The AP1000 received DAC in the UK in March 2017 and the developers forecast that construction will start in 2020 on three AP1000s at the Moorside site.

[12] http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx (Accessed April 4, 2017)
[13] https://www.toshiba.co.jp/about/press/2006_02/pr0601.htm (Accessed March 22, 2017)

Thomas (2015) shows that all the AP1000s are substantially delayed and the ones where costs are known, the US plants, are far over budget. The pattern of problems appeared to be related to problems in the supply with the Reactor Coolant Pumps (RCP) a particular, but by no means the only problem. The US customers were taking legal action against Toshiba. Since then, things have deteriorated. In July 2015, Toshiba admitted that it had overstated its profits during the period 2008-14 by Yen152bn.[14] This led to a large number of board member resignations and a record fine imposed by the Japanese Stock Exchange of Yen91m. An investigation on this issue by the US Securities & Exchange Commission is still ongoing.

Table 2 Construction record of the AP1000

Site	Construction start	Original/latest completion date	Original/latest cost estimate
Sanmen 1	2009	2013/2017	?
Sanmen 2	2009	2014/2018	?
Haiyang 1	2009	2014/	?
Haiyang 2	2010	2015/	?
Summer 2	2013	2016/2020	$5.2bn/
Summer 3	2013	2018/2020	$5.2bn/
Vogtle 3	2013	2016/	$6.65bn/
Vogtle 4	2013	2018/	$6.65bn/

Source: Various

In October 2015, in response to a view that the problems with the AP1000 were in large part due to failures, particularly of quality control, with its equipment suppliers, it took over the nuclear business of its major supplier Chicago Bridge & Iron (CB&I). The CB&I assets included Stone & Webster, an architect engineering company with experience in nuclear power and the Shaw Group.[15]

In October 2015, it also renegotiated the Engineering Procurement and Construction (EPC) contracts for its Vogtle and Summer projects on a fixed price basis as a way to settle disputes that had arisen with the customers for these plants. At the time, Westinghouse was claiming it could improve efficiency by 30%, a target it has totally failed to meet and a year later, it admitted that the fixed price contracts underestimated costs by at least US$6.1bn and as a result, the Westinghouse nuclear division of Toshiba was cast adrift from the Toshiba main group, put into Chapter 11 bankruptcy protection and is for sale. By April 2017, it was not clear whether buyers for Westinghouse would be found and whether the US plants would be completed

3.2. EPR

The EPR had its origins in a joint venture between Framatome and Siemens in 1992 which aimed to produce a design that could be licensed across Europe, the European Pressurised Reactor (EPR). It

[14] The Independent 'Accounting scandal forces mass resignations at Toshiba; Chief executive and senior board members step down over inflated profits' July22, 2015

[15] Nuclear Intelligence Weekly 'Westinghouse's Strategy in CB&I Stone & Webster Acquisition' Oct 30, 2015

contained elements of the companies' most recent designs, the Framatome N4 and the Siemens Konvoi. While the four N4s had very long construction periods – 12-15 years – and their reliability has been mediocre the three Konvoi plants have operated outstandingly reliably and their construction time was about six years, longer than predicted for Gen III+ but better than many plants. In 2002, the joint venture was converted into a division, Areva NP (66 per cent Areva, 34 per cent Siemens) of the newly formed unified French nuclear company Areva. Siemens withdrew from the division in 2010 leaving Areva as 87 per cent owned by the French state.

Construction of the first unit, Olkiluoto (Finland) did not start until 2005, followed by Flamanville (France) in 2007 and two units in China (Taishan) in 2009/10. In 2012, the EPR received a DAC from the UK authorities and a consortium led by Electricité de France plans to build two EPRs at the Hinkley Point site with construction expected to start in 2019.

Thomas (2015) showed that all the EPRs under construction are heavily delayed and where costs are known, grossly over-budget (see Table 3). However, unlike the AP1000 the problems appear much more to do with on-site quality with issues of poor quality concrete, welds, and steel, typical of the problems that previous design generations suffered. This seems to reflect the fact that EPR is not a radical new design, rather an updated and more complex version of designs

Table 3 Construction record of the EPR

Site	Construction start	Original/latest completion date	Original/latest cost estimate
Olkiluoto	2005	2009/2018	€3bn/€8.5bn
Flamanville	2007	2012/2018	€3.3bn/€10.5bn[16]
Taishan 1	2009	2014/2017	?
Taishan 2	2010	2014/2018	?

Source: Various

The problems for the EPR were compounded by financial and quality control problems with Areva that became pronounced in 2015. In March of that year, Areva declared losses for the fifth consecutive year, this time of €4.8bn and it became clear that Areva could not continue to trade with powerful backing by the French state. The rescue of Areva is complex but is based on splitting it back into its component parts, the fuel cycle business and the reactor supply and servicing business. By April 2017, the rescue of the fuel cycle business appeared be on course but the rescue of the reactor business was far more problematic. This was expected to require EDF to buy 80 per cent of the shares for about €2.1bn with a plan to sell on 29 per cent to a third party.[17] However, this deal was subject to the successful resolution of quality control issues discussed below as well as approval by the competition authorities including the European Commission determining whether the rescue broke state-aid rules.

The scale of the reactor business's historic liabilities is such that a rescue may be impossible. One major liability is the cost of the overruns at the Olkiluoto plant. Areva gave a fixed price contract for

[16] https://www.bloomberg.com/news/articles/2017-01-11/bouygues-gets-1-8-billion-hinkley-point-nuclear-plant-contract (Access 21 March 2017)
[17] https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/rachat-areva-va (Accessed April 5, 2017)

€3bn to build the plant, but current estimates are that the final cost will be at least €8.5bn.[18] Areva has long disputed its responsibility for all the cost overruns and the case is being heard in the International Chamber of Commerce although a final verdict is not expected soon. The liability is likely to be in the order of €2-3bn and the French government has agreed to meet the liability with the project being completed by Areva SA.

In April 2015, the French nuclear safety regulator, Autorité Sûreté Nucléaire (ASN), announced that the reactor bases and lids Areva had supplied from its Creusot forge to the Flamanville and Taishan reactors did not meet specification with too much carbon in the steel.[19] The reactor vessel is of key importance to the safety case and a reactor vessel failure must be not credible. Since the admission of the problem, Areva has been putting together the case that these parts are strong enough and it was reported this would be delivered to the French safety regulator, ASN, in December 2016 (its delivery has not been confirmed).[20] ASN said it would need at least 6 months to evaluate the case, although, as discussed below, reviews of a reactor not yet in service may not be the highest priority.

As these parts had been installed a few years earlier, they will not be readily accessible and thus reparable or replaceable and if they are not the Flamanville and Taishan plants will have to be abandoned. It would seem inevitable that Areva would be held responsible and would be liable for a large amount of compensation.

As a result of this problem, ASN asked Areva to review its records at the Creusot plant going back ten years. Areva clearly found additional serious problems and extended the review back to 1965 and brought in two other plants, Jeumont and Saint-Marcel.[21] No information had been given on the findings at these other two plants by March 2017. However, an initial review covering 9000 records at Creusot found 400 irregularities for equipment such as reactor vessels, steam generators, main primary system piping and transport packaging. This equipment has been installed not only in France but other countries that have bought Areva parts including the UK, USA, China, Japan and Switzerland. The French prosecutor is examining bringing criminal charges against Areva.[22]

In October 2016, the President of ASN, Pierre-Franck Chevet stated: ‘this "purge" of documentation irregularities would continue. There is still one to two years’ work. We will find other irregularities. It is obvious.’ While the President of Areva, Bernard Fontana, said: ‘This [audit] will take place throughout the year 2017, with priority given to files related to the operating fleet. We are expecting

[18] http://uk.reuters.com/article/uk-tvo-areva-olkiluoto-arbitration-idUKKBN1350UA (Accessed March 22, 2017)
[19] http://www.french-nuclear-safety.fr/Information/News-releases/Flamanville-EPR-reactor-vessel-manufacturing-anomalies (Accessed March 22, 2017)
[20] http://www.areva.com/EN/news-10753/flamanville-epr-advancement-of-reactor-vessel-testing-programme.html (Accessed March 22, 2017)
[21] http://www.areva.com/EN/news-10777/quality-audit-at-the-le-creusot-plant-end-of-may-status-update.html (Accessed March 22, 2017)
[22] http://www.french-nuclear-safety.fr/Inspections/Supervision-of-the-epr-reactor/Anomaly-affecting-the-Flamanville-EPR-reactor-vessel/Falsification-of-materials-analysis-reports-ASN-is-collaborating-with-the-ongoing-judicial-inquiry (Accessed March 22, 2017)

to find the same type of practices to those discovered as part of the marked files.'[23] In March 2017, Areva said: 'For now we have had no claims from any clients. We are in talks with the clients & regulators concerned.'[24] The clear implication is that they expect claims and if they have installed equipment that does not meet the required specification, especially if the QC documentation has been falsified, it would be surprising if there were not such claims.

Also in March 2017, the head of nuclear equipment at ASN, Remy Catteau said that an inspection of the plant late last year showed that it did not have the right equipment to produce the parts for the nuclear reactors.[25] 'Creusot Forge is at the limit of its technical capacity. The tools at its disposal are not adequate to manufacture such huge components. In such a situation, errors are made. The inspection brought to light the fact that the safety culture in the plant is not sufficient to produce nuclear components.' It seems unlikely the Creusot plant can survive such a crushing condemnation.

3.3. ABWR

GE, Hitachi and Toshiba have been long-term collaborators in the development of GE's BWR design, especially for the Japanese market. The plan to produce an Advanced Boiling Water Reactor (ABWR) design was announced around 1980 and the first orders placed in the late 1980s. Four reactors were completed in Japan using this design with a further two under construction in Japan and two more in Taiwan. The four in Japan have produced minimal amounts of power since the Fukushima disaster in 2011 while the two under construction in Taiwan have been mothballed since 2013 and are unlikely to be completed. It is also not clear whether the two under construction in Japan will be completed.

Table 4 Record of the ABWR

Site	Vendor	Construction start/ Commercial operation	Lifetime load factor to end 2010 (%)
Hamaoka 5	Toshiba	2000/2005	47.4
Kashiwazaki Kariwa 6	Toshiba/Hitachi	1992/1996	71.2
Kashiwazaki Kariwa 7	Toshiba/Hitachi	1993/1997	68.6
Shika 2	Hitachi	2001/2006	49.7
Ohma	Hitachi	2010	-
Shimane 3	Hitachi	2007	-
Lungmen 1 (Taiwan)	GE	1999	-
Lungmen 2 (Taiwan)	GE	1999	-

Source: https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP (Accessed March 20, 2017).

Note: Load factor is calculated as power produced as a percentage of the power that would have been produced had the plant operated uninterrupted at full design rating.

The design was submitted to the US NRC and received design certification in 1997. However, when Toshiba bought Westinghouse in 2007, this marked the end of the three-way collaboration. Toshiba has continued show its ABWR design as available for order but it has no realistic prospects of selling

[23] European Power Daily 'Further Areva review likely to find irregularities' October 27, 2016.
[24] http://uk.reuters.com/article/us-areva-results-idUKKBN1683H0 (Accessed March 22, 2017)
[25] http://uk.reuters.com/article/uk-areva-safety-creusot-idUKKBN16N1SL (Accessed March 22, 2017)

any ABWRs in the short- to medium-term. Hitachi and GE formed two joint ventures, Hitachi-GE (80 per cent Hitachi) to operate outside the USA and GE-Hitachi (80 per cent GE mainly) for activity in the USA. GE-Hitachi had no serious sales prospects by April 2017 while Hitachi-GE's best prospect was sales of two ABWRs to the UK for the Wylfa site with construction start forecast for 2020. ONR and Hitachi-GE expect an updated version of the ABWR to be awarded a DAC by the end of 2017.

The ABWR is sometimes presented as a proven design, but all the construction and operating experience is with a 30 year old version of the design that does not meet the criteria for Gen III+. Construction of the four completed ABWRs seemed to go smoothly but the operating performance has been poor (see Table 4). How far this experience is relevant to performance with the current version of the design is difficult to determine.

3.4. ESBWR

The GE-Hitachi Economic Simplified Boiling Water Reactor (ESBWR), as the name implies represents, along with the AP1000, a more radical redesign of the previous LWRs than the other Gen III+ designs. It was submitted to the US Design Certification process in 2007, completing in 2014. However, it was withdrawn from the UK GDA process in 2008.[26] In the USA, by the end of 2008, five projects involving ESBWRs had been submitted to the NRC but none of these is likely to proceed. A common issue was the inability of GE-Hitachi to specify the design sufficiently for a reactor order to be placed. For example, in 2008, a large US utility, Exelon announced it was effectively abandoning the ESBWR saying: 'an internal analysis conducted over the summer raised questions about the "commercial and schedule certainty" for the ESBWR.'[27] There has been no serious interest in the ESBWR outside the USA

3.5. APR1400

The Korean Electric Power Company's (KEPCO) Advance Power Reactor 1400 (APR1400) design based on the System 80+ reactor licensed from Combustion Engineering (now part of the Westinghouse division of Toshiba). The System 80+ design achieved Design Certification in 1997 but the design was not seriously marketed. KEPCO submitted an application to the US NRC for Design Certification in December 2014, but it by April 2017, it had no prospective US customers.

One reactor of this design is complete and three more are under construction in Korea. In 2010, KEPCO won its first reactor export order for four reactors to be supplied to the UAE. The winning bid was spectacularly low, equating to about US$3600/kW, about 30 per cent lower than the next cheapest bid (for EPRs). The Areva CEO, Anne Lauvergeon was highly critical of the safety features in the APR1400 claiming it was like a car without airbags and seatbelts.[28] KEPCO acknowledged the design did not contain expensive features such as a double containment to protect against aircraft impact and a core-catcher that would be required in Europe.

[26] http://www.onr.org.uk/new-reactors/reports/step3-edf-areva-public-report-gda.pdf (Accessed April 5, 2017)

[27] Nucleonics Week 'Exelon drops ESBWR, looks at other reactor designs for its Texas project' November 27, 2008

[28] Nucleonics Week 'No core catcher, double containment for UAE reactors, South Koreans say' April 22, 2010

Construction of the first two units of this design was delayed due to the discovery of large scale falsification of quality control documents for more than 2000 components (see Table 5).[29] As with the ABWR, it is difficult to evaluate the APR1400, which in the form it has been built does not meet the criteria for Gen III+ because of lack of construction experience and regulatory evaluation with a design that would satisfy European or US regulators.

A further complication is the continued support of the Korean government, an element that was important in winning the UAE order. In the May 2017 election, all three of the leading candidates were promising to suspend existing construction, cancel or at best suspend new-build plans and not grant any life-extension to existing plants.[30] In that context, it would be unlikely that a future Korean government would put its weight behind Korean reactor exports.

Table 5 Record of the APR1400

Site	Construction start	Commercial operation
Shin Kori 3 (Korea)	10/08	12/16
Shin Kori 4 (Korea)	08/09	-
Shin Hanul 1 (Korea)	07/12	-
Shin Hanul 2 (Korea)	06/13	
Barakah 1 (UAE)	07/12	
Barakah 2 (UAE)	04/13	
Barakah 3 (UAE)	09/14	
Barakah 4 (UAE)	07/15	

Source: https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP (Accessed March 20, 2017).

4. China and Russia

There is an increasing perception that if new reactor orders are to be placed in the next decade or two, they will almost all be supplied by Chinese or Russian designs. However, assessing the record of the Chinese and Russian nuclear industries is difficult. There is little independent, authoritative information on reactor construction and operation, the regulatory bodies are not transparent and there is no reliable cost information. There is little experience of either country exporting reactors to countries, which, at the time of construction were open, had strong independent regulatory bodies and provided reliable costs.[31] Information is therefore often fragmented and sometimes anecdotal.

The advantages China and Russia are often seen as having are:

- Designs claimed to meet all the requirements of European and US regulators;
- Ability to provide a full package including finance;
- Expected to be cheaper than other suppliers;
- Designs not yet so tainted by escalating costs and construction delays;

[29] http://www.world-nuclear-news.org/RS-Indictments_for_South_Korea_forgery_scandal-1010137.html (Accessed April 5, 2017)
[30] Nuclear Intelligence Weekly 'South Korea: Is a Nuclear Phase-out in the Offing?' March 31, 2017
[31] Two Russian reactors were exported to Finland in the 1970s but these incorporated Westinghouse containments and Siemens instrumentation and control systems and are therefore not representative.

- A viable home market to prove new designs; and
- Government seen to back reactor sales as a policy tool.

In the next section we look at how justified these perceptions are.

4.1. Russia

Russia has more than 60 years of designing and supplying power reactors. Up to 1986, it had completed 25 reactors for the Russian market with a further eight under construction and subsequently completed. Its reactor exports were to former Soviet Republics and to Comecon countries. Its exports to Soviet Republics were to Ukraine, Lithuania and Armenia with 16 completed and 7 under construction and later completed. Its exports to Comecon countries were to Czechoslovakia, Bulgaria and Hungary with 14 completed, eight later completed and two still under construction in 2017. Two reactors were exported to Finland in the 1970s but these incorporated Siemens instrumentation & control systems and Westinghouse containments and are therefore not representative.

Following Chernobyl and from 1987-2007, no new orders were placed for the home market orders and only four exports, two each to China and India were won from 1986-2007 using designs, AES-91 and AES-92 respectively with some (such as a core-catcher), but not all of the Gen III+ features (see Table 6). The plants for China took seven or more years to complete, much longer than contemporary plants supplied by Chinese vendors. The plants for India took 12-15 years to complete.

In 2005, all parts of Russian nuclear industry were consolidated into a new company, renamed Rosatom in 2007, with the clear backing of Vladimir Putin who installed a key ally, Sergey Kiriyenko, who had no previous experience in the nuclear industry, as CEO. In 2006, the AES-2006 PWR design was announced which was claimed to meet all Gen III+ requirements including a core-catcher, passive safety and aircraft protection. Four orders were promptly placed for the home market with an expectation that ordering would continue at a rate of about three reactors per year for Russia. However, by 2017, only three more PWRs had been ordered for the home market, two using a pre-Chernobyl design while the one order for an AES-2006 was for the Kaliningrad enclave and construction was suspended in 2013 after only a year of work. There are projections of eight orders being placed by 2025, but there must be doubts whether many of these will materialise.

As previously, the St Petersburg and Moscow design offices produced their own versions, with significant differences between them, of what is generally seen as a single design. The Moscow office produced the AES-92 and their version of the AES-2006 used a reactor design designated V-392M. The St Petersburg office produced the AES-91 and their version of the AES-2006 used the V-491 reactor. In 2010, Rosatom announced a new design, VVER-TOI produced by the Moscow office, which would supersede the AES-2006 with 20 per cent lower costs and a construction time of only 40 months. However, by 2017, there were no firm orders for this design.

However, export orders were won in large numbers from 2010 onwards and by 2017, about 25 orders for AES-2006 – Belarus, India, Turkey, Bangladesh, Vietnam, Finland, Hungary and Egypt – had been placed along with six for older designs – China (AES-91), Iran (AES-92), Jordan (AES-92) (see

Table 7). Of these, construction had only started on the two reactors in each of China and Belarus and many of these orders, for example Vietnam and Jordan, appeared in doubt.

The four AES-2006 reactors under construction in Russia seem likely to take about 9 years to build. There is little information on what has caused these delays (Thomas, 2015) but Russia's Audit Chamber seemed to put the blame squarely on shortage of funds in a report from January 2015.[32] However, there have been reports of poor quality work and materials, and of corruption. For example, in July 2011, steel structures for the containment building at the Leningrad site collapsed requiring 1200 tonnes of reinforcing steelwork to be dismantled to rebuild the destroyed wall of the containment building.[33] In February 2012, Rosatom subsidiary, ZiO Podolsk, supplier to Leningrad 2 and Novovoronezh 2 was accused by the Federal Prosecutor of 'buying low quality raw materials on the cheap and pocketing the difference.'[34]

In July 2016, the reactor vessel for unit 1 at Ostravets was being manoeuvred into position when the vessel was dropped from a height of about 4 metres. Rosatom claimed the impact was a slow one and the vessel was not damaged.[35] A replacement vessel was installed in April 2017 but it appears completion of the plant will be delayed by a year or more.[36]

A key concern with the export orders is the capability of Russia to provide the finance and the supply chain capacity to fulfil more than a small part of the orders. All the orders on which construction has yet to start will require the bulk of the finance to be supplied by Russian sources. If we take the Hungarian deal as a model, Russia will provide 80 per cent of the finance amounting to about €5bn per reactor. Even if reactors can be built this cheaply, this would require Russia to more than €150bn for reactor exports over the next decade. The low oil price and international sanctions mean the Russian economy was in a poor state by 2017. For example, Vnesheconombank (VEB) was chosen to lend the money for the Hungarian Paks project having already lent money to the Belarus project, however, by December 2015, it was in deep financial difficulties, requiring US$16bn to bail it out.[37]

Table 8 **Recent cost estimates for AES-2006 exports**

Country	Site	Cost estimate US$ per reactor	Date
India	Koodankulam 3, 4	3bn (Rs19,375 crore)	10/16
Turkey	Akkuyu 1-4	5.5bn	10/14
Egypt	Dabaa	6.5bn	5/16

[32] Nuclear Intelligence Weekly 'Auditor Report Illuminates Rosatom's Financial Challenges' January 23, 2015
[33] Bellona 'Corruption: A new Russian Fukushima in the making?' September 27, 2011. http://bellona.org/news/russian-human-rights-issues/access-to-information/2011-09-corruption-a-new-russian-fukushima-in-the-making (Accessed February 27, 2015)
[34] Bellona 'Rosatom-owned company accused of selling shoddy equipment to reactors at home and abroad, pocketing profits' February 28, 2012 http://bellona.org/news/nuclear-issues/nuclear-russia/2012-02-rosatom-owned-company-accused-of-selling-shoddy-equipment-to-reactors-at-home-and-abroad-pocketing-profits (Accessed February 27, 2015
[35] Nucleonics Week 'Rosatom says Belarus vessel undamaged in incident' August 11, 2016
[36] http://www.world-nuclear-news.org/NN-Russia-installs-RPV-at-Belarus-plant-03041701.html (Accessed April 6, 2017)
[37] Channel News Asia 'Putin removes head of VEB state development bank as crisis bites' February 18, 2016.

Bangladesh	Rooppur 1, 2	6.6bn	12/15
Hungary	Paks	6.7bn (€6.25)	6/14
Finland	Hanhikivi	7-7.5bn (€6.5-7bn)	8/15
Vietnam	Ninh Thuan 1, 2	9bn	10/16

Sources: India: http://www.thehindu.com/news/national/modi-putin-to-inaugurate-kknpps-unit-3-4-civil-works/article9218690.ece
Vietnam: http://www.dw.com/en/vietnam-ditches-nuclear-power-plans/a-36338419
Finland: http://www.fennovoima.fi/uutiset/uutiset/vastaus-greenpeacen-avoimeen-kirjeeseen
Bangladesh: Nucleonics Week 'Bangladesh, Russia initial contract for construction of Rooppur' December 17, 2015
Turkey: http://www.hurriyetdailynews.com/construction-of-first-turkeys-nuclear-plant-to-begin-next-spring-in-akkuyu.aspx?PageID=238&NID=72824&NewsCatID=348
Egypt: Rusdata 'Moscow, Cairo to ink $26bn nuclear plant construction deal in Q1 2016' December 30, 2015
Hungary: Nucleonics Week 'Hungary approves Eur10 billion Russian funding for new Paks units' June 26, 2014
Notes:

1. All internet sources accessed November 15, 2016.
2. Based on exchange rates on November 15, 2016.
3. The reactors for Koodankulam 3 & 4 are expected probably to use the AES-92 design.

The capability of the supply chain is difficult to assess but given that Rosatom started construction on only ten reactors in the past decade and that to fulfil its order book would probably require five construction starts per year. The Finnish regulator, STUK, which is reviewing the Hanhikivi project has raised a number of issues related to the supply chain. STUK stated that a "slower than expected build-up" of organizational and project management teams has delayed the original document submission timetable for Hanhikivi by about 9 months.[38] A lack of resources in Rosatom was blamed.

The only estimates of cost are for plants on which construction has yet to start, seldom a good indicator of actual costs (see Table 8). The two projects on which construction is nearest and for which there are recent estimates are the Finnish and Hungarian plants which equate to about €6500/kW or about $7000/kW. This is of the same order as the estimates for the UK's Hinkley Point C EPR project. So on this limited evidence, there does not seem much justification for an assumption that Russian reactors will be cheap.

4.2. China

China's widespread adoption of nuclear power came much later than that of Russia with a large construction programme only launched in 2008. It has three established reactor vendors:

- China National Nuclear Corporation (CNNC) has its roots in the 1960s in military nuclear applications;
- China General Nuclear (CGN), which was set up in 1994 from the organisation set up to participate in the construction of the first large reactors, the two Daya Bay reactors imported from France; and
- State Power Investment Corporation (SPI), which was set up in 2007 to participate in the construction of the four Westinghouse AP1000s ordered then and to import AP1000 technology which was expected to form the basis for future nuclear orders for China.

[38] Nuclear Intelligence Weekly 'Finland: Dearth of Qualified Personnel Stalls Hanhikivi' February 24, 2017, p 6

CNNC would appear to be the most powerful and well connected of the three because of its history and its position appeared to be reinforced in 2017 when it announced its intention to merge with China National Engineering Corp (CNEC), the effective monopoly constructor of reactors in China. The position of SPI was also strengthened in 2013 when the State Nuclear Power Technology Company (SNPTC), the company set up to import AP1000 technology was merged with one of the five large Chinese electric utilities, China Power Investment Corporation (CPIC) to form SPI.

From 2008-10 construction work started on 25 reactors, four of which were the imported AP1000s, two were imported EPRs, two used an indigenous 650MW PWR design, but the remaining 17 used the design, M-310, designated CNP-1000, built at Daya Bay, and licensed to both CGN and CNNC. After the Fukushima disaster, there was a marked slowdown in construction with existing construction delayed and from 2011 to the end of 2016, construction started on only 13 reactors with little sign that the previous pace of construction would return. These 13 orders were split between five technologies: three CNP-1000s, two AES-91s imported from Russia, four CGN ACPR-1000s, two CGN Hualong Ones and two CNNC Hualong Ones.

While the slowdown in construction is often attributed to the Fukushima disaster, it appears likely other factors were involved including:

- The strain on resources imposed by the large amount of construction already in place;
- The failure of the either of the imported technologies (AP1000 and EPR) to meet expectations;
- The need to develop indigenous advanced technologies to replace these designs; and
- A ban on construction at inland sites and over-capacity in coastal regions.

CGN and CNNC both began to produce their own advanced designs, ACPR-1000 and ACP-1000 respectively, building on the M310 rather than the EPR. Four of the ACPR-1000 design have started construction in China and two of the ACP-1000 are under construction in Pakistan.[39] However, in 2013, the Chinese government required CGN and CNNC to merge their advanced designs to form a unified one, Hualong One. Since then four reactors designated Hualong One have started construction in China but by 2017, it was clear the designs had not been unified and these were CGN's and CNNC's distinct versions of the Hualong One. SPI has also been developing its own scaled up version of the AP1000, the CAP1400 although by April 2017, it had not been approved by the Chinese safety authorities and no construction had taken place.

Paradoxically, SPI seems to retain its position as the company that would lead future construction but this position is not translated into actual construction. In 2017, the government's planning body, the China Nuclear Energy Association, approved eight reactors for construction, six AP1000s and two CAP1400s. Whether any of these actually proceed remains to be seen.

Table 9 Construction time and operating performance of CNP-1000 reactors by year

Year construction start	No of units	Mean construction time (months)	Lifetime load factor (%)

[39] Pakistan has ordered 6 reactors from CNNC dating back to 1993, four using a Chinese 300MW PWR design and two using the ACP-1000 design

2005	1	57	84.1 (1)
2006	1	62	87.5 (1)
2007	1	70	79.2 (1)
2008	6	68	88.3 (3)
2009	5	75	-
2010	6	67	-

Source: IAEA PRIS database. https://www.iaea.org/PRIS/home.aspx (Accessed August 15, 2016)

The delays that followed the Fukushima disaster are reflected in the completion times of the CNP-1000 (see Table 9). The record for the imported reactors is much worse (see Tables 2 and 3) with all six plants at least four years late.

There are concerns about the strength of the safety regulatory regime in China and about the quality of work. Philippe Jamet, one of the French regulator's five governing commissioners, testified before French Parliament in February2014: 'Unfortunately, collaboration [with China] isn't at a level we would wish it to be. One of the explanations for the difficulties in our relations is that the Chinese safety authorities lack means. They are overwhelmed.[40] In 2015, referring to the prospects for Chinese nuclear power plant exports, a senior expert at China's SPI said: 'Our fatal weakness is our management standards are not high enough. There is a big gap with international standards.[41]

From 2013 onwards, the three Chinese companies began to target reactor exports with the support of the Chinese government. It appears the markets targeted are coordinated by the China Atomic Energy Authority and the National Development and Reform Commission and the three companies do not compete in the same market. The main markets were:

- CGN: UK, Romania and Kenya;
- CNNC: Argentina, Algeria and Sudan;
- SPI: Turkey and South Africa.

However, by 2017, apart from Pakistan no firm orders had been placed. The initial orders for Argentina and Romania would be to build reactors imported from Canada using the Candu design. An apparently firm order had been placed for two AP1000s and two CAP1400s for Turkey but by 2016, the order appeared to have collapsed. Strategically, the most important market may be the UK where CGN plans to build an unspecified number of its Hualong One at the Bradwell site. However, the safety regulatory review process, which typically takes at least five years, only started in 2017 so, realistically, a firm order is unlikely to be possible before about 2024. This failure to win firm export orders is perhaps surprising given the success of Chinese industry in almost all other markets.

It seems clear China does have the supply chain to support a significant number of reactor exports. The China Development Bank (CDB) and the Export and Import Bank of China are supporting state-backed companies, with CDB offering government- to-government low interest loans to Argentina and Algeria for their nuclear programmes as well as loans to CGN for the UK's Hinkley Point project.

[40] http://www.bloomberg.com/news/articles/2014-06-18/french-nuclear-regulator-says-china-cooperation-lacking (Accessed 7 April 2017).
[41] http://www.firstpost.com/fwire/made-in-china-nuclear-reactors-a-tough- sell-in-global-market-2140127.html (Accessed 7 April 2017)

The Industrial and Commercial Bank of China has agreed to offer loans of €10billion to support CGN's nuclear project in Romania (Yu, 2015b).

4.3. Strengths and Weaknesses of the Chinese and Russian nuclear industries

The strengths and weaknesses of the Chinese and Russian nuclear industry are summarised in Table 10. The perceived potential advantages of Russia and China in export markets were:

Designs claimed to meet all the requirements of European and US regulators. This remains unproven. If the projects in Finland and Hungary go ahead, this will provide some information on the AES-2006, while the UK's review of Hualong One will similarly test the capability of CGN.

Ability to provide a full package including finance. In neither case is this tested. Russia is clearly willing to back its nuclear industry but it is likely to lack the capacity to support more than a handful of orders, while China's commitment to support its nuclear exports is yet to be tested.

Expected to be cheaper than other suppliers. The limited evidence from Rosatom suggests their costs are not significantly less than their competitors while there is little useful information yet on Chinese costs.

Designs not yet so tainted by escalating costs and construction delays. The experience with the AES-2006 is little better than that with the EPR and AP1000. For China, while it appears capable of building old designs reasonably efficiently, its experience with modern imported designs is poor and its own designs are untested.

A viable home market to prove new designs. There is little sign that the Russian home market will be able to provide more than a handful of orders. The Chinese home market looks more healthy but there are issues about siting, technology choice and capacity need that mean the home market may be smaller than expected.

Government seen to back reactor sales as a policy tool. While this is a strength at present, this support is vulnerable to political changes of emphasis. For China, despite the size of the home nuclear programme, nuclear will continue to account for only a small percentage of electricity supply. If costs are high and continue to rise, the cost of renewables continues to fall and export markets continue to be hard to crack, the Chinese government may decide that it would be more advantageous to put its emphasis behind other sectors.

5. Is this the end for Light Water Reactor technology

The promise of Gen III+ technology was that it would solve the problems of cost, financeability and safety that it was perceived had led to a collapse in nuclear ordering in the 1990s. There were several pillars on which this promise was built: standardisation; simplification; passive safety; and modularisation. Evaluating safety is outside the scope of this paper and is not considered.

5.1. Simplification and passive safety

Simplification was the fundamental pillar that would lead to lower costs. However, of the eight designs that have made some progress towards ordering, six are basically previous designs with added safety features. It seems implausible that adding systems and layers of defence can simplify the design and experience with the EPR seems to suggest the design is more complex and therefore more difficult to build. The two more radical designs, AP1000 and ESBWR, rely for safety much more on passive features rather than active safety systems and this was the justification for the claim of lower costs. Experience with the construction of the AP1000 is no better than that with the EPR and where it has competed in a tender with the EPR, it does not appear to have bid lower.[42]

While the ESBWR, which has strong passive safety feature, was initially chosen by five US utilities for new construction, none has proceeded and a common concern was the inability to specify the design sufficiently to allow the plant to be costed and ordered. There has been no significant interest in the ESBWR outside the USA and it appears unlikely the design will win orders.

5.2. Modularisation

Modularisation was one of the main factors in the claim that plants could be built quicker and with more predictability by moving construction work from the site to a more controllable environment in a factory. As with passive safety, the six designs evolved from existing ones have minimal modularisation and there is no experience of construction of the ESBWR so the only experience is with AP1000, which is poor. Quality control problems appear just to have been moved from the site to the factory with no net gain.

5.3. Standardisation

Standardisation is an objective the nuclear industry has claimed would bring large economic benefits since the 1970s when the Standardised Nuclear Unit Power Plant System (SNUPPS) was proposed for five reactors in the USA and the French nuclear power programme was launched. Those advocating standardisation tend to ignore two basic questions. What do they mean by standardisation and why if it is such a sensible strategy has it not occurred?

Standardisation can cover a range of models from the production of essentially identical units – the Model T Ford example – to a more functional standardisation – for example, the QWERTY keyboard. For the Model T model to work, the technology needs to be mature so that standardisation does not block the introduction of important technical progress or the incorporation of experience and the volume of sales needs to be large enough that the benefits of standardisation are reaped before there is a need to move on to more advanced designs. Experience is with nuclear power is still evolving rapidly, sales volumes are likely to remain low, and the long feed-back loop from experience to improved designs is very long. For example, the generation of reactors that embody the lessons from Chernobyl is only beginning to enter service 30 years after the event. It is hard to see what major benefits a more functional concept of standardisation would bring.

Experience with attempts at standardisation is not encouraging. Only two reactors using the SNUPPS design were built and their record of construction and operation is far from outstanding. The French programme of 58 reactors was split into seven 'tranches', covering three different output sizes with design changes between each tranche. It is now emerging far from decreasing over time, the real

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[42] The AP1000 was chosen over the EPR in China but this appeared to be in part due to Westinghouse's greater willingness to transfer technology to China. Nucleonics Week 'Westinghouse may win China bid as Areva balks at tech transfer' March 16, 2006, p 15.

cost of the these increased significantly and the final tranche, the N4 design, had a very poor construction record with the four reactors taking 11-16 years to complete.

While standardisation was not a central plank of Gen III+, there appears to be little evidence that it would be an effective way to reduce costs and control construction times.

6. Where now for reactor technology?

All the ideas to save LWR technology appear to have been embodied in Gen III+ and far from reducing costs and uncertainty in construction, these appear to have been made worse. The cost gap between nuclear power and natural gas is now huge and in many cases, renewable costs are lower than nuclear and, unlike nuclear costs, they are continuing to fall in real terms. It also appears unlikely that reactors from Russia and China will solve the issues of cost and uncertainty in construction. This implies that while the existing stock of LWRs might continue in service for several decades, they will not be replaced by improved LWRs. So if the nuclear industry is to have a future, it would appear to be either in more radical redesigns, particularly so-called Gen IV reactors or Small Modular Reactors (SMRs). A full evaluation of these options is beyond the scope of this paper but it is useful to outline the main arguments

6.1. Gen IV

In 2000, a new international organisation, the Gen IV International Forum (GIF) was set up to stimulate R&D in a new generation of nuclear designs that would be radically different to existing designs.[43] By 2016, there were 14 partners including USA, UK, China and Russia. Six reactor technologies were selected for further development. Two, the Very High Temperature Reactor (VHTR) and the Sodium-cooled Fast Reactor (SFR), were based on concepts that had already been built in prototype and demonstration form, while the other four were new concepts. The two established concepts both have a 60 year history of development and despite several independent attempts in about five separate countries to commercialise this technology, the technologies have proved problematic. The other four technologies will significant technical advances for them to progress. Realistically the more expensive phase of building and operating demonstration plants will only go ahead with large public subsidies and even if these are available there is no guarantee that commercially viable designs will be developed

6.2. SMRs

Small Modular Reactors (SMRs) have been talked about for more than a decade. They can be divided into two categories: those based on scaled-down LWRs and those based more radical reactor concepts. It is hard to see how scaling LWRs would reduce the cost per unit of capacity over large LWRs, it seems more likely to raise the cost given the loss of scale economies. As with Gen IV, these will require major development work and without large government subsidies, these are unlikely to be pursued by private companies. For a review of SMR developments see Ramana & Ahmad (2016) and Cooper (2014).

[43] https://www.gen-4.org/gif/jcms/c_9335/charter (Accessed April 11 2017)

7. Conclusions and policy implications

There is mounting evidence that Gen III+ reactors, based on evolutionary design changes to existing Light Water Reactor technology, and the Nuclear Renaissance it was meant to drive have failed. The promise that measures such as rationalisation of safety systems, use of passive safety and modularisation would dramatically reduce costs and the risk of construction time overruns now appears to have been an illusion. If Gen III+ has failed it is hard to see what other options could be tried to take LWR technology out of the spiral of increasing real costs and complexity that have made LWR increasingly commercially unattractive over the past four decades.

In the past, the stock of existing reactors has provided a buffer giving a steady flow of servicing, maintenance and repair work to keep reactor vendors going. However, many of the existing reactors are near or beyond their design life, their economics are deteriorating and may begin to close in large numbers over the next decade. So the servicing market will decline and with continuing cost reductions for renewables, the suggestion that nuclear was the key technology to reduce carbon emissions from electricity generation is less credible. The two largest OECD reactor vendors, Westinghouse and Areva, are already in desperate financial difficulties and if they survive, it may be only as maintenance, service and repair companies.

The evidence available suggests that Chinese and Russian designed reactors are not significantly cheaper or easier to build than their competitors. Russia seems unlikely to be able to provide finance on the scale required to fulfil more than a small proportion of its order book while China has found it difficult to find customers for its technology, in contrast to its success with other technologies. In both cases there are serious concerns about quality of components and work, safety culture and many countries would be reluctant to allow Russia or China to supply such sensitive equipment. There is also little evidence yet as to whether these designs would satisfy experienced and independent regulators.

The often repeated suggestion that one or two major reactor accidents would destroy the nuclear industry appears not to apply and in many countries, there has been little visible impact in terms of government and public support for nuclear power. Nevertheless, many governments appear to have a seemingly inexhaustible capacity to discount past failed promises from the nuclear industry and be prepared to give the nuclear industry one more chance to prove itself. This willingness to continually give nuclear power another chance has serious implications for other technologies which will inevitably be pursued less vigorously if the assumption is that nuclear will provide the answers.

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Table 1 Generation III+ designs

Design	Vendor	Passive safety	Core-catcher	Modular construction	NRC approval	ONR approval	Under construction	In service
AP1000	Westinghouse	Yes	No	Yes	2011	2017	8	0
EPR	Areva	Minimal	Yes	No	Process abandoned	2012	4	0
AES-2006	Rosatom	Minimal	Yes	No	Not submitted	Not submitted	5	1
ABWR	GE/Hitachi/Toshiba	Minimal	Yes	No	In progress	In progress	4	4
APR1400	KEPCO	Minimal	?	No	In progress	Not submitted	7	1
ESBWR	GE-Hitachi	Yes	Yes	Yes	2014	Process abandoned	0	0
Hualong One	CNNC/CGN	Minimal	No	No	Not submitted	Submitted 2017	4	0
CAP1400	SPI	Yes	?	Yes	Not submitted	Not submitted	0	0

Table 6 Russia nuclear orders post-1986

Country	Site	Technology	No of units	Construction start	Commercial operation	Construction time months	Lifetime load factor
Russia	Beloyarsk	Breeder	1	2006	2016	123	-
Russia	Baltic	AES-2006 St Petersburg	1	2012	?	-	-
Russia	Leningrad	AES-2006 St Petersburg	2	2008-10	2017, 18	108, 96	-, -
Russia	Novovoronezh	AES-2006 Moscow	2	2008-09	2017, 18	104, 108	-, -

Russia	Rostov	VVER-1000 (V320)	2	2009-10	2015, -	72,	98.2
Belarus	Ostravets	AES-2006 St Petersburg	2	2013-14	2019, 20	72, 72	-
China	Tianwan 1, 2	AES-91	2	1999-2000	2007	91, 83	86.1, 88.4
China	Tianwan 3, 4	AES-91	2	2012-13	-	-, -	-, -
India	Koodankulam	AES-92	2	2002	2014, -	153, 171	40.0, -

Source: IAEA PRIS reactor data base: https://www.iaea.org/PRIS/home.aspx (Accessed September 8, 2016)

Notes

1. For reactors not yet complete but claimed to be within 2 years of completion, the construction time is estimated from the most recent estimate.
2. Includes only reactors with output greater than 150MW and on which started construction after 1986.
3. Construction of Baltic 1 was suspended in 2013.

Table 7 Russia's order book in 2016

Country	Site	Units	Technology	Original start to on-line	Status	Expected completion
India	Haripur	6	AES-2006			
India	Koodankulam	2	AES-92/AES-2006	2014 – 2019		Preliminary works sar
India	Koodankulam	2	AES-92/AES-2006	2014 – 2019		
Turkey	Akkuyu	4	AES-2006/VVER-TOI Moscow	2011 – 2016	Deal signed 5/10[44]	Construction start 20
B'desh	Rooppur	2	AES-2006	2008 – 2013	Deal signed 1/13[46]	Construction start 20 onwards[47]
Vietnam	Ninh Thuan	2	AES-2006 St Petersburg	2014 – 2020	Deal signed 4/10[48]	Construction start for line 2028
Finland	Hanhikivi	1	AES-2006 St Petersburg	2018 – 2024	Deal agreed 9/13[50]	Construction start 20
Iran	Bushehr	2	AES-92	2015 -	Deal agreed 10/14[51]	Construction start for
Hungary	Paks	2	AES-2006 St Petersburg	- 2023	Deal agreed 1/14[52]	Construction start for line 2025-26[53]
Jordan	Al Amra	2	AES-92	- 2020	Deal agreed 10/13[54]	Completion 2025[55]
Egypt	Dabaa	4	1200MW	2016 -	Deal agreed 11/15	Construction start 20
Nigeria	Geregu/Kogi	2		2016 – 2025	Deal not complete	2025
S Africa	Several	8	1200MW	- 2022-29	No deal confirmed	2026
S Arabia	Not known	16	Not known	- 2030	No deal confirmed	

Source: Author's research. Note: Includes only reactors on which construction had not started by September 2016

Table 10 Strengths & Weaknesses of the Russian and Chinese nuclear industries

	Russia	China
Finance	Political support but doubtful capability	Political support, strong apparent capability but untested
Design capability	Long-established	Little tested
Ability to satisfy experienced, independent regulator	Little tested	Untested
Export order book	Larger than it can handle	No firm orders
Supply chain	Weak, quality untested in open markets	Strong, quality untested in open markets

44 Nucleonics Week 'Akkuyu plant construction to begin in 2011, says Turkish energy ministry' May 27, 2010
45 Nuclear Intelligence Weekly 'Moscow Meeting Breathes New Life into Akkuyu' July 29, 2016, pp 4-5.
46 Nucleonics Week 'Bangladesh, Russia initial contract for construction of Rooppur' December 17, 2015
47 Ibid
48 Nucleonics Week 'Russian industry to build Vietnam's first nuclear plant' April 29, 2010
49 Prime Tass 'Rosatom to start designing Vietnamese nuclear plant in 2013' November 12, 2012
50 Power in Europe 'Fennovoima aims for 2024' September 16, 2013
51 ITAR/TASS 'Iran to fund construction of 2 new nuclear power units in that country' November 11,2014
52 Nucleonics Week 'Russia financing new units at Hungary's Paks' January 16, 2014
53 Nucleonics Week 'Hungary to go ahead with Paks II plan despite EU concerns: government' November 26, 2015
54 BBC Monitoring Middle East 'Jordan's first nuclear reactor to start operating by 2025 – official' March 20, 2016
55 Ibid

Costs	Little evidence but Finland & Hungary suggest comparable to Areva/Toshiba	No evidence
Home market	Weak, consistently overestimated	Potentially strong but issues of siting, over-capacity & technology choice
Construction record	Mostly poor especially with AES-2006, construction mishaps	Good with old design, experience with imported modern designs poor, new designs untested, concern about quality
Industry structure	Consolidated into one massive but unwieldy company	Split between three bitter rival companies

Source: Author's analysis