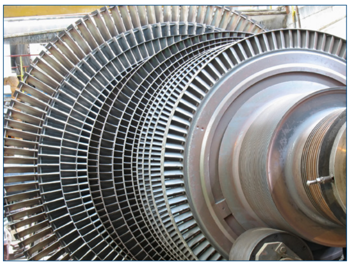
NATIONAL NUCLEAR LABORATORY

Small Modular Reactors (SMR) Feasibility Study



December 2014

This report has been produced on a cost share basis with HMG by the following parties –

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Executive Summary

This Feasibility Study has been produced as a result of UK Government requesting the UK Industry view on Small Modular Reactors. Government asked Industry to undertake a review to determine a) whether SMRs are viable; b) the potential UK industry role; and c) the possible role that Government might play in that process. This request was driven both by recognition from Government of a need for further industrial development, and for low carbon, secure and affordable energy supply.

The study was required to cover the following scope:

1. Global market assessment
2. Technical assessment
3. Investment in innovation
4. Financial assessment (including cost reduction assessment)
5. UK commercial opportunity assessment

These 5 areas are expanded on below, with a high-level summary of the findings of the overall study.

1. GLOBAL MARKET ASSESSMENT

This section includes:

- Indication of the potential global market and the type of technologies which could succeed in particular markets
- The size of the potential global market - geographical and political
- The markets or the components of markets which are expected to be closed to UK companies, either acting alone or in collaboration with international partners,
- Assessment of market segments, e.g. power, heat, desalination, energy for industry

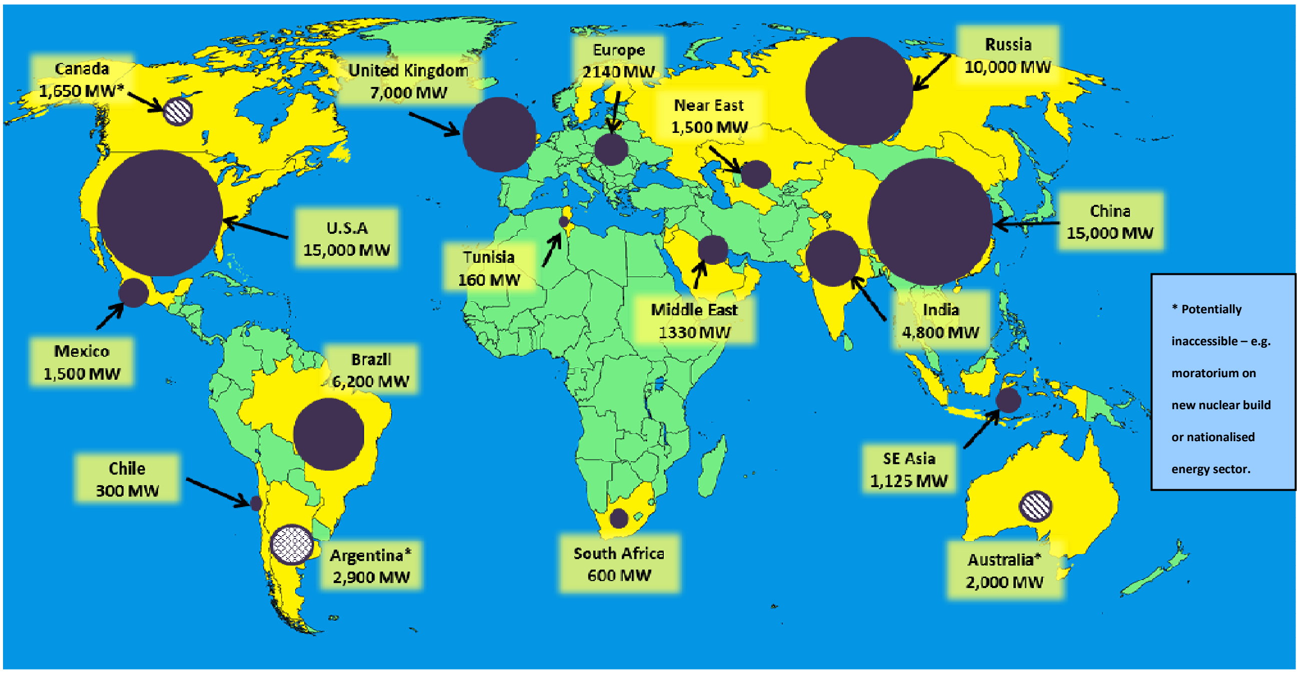

Figure 1 - Global market assessment

The market study concludes that there is a very significant market for SMRs where they fulfil a market need that cannot, in all circumstances, be met by large nuclear plants. The size of the potential SMR market, is calculated to be approximately 65-85GW by 2035 (as shown above), valued at £250-£400bn, if the economics are competitive. In a regional assessment, the study also determines that there could be a UK market for around 7GW of power from SMRs by 2035, based on a demand for low-carbon generation and site availability for small nuclear reactors (less than 300MW). To gain access to larger potential markets for SMRs, it would be desirable for the UK to partner with another country in order to help access the international market.

A brief top-down analysis of desalination has indicated that the market for niche, alternative applications to traditional grid connection electricity production, could be in the hundreds of billions of pounds (UN water agency, European environment agency 2030/2035) based on demand and deficit.

2. TECHNICAL ASSESSMENT

The Technical assessment investigated current SMR designs most likely to be commercially successful globally, noting political and other factors which might have an impact. This included interviews with a set of down-selected SMR vendors. Through engagement with the vendors, an initial assessment of key unsolved issues and technical challenges requiring resolution before a successful SMR can be brought to market were identified. The technical assessments spanned across fuel cycle design, materials, manufacture, fabrication, construction, licensing, operation, sites, safety and security. A key criterion for suitability was the potential for deployment within a ten year timescale.

An initial assessment of the available SMRs based on the following criteria was undertaken:

- Technical maturity and viability
- Maturity of Safety Case and certification
- Key strengths and areas for development
- Programmes to address development needs
- Available resources – people, capability, facilities and funding
- Economic viability

A shortlist of six reactor designs technologies was identified as potentially meeting both the technical and financial requirements:

- ACP100+ - CNNC
- ANTARES - AREVA
- mPower – B&W and Bechtel
- Westinghouse SMR - Westinghouse
- NuScale - Fluor
- U-Battery - Urenco

Discussions with AREVA revealed that they were no longer considering the HTR Antares design and although they are considering an alternative PWR SMR design, they are not planning to proceed with this within the timeframe of this study. As a consequence the AREVA option was discounted from further investigation.

Discussions with U-Battery identified that their design was targeted at a different market and potentially in a longer timescale. It was concluded that ongoing discussions were better suited to a separate NIRAB (Nuclear Innovation Research Advisory Board) grouping which is considering alternative technologies and a longer timeframe. So this option was also discounted from this study.

The four remaining integral PWR reactors are all potentially viable within the 10 year time frame, in all cases there is the possibility for UK involvement in the design and all have indicated that they would be interested in further developing discussions about collaborative partnerships with the UK. There is however, a narrow window of opportunity in which the UK can join the respective programmes as there are other interested parties and also a cut-off point by which time there will no longer be an opportunity for the UK to contribute to design in a way that will provide substantial Intellectual Property Rights (IPR).

The feasibility of achieving regulatory and licensing approvals to develop and commercialise SMRs is also considered in the study. Based on discussions with the Office for Nuclear Regulation (ONR), it is likely that the regulatory process for SMRs would be via Generic Design Assessment (GDA), as is the case with large reactors. ONR have indicated that they will judge SMRs on the basis of risk. Whether or not the GDA process will be simpler for small reactors is too early to judge and would only become clear when a reactor goes through the formal process

3. INVESTMENT IN INNOVATION

A number of technical areas (21) have been identified that provide innovation opportunities. These include concept design areas that are challenging for the current designers, detailed design issues that are likely to be important for regulatory approval in the UK and 3 generic design subjects that have the potential for significant cost reduction of any of the designs.

An ‘Alternative Technologies’ section has also been developed. This section addresses the less mature designs with low Technology Readiness Levels (TRL), and therefore do not meet a 10 year deployment timeframe, but may present an interesting and viable opportunity for investment in innovation for a longer timescale.

4. FINANCIAL ASSESSMENT (INCLUDING COST REDUCTION ASSESSMENT)

The financial analysis provides evidence on the potential costs of energy from small nuclear reactors, as well as how they compare with other energy generation forms. The overnight capital cost and the levelised cost of energy (LCOE) have been assessed from a number of selected SMR vendors, and compared with historical OECD data.

This analysis shows SMRs to be comparable with large scale nuclear on a First Of A Kind (FOAK) basis and through the use of modular construction and factory production techniques, conceivably more competitive on Next Of A Kind (NOAK) basis. Large-scale reactors require significant up-front capital investment and long costly construction; by contrast SMRs will require less capital investment before producing returns and have the potential for quicker construction. This provides an attractive proposition to potential investors of a faster return on a lower amount of money.

The four integral PWRs that have been selected and assessed in detail require between £0.5-1.0bn to reach production level maturity over a 5-7 year period. None of the designs have completed the development phase but some are planning to start licensing approval with their national regulators in the next 12-18 months. If the UK was prepared to invest in a joint development programme with a current developer, it could expect proportional involvement in the manufacturing and deployment of the reactor, wherever it sold globally.

5. UK COMMERCIAL OPPORTUNITY ASSESSMENT (GOVERNMENT INVOLVEMENT OPTIONS)

In all countries where SMRs are being developed government involvement is supporting the companies with the relevant technology capabilities. The financial risks for industry to develop SMRs here in the UK are judged to be too great without government support and commitment on a similar scale. Financial involvement by the UK Government in the UK Nuclear Industry is a significant decision but consistent with the requirement to deliver the strategy laid out in the “UK Nuclear Future”.

The UK today has all of the necessary skills to design, develop manufacture and build SMRs. There are also likely to be significant advantages in being involved at the beginning of a programme. As such the commercial opportunities for a broad range of companies, across various industries are significant.

The study investigated how, and in which areas the UK can secure commercial value from SMRs. The options considered included:

- Going it alone (development of a UK SMR)
- Purchase of an existing SMR designer/vendor
- Partnership with an existing SMR designer/vendor
- Supply of work to a vendor through commercial contracts in specific areas

The last of these will enable work to come to the UK associated with the manufacturing of components for UK reactors but is unlikely to provide any opportunities in the international market or for UK IP ownership.

The first three all require government involvement, principally in an engineering research and development programme to ensure that the UK has the capabilities to be a legitimate partner with the current reactor vendors. Commitment to this engineering programme may well create the conditions where UK industry can see a viable commercial route to proceed through the exploitation phase.

Conclusion

The report concludes that there is an opportunity for the UK to regain technology leadership in the ownership and development of low-carbon generation and secure energy supplies through investment in SMRs. This has the potential to position the UK as a global technology vendor in these fields, and consequently to spearhead the development of the UK supply chain, enabling British businesses to develop their capability, and increase international trade.

After two decades of development on SMRs, the last 3-4 years has witnessed a significant acceleration in the pace of the technology progression by many of the major reactor vendors across the globe, bringing SMRs much closer to market as a low-carbon, large scale energy source, and making them a potentially attractive technology.

There is a clear need for deeper investigation into the individual technologies and the capability required to deliver them to market, further financial analysis to clarify the economics case, and a testing of the possible engagement models for the UK to partner with a selected SMR technology vendor. Overall however, on initial review, this study concludes that there could be a significant market for SMRs and the UK has a narrow window of opportunity to participate in a joint development with a partner country, which could offer the UK a position as a market leader in nuclear low-carbon generation.

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1 Introduction

The world demand for electricity is likely to almost double over the next 25 years; a demanding challenge when combined with international concerns on global warming. The nuclear industry today provides 11% of the world's electricity.

Large nuclear reactors, are capable of fulfilling much of the future demand but face significant financing and infrastructure challenges, SMRs could provide a viable alternative, particularly in locations and countries that are not suitable for large reactors.

In 2011 the House of Lords Select Committee on Science and Technology produced a paper on Nuclear Research and Development Capabilities, which contained 13 recommendations on Nuclear R&D. In response the government produced a paper setting out the UK's Nuclear Future, with a vision of "a vibrant UK nuclear industry that is an area of economic and strategic national strength, providing the UK with a safe reliable and affordable supply of low-carbon electricity". There were a number of key objectives identified:

- To be a 'top table' nuclear nation, working in international partnerships leading the direction of future technology advances across the fuel cycle.
- To be a key partner of choice in commercialising Generation III+, IV and SMR technologies worldwide.
- To have a joined up approach to nuclear R&D.
- For the research base to be underpinned by world-leading facilities.
- To be a respected partner contributing to appropriate international research programmes
- To have the right level of nuclear innovation and R&D to ensure near-term commercial success in domestic and global markets.
- For industry to be supported by a workforce with the skills, capability and capacity required to successfully deliver current and future UK nuclear programmes.

In response to the requirement to be a partner of choice on SMRs and to develop a roadmap Ministers asked for a workshop, led by Dame Sue Ion to be convened with the organisations in the UK that the Department for Business, Innovation and Skills (BIS) knew to be principally interested in this agenda. This workshop was convened in December 2013.

The workshop found that there was a lack of evidence to inform a robust investment case in this area. The workshop recommended that further work should be conducted, by way of a feasibility study, to draw together the evidence in order to form a view. The study would particularly investigate whether SMRs would reduce the cost of nuclear power generation, and therefore electricity in the UK, whether - and in which areas - UK industry might have a role, the size of the market opportunity, the role innovation might play and the technologies best-suited to a UK partnership, and market applications.

The consortium commissioned to undertake the feasibility study included representatives from the National Nuclear Laboratory (NNL), Amec, Atkins, KPMG, Lloyds Register, NAMRC, Rolls-Royce, and The University of Manchester; Gordon Waddington was asked to act as an independent Project Director.

The terms of reference for the study required a focus on technologies that are deployable within a 10 year timeframe. Five packages of work were defined:

- Global market assessment
- Technical assessment
- Investment in innovation
- Financial assessment (including cost reduction assessment)
- UK commercial opportunity assessment,

There were deemed to be two overriding requirements for SMRs to be developed in partnership with the UK: nuclear power at a competitive price, and long-term industrial capability within the nuclear sector. This latter point was only seen to be achievable if IP could be created and owned by UK companies. The consortium took an open-minded approach to the nature and extent of the IP and all parties believed that acquiring the IP would require investment and could not solely be obtained by acquisition, as it is considered critical that capability would need to be held by the UK nuclear workforce.

2 Global Market Assessment

2.1 Introduction to methodology

This market study is the product of a collaborative effort between market analysts and technical experts across a range of parties interested in the future development of the UK nuclear industry. The analysis that follows is a conservative projection of the possible future market size for SMR technology in nations that are, or may in due course, be amenable to SMR deployment. It excludes the markets for heating and desalination, which, in some parts of the world, may make the market significantly larger. These markets are briefly discussed in this section, with an outline of the challenges faced in evaluating their potential size.

This market analysis is SMR-technology agnostic. Firstly, a list of nations that are amenable for SMR deployment was determined. These nations were then characterised in further detail including an analysis presentation of potential installed SMR capacity (GWe) in 2025 and 2035. A qualitative evaluation of potential drivers and barriers of SMR deployment in each nation is also presented; recognising that many different drivers and barriers affect different parts of the world.

In order to conduct such an analysis, a number of fundamental assumptions were made:

- Globally, nuclear energy will continue to play an important role in primary electricity production and mitigation of carbon emissions. This report assumes large and small nuclear power retains a 12.5% share of global primary electricity production through to 2035 (a 'no relative growth' scenario based on the IEA 'Current Policies' scenario). It is assumed that as old power plants are taken off-grid they are replaced with power plants in keeping with IEA future installed capacity predictions.
- In one of the two examined scenarios it is assumed that SMR technology can be developed and engineered such that it is cost-competitive for use in primary electricity production. This is supported by the financial analysis.
- Developmental, technical, regulatory and financing barriers can be overcome to enable deployment of SMR technology internationally on a significant commercial scale.
- SMR technology is considered to be complimentary to large-scale nuclear power, and would largely occupy sites, or caters to geographies, where large plants would not be suitable.

It is also important to recognise that only one SMR technology is ready to be commercially deployed, a Russian developed barge mounted reactor. Other systems are in development; although some technologies are more mature than others (as is described in later sections of this report).

As with all work of this type, projecting demand for electricity, and in turn nuclear-based electricity, must be considered in the context of market sensitivity towards political, economic, social and technological change. The projections contained within this report are based on current best estimates generated through analysis of extensive studies published by organisations such as the International Energy Agency (IEA), United States Energy Information Administration (US EIA), Organisation for Economic Co-operation and Development (OECD) and the World Bank; all of which are publicly available. Projections beyond 2035 are not made within this report; data for such projections is difficult to source and projections so far into the future are not deemed to be sufficiently reliable or accurate. It should be noted that unanticipated global economic shocks, such as global financial recession, are not accounted for in these projections. Table 1 showing the various drivers considered (and metrics used) is shown below. Steps 1-5 were used to create the 'shortlist' of nations to be studied in further detail (as they were deemed to be most amenable to SMR deployment in the time to 2035). Steps 6-15 were used to project the potential size of the grid electricity market that is feasible in the 2020 and 2035 time frame for each of these nations.

Step #	Driver	Metric (data from IEA/World Bank/CIA Factbook)
1	High per capita demand combined with high population drives requirement for more electricity	Population growth rate vs. per capita energy consumption analysis
2	Purchasing power (national)	Gross Domestic Product must be high enough to suggest nation state can afford a nuclear power programme
3	Energy Security	Percentage of current electricity generation from indigenous fossil reserves. Years of remaining indigenous fossil reserves
4	International Non-Proliferation	Treaty signatories
5	Failed States Index	‘Alert’ level ruled out
6	SMR size vs large plant size on a small grid	40% limit of single plant on grid used. This is higher than normal but accounts for ‘brown-out’ possibility which is common in much of the world
7	20 year per capita energy consumption growth rate (extrapolation to 2035)	A basic linear regression of World Bank data sets is used
8	Energy Imports	% of electricity from energy imports
9	Education	% of workforce who have received tertiary (university) education
10	R&D Spend	% of GDP spent on research and development
11	Researchers per million population	Number of researchers (all disciplines) per million population
12	Nuclear power sees continued usage	12.5% (IEA) nuclear baseline combined with CIA Factbook and IEA 2035 grid installed capacity extrapolation
13	SMR parity	SMR can be cost competitive / attractive compared to large nuclear plants
14	Local geographic drivers	Specific drivers within individual nations
15	Competition / Energy Mix	Inferred geo-political, trade and technology transfer relationships in 2035 (this is very approximate and examples shown later are intended to be illustrative only)

Table 1 - Selection criteria for shortlisted nations (drivers and metrics).

Several new SMR designs (e.g. U-Battery), due to their limited electrical capacity, are not seen to be as well suited to primary electricity production. In these cases, the target market is potentially different to that discussed in this report. These novel, niche or alternative applications (such as off-grid site power, industrial process heat-production, district heating and desalination) present additional market opportunity, above and beyond that which is presented. As such, this report is conservative in terms of outlining a possible market size, with considerable space for further market potential.

Evaluating the size of these alternative markets is challenging, for a variety of reasons:

Off-grid site power and industrial process heat-production are both linked closely to the number of amenable industrial sites that require large amounts of electricity or process heat. The only way to do a reasonable logical analysis of this potential market is to do a site-by-site analysis of the world's industrial facilities. Additionally, this analysis would need to be based on projections for the existence of such facilities in the future timeframe to 2035. The availability of data to support such an analysis is very poor and therefore drawing conclusions about this market is challenging at the current time.

District heating is often cited as a viable market for small nuclear power plants, with proponents coupling the smaller size of the plant to a perceived ability to distribute multiple plants around semi-urban areas in support of a domestic heat network. The challenge in evaluating the future market for such an application is around two major issues; firstly, what is the likelihood of mass population (and political) adoption of nuclear distributed heat networks? Secondly, establishing the infrastructure for district heating networks is likely to be a barrier to adoption. However the long-term use of excess heat from power stations, established first and foremost to provide base load power, can reasonably be expected as part of an economy where a strategic objective is reduction of the carbon footprint.

Desalination demand is likely to be driven by population growth and additional water demand from intensive agriculture and industrial process requirements. Such demand increases take place in the timeframe to 2035 where many scientists are predicting significant climate change that may disrupt the level of rainfall received in many areas of the world. An industrial desalination capability that allows for reliable control of fresh water supply is likely to be desirable to many nations, particularly those already predicting a shortfall in fresh water capacity. The UN World Water Development Report (2014) and the European Environment Agency both suggest that 'business-as-usual' approaches to the provision of fresh water will not be sufficient in the time to 2030. This applies to both developed and developing nations. The European Environment Agency predicts a deficit of around 3000 billion cubic metres of fresh water in the EU in 2030 (around 40% of the projected total demand), driven largely by increased demand from intensive agriculture (based on analysis of European agriculture production data by the International Food Policy Research Institute, 2010). This situation is likely to be mirrored globally according to UN projections. As such, it seems likely that there is the possibility for a substantial market for industrial desalination technology and this could allow for a substantial (£100bn +) global market for SMR based desalination. The greatest degrees of uncertainty around this figure are the potential reduction in available supply from climate change and the availability of competing non-nuclear desalination technologies.

With the significant uncertainties associated with these markets, in mind, this report presents a conservative baseline market size based on grid electricity production in niche markets that are more amenable to SMR deployment. Two baseline scenarios are considered:

The two scenarios are:

- Scenario A – SMR niche, where SMR technology is not considered cost-competitive with large scale nuclear plants and is therefore only considered in geographies where a large plant would be unsuitable.

- Scenario B – SMR parity, where SMR technology is considered cost-competitive with large-scale nuclear plants and both are deployed. In this scenario, 'bottom-up' estimates have been generated for the USA, Russia and China (as 'top-down' analysis of IEA projections showed these nations to be the largest national markets). For other nations, the rate of deployment across USA, Russia and China is extrapolated to provide a global figure. The UK market analysis is highly dependent on the availability of suitable sites and hence within Scenario B three possible outcomes are projected.

The figures presented for each scenario are representative of the total grid electricity market potential within a given region or nation. It seems likely that a small number of technologies will reach maturity and compete in an international SMR market, mirroring the current situation with large nuclear plants.

2.2 Scenarios

Scenario A – SMR Niche

In this baseline scenario it is assumed that SMRs do not become economically competitive when compared against large nuclear plants and only niche deployment of SMRs takes place. This niche deployment is defined as '*deployment on electricity grids where a single large nuclear reactor would be considered too big when compared to the total grid size*'. The IAEA defines this limit as '*no single nuclear reactor being more than 10% of total grid size*' (in terms of electrical power installed capacity). Whilst this may be the case in some developed nations, it is not the norm in other parts of the world and it is important that a broader international perspective should be taken.

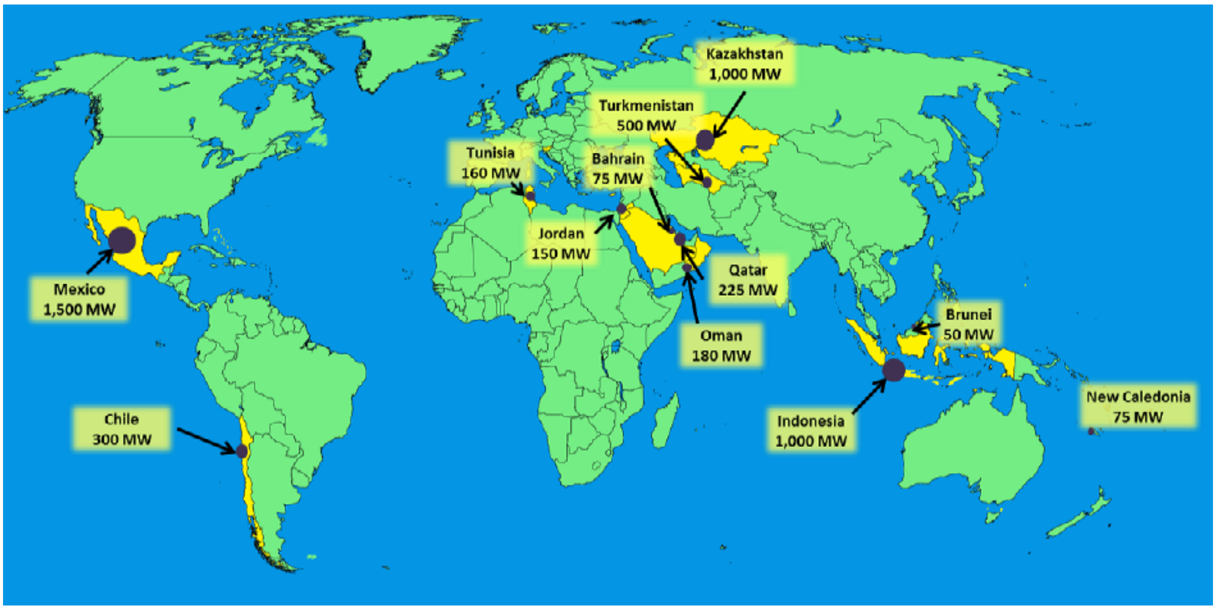


Figure 2 - Global markets for SMR in Scenario A

The market capacity for Scenario A is generated from a combination of top-down analysis of total power demand and installed capacity figures, and a bottom up appraisal of future market opportunities and potential SMR locations.

Additional factors may also play a significant role if Scenario A transpires. In some of the nations considered in Scenario A, it is assumed that extensive international collaboration is brought to bear in order to allow for a nuclear regulatory environment in the host nation because it is not currently a nuclear nation. There is some precedent for doing this in relatively high GDP nations (United Arab Emirates has recently been through such a process) but it may be more challenging for this to occur in low GDP nations. Whilst this effect is also noted in Scenario B, it is likely to exert relatively greater influence over the potential magnitude of projected installed capacity in Scenario A.

Scenario A finds that if SMRs are not considered cost-competitive with large nuclear plants, then the global market for niche nuclear electricity production, that only SMRs can serve, requires approximately 5.2GW of installed SMR capacity in 2035 (with a potential undiscounted total value of approximately £20-25bn in 2012[1] terms). As previously stated this does not take into account SMR niche markets such as remote off-grid power, desalination, process heat production or combined heat and power (CHP).

A number of countries with relatively small electricity grids have previously had nuclear power plants (e.g. Slovenia which had an installed capacity of 3,193MWe in 2010 (IEA, 2013)). This is partly due to the smaller power output of older nuclear plants (often in the region 400-700MWe) and partly due to the ability of some nations with smaller grids to share power production (this is the case in Slovenia which shares power from the 696MWe Krsko nuclear power plant with Croatia). Nations with established grid infrastructure (or plans to install significant grid infrastructure in the 2020-2035 timeframe) are therefore not considered within this scenario.

In some nations (particularly large nations such as the USA or Brazil) the cost of installing or upgrading grid infrastructure may play a significant role in choosing between a series of SMRs or a single large plant with a wider grid network. Estimates for the cost of installing grid infrastructure vary significant based on the type of grid being installed, the geography of the terrain in which it exists and local economic factors (such as capability or labour rates). As such, an in depth investigation of the cost of grid infrastructure is beyond the scope of this report but this may have a significant effect on the final size of the SMR market.

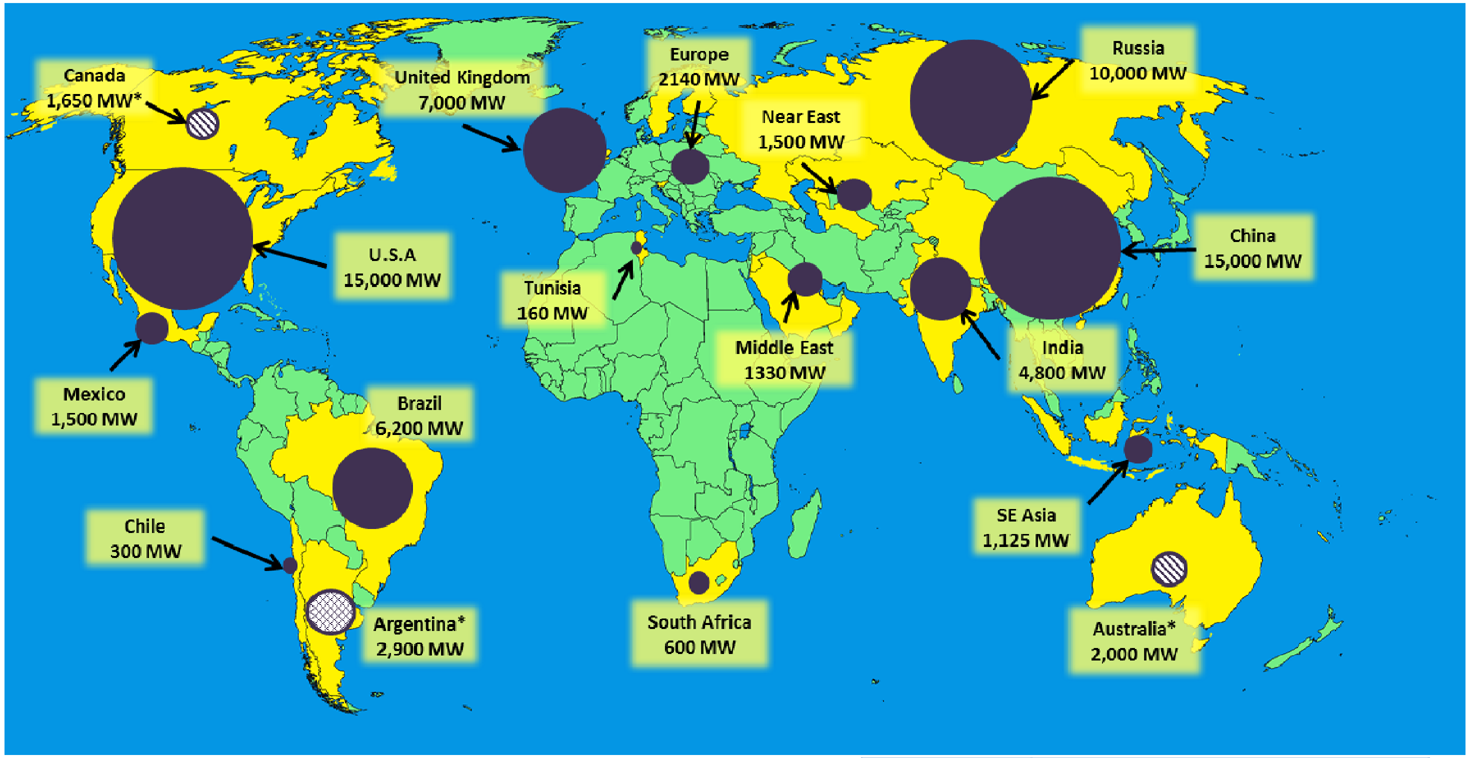
Scenario B – SMR Parity

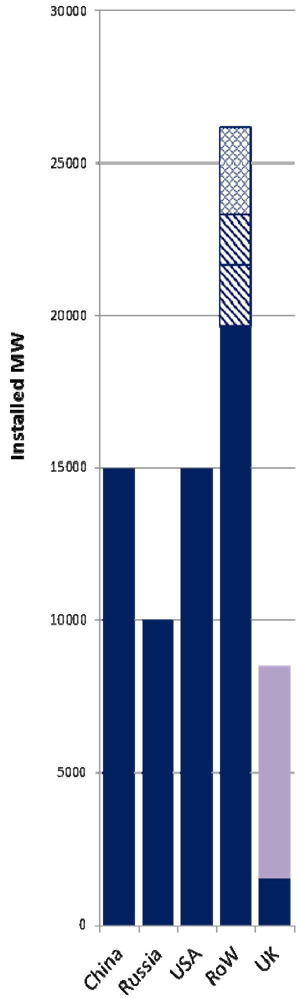
In Scenario B the assumption is made that SMR technology is cost-competitive with large nuclear power plants across a global range of sites. Large nuclear plant replacement markets are considered in the 2035 timeframe (as most existing nuclear plants in the world are due to be retired before this date). Whilst it is possible that some existing nuclear plants will see life extensions beyond the 2035 timeframe, the overwhelming majority of current nuclear plants (as of 2010) will require replacement by around 2035-40. No nuclear replacement market is included for the 2025 projection.

This study projects that the global SMR market to 2035 for electricity production will be 65-85GW of installed capacity (with an undiscounted market value of £250-400bn+ [1)]. These alternative markets may enhance the total market significantly, particularly in the Middle East.

A key finding of Scenario B is that the global market is likely to be dominated by three current 'nuclear nations', each of which has their own SMR development programmes; USA, China, and Russia. It is likely that if UK industry enters into partnership, collaboration or support of one of these other countries, then the SMR market opportunity in the other two may be reduced. This would mean that only 60-70% of the total global market could ever be available to UK industry. It is also highly likely that this will ultimately be an internationally competitive market with a number of different SMRs available. However the advantage of being an early adopter is likely to be significant. This early-adopter effect is driven by the volume production of SMRs compared to the low numbers of large plants seen to date. Once a given SMR technology reaches maturity it may be able to win orders in a large number of nations. Though other SMR technologies may reach maturity before these orders are fulfilled, the opportunity to bid to win the contracts will already have passed and they will be locked out of the market. This effect is not seen with large nuclear plants due to the low number of plant opportunities open for bidding at a given time (though some Generation III plants which have been developed have been unsuccessful in achieving any market penetration such as General Electric's ESBWR and Mitsubishi Heavy Industries' APWR).

[1] See Financial of the report - section 5.5





Region	Nation	Market Potential (2035)
Europe	Finland Lithuania Slovenia Sweden	1,320 MW 400 MW 150 MW 270 MW
Middle East	Bahrain Jordan Oman Qatar Saudi Arabia	75 MW 150 MW 180 MW 225 MW 700 MW

Region	Nation	Market Potential (2035)
SE Asia	Brunei Indonesia New Caledonia	50 MW 1,000 MW 75 MW
Near East	Kazakhstan Turkmenistan	1,000 MW 500 MW

**United Kingdom	1,520 MW based on current policy scenario. 21,000 MW based on ETI ESME model projections for optimised cost of future electricity with large nuclear site limitations
*Argentina	May not be accessible due to nationalised energy sector and indigenous technology (CAREM)
*Canada	Currently a moratorium on new nuclear build
*Australia	Currently a moratorium on new nuclear build

Figure 3 - Global SMR market in 2035 (Scenario B)

The baseline figure projected for UK deployment is relatively modest, approx. 1500MW. This is based on a ‘current policies’ scenario where no specific provision is made to enhance the case for deployment of SMR and energy policy remains focussed around large-scale nuclear power. Projections for future energy mix generated by the ETI and UCL suggest that there may be a significantly larger market for SMR in the UK if future energy policy is shaped to take account of novel SMR technologies. ETI modelling using the ESME tool suggests that in the 2035 timeframe around 40 GW of nuclear power on the UK grid would lead to the lowest overall cost of electricity. The UK currently has 8 approved sites for new nuclear power with a potential maximum capacity of ~19GW. If there is a future requirement for 40GW of power from New Nuclear the remaining 21GW will have to be on additional sites. The number of sites suitable for large reactors may be limited and this issue is the subject of a separate ETI study. However if sufficient sites cannot be found this issue may necessitate the requirement to try and identify places where smaller (SMR) power plants would work, e.g. along the major UK rivers. The requirement for UK power from SMRs can therefore be bracketed between 1.5GW (using only the limited space on existing defined sites) and 21GW (where no other suitable sites are found for large reactors) A conservative mid point of 7GW has therefore been used for the remainder of the analysis.

A mid-range estimate of around 7 GW of SMR installed capacity potential in the UK in 2035 is assumed in this report. This estimate is based on reduced exploitation of SMR technology in the UK. In the 7 GW scenario, SMR deployment is limited to current nuclear licensed sites (approx. 4 GW alongside existing or future large plants in some cases) and limited deployment (approx. 3 GW) at government owned sites (e.g. former military sites). Predicting the availability of future sites available or amenable to large or small nuclear plants (in the 2035 timeframe) is beyond the scope of this report; as such this scenario is intended to be an indicative estimate only.

It is important to consider that different market forces act within different nations. The US market is largely a replacement market (where small aging coal fired power stations are potentially replaced with SMRs). Since 2000 shale gas has gone from 1% of US natural gas production to over 20% today. The US Energy Information Administration (EIA) predicts that by 2035 shale gas will constitute over 45% of the US gas supply, and predicts that the retiring coal and nuclear capacity will be replaced predominantly by natural gas-fired combined cycle units “because of their low fuel prices and relatively moderate capital costs”[2]. This today has suppressed the immediate demand for SMRs in the USA, even though shale gas is still a CO_2 producing energy supply source. The US potential demand over the next 20 years for more nuclear power has a very high degree of variability. The US predicted demand for 15GW needs to be seen in this light. This figure is perceived to be neither conservative or optimistic as some factors (e.g. lack of gas infrastructure, financing cost, greenhouse gas emissions) may enhance the case for a larger market whilst other factors (availability of shale gas, slow implementation of greenhouse gas emission regulation) may reduce the size of the market. Note - The US DOE estimate is that domestic output from SMRs for the US could be as high as 50GW by 2035.

China and Russia are growth markets, where rural populations and industry need reliable electricity, fuelling growth and an uplift in standards of living. SMRs have an advantage over gas in these rural markets, as they do not require additional fuel pipeline and storage infrastructure to be established over many thousands of kilometres. It is likely that nations with indigenous SMR programmes would be launch markets for their own technology, with ‘non-developer’ nations being considered as growth markets once SMR technology has been proven.

Analysis is also required to understand asymmetry in export potential between countries where design and manufacture of nuclear technology is high or low cost. Such asymmetry may limit the options available for internationally collaborative SMR programmes.

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[2] Page IF-36, ‘Annual Energy Outlook 2014 with Projections to 2040’, US Energy Information Administration, April 2014

With the aforementioned market dynamics in mind, it is difficult to see how an indigenous UK SMR design could achieve significant global penetration of the market for grid electricity without first mover advantage or international collaboration. The same market dynamics may impede a UK SMR designed for alternative purposes, such as desalination or industrial process heat.

Further investigations should be carried out to map each SMR technology against the respective potential global market (for grid electricity as described in this report, as well as for desalination and industrial process heat). Such analysis will provide a steer towards how the UK can benefit most from collaboration with technology partners, should it choose to pursue a collaborative route forward.

The total market potential is shown in Table 2.

2025		***2035***	
USA	7.5 GW	USA	15 GW
Russia	5 GW	Russia	10 GW
China	2.5 GW	China	15 GW
Scenario A nations	0 GW	Scenario A nations	5 GW
Other nations	~5 GW	Other nations	~20 GW
UK	0-1.5 GW	UK	7 GW - 21 GW**
TOTAL	**20-21.5 GW**	**TOTAL**	**70 GW / 85 GW***

Table 2 - Projected SMR Market Capacity – Scenario B

* Mid-point figure for the UK based on SMR deployment alongside existing/future plants at currently licensed nuclear sites (approx. 4GW), plus a small number (approx. 3 GW) of additional SMR deployment at government owned (e.g. former military) sites

** Expanded figure for UK based on ETI projections using the ESME model to understand greater role for nuclear in future lowest cost energy mix

For the UK, USA, Russia and China estimates have been generated based on potential scenarios for SMR deployment. The UK is potentially a mid sized market with larger potential. The USA market, based around small coal power stations is still thought to be significant in spite of the rise of shale gas, in Russia and China the markets are expanding to aid rural development and remote industrial support.

For the other nations in this study, a top down analysis of IEA future installed electrical power capacity and demand figures was conducted. The IEA figures for levels of projected nuclear power generation in 2035 were cross-referenced against other figures produced by the OECD, World Nuclear Association and various other national bodies. Specific projections for SMR capacity do not exist, however comparison between the analyses conducted for USA, Russia and China and the top-down projections for these nations yields an averaged figure for SMR take-up to 2035 of around 20%[3] compared to the total potential nuclear market in those nations.

[3] USA approx. 15 GW SMR to 100 GW nuclear (15%) Russia approx. 10 GW SMR to 45 GW nuclear (22%), China approx. 15 GW SMR to 125 GW nuclear (12%).

There is some potential for SMR deployment in India, as it is likely that in such a large nation sites and locations that require power will exist, that are not suited to large nuclear plants or other forms of electricity generation. There is also the potential for a significant Indian market for nuclear-based desalination and industrial process heat; as previously stated these two markets have not been considered in this report.

It should be recognized that a number of SMR technologies are nearing maturity and therefore it is likely that there will be competition within the SMR market space between SMRs of different design. This may limit the total accessible market if UK industry capability and relationships are more aligned with one design or technology over another. All of the scenarios portrayed below assume that SMRs will be successfully developed and/or be ready to be deployed in the short-medium term. For 2025 figures, it is likely that any given SMR design would need to be finalised by around 2022 at the latest, and for 2035, the completion date shifts to around 2030. This would then allow time for a licensing process to take place. The figures for installed capacity of SMR (Scenario B) in 2035 are presented in relation to total projected installed SMR capacity for each nation:

Country	Grid Size – total installed grid electricity capacity (MW, IEA projected 2035)	SMR installed capacity (MW, 2035, Scenario B)	SMR as % of grid size (2035, Scenario B)
China	3,205,366	15,000	0.47
United States	1,299,854	15,000	1.15
Russian Federation	375,097	10,000	2.6
United Kingdom	122,845	7,000	5.7
Brazil	226,771	6,200	2.73
India	793,567	4,800	0.6
Argentina	63,982	2,900	4.53
Australia	77,730	2,000	2.57
Canada	179,963	1,650	0.92
Mexico	109,467	1,500	1.37
Finland	21,927	1,320	6.02
Indonesia	52,451	1,000	1.91
Kazakhstan	30,729	1,000	3.25
Saudi Arabia	115,917	700	0.6
South Africa	99,660	600	0.6
Turkmenistan	4,679	500	10.69
Lithuania	5,022	400	7.97
Chile	28,620	300	1.05
Sweden	47,994	270	0.56
Qatar	11,563	225	1.95
Oman	9,149	180	1.97
Tunisia	8,223	160	1.95
Jordan	7,416	150	2.02
Slovenia	4,197	150	3.57
Bahrain	7,489	75	1
New Caledonia	656	75	11.43
Brunei Darussalam	1,794	50	2.79

Table 3 - Installed Capacity of SMR vs. total grid size

Top Down Analysis; Scenario Generation Method

The following section of this report outlines how the initial 'shortlist' of nations was arrived at. The steps are outlined in brief in the Table 4, followed by a more detailed description of each of the steps taken.

Step #	Driver	Metric (data from IEA/World Bank/CIA Factbook)
1	High per capita demand combined with high population drives requirement for more electricity	Population growth rate vs. per capita energy consumption analysis
2	Purchasing power (national)	Gross Domestic Product must be high enough to suggest nation state can afford a nuclear power programme
3	Energy Security	Percentage of current electricity generation from indigenous fossil reserves. Years of remaining indigenous fossil reserves
4	International Non-Proliferation	Treaty signatories
5	Failed States Index	'Alert' level ruled out

Table 4 - Shortlisted nations, selection drivers and metrics

Step 1 – Energy consumption per capital

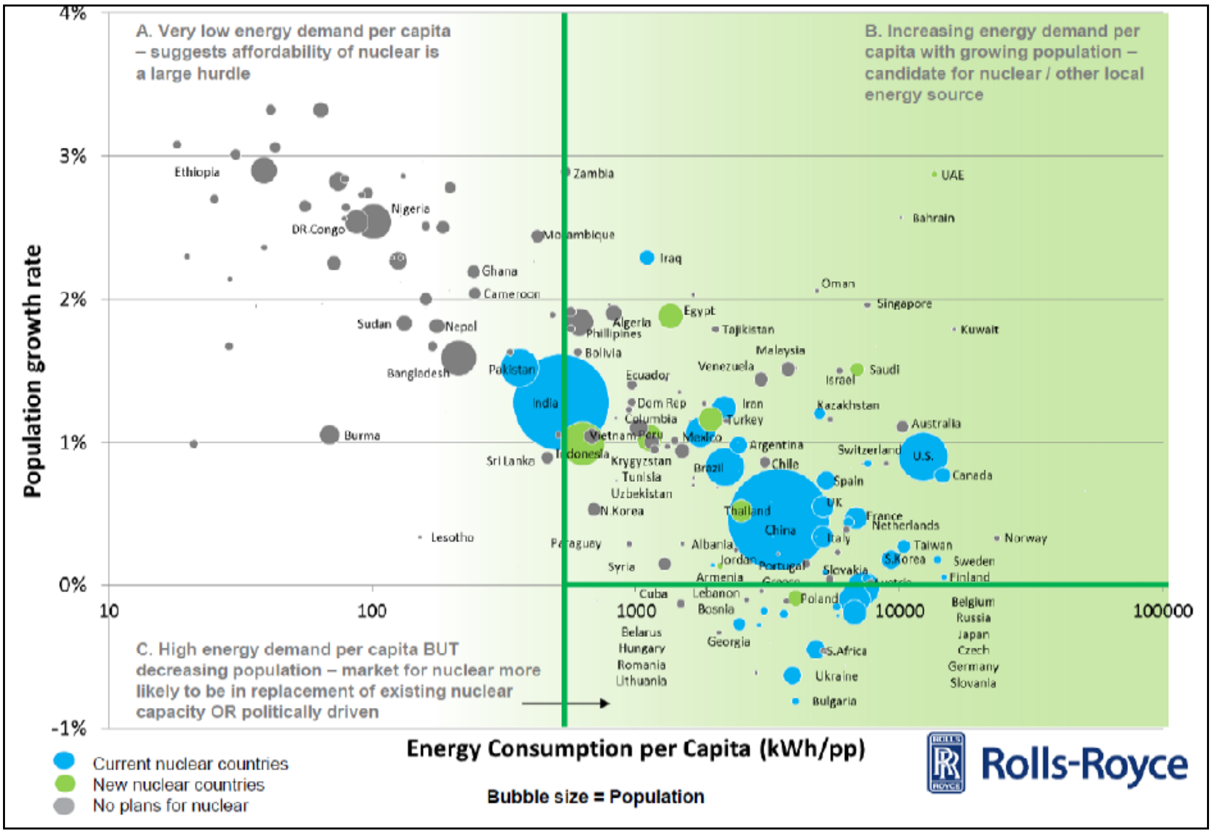

Figure 4 - Energy Consumption per Capita (kWh/pp) vs. Population Growth Rate (annual %) with overall population size reflected through bubble size. (Data from CIA Factbook, 2013)

Future demand for electricity is likely to come from countries with high population growth rates and high energy consumption. A key aspect of any large infrastructure project is the availability of capital or financing to procure the asset in question.

Step 2 – Purchasing power

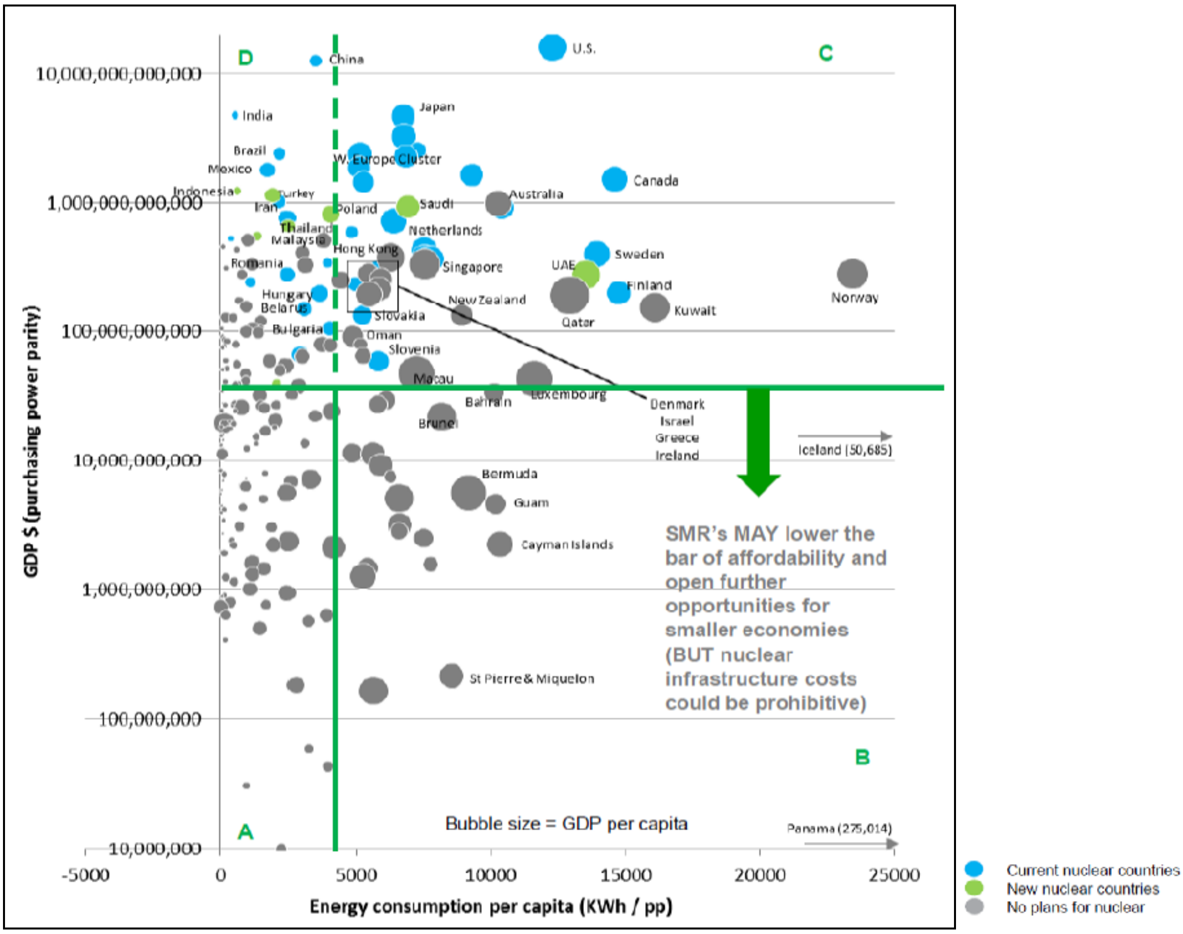

Figure 5 - Energy consumption per capita (kWh/per person) vs GDP (US $) where Bubble Size reflects GDP per Capita. (Data from CIA Factbook, 2013)

In Figure 5 countries in band 'A' tend towards energy poverty and are not considered to be viable target markets for nuclear energy. Countries in band 'B' are also not considered likely for large scale nuclear deployment, but some countries with high GDP per Capita may be suitable for limited deployment of SMRs. Many of the countries in band 'C' are existing nuclear nations, and future reactor deployment (both large and SMR) is considered likely. Some countries in band 'D' are existing nuclear countries. This is usually because they are former Soviet Union nations or countries where overall wealth is concentrated. Other countries in band 'D' also exhibit the potential for substantial future growth, as they currently exhibit low energy consumption per capita but have significant wealth.

An important factor in determining energy policy is the security provided by different means of supply. Countries with large indigenous resources of fossil fuels are currently well placed, though increasingly a drive towards reducing greenhouse gas emissions is placing some pressure on historical fossil fuel based power generation technologies. It is likely that nuclear power will be attractive to countries with low indigenous fossil fuel reserves, as it provides a means to de-couple the cost of energy production from the fluctuating cost and availability of fossil fuels.

Step 3 – Energy security

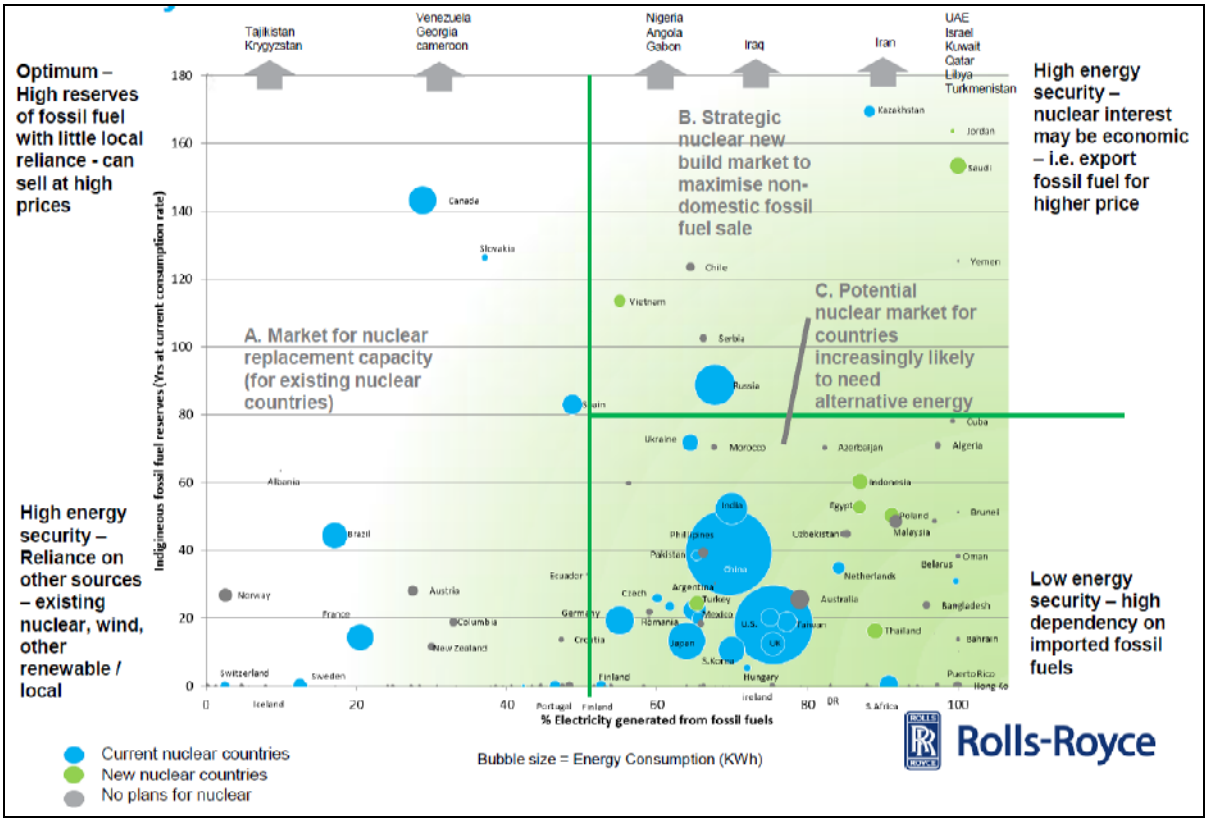

Figure 6 - Percentage of electricity generated from fossil fuels vs. Indigenous fossil fuel reserves where Bubble Size reflects total energy consumption in 2010 (kWh). (Data from CIA Factbook, 2013)

Countries that occupy the lower right quadrant of Figure 6 are likely to seek alternatives to large-scale fossil fuel deployment in the future as the availability of fossil fuel supplies (and their associated cost) remains variable. Countries in the upper right may decide in the future to make a strategic choice to export their fossil fuel reserves and would therefore require alternative energy generation technologies (such as nuclear).

A second aspect of energy security can be mapped through understanding nations and regions of the world where electricity is imported directly into the country.

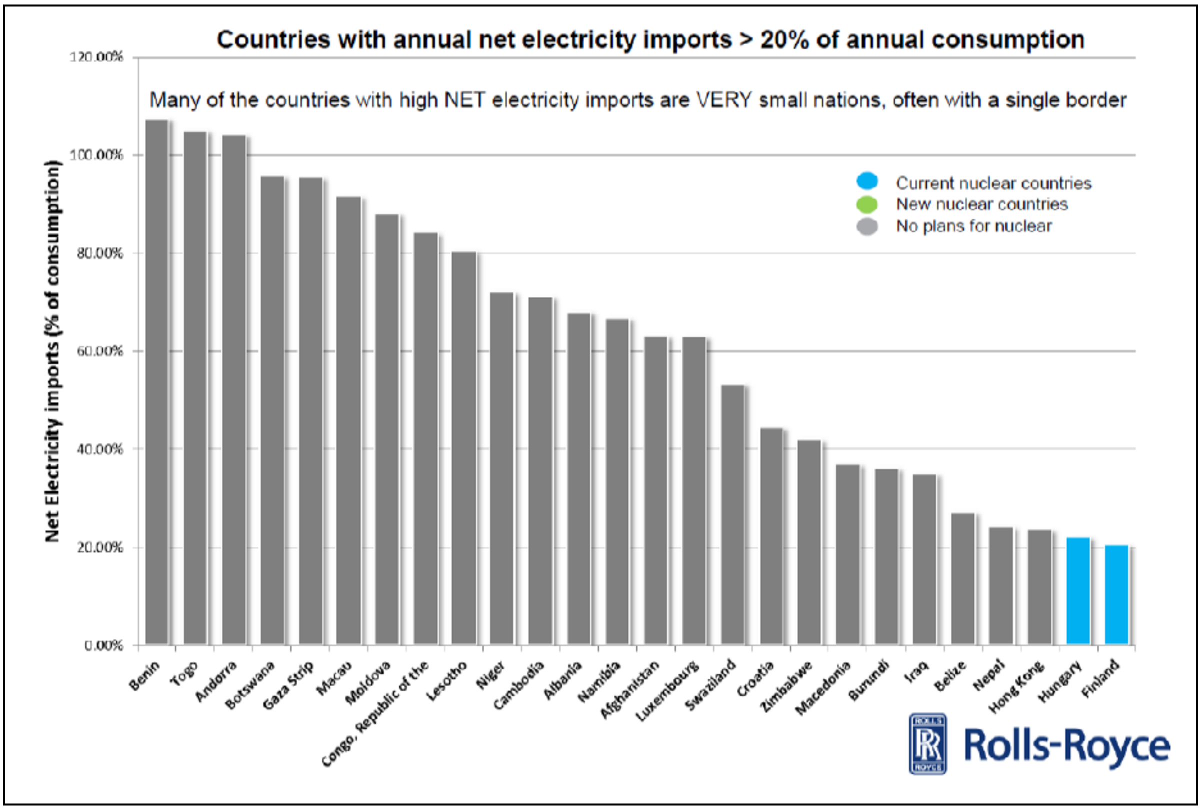

Figure 7 - Nations with net electricity imports > 20% annual consumption. (Data from CIA Factbook, 2013)

As is demonstrated in Figure 7 many of the nations that import large quantities of electricity are in the lower quartile of developmental metrics (e.g. Togo, Lesotho) or are very small (e.g. Hong Kong, Luxembourg).

Step 4 – International non-proliferation

As of August 2014, there are 33 nations that either currently, or have previously, operated nuclear power plants for purpose of electricity production. The operation of nuclear plants in a safe and reliable way requires considerable technical capability and financial investment. Not every nation has the resources available to achieve this, and such an endeavour is subject to widespread national and international scrutiny. Most current nuclear nations are party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which came into force in 1970 and was extended indefinitely in 1995. Currently, India, Israel, North Korea, Pakistan and South Sudan are not signatories of the NPT. Of these nations, India has by far the largest civil nuclear power generation programme. In recent years international collaboration with India around its civilian nuclear programme has opened up, with a number of countries signing memoranda of understanding or collaboration agreements. For the purposes of the rest of this review it has been assumed that one of the countries currently developing SMRs will be prepared to supply them to India, provided that India adds the SMR(s) to its list of nuclear facilities subject to IAEA safeguards.

Step 5 – Failed State Index

Beyond the NPT it is important to consider the stability, security and integrity of nations that UK organisations might deal with in deploying nuclear technologies overseas. The independent Fund For Peace organisation publishes a 'Failed States Index' that seeks to score each nation based on 12 different metrics to determine the stability of a given nation.

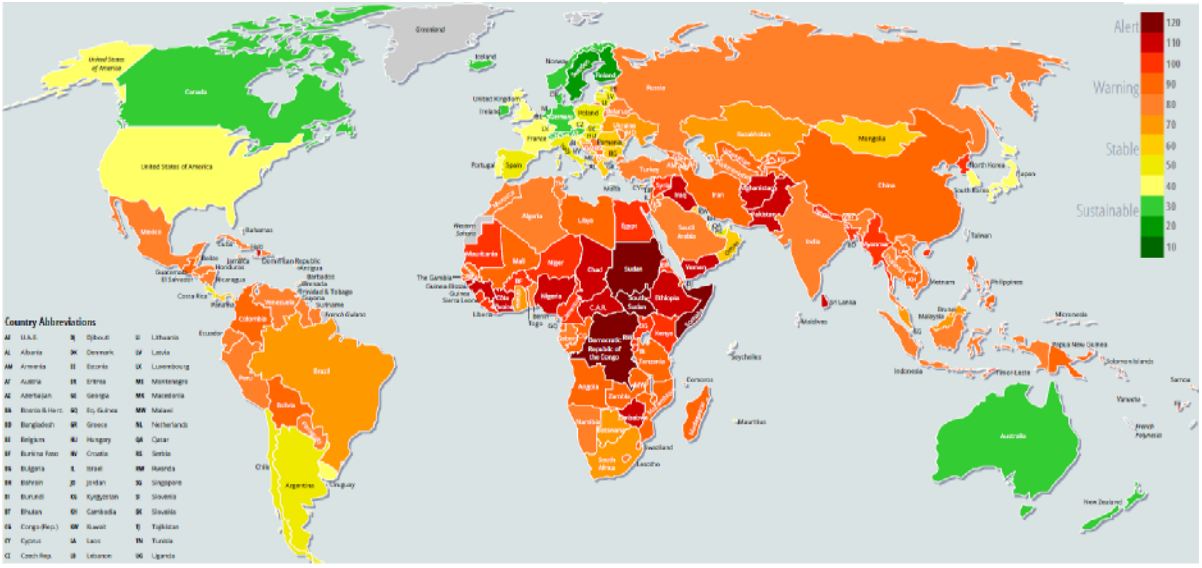

Figure 8 - Map of the world showing 2013 Failed States Index (red is high ranking implying low stability). (Fund For Peace Organisation 2013)

Defining a specific boundary for which nations could (and should) be considered viable for nuclear technology deployment is challenging. For the purpose of this analysis, nations that are displayed in the 'Alert' band are discounted as being too unstable for nuclear technology deployment.

Shortlisted Nations

As a result of the application of these steps, a short list of nations can be generated. These shortlisted nations are those that meet the various criteria discussed in the Scenario Generation Method;

Figure 9 - Nations shortlisted to be considered in Scenarios A, B of this report. (Macao will be considered within the China analysis as it is grid connected).

It is important to note that this is a very diverse set of nations. This diversity includes significant differences in energy market dynamics, from centralised government control through to liberalised 'free-market' approaches. Different levels of development, industrialisation, education, existing and planned infrastructure and growth opportunity are present. This can make comparisons at a global and regional level difficult, as establishing a 'fair' baseline for comparisons is not always readily achievable. Best effort has been made in this top down analysis to look at objective measures and present a 'facts and figures' analysis, however this does not necessarily capture some of the key nuances affecting the potential of different nations' abilities to host new nuclear power plants.

Several current nuclear nations are omitted from this list;

Japan: Japan is not considered a viable target market at this time for three combined reasons:

1. Following the Fukushima accident, it is difficult to imagine the Japanese public accepting SMR technology (i.e. a large number of additional nuclear plants) being located close to urban areas on new sites. This is compounded by the fact that;
2. Real-estate is at a premium in Japan due to its very high population density and urbanisation;
3. Japan has significant national grid infrastructure, which is suitable for the transmission of electricity generated from large nuclear plants.

France: France has long had a significant amount of large-scale nuclear generating capacity and it is likely that this will continue into the future. It is unlikely that a supplementary SMR market will be valuable in the short term. Additionally, it is unlikely that international companies would lead the deployment of SMR technology within France, as the indigenous French nuclear industry is in a dominant position within the French nuclear electricity generation market. Combined with this France has made a statement that they intend to reduce the nuclear generation mix from the current 80% to 50% making SMRs in the next ten years unlikely.

Germany: Germany is not included due to its current policy to move away from nuclear energy. This stance seems unlikely to change in the near/mid-term.

Eastern European nations do not feature, mainly due to electricity grid interconnectivity with the broader European community. This effectively increases the size of the overall electricity grid such that building and sharing large plants is a more viable option.

Against each scenario, steps 6 -15 were considered to see if they had any material effect on the estimated size of the potential for each of the countries.

2.3 Potential Partnering and Competition Effects

The analysis thus far has provided an absolute figure for the total market potential for grid electricity SMR deployment to 2035. However, there are multiple SMR designs under development across several nations and it is likely that several of these will reach maturity at a similar time (2015-2020). As such, any SMR technology will likely need to compete on the international stage with other SMR technologies. Additionally, different market access and dynamics evolve if the UK nuclear industry decides to 'go-it-alone' or partner with one or more international SMR developers.

The following sub-section presents a brief overview of two markets that might be realised by partnering with different SMR technology developers. This is intended to be indicative only, but clearly shows how decisions around partnering can have a significant effect on the size and location of markets being addressed.

A great number of assumptions are required to provide a representative outlook of possible partnering dynamics in 2035, particularly around international relations, development and trade. As such the information below is illustrative only.

<u>Example 1 – USA partner</u>

In this example it is assumed that UK industry partners with a reactor vendor based in the USA. This allows access to the large US and UK markets as well as a range of markets in Europe, the Americas and South-East Asia. The large markets in Russia and China are closed to the partners due to strong indigenous offerings dominating. Some of the global market is assumed to be lost to these exported alternative Russian and Chinese offerings. In the example shown in Figure 10 the accessible global market is evaluated to be 30-35 GW in 2035.

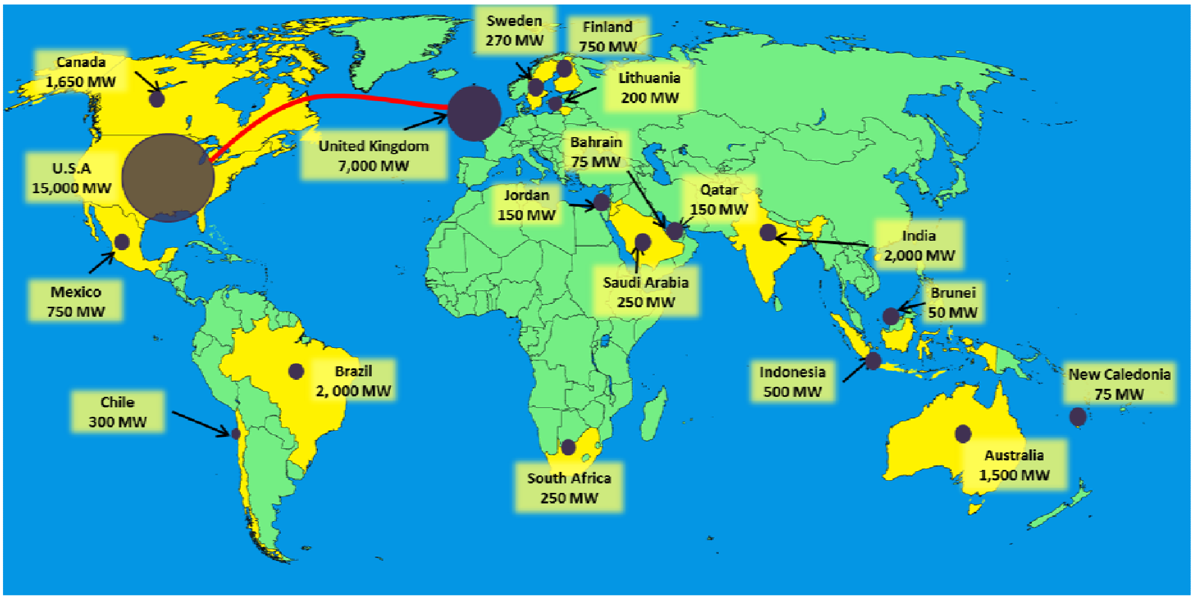

Figure 10 - Example 1 showing potential accessible global SMR market, if UK industry partners with US SMR vendors (illustrative only)

Example 2 – Chinese partner

The second example presented shows an alternative partnering dynamic whereby UK industry partners with a Chinese SMR vendor. In this situation the markets in the USA and Russia are ruled out (due to strong indigenous offerings) but the Chinese, UK, Asian, Middle-Eastern and some American markets are accessible. Again competition from US and Russian SMRs is assumed to be present and as such some of the accessible market sizes are reduced. In this example, Figure 11, the accessible global market is evaluated to again be 30 - 35GW in 2035.

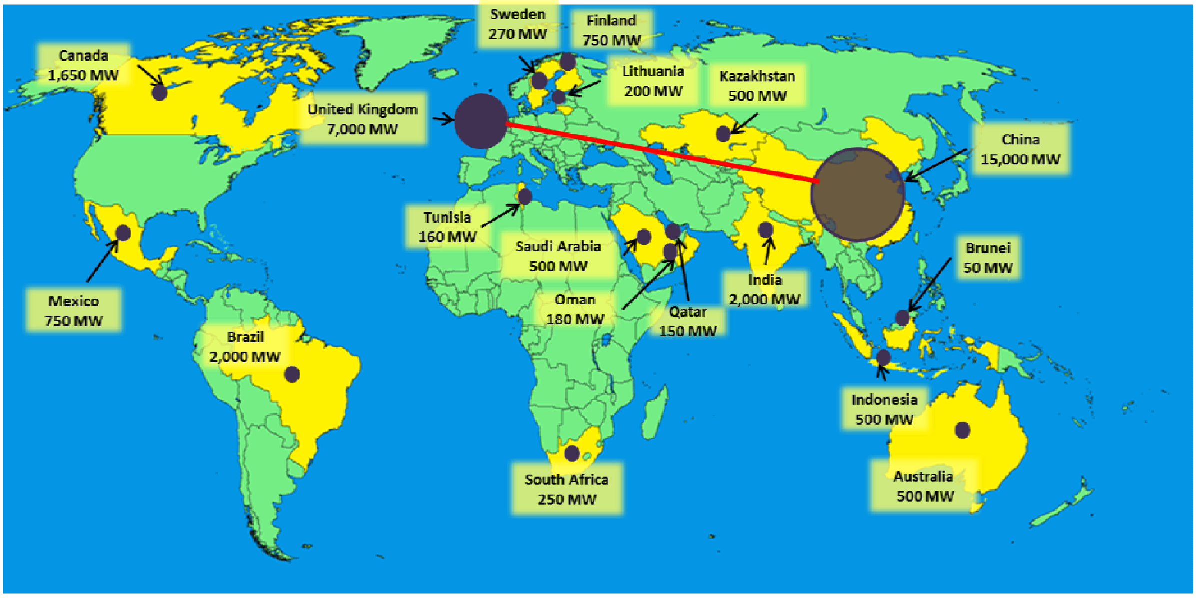

Figure 11 - Example 2 showing potential accessible global SMR market if UK industry partners with Chinese SMR vendors (illustrative only)

2.4 Conclusions

This report concludes that there is a plausible market for SMRs in the 2035 timeframe if the technology can be made cost-competitive in comparison to large nuclear plants. This market potential is projected to be in the region of 65-85 GW globally, with large markets in the USA, China, Russia and potentially the UK.

Understanding how different markets can be accessed by technologies developed by different nations is fundamental to understanding the market accessible to the UK. Competition, and partnering strategies, will likely reduce the size of the accessible market to somewhere in the region of 30-35GW by 2035. However partnering with another major SMR technology-developing country will give the UK access to a large proportion of the global market, which it would have to compete with if the UK attempted to develop an SMR technology on its own.

If SMRs are not cost-competitive with large nuclear plants then the total global market potential is significantly smaller, around 5GW in the 2035 timeframe. This suggests that any development of SMR technology must include significant efforts to ensure that cost-competitive manufacture and deployment of SMRs is achieved.

Analysis suggests that there is a window of opportunity in key international markets where SMR technology could fulfil a role. However, future gas, particularly shale gas has the potential to be a significant alternative power source.

At present, the overall market for SMRs has not been evaluated, as the markets for desalination and process-heat have not been included in this analysis. Access to these markets may be dependent on the SMR technology in question, and therefore future analysis will likely have to move away from the technology agnostic position taken with this report. Very early indications from a brief assessment of literature covering water demand suggests that the potential global market for cost-competitive and reliable fresh water production (desalination) technologies could be substantial (£100s bn) in the 2035 timeframe. SMRs that have been designed with this functionality could be an attractive proposition to fulfil this demand. As such, desalination may be an additional large market for SMRs.

District heating also presents an additional opportunity for amenable SMR technology. Questions remain around the public perception of such systems and the level of infrastructure required to transport heat 'to-the-home'. This study was unable to draw a conclusion as to the prospective size of this market. Industrial (off-grid) electricity and heat demand could be fulfilled by some SMR designs.

3 Technical review

3.1 Introduction to methodology

The technical review of prospective Small Modular Reactors has been undertaken in two parts,

- An initial review in January to March 2014 which focused on those reactor technologies that represented a credible technology option with estimated deployable in-service dates within a 10 year timeframe This list was then assessed further against a number of criteria including economic viability; the opportunity for IP and work for the UK Nuclear Supply Chain and wider issues for a nuclear partnership.

- A second, more in-depth review phase which considered only the reactors that met the initial criteria and included direct discussions with the vendor

The potential opportunity for a UK designed SMR concept was also considered.

3.2 Preliminary technology assessment

The initial review centred on the collation of knowledge and data to identify the potential nearer term technology offerings that should be explored. Prospective reactor technologies were appraised at a workshop against a broad set of assessment criteria, agreed by a cross industry and academic collaborative group.

The high level appraisal was based on available public information and allowed a coarse filter of the technologies, considering criteria related to:

- Technical maturity and viability
- Maturity of safety case and certification
- Key strengths and areas for development
- Programmes to address development needs
- Available resources – people, capability, facilities and funding
- Economic viability, including IP ownership.

This appraisal enabled a down-selection of promising technologies, for the purposes of this study, that covered a broad range of technology from different vendors across the globe, including reactors developed in the UK, France, US and China

Technologies that may be viable but that do not fit into the 10 year timeframe are discussed at the end of this section. Such technologies areas may represent future opportunities that although not mature enough to be part of the near term 10 year timeframe or considered as viable UK opportunities currently, may offer commercial advantage and step changes that may make them viable future technologies. It is worth considering further engagement as part of the longer term strategic plans.

On this basis, the technologies that were originally identified for further focused review were:

- ACP100+ - CNNC
- ANTARES - AREVA
- mPower – B&W and Bechtel
- Westinghouse SMR - Westinghouse
- NuScale - Fluor
- U-Battery - Urenco

In addition, as part of the review the gas cooled HTR –PM Chinese reactor was discussed during the initial China visit (see section 3.3 below).

The Korean SMART reactor was also considered: preliminary discussions indicated that there was relatively little design and development work required to bring this reactor to market. The lack of opportunity to participate in the development programme meant it was discounted from the feasibility study at this stage. If, in the development of Government policy, IP ownership and involvement in the development of the design is not considered as an important factor this reactor should also be assessed.

This range of technologies covers the more mature and well known Pressurised Water Reactor technology and also explores the status of identified leading High Temperature Gas Reactors, in order to understand the viability of these offerings to the UK. The Urenco U-battery concept is essentially a UK owned concept and targets a different design space and niche market as a very small reactor, so was included to understand the viability of this opportunity.

3.3 Detailed technology assessment

The next part of this review took the form of approaches to the reactor vendors identified, utilising a defined question set which originated from the initial workshop; these questions were derived from consideration of the key assessment criteria.

Cross industry assessment teams were assigned to review the reactor technologies, with the National Nuclear Laboratory (NNL) providing a consistent presence at all assessments. Face to face engagements and reviews were undertaken with all the identified vendors.

Preliminary vendor discussions

AREVA- Early engagement with AREVA confirmed that they are not at present pursuing High Temperature Gas Reactor technology towards a commercial SMR so the ANTARES reactor is not a near term option to pursue. This has been discounted by AREVA based on low power density and higher costs, making it unviable for the target SMR market. This technology therefore falls into the group of future technologies (which are appraised later in this section), and was, subsequent to the discussions, discounted from the leading near term group of viable technologies for the UK. However, AREVA did share details of a proposed Integral PWR SMR, which they indicated they were interested in developing. This was subsequently ruled out as discussions indicated that it was unlikely to be developed within the ten-year timeframe.

HTR-PM - The Chinese HTR-PM reactor is a mature design, based on a previous smaller demonstration unit. The design was identified as being a further demonstration reactor not ready for commercial application. It is part of a GenIV large reactor development programme. The opportunity for engagement is considered to be limited at the present time. This design is considered further in the future technologies section of the study and can be considered as part of longer-term strategic options.

The final list of SMRs that were assessed in more detail during this phase are summarised in the table below.

SMR	**Vendor / Developer and Country**	**Basic Description**
NuScale SMR	NuScale Power LLC (Fluor) - US	160MWth / 50MWe gross passive natural circulation Integral Pressurised Water Reactor modules, deployed as up to 12 modules per site (600MWe site nominal)
B&W mPower SMR	Generation mPower LLC (Joint venture between Babcock &Wilcox Company and Bechtel Power Corporation) - US	530MWth / 180MWe Integral Pressurised Water Reactor, deployed in up to 2 reactors per building (360MWe).
Westinghouse SMR	Westinghouse Electric Company – US	800MWth / 225MWe Integral Pressurised Water Reactor.
ACP100 SMR	China National Nuclear Corporation (CNNC) – China	310MWth/100MWe Pressurised Water Reactor.
AREVA SMR	AREVA - France	~150MWe Integral Pressurised Water Reactor concept. Parametric outline concept.
U-battery	Urenco – UK	2 x 10MWth High Temperature Gas Reactor modules, delivering 8MWe, utilising TRISO fuel and a helium/nitrogen Brayton cycle power conversion system

Table 5 - Selected SMRs with overview of technology

The next section outlines the key conclusions of the technology appraisal for each of the six SMRs.

NuScale SMR

The Nuscale SMR is based on a vision to deliver a simple design of reactor with passive improved safety functionality. They are backed by extensive NRC engagement and programmes of work funded by Fluor and a December 2013 US DoE award of $217M (approx £138M) over 5 years. The NuScale design was judged to be an innovative approach to passive safety.

The technology is judged as credible with a well developed conceptual design but there are still significant technical challenges. Some component parts were judged to be a relatively low TRL albeit there are development and testing programmes designed to address these. In terms of operation, there remain challenges as the model for this reactor is based on a configuration of 12 units installed, commissioned and operated sequentially. This needs further consideration to address the technical, regulatory and human performance issues.

There has been significant engagement with the US regulator with regard to licensing, and development of a supply chain to establish manufacturability of the key components.

Opportunities for UK involvement in the development may be time limited as NuScale are currently seeking global investors to support them through to a design certification application (2016), after which the scope for design change and resultant IP reduces. The US government financial support is in the form of a co-operative agreement between NuScale and the US DoE which gives the US government IP rights but may not preclude the involvement of another country or UK companies being involved in the development of the design.

The challenge for this design will be to maintain the simplicity of the overall engineering concept and demonstrate the economic case. This is a part of the FOAK (First of a Kind) engineering programme, representing a key opportunity.

B&W mPower SMR

The mPower integral PWR SMR (supported by Bechtel) has also had substantial DoE funding - $226M (approx £143M) DoE SMR award in December 2012, and is arguably one of the more mature SMRs globally. B&W have also engaged with the US regulator, but have little experience of licensing in the UK and the GDA process.

The technology is a more traditional integral PWR concept and has been assessed as viable but has FOAK technical challenges associated with internal configuration and component detailed design. Mid-TRL levels have been claimed for the majority of the components and a significant proportion of the Nuclear Steam Supply System (NSSS) design is complete. The design has a complexity associated with a higher component count; this may be an economic and technical challenge. Fully developed test programmes to underpin these challenges have been identified.

In early 2014 B&W announced that it was to scale back spending on the mPower SMR due to funding constraints. However, the relative maturity of the design and progress to date does suggest this is a viable opportunity to consider for the UK. The risks and opportunities are expected to be centred on detailed FOAK engineering challenges and the IP prospects for the UK. The scope for collaboration and UK engagement to support to B&W is unclear at this stage. This would need to be clarified before the UK opportunity could be completely evaluated, given the key requirement for stimulating and supporting capability, skills, and industry development. The maturity of the mPower design potentially reduces the overall programme risks.

Westinghouse SMR

The Westinghouse SMR concept is believed to be a mature concept however competing designs were successful in securing the 2012 and the 2013 competitions for DoE funding, resulting in limited progress on detailed design. The Westinghouse SMR is a more traditional integral PWR SMR based on largely proven technology and experience, with a relatively high power output of 225MWe which is considered to be a viable design. The reactor is fully integral design with internal Control Rod Drive Mechanisms (CRDMs), so faces similar challenges to mPower. The design has relatively few control rods with a resultant reduction in internal complexity. Much of the componentry is based on existing AP1000 designs, so comes with a degree of confidence. Westinghouse has a fully developed programme to address the challenges and has suggested this could include collaboration with a UK facility to undertake substantiating R&D. One area that has been suggested as a potential area for collaboration is the design of a modularisation methodology to support implementation and construction.

The forward development plan for this reactor is ready but awaiting a suitable funding mechanism. However it clearly represents a potentially viable technology, should a suitable investment vehicle be found. Westinghouse also has the complete capability to rapidly progress an SMR programme if the market opportunity was sufficiently attractive and funding was available, subject to the deployment of resource away from current larger plant development. Westinghouse already has an existing presence in the UK in the fuel-manufacturing sector.

Westinghouse knows the GDA licensing mechanism as a result of the AP1000 review. Westinghouse has also expressed a desire to collaborate, giving confidence that a partnering opportunity rather than just an equity investment was possible.

ACP100 /ACP100+

The ACP100 is a mature technology developed for the Chinese market. The opportunity for ACP100 engagement and IP potential is limited due to the maturity but CNNC did suggest that they were looking to develop an ACP100+, which would focus on delivering a more efficient, higher power design that was capable of being exported globally.

The ACP100+ represents a potentially attractive option for engagement for the UK in a new design programme and the Chinese appeared very open to collaboration. Further work would be required to understand the detailed intent for the ACP100+ and the opportunity the UK may be able to play in this collaboration and the wider access to market it would deliver. A Chinese collaborative opportunity represents a viable offering to explore further with the confidence of strong state support and a mature starting point in the ACP100. It is anticipated that the ACP100+ is a likely to be a significantly different design employing more integral reactor features and does therefore ultimately represent an immature starting point.

The practicalities of working with CNNC on a collaborative SMR design programme would also need to be thoroughly evaluated to understand the UK benefit of this opportunity further. In principle this could offer significant IP opportunities with a sustained funding stream and access to one of the largest markets in the world.

AREVA SMR

The Integral PWR presented was very high level. AREVA plan to engage with the "French Family" of AREVA, EDF, DCNS and CEA to progress SMR technology and apply for French government funding, in late 2014/early 2015. They would look to develop a programme to take the concept to basic design maturity, over a 3-4 year period, ready to consider licensing application and further detailed design.

With a very immature plant concept, the key to this proposition is not the current concept but the informed position on reactor design and application that AREVA have and the wider opportunity for Anglo-French engagement in an industry dominated by state backed development programmes. This option would initially require modest levels of investment from both sides to fund ongoing development, however would ultimately need a substantial ramp up in investment to take through the detailed design phase once the 3 year basic design was complete.

With the correct framework it could enable skills and capability development and a very credible partnership for production should the market emerge. Further detail on a collaboration framework would be required to understand the benefit of engagement and the IP opportunity. The progress of this would also be dependent on French funding in both the short and medium term.

Since the AREVA review further contact has indicated that AREVA will not be looking to develop SMR technology in the near future so this does not now represent a viable option to pursue at this time.

Urenco U-Battery

This concept is considered to be reasonably well developed in some areas, but as a total system, relatively immature, with some potential technical, licensing and economic challenges. The HTGR technology low power density limits power level for a given transportable size limit and this represents a challenge for the economics. The U-Battery is a micro reactor concept targeting a niche market around industrial power units and remote off-grid applications.

This concept fundamentally relies on the inherent safety associated with TRISO fuel containment preventing release of radioactive material. This not only reduces the need for additional safety systems, it can also potentially remove the need for an exclusion zone potentially allowing the reactor to be located directly adjacent to industrial units and populations. The concept has challenges associated with fuel integrity demonstration, helium management and economics, heat exchanger development and power conversion systems. The significant attraction of this opportunity is that it is a UK option and offers a very interesting alternative approach, but it would require a major development programme.

It was concluded that this technology is best placed in a future technologies category and should be considered by NIRAB as part of longer term programme, should HTGR technology be an area for development as part of the UK Nuclear strategy.

Development of a UK SMR (going it alone)

Development of a UK PWR SMR is an option that would enable the UK to develop a competitive SMR technology, based on prior PWR design expertise, developing key IP throughout the programme. This would provide the UK with the opportunity to directly influence the SMR market whilst developing the UK Nuclear capability. Over a 3-4 year period the UK could develop an SMR design to a basic design / prelim design level of maturity which would enable the UK to build and maintain capability to support a sustainable future in the nuclear industry whilst developing an exportable product that is fit for domestic and overseas markets. The UK has the skills and manufacturing capability to design a UK only reactor. This will also enable more direct exploitation of design, manufacturing and support opportunities for UK industry and allow more rigorous investment decisions to be taken as to market viability at that time. This would then position the UK more appropriately to either engage with others to apply the UK industry capability to develop and exploit opportunities or take the UK offering direct to market.

The challenges with this approach include:

- Significant investment (money and resources) would be required to deliver something from pre-concept to commercial deployment.
- Difficulty in realising a completely new design in the 10 year timeframe
- Access to the larger market opportunities globally, as countries with indigenous reactor programmes may not accept a UK offering which may limit the size of opportunity and a resultant inability to realise economy of multiples
- Poor prospect of being first or early to market

Comparison of SMR Options

As seen above the various SMRs all provide different offerings, as such it is difficult to provide direct comparisons between the options. A multi parameter appraisal, see figure below, of the main reactor concepts has been developed to represent pictorially which option could provide most viable opportunity for the UK, providing relative scorings on a 1-5 basis (5 being most favourable), against the following criteria :

1. Technical maturity
2. Regulatory progress (relevant to UK)
3. Technical viability (acceptable level of risk)
4. Programme viability (maturity of existing plans and support / resources)
5. Economic viability
6. IP Opportunity
7. Collaborative opportunity

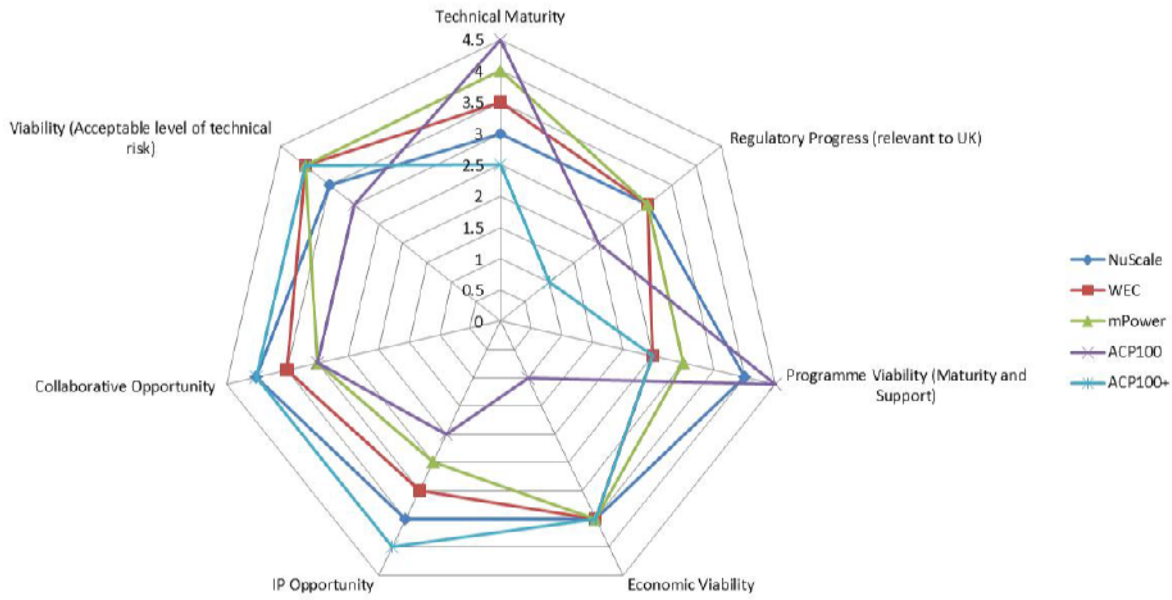

Figure 12 - Comparison of selected SMRs

A key conclusion to draw from this is that the recommendation and selection of the most appropriate technology is complex and depends on what proposition is being sought. Depending on whether the aim is to select the technology that is least risky, most mature and nearest to market or one that offers most opportunity to engage and develop capability and IP the recommendation will be different. The balanced offering is likely to be the one that is economically competitive; that carries acceptable technical risk but still has potential for UK to engage and collaborate on development to enable UK industry to exercise and develop its capability and IP. There is insufficient data at the moment to narrow the recommendation to a narrower scope than the four outlined above. Generic capability and IP that can be developed to apply across other SMR technology will also maximise the chance of UK involvement in the SMR market and maximise the return from any UK investment. An opportunity that is a pure equity investment will not support the growth and strengthening of the nuclear industry skills and capability in the UK.

Technical Assessment Conclusions

The SMRs that are closest to commercial operation and represent most viable options to pursue are integral PWR reactors, drawing on existing technology and global capability. In the longer term, emerging reactor technologies are being developed that are expected to exploit wider applications and promote further improved performance and attributes.

A key part of the technical review has been to determine feasibility of the design concepts as presented by the vendors. It is clear there are both a number of generic and reactor specific design issues, covering the lifecycle of the proposed designs.

In conclusion, it is recommended that the U-battery concept is considered as part of future technology to be explored within a longer term plan, and is best considered by NIRAB. The other opportunities (NuScale, Westinghouse, B&W mPower and ACP100+) all warrant further detailed review to explore:

- The detailed technical challenges and assessment of how feasible they are to overcome, separated into more general SMR challenges and specific to reactor challenges; this will also further inform the UK opportunity to engage and develop IP.

- The collaborative frameworks and the UK opportunity that may result.

3.4 The regulatory framework

A review with ONR was held to explore their views of SMR technologies and ascertain early identification of any key challenge areas that ONR felt could be focus points during SMR assessment through the licensing process.

The summary findings from the engagement are:

- The risks associated with any particular SMR design is the key point from a licensing and regulation perspective. The view of ONR is that it is only likely to be those designs at the much lower end of the 0-300 MW power range, with simple designs, that will pose a significantly lower risk and therefore deliver significant savings in licensing time and cost. The U-battery type designs falls into this category.
- The technology used does not impact the time and cost of the licensing process. Moreover it is the robustness of the safety case and the understanding of the submitting vendor of the UK GDA process that will have most impact on the time and cost of the licensing process.
- ONR understand that UK Government will request that one SMR design is assessed for the GDA, subject to a policy decision to pursue SMRs.
- ONR appreciates that it would be helpful to do an initial pre-GDA assessment of up to 3 SMR designs, as undertaken with the Pu Disposition reactors recently.

From the preliminary discussions, the importance of continued close engagement with ONR as the SMR opportunities progress can be seen to ensure that appropriate focus is placed on the issues of most significance in the critical area of safety case and licensing.

In summary –

- Assimilation of key SMR technical issues and deeper study by the UK to understand how addressable these challenges are and the impact on overall plant technical and economic viability

- Develop UK capability in key areas to support IP potential in the SMR domain

- UK/US intergovernmental meeting to explore the opportunities available for the UK to acquire IPR from the US reactor designs, acknowledging that some of the IPR has been developed under the DoE funding
- ONR agreed to participate in a technical/economic assessment of a limited set of SMR technologies to assist in review of the technical feasibility of a design and to comment on the licensing of each design

4 Innovation

There are potentially a significant number of areas where innovation is likely to play a key role in bringing any of the SMRs to market. The generic design challenges listed below represent a broad range of areas where innovation is likely to play a key role in creating the final detailed design. In addition each of the four integral PWRs have specific challenges, identified above that need addressing. There are also three discipline areas where innovation will be required and where it is already clear the reactor vendors would potentially welcome UK involvement.

The opportunities across the range of reactors is broad and spans the lifecycle of design, demonstration, manufacturing, supply and support in a comprehensive range of technical areas. SMR engagement represents an opportunity to further develop UK nuclear Industry capability and expertise, leading to significant potential UK revenue opportunities on a global basis. The skills and capabilities are relevant and transferable to the wider nuclear industry.

The key generic challenges that need to be further addressed for SMRs include the following

- Integral vessel internals layout, configuration and assembly
- Steam Generator design, manufacturing and assembly
- Demonstration and validation of natural circulation thermal hydraulics and passive safety systems
- I&C in integral reactors / Electrical and cable routing in compact spaces and harsh environment
- Plant operation and control e.g. warm up and transients / load following
- Wider plant configuration of multiple smaller units - both technical and regulatory
- Continuity of operation
- Reduced manning / single operator / room monitoring of multiple reactors – human factors assessment, control and display systems
- Global regulatory frameworks and licensing support for export of concepts that have been developed based on in country experience and regulatory frameworks. May face strong challenges and need to change design for export to other countries (e.g. introduce different safety systems / measures)
- Advanced digital systems for monitoring and control
- Maintenance and inspection concepts - heavily integral reactors may need advanced techniques for monitoring / inspection and maintenance free components.
- Pumps – some novel design and mounting challenges and concepts
- Internal CRDMs
- Test and demonstration facilities
- Refuelling methods / systems and equipment – some novel challenges with integral reactor refuel and multiple integral reactors
- Management of spent fuel
- Decommissioning
- 60 Hz design

The specific configurations and plant schemes deliver differing levels of complexity and novelty and must be considered on a case by case basis to evaluate the potential to address them and the impact this may have on economic viability. Broadly, the review has concluded that these challenges can all be addressed but a much deeper review is required to evaluate what this means to overall economic viability and what opportunities this will deliver to the UK.

The three discipline areas that need to be considered:

- Modular design

One of the key aims when designing an SMR is the transportability of the units. In the case of all the US SMR designs the criteria for maximum size of any unit is governed by its ability to be transported by rail. This requires consideration at all phases of the SMR lifecycle from design through to decommissioning. Development of the supply chain management model and modular construction methodology through a first-build project in the UK, which can be rolled-out for global construction could provide an opportunity for the UK.

- Manufacturability

The UK has a pedigree in manufacturing across a wide range of industries. There is an opportunity in being able to develop progressive manufacturing processes which enable SMRs to be manufactured in a more predictable, cheaper, or novel manner. This needs to include transportability. The Nuclear AMRC has been specifically created to ensure the UK retains a leading capability in this area. SMRs have the potential for a far greater proportion to be manufactured in factories with all of the associated benefits. However to fully exploit this potential the UK will need to be involved in the design as the detailed design work is undertaken.

- Associated Civil Engineering

The most significant component of the overnight capital cost of an SMR is the cost of the civil construction and in particular concrete. Since all the SMR concepts considered have yet to undergo construction, there is an opportunity in which to develop innovation in the design and construction of SMRs. Many of the designs have not yet incorporated advanced construction techniques into their designs.

4.1 Skills: Maintenance and Development

The demographics of the nuclear workforce across the UK are a concern and is resulting in an industry unable to recruit enough high calibre individuals across a wide range of skills. Investment and innovating in the SMR industry will inevitably make the future of the industry more attractive for the future workforce.

The innovation opportunities from UK involvement in the SMR cross a wide variety of engineering disciplines; civil; mechanical; electrical and electronic, chemical and nuclear. The breadth of opportunities is likely to involve the supply chain, not only Tier 1 organisations but also Tier 2 and Tier 3 companies. Manufacturing, design, consultancy, safety system assessment etc will all potentially be involved. The specific opportunities will always be constrained by the exact areas of involvement however the broad range of skills already employed in the nuclear industry means that any of these areas could benefit from UK involvement in the design, development, manufacturing, deployment and operation of SMRs.

It should also be recognised that the growth of requirements for the nuclear industry demands a growth in the number of people particularly highly skilled engineers. The attractions of an industry involved in the next generation of reactors as well as the challenges of decommissioning is clear when new graduates are contemplating their chosen career path. Many of these companies will need more apprentices, individuals who go on to become highly skilled employees working in a difficult environment. Finally the nuclear industry require Subject Matter Experts, the UK is losing the current generation of experts as they retire and without new challenges they will be impossible to replace.

4.2 Alternative technologies

As seen in the Technology Review section the SMRs that are closest to commercial operation are integral PWR reactors combining features from large PWRs designs and marine propulsion reactors. However, in the longer term, other technologies are being developed with improved operational characteristics. It is those technologies that are identified here to inform UK strategy for SMRs beyond a 10 year horizon, where the UK interest is in involvement with an SMR technology that has a significant volume of sales in an international market.

The following table identifies the status of current SMR designs that are viewed as being outside the timeframe of the feasibility study –

Category 1:Reactors that have established projects for construction and could be available within 15 years	
SVBR-100 (Russia) The reactor is a 100 MWe Pb-Bi alloy cooled fast reactor with enriched uranium fuel intended for small reactor applications.	The concept is being demonstrated at Dimitrovgrad with planned start of construction in 2017.
AHWR (India) – the Advanced Heavy Water Reactor is a 300MWe vertical pressure tube reactor, cooled by light water but moderated by heavy water. The reactor is intended to work with a thorium cycle with initial Pu seed.	The detailed design work on the reactor was completed in 2014 and it is anticipated that construction of the first demonstration plant with be in 2016 with operation by 2025.
HTR-PM (China) The system is a 211 (2 x 105) MWe pebble bed high temperature gas cooled reactor with a steam cycle.	The first example has started construction in Shandong province and is expected to complete building in 2017.
ANTARES (France, Germany and USA) The reactor is a 250 MWe very high temperature system using a gas turbine for generation.	This design is based on the GT-MHR projects and a joint project between AREVA in France, Germany and the USA. The project hoped to get USDOE support but it is now confirmed it is no longer active.
Category 2: Reactors that could be of interest but will have longer timescales than 15 years	
Gen4 Energy (USA) The current concept offered is for a 25MWe Pb-Bi alloy cooled fast reactor with uranium nitride fuel.	Despite the availability of a demonstration site offered by USDOE at Savannah River, there is no current project for a demonstration reactor. In June 2013 the USDOE gave a small grant to Gen4 Energy for computer simulation of Pb-Bi natural circulation.
4S (Japan and USA) This sodium cooled small pool reactor concept has been offered in 10 and 50 MWe versions.	Toshiba has informed the USNRC of intention to seek design approval but has not yet submitted the design. In June 2013 USDOE awarded Westinghouse a small grant for development of sodium thermohydraulic computer simulation tools as part of the 4S project.
PRISM (USA, Japan) is a compact pool type sodium cooled fact reactor with metal U, Pu, and Zr fuel. At 311 MWe the Prism reactor lies just above the USDoE and IAEA range defining SMRs	Despite the availability of a demonstration site offered by USDOE at Savannah River, no demonstration of this reactor has yet been announced and USDOE backing has been limited to some specific component development. In June 2013 the USDOE gave a small grant to GE-Hitachi for development of electromagnetic pumps. PRISM is being considered through the NDA's work on credible options for plutonium disposition
Flexblue (France) is a design study for a reactor power source (50-250MWe, with reference design at 160 MWe) that can be placed on the seabed 1- 2 km off the coast to provide power on-shore.	The design study was announced in January 2011 but the only other information available in the 2012 IAEA SMR update. It is understood that the sub-sea concept is being re-worked for deployment on land.

EM^2 (USA) – Energy Multiple Module. This is a 250MWe concept for a gas cooled fast reactor based on HTGR technology, using gas turbine generation with silicon carbide composite clad nitride fuel.	This project is still at an early stage of development. In June 2013 USDOE awarded General Atomics a small grant for development of silicon carbide cladding for the EM^2 project
HTMR (South Africa) This is a 35MWe HTGR (pebble bed) reactor with steam turbine and once-through pebble fuel.	Steenkampskraal Thorium Limited (STL) has continued development of the South African PBMR project, mothballed in 2010, with more realistic aims (smaller output, steam cycle and once-through fuel).

Table 6 - Future SMR technologies

The advantages and disadvantages of the different types of technology are identified below -

	Advantages	Disadvantages
Thermal reactor moderator/coolant types		
Light water	Well understood, compact	Poor fuel efficiency
Heavy water/light water	Good fuel efficiency	Positive void coefficient, low power density, complex
Helium/graphite	High thermal mass, good thermal efficiency	Low power density
Molten salt/graphite	Low pressure, high thermal mass, good thermal efficiency	Less understood particularly on corrosion
Fast reactor coolant		
Sodium	Well understood, good heat transfer characteristic	Reactive with water, positive void coefficient
Pb or Pb-Bi	High boiling point, less reactive to air and water	Heavy, poor heat transfer, Bi expensive and Po-210 build-up
Helium	Inert, no phase change, no void reactivity coefficient	Low thermal mass and relatively poor heat transfer
Thermal reactor fuels		
UO_2 zirconium alloy cladding	Well understood	Zr reactive with steam to make hydrogen
TRISO particles	Improved fuel resistance to proliferation and fission product retention, no hydrogen production	Lower fuel density, no experience on reprocessing
Zr-U alloys	High fuel density, cheap	Zr reactive with steam to make hydrogen, low melting point, high swelling
Advanced ceramic fuels	No hydrogen production	Not well understood, manufacturing difficult
Fast reactor fuels		
$(U,Pu)O_2$ (MOX)	Well understood, high melting point, high burnup	Low thermal conductivity- high fuel temperatures, reacts with sodium
(U,Pu)N	High fuel density, high effective melting point, compatible with sodium	Less well understood
(U,Pu)C	High fuel density, high melting point, compatible with sodium	Limited power rating because of swelling
(U,PU)Zr alloy	High fuel density, compatible with sodium	Low melting point, high swelling, incompatible with Fe alloy cladding and Pb coolants
Fuel cycles		
Uranium fuel cycle	Well understood, large stocks of depleted uranium	Breeding limited to fast reactor systems, minor actinides in HLW
Thorium	Can breed in thermal and fast reactor systems, shorter life HLW, good availability of Th ores in countries like India and Brazil	Less well understood, needs U-cycle to initiate Th-cycle, hard gamma in recycled fuel (advantage for non-proliferation)

Table 7 - Assessment of future technologies

From this assessment it can be seen that some of the above technologies may present an interesting and viable opportunity for investment. It is therefore suggested that technologies in this category should be considered by NIRAB as part of a longer-term UK nuclear strategy.

5 Financial case

5.1 Introduction

The Government's policy of increasing the use of low carbon technologies is a key part of delivering the UK's energy requirements. The 2008 Climate Change Act enshrined in law the requirement to reduce the UK's greenhouse gas emissions by 80% by 2050. The underlying strategy to achieve this requires support of a diverse set of technologies including nuclear. Furthermore, the UK's nuclear policy is to also promote diversity of the technologies and vendors. There is an opportunity for SMRs to be integral to the UK's nuclear, energy and low carbon agenda.

However, in order to justify further involvement with SMRs they need to make sense economically. The price of power from these reactors will need to be competitive with large nuclear reactors and arguably the next of a kind (NOAK) costs of large rectors.

The purpose of this section is to provide a high level overview of the project economics of SMR projects based on the findings from the engagement with the down selected SMR technology providers to date. For confidentiality purposes none of the figures noted in this section will be identifiable to any specific SMR technology provider.

5.2 Reactor Economics

As part of the initial economic case for SMRs, this section considers two key metrics:

- The Overnight Capital Cost; and
- The Levelised Cost of Energy ("LCOE").

Both of these metrics are industry standards for benchmarking and determining the project economics of nuclear, and more broadly, electricity generation assets.

The Overnight Capital Cost is a term used in the electricity generation industry to describe the cost of building a power plant overnight and is a proxy for the amount of capital that would be required to build the plant. The metric is useful for comparing the economic feasibility of building various plants but ignores financing costs or escalation, and hence is not an actual estimate of construction cost, in order to compare plants of different sizes and configurations the Overnight Capital Cost is expressed in this report as £/kWe. The Overnight Capital Costs does not take into consideration operating expenses and the generation performance of the plant.

The Levelised Cost of Energy (LCOE) is an economic assessment of the unit cost of generating electricity over the economic life of a generation asset in net present value terms. This is achieved by discounting the sum of capital costs, O&M costs, fuel costs, and decommissioning costs and then dividing by the discounted electricity generation. It can be considered as a proxy for the price at which electricity must be generated from a specific source to break even over the lifetime of the project. The LCOE is very useful in comparing the costs of generation from different sources that have varying configurations and asset lifespans. It is important to note that the definition of LCOE relates only to those costs due from the owner/operator and does not cover wider costs borne by others (for e.g. system balancing, air quality impacts, and network investment). Furthermore, LCOE does not explicitly include the financing costs attached to a particular generating asset, although the choice of discount rate can be considered a proxy for the project return. In order to compare data from various sources LCOE tends to be presented using "standard" discounts rates, typically 5% and 10% (real). Levelised cost estimates are highly sensitive to the underlying data and assumptions including those on capital costs, fuel and carbon costs, operating costs, operating profile, load factor and the discount rate; and future levelised cost estimates are significantly driven by assumptions of global and UK deployment and assumed learning rates (see more on this later in the section). The LCOE is expressed in this report as £/MWh.

LCOE estimates should not be considered equivalent to Strike Prices under the Contracts for Difference (CfD) being introduced as part of Electricity Market Reform. While the LCOE may form the basis for a Strike Price, the detailed calculation will consider other aspects such as: wholesale market prices during the CfD, revenues post CfD, other revenues and costs (land), contract terms including length and risk allocation; actual financing costs and tax considerations. In addition, CfDs are for a defined period which is not necessarily the full life of the reactor. Although as a benchmarking tool it is expected that the LCOE and Strike Price would not be significantly different, where comparable discount rates / hurdle rates are used.

5.3 Large Reactors Economics

As stated in the introduction, SMRs must be competitive with large reactors currently being built and planned in the UK. The data for the Overnight Capital Costs and LCOE for large reactors varies considerably and therefore, in the UK context it would seem appropriate to use the data compiled on behalf of the Department of Energy and Climate Change (DECC) as part of its Electricity Generation Costs Updates series.

For nuclear reactors the critical parameters that determine the cost of generating electricity are: the capital cost of constructing the facility, the annual fuelling, operations and maintenance costs, the waste management expenses and the costs of decommissioning the reactor.

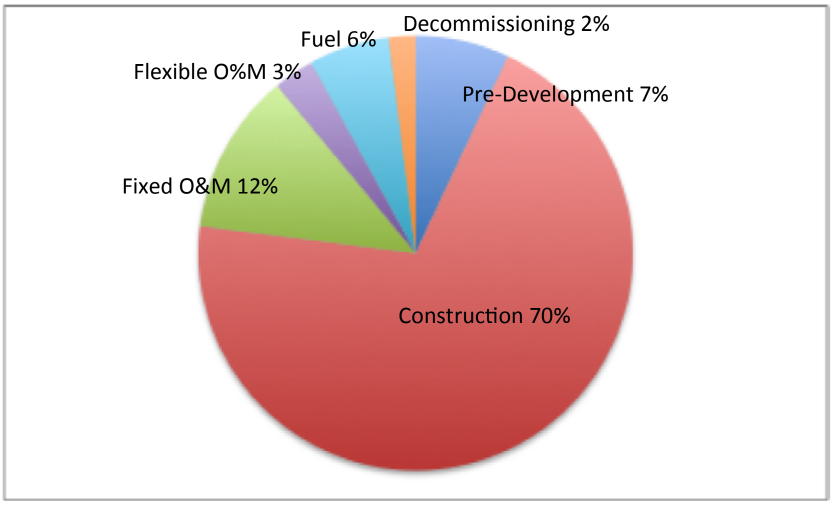

Figure 13 - Wholesale Power Price

The economics of large nuclear power have, to date, been dominated by the construction costs of reactors. This has been a key barrier; current estimates from the US indicate that the capital cost of unsubsidised large nuclear projects are increasingly out of reach of investor owned utilities. In the US, investor owned utilities compromise 70% of the nuclear generation and average $13bn (approx £8.3bn) in annual revenues. A twin unit conventional nuclear power project costing $11bn (approx £7bn) would represent 90% of their annual revenues in a single project.[4] According to Moody's Investor Service this level of risk concentrated in a single project represents a '"bet the farm" endeavour for most companies, due to the size of the investment and the length of time needed to build a nuclear power facility."[5] A more analytical 2008 paper by Moody's concedes that whilst it does not expect 'near term rating or rating outlook changes associated solely with the decision to pursue new nuclear generating capacity", a utility that " builds a new nuclear power plant may experience an approximately 25-30% deterioration in cash-flow related credit metrics, effectively reducing the ratio of cash-flow from operations as a percentage of debt from roughly 25% to the mid-teens."[6] The long-term implications for the utility are that it will need to: curtail its future dividend, reduce baseline capital expenditures, seek equity partners or pursue Government loan guarantees. Of these the dividend option is not attractive to shareholders, the reduction in capital expenditure is hard to achieve with a fleet of operating assets that will require ongoing maintenance and investment and the creation of a special purpose investment vehicle will be hard to structure off the balance sheet due to the size and risk of the investment. This leaves the utility reliant upon government subsidy: "Most of the utilities currently contemplating new nuclear generation are basing their decisions, in part, on the availability of federal government subsidies and/ or other federal incentives."[7]

The Charts below show the latest DECC published data for nuclear (Overnight Capital Costs and LCOE). A range is shown to reflect "high", "central" and "low" estimates of capex and also fuel costs. The data is presented for projects commencing in 2013 and 2019 and therefore the assumption has been made that these represent First of a Kind (FOAK) and Next of a Kind (NOAK) estimates[8, 9]. A discount rate of 10% (real) was used.

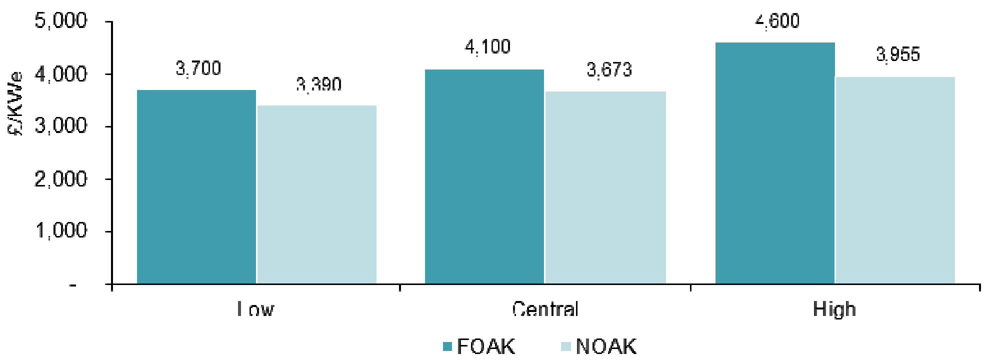

Figure 14 - Overnight Capital Cost Large Scale Nuclear (£/kWe)

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[4] Page 6, 'Small Modular Reactors- Key to Future Nuclear Power Generation in the US', Rosner and Goldberg, Energy Policy Institute at Chicago, 14 July 2011

[5] Page 6, 'Small Modular Reactors- Key to Future Nuclear Power Generation in the US', Rosner and Goldberg, Energy Policy Institute at Chicago, 14 July 2011

[6] Page 2, 'New Nuclear Generation Capacity, Potential Credit Implications for U.S. Investor Owned Utilities', Moody's Corporate Finance, May 2008

[7] Page 13, 'New Nuclear Generation Capacity, Potential Credit Implications for U.S. Investor Owned Utilities', Moody's Corporate Finance, May 2008

[8] Electricity Generation Costs (December 2013), Department of Energy and Climate Change.

[9] NOAK Overnight Capex Costs are not presented in the December 2013 DECC updates, so data has been taken from the supporting document - Electricity Generation Cost Model – 2013 Update of Non Renewable Technologies, April 2013, prepared for DECC by PB Power.

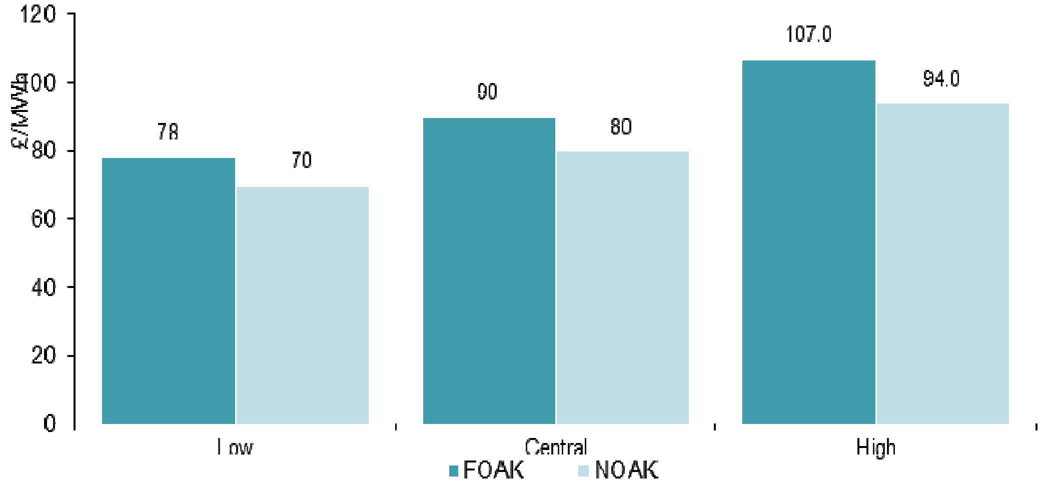

Figure 15 - Levelised Cost of Large Scale Nuclear Energy (£/MWh, 2012, prices 10% discount rate)

It is interesting to note (notwithstanding the comments above re LCOE not being a direct equivalent of a Strike Price) that the Strike Price for Hinkley Point C (HPC) is currently expected to be between £89.50 and £92.50 / MWh, which sits within the central range presented. Indeed, when applying technology specific hurdle rates the LCOE estimates show a central (FOAK) case of £89 / MWh for nuclear.[10]

Economies of scale indicates that the larger the reactor the lower the ultimate LCOE. The rate reduction of unique set up costs in investment activities, the more efficient use of raw materials, the higher performance characteristics of larger equipment and the lower per unit operating costs all favour the construction of larger capacity plants. This basic tenet has driven the increase in the size of reactors from 500MW in the 1970s and 1980s to 1000MW-1600MW in the 21st Century.

It is also noted that there is an assumption that costs will reduce as a fleet of reactors is constructed. This is in line with the generally accepted view that repetition leads to cost savings, however nuclear reactors have actually got more expensive per KW. This is borne out from the actual build costs of nearly all reactors in the last 50 years and runs against the theory that technology costs should reduce over time. When considered in more detail it is perhaps not so surprising, if we consider the cornerstones of what it is assumed leads to reductions in unit cost: value engineering; learner curve reductions; economies of scale and modularisation.

Bupp and Derien cite evidence from the American build programme between 1966 and 1977 that on average plants that entered service in 1975 were about three times more costly in constant dollars than early commercial plants completed five years earlier.[11] Much of the additional cost and complexity is driven by nuclear safety measures: "safety variables (fines and the number of safety standards and rules adopted by the NRC) are the most consistent predictors to explain cost escalation in the US"[12]. As reactors have increased in size; driven by the view that unit cost should reduce in line with economies of scale theory; the number of plants actually being built reduces and the time between repetition of construction (the "drum beat") increases which actually "slows" the realization of Learner Curve Reductions and does not lend itself to the maximization of modularisation. The long duration between builds means that the ideal of not repeating mistakes, building

[10] As per reference 1, page 36, referencing returns based on work carried out for the December 2013 EMR Delivery Plan reflecting the latest information from the published Hinkley Point C deal.
[11] Quoted in page 16, 'The Economic Failure of Nuclear Power and the Development of a Low Carbon Electricity Future', Mark Cooper, May 2014
[12] Page 8, "Revisiting the Nuclear Power Construction Costs Escalation Curse", Rangel and Leveque, 2012, *Interdisciplinary Institute for Innovation*, Working Paper

up the supply chain and reducing development costs all leading to reduced costs and control of over runs, has not happened. In addition, as plant sizes have increased, this has naturally led to first of a kind design for each build and therefore the savings associated with design repetition and lowering of pre-development and overheads have not been maximized. Furthermore, with larger plants it has been shown that moving even mature design to a different site re-introduces new first of a kind costs (FOAK) and programme control challenges.

In a widely quoted analysis of the costs of nuclear power G McKerron highlights some of the key reasons for this increase in capital cost. The report indicates that the increase in scale failed because the technology was immature and incurred unforeseen extra cost, there was an increase in complexity driven by constantly improving design standards and site assembly leads to poor productivity and low quality[13].

A. Grubler's comprehensive review of the French nuclear programme indicates rising construction times and rising costs as the reactors become larger with greater complexity and that the introduction of new designs after relatively small volumes of production within the existing fleet significantly limited the impact of any learner reductions.

Order Series	Reactor Type	Reactor Size MWnet	Number Built	Constructed Between	Mean Construction Time Months	Mean Investment costs, "best guess" and uncertainty range (1000FF98/kWgross
CP0	PWR Westinghouse license	900	6	1971-1979	63	4.9 (4.02-5.9)
CP1	As CP0	900	18	1974-1985	65	5.5 (5.0-6.0)
CP2	As CP1	900	10	1976-1987	67	6.5 (6.1-7.2)
P4	Westinghouse license	1300	8	1977-1986	78	6.9 (6.5-7.1)
P'4	P4 (French version)	1300	12	1979-1993	90	8.4 (8.0-8.8)
N4	PWR	1500	4	1984-1999	126	11.0-13.3 (10.3-14.5)
EPR	EPR	1600	1	2007-		

Figure 16 - Learner savings from 'The Costs of the French nuclear scale-up: A case of negative learning by doing', in Energy Policy, A. Grubler, 2010

Learner benefits from building large reactors on the same site appear to have been delivered when the reactors have been built in continuous succession. Tony Roulstone, (Department of Engineering Cambridge) speculates a cost reduction of 15% should be expected for second and subsequent plants, however, an exhaustive study of all nuclear new build projects has demonstrated no learner effect across the build programme. He concludes that a second build within 50 miles of the first build will enjoy no learner effect from the nearby site.[14] There are a number of reasons for this:

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[13] Tony Roulstone and Guan Zhenjun NIA conference Manchester September 2014
[14] Tony Roulstone and Guan Zhenjun NIA conference Manchester September 2014

- Constant evolution of design with many local/ site based variations
- Complex construction sites inhibit co-ordination, communication and learning
- Constantly changing supply chains- competition based procurement decisions
- Detailed design repeated by site based teams not replicated
- Construction sites with inherently weak quality and low productivity
- Geographically dispersed sites with new site construction teams each time
- Long periods between projects or between the same task on repeat projects

5.4 Small Reactor Economics Previous Research

There is little available open source information on SMR costs that can be relied upon to realistically assess the economics of SMR projects and the figures that are published in open sources are neither validated nor given on a like for like basis to enable reliable comparison both against the range of SMRs and against larger reactors.

An often-quoted OECD[15] report is used to support the economic benefits of SMRs. The Overnight Capital Costs and LCOE of a range of different SMR designs and configurations[16] (between 1 and 5 modules, the outputs shown in the following figures represent the total) from this report are presented below and show a wide variation.

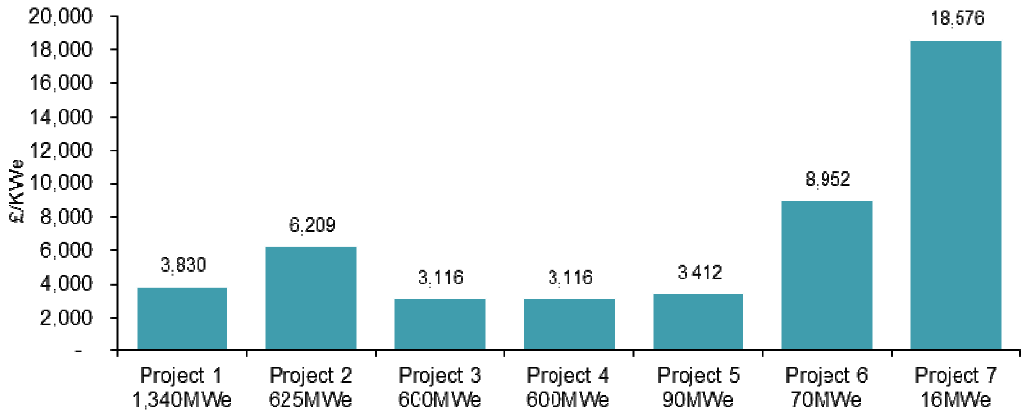

Figure 17 - Overnight Capital Cost (£/kWe) from OECD data

Considering the LCOE, a range of ~ £30/MWh for an in-service Russian plant up to ~ £130/MWh for an immature Gen IV design (at a 5% real discount rate) and ~ £50/MWh to ~ £245/MWh (at a 10% real discount rate). In general terms SMR developers indicate a likely final LCOE range of £65/MWh - £95/MWh[17]. However the spectrum of these estimates is an indication that the designs of SMRs are still under various stages of development and the final build and operating cost have yet to be finalised by the vendors.

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[15] Current Status, Technology and Economics of Small Modular Reactors, OECD Report, 2011
[16] The outputs shown in Figures 17 to 19 represent total outputs for each configuration which range from 1 unit to 5 units.
[17] Current Status, Technology and Economics of Small Modular Reactors, OECD Report, 2011

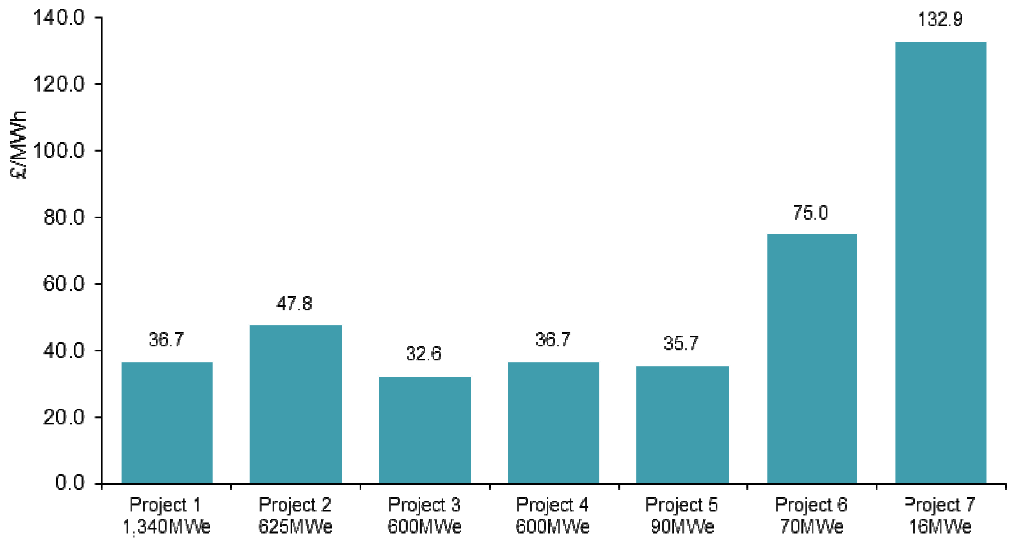

Figure 18 - Levelised Cost of Energy (£/MWh,2012 prices, 5% discount rate) - OECD data

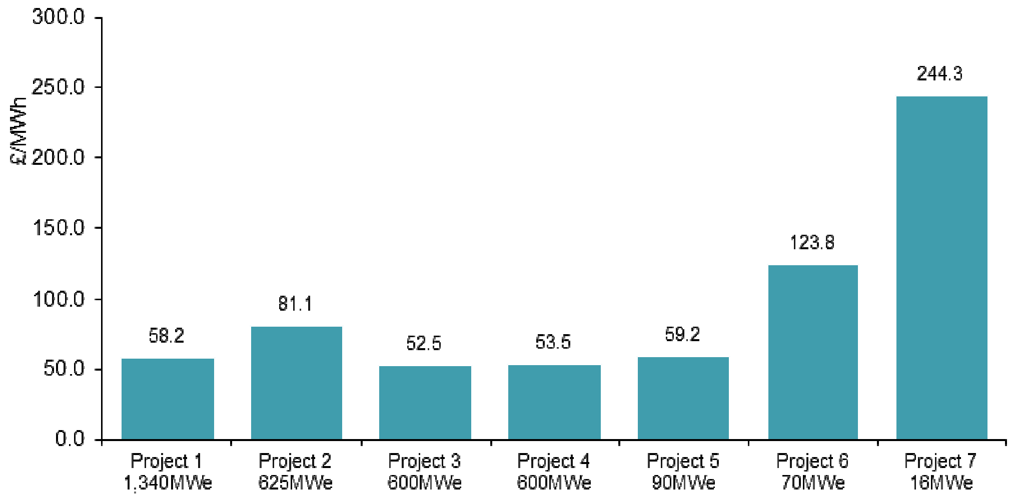

Figure 19 - Levelised Cost of Energy (£/MWh, 2012 prices, 10% discount rate) - OECD data

5.5 SMR Economics – Current Findings

In order to supplement this data with more contemporary information the Consortium was given access to data from four of the leading SMR designs in the market today[18].

Two sets of outputs are show below: "unadjusted" being the raw data provided and "adjusted" being the raw data adjusted subject to technical review by the Consortium. The review considered the appropriateness of the cost estimates based on considerations such as: maturity of design, complexity of design and an assessment of local costs (regulator fees or country specific costs). Each of the vendors was asked to provide their cost data under the following categories:

[18] For PWR designs – provided under Non Disclosure agreements and as such the projects have been annonomised.

Capex:

a) Total Building and Structures
b) Total Reactor plant equipment
c) Total Turbine generator plant equipment
d) Total Electrical, instrument, and control equipment
e) Total Water intake and heat rejection
f) Total Miscellaneous plant equipment
g) Total Special materials
h) Total Engineering design and site layout
i) Total Other costs

Opex:

a) Fuel
b) Nuclear waste fee/management
c) Staff costs (including training)
d) License
e) Insurances

Adjustments have been carried out on a case-by-case basis and have varied as more detailed data has been gathered. Separate consideration has been given to owners costs, first fuel load, capex, opex, nuclear waste management, insurance, licensing, bought in maintenance, uranium, enrichment and decommissioning. The adjustments varied considerably between vendors.

It has been assumed that the data provided is indicative of a FOAK costs, and would therefore be expected to reduce over time as the technology improves and developers benefit from learning (economics of multiples) and economies of scale.

The LCOE analysis does not make any assumptions with regards to financing costs associated with the build of each of the specific SMR projects or the financial status of the vendors. The LCOE has been calculated based on a range of discount rates: 5% and a 10% (real) being the rates typically used and allowing comparison against other published data and in addition, a discount rate of 8% (real). The later discount rate has been used to provide a more realistic approximation of the true cost of finance on the following basis: HPC has referenced a nominal project IRR of c. 10%[19] This suggests that on a real basis the project IRR would be less than 10% and somewhere in the range of 7.5% - 8.5% (i.e. assuming inflation of between approximately 1.5% and 2.5%).

[19] EDF – Update on the UK Nuclear New Build Project (21 October 2013)

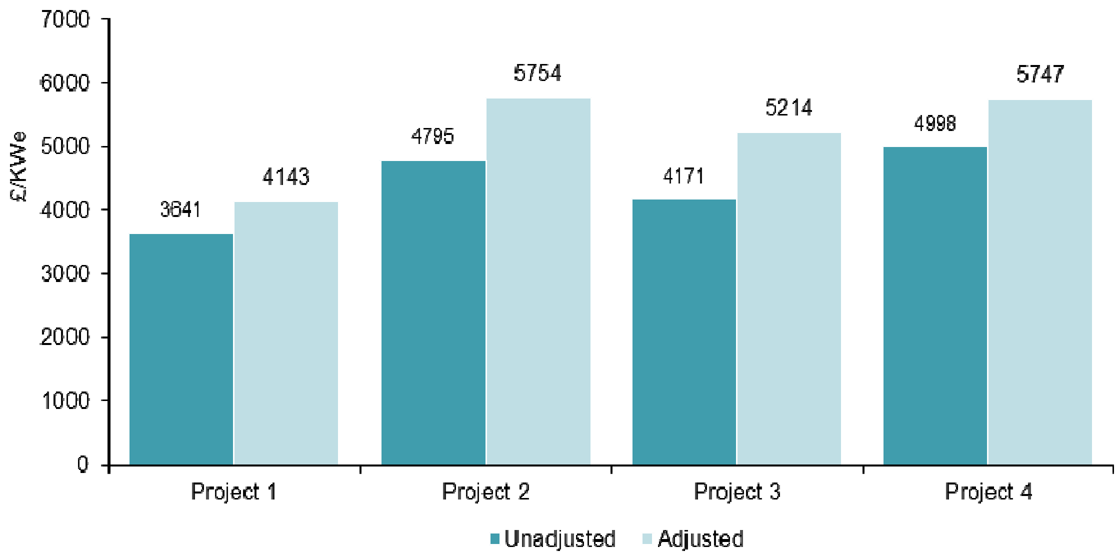

Figure 20 - Overnight Capital Cost for selected SMR Designs (£/kWe)

Considering the current data set the designs are at varying levels of maturity and hence a straight average of the data may be misleading. Therefore, in the following chart two sets of averages are presented: all data (adjusted and unadjusted) and a subset considering only those down selected designs (mature) where a full concept exists (adjusted and unadjusted). The current SMR study estimates appear broadly in line with the majority of costs presented in the OECD report with the adjusted Overnight Capital Costs slightly higher than the upper end of the DECC estimates. However, the adjusted mature Overnight Capital Costs are approximately equal to the DECC Large Nuclear Data (see "Overnight Capital Costs Large Nuclear") FOAK case. It is expected that further design development should improve this comparison.

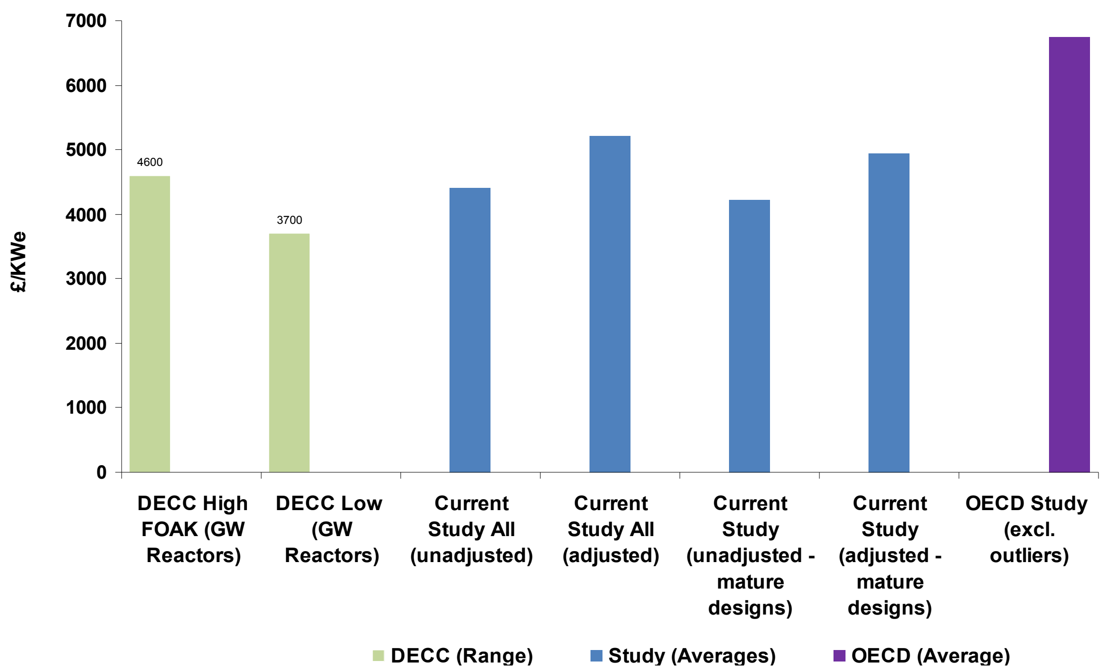

Figure 21 - Overnight Capital Cost Comparison (£/kWe) for all Nuclear sectors

The LCOE results from the study showed significant variation between the designs and the maturity effect of the designs being more apparent.

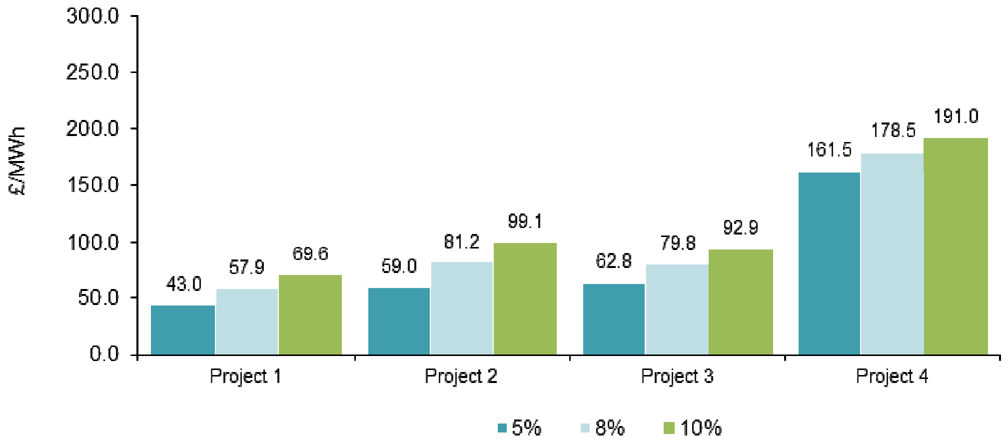

Figure 22 - Levelised Cost of Energy at discount rates of 5%, 8% and 10% (£/MWh, 2012 prices) unadjusted, for selected SMRs

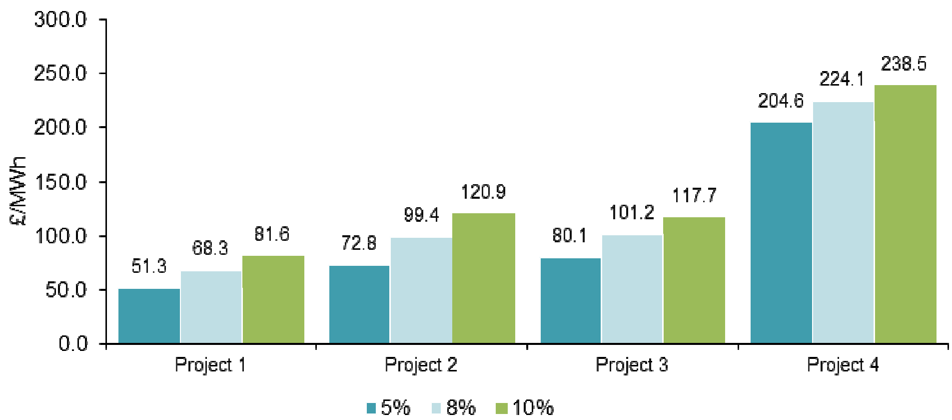

Figure 23 - Levelised Cost of Energy at discount rates of 5%, 8% and 10% (£/MWh, 2012 prices) adjusted, for selected SMRs

The current study results for LCOE are generally higher than those presented in the OECD report, however the following should be noted with respect to the OECD report:

- The figures do not include a decommissioning cost estimate.
- They also include a scaling factor whereby larger projects involving more than one module benefit from an assumed economy of scale
- The estimates cover a variety of geographies but not the UK.

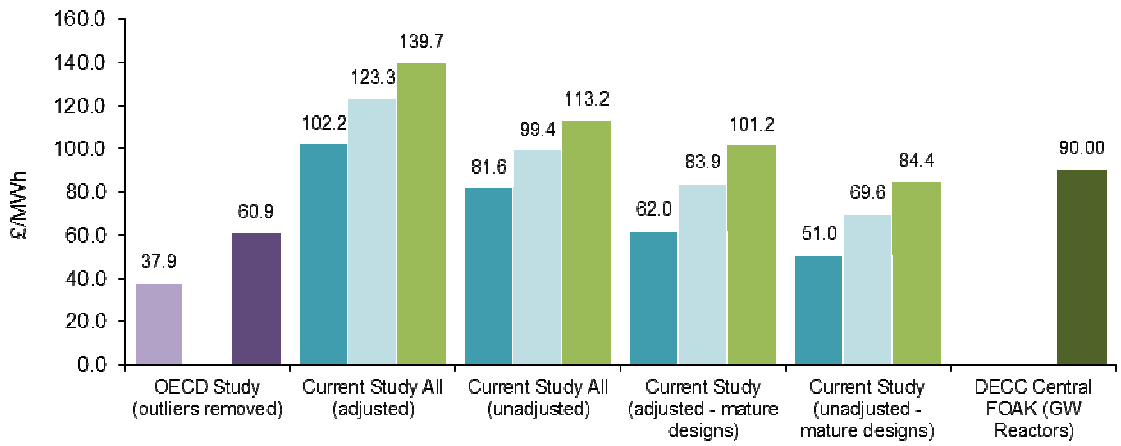

Figure 24 - Levelised Cost of Energy comparison (5%, 8% and 10% discount rates (£/MWh), as at 1 Jan 2012)

The adjusted mature designs LCOE result of ~ £84/MWh with a 8% real discount rate is lower than the publicly quoted CfD Strike Price range for HPC, and at a 10% discount rate is less than the DECC high case estimates. The unadjusted LCOE of the mature designs is considerably lower than the HPC figures at ~ £70/MWh (for an 8% discount rate). The results are even more material when comparing them to other low carbon technologies such as onshore wind at ~ £101/MWh, Biomass Conversion at ~ £108/MWh, offshore wind at ~ £122-129/MWh, and Large Scale Solar PV at £158/MW. [20]

It is important to highlight that the abovementioned costs do not reflect deployment in any specific country and could be significantly different in the UK market because of uncertainties in the design requirements for the UK and therefore the figures noted above are included for comparison only. In addition the nuclear industry has a history of cost escalations during the design and build phase of First of A Kind reactors ("FOAK"). Whilst the current designs of SMRs require a smaller upfront capital investment and have less financial risks associated with their construction when compared to the conventional large scale reactors and will be less susceptible to site related assembly issues, additional cost escalations should be expected during the deployment phase of the FOAK.

5.6 SMR Cost Reduction Opportunities

Based on the data provided by the SMR reactor vendors and the assessment of the Consortium of the raw data the LCOE may vary anywhere between ~ £60/MW up to ~ £100/MW (for a real discount rate of 8%). The bottom of this range appears low for FOAK and the top of the range would be unlikely to be competitive in a UK nuclear context. However if we take the LCOE of the mature designs (adjusted) of £84/MWh this could be used as a realistic starting point from which point improvements in LCOE can be judged.

The nuclear industry has a history of cost escalations during the design and build phase of FOAK rectors as previously noted, and whilst the current batch of SMRs are unlikely to be as complex to build as the conventional 3rd Generation Nuclear Power Plants (NPPs) and will be less susceptible to site related assembly issues, the challenges outlined are not the exclusive preserve of conventional large nuclear build programmes;

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20 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf

SMRs may also be affected by a number of them. However, the scale, the volume and the emphasis on factory design and assembly make SMRs more affordable for commercial operators and present a significant opportunity to benefit from a manufacturing environment where cost reduction opportunities could be delivered.

SMRs have attributes that make the likelihood of NOAK cost realization far more likely. Twenty 180MW reactors would be required to produce the same power planned as Hinkley Point C, if these were built on the same site a full reactor build cycle would be repeated over a much shorter time when compared to large reactors. This provides for the potential of significant reductions compared to the costs associated with the FOAK.

Bearing in mind the uncertainty over the current cost estimates published by the vendors there is a requirement to conduct more detailed due diligence on those specific areas that could have most effect on the economics of SMRs before a robust view can be formed of their relative competitiveness with conventional GW NPPs or other electricity generation methods. However, the following sets out how costs could be reduced.

- Learner Curve reduction:

SMRs offer the opportunity to minimise the inefficiencies associated with site assembly by maximising the scope of the reactor and supporting systems that are built and assembled within the controlled conditions of a manufacturing facility. Whilst it is common to associate the benefits to be accrued from controlled conditions purely with the manufacture and assembly of the reactor module itself, this accounts for less than 20% of the overall capital cost on large reactors and, as designed today is likely to account for only 30% of the capital costs of an SMR. So any learner effect will be diluted.

However a more radical approach to the whole plant design, with greater focus on design for manufacture across the whole project scope, and not just the reactor module has the potential to deliver enhanced learner benefits. Engineering companies with little knowledge of, or incentive to consider, the exigencies of factory assembly, have traditionally designed many of the ancillary systems and structures. The scale of conventional plants has dictated site based construction and assembly.

A review of the learners achieved in capital industries operating within a manufacturing environment is instructive.

Industry	Progress Rate	Comment	Source
Aircraft	19%	Original work by Wright in aircraft manufacturing confirmed by Archian, 1950 and Benkard, 2000	Chen & Goldberg [15] Appendix A
Shipbuilding	10-15%	Stump 2012 & Smallman 2011 with variations by type of work: 5-25%	Man-time learning
Semi-conductors	20%	Irwin 1996, dependant on low process losses	
PV	20-35%	Margolis, 2002 wide range of values depending on degree of investment in automation	
Wind turbines	4-12%	NEEDS 2006, depending on scale	
Gas pipelines	4-24%	Zhao, 1999 onshore & offshore in US to 1997	McDonald & Schrattenholzer [16] pg. 257
Gas turbines	10%	MacGregor, 1991 world-wide to 1980	
Coal Power	8%	Kouvaritakis, 2001 OECD to 1993	
GTCC	26%	Claeson, 1997 world-wide to 1997	Learning rates on overall cost, they include all times of improvement
Wind	17%	Kovaritakis, 2001 OECD to 1995	
Ethanol Prod.	20%	Goldemberg, 1996 Brazil	
Solar PV module	20%	Harmon, 2000 world-wide to 1998.	

Figure 25 - Learner savings - Source: 'Nuclear Construction Cost Estimates & SMRs' Tony Roulstone, July 2014

The implications for SMRs are clear. An increased focus on factory build, particularly in areas outside the nuclear island not traditionally subjected to such rigorous "Design for Build" attention at conceptual design phase, should mean that SMRs built in sufficient volume could realistically benefit from a meaningful cost reduction between successive plants.

Where data is available for defence reactor programmes it would suggest that learners comparable to those achieved in other industries are achievable. Examples from a Russian naval reactor programme show that the manufacture of the OKBM Afrikanatov naval propulsion plant realised savings of 15% on the second of a kind plant and at least 5% for the 3rd, 4th and 5th plants[21].

A study by the Illinois Institute of Technology and Argonne National Laboratory, funded by the US Department of Energy, focuses on the learning rates achievable during the production of factory built components contained within the integrated reactor vessel (IRV) of an SMR. It indicates approximately 25% costs savings can be achieved across a lot of 5 IRVs manufactured in a dedicated facility[22]

Taking into account the evidence from similar capital intensive manufacturing industries, the examples achieved in the nuclear defence programme and the parametric modelling of SMR manufacture it could be assumed that cost reductions of 10% for every doubling of volume should be achievable. If it is assumed that the relevant components make up 30% of the cost of construction, and that no learner effect was applied to the remaining 70%, and it is also assumed that the UK built 15 plants (a total of 5.4GW) then a significant cost reduction could be expected by the last of this relatively small production run with further reductions possible.

- Modularisation

The cost reductions outlined above assume that only 30% of the design could be produced in a factory and therefore benefit from the benefits of learner curve reductions. The emphasis for SMRs needs to be on Modularisation (as well as Small). Significant further work needs to be carried out on the percentage of capital

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[21] *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors NEA June 2011*

[22] ,'Small Modular Reactors: Parametric Modelling of Integrated Reactor Vessel Manufacturing Within a Factory Environment Volume 1' X.Chen, S Goldberg, August 2013

cost that could be genuinely modularized and factory produced, and in particular considering the UK context. A reasonable starting position should be that the vast majority of the design could be manufactured off site (with the exception of the aircraft protection and the base concrete).

If we assume 50% (as opposed to the 30% used above) is factory produced then the percentage cost reduction of the 15th unit NOAK would further reduce. Clearly the learner effect will have a powerful effect on follow on costs. The factory design emphasis of an SMR must, as a consequence, extend well beyond the high technology NSSS components. It needs to include all of the systems and much of the build that is the traditional preserve of the construction industry.

- Value Engineering

The national investment in the skills being developed by the NAMRC applies to a whole range of manufacturing challenges. None of the above costing assumes any benefit from their work. Their work, with member companies, large and small, is expected to deliver further cost reductions.

Recent investment in manufacturing technology within the UK, coupled with the smaller size of the components within SMRs means that new techniques are being developed that have the potential to significantly reduce the current manufacturing costs of SMRs. These techniques are not ready for commercial deployment as yet so the final benefits have yet to be externally proven however initial indications are extremely positive. To give two examples:

- Local Vacuum Electron Beam (LVEB) Welding can significantly decrease the time and cost of welding thick section components. The current technique requires multiple welding passes with Non-Destructive Examination between each pass to verify the quality of the weld. LVEB Welding will achieve the same result in a single pass, with fewer defects and reduced shrinkage and distortion of the weld. By way of example a 140mm section weld currently takes 120 days to complete. The LVEB weld can reduce this to 20 days. The time and cost benefits in the manufacturing of heavy nuclear vessels will be significant. The technique is expected to be ready for deployment in 2016.

- Laser cladding can significantly reduce the cost of protecting the ferretic materials within a PWR reactor against corrosion. Current cladding techniques require three layers of cladding to be laid down and then machined once down. Diode Laser Powder Deposition Cladding enables a single layer of clad to be applied with no requirement for subsequent machining. It is assessed that such techniques can reduce the cost of cladding by up to 40%. The technique is expected to be ready for deployment in 2016.

A recent study conducted by Rolls-Royce concluded that advanced manufacturing techniques would deliver significant cost reductions in almost all components. The only components within the SMR reactor module where costs would not be reduced by application of these techniques were the reactor controls and core instrumentation. It was assessed that the overall cost of the module (30% of the total plant cost) could be reduced by 20-30%.

If it is assumed that this type of Value Engineering is applied across the 50% of the capital costs associated with a factory build it would only need a 7% cost reduction applied at the mid point of a production run of 15 units to deliver an overall cost reduction of 20% from the FOAK by the 15th unit. If it were assumed that the FOAK of an SMR is £84/MW (see above) this would result in a reduction to £67/MW.

The points above do not only apply to the NSSS vendors but to the supply chain through all the various tiers. Considering the gaps between build programmes large Nuclear tends to re-compete the supply of components with all of the associated risks and costs. Supply chains that can see production runs of more than one will take a very different view to investment, management controls, quality systems etc. There is much evidence that moving to new suppliers carries significant costs that ultimately flow through to the vendor costs.

- Operating Cost Opportunities

The terms of the site license coupled with regulatory requirements for reactor operations will impose a fixed cost burden for each licensed site. This will largely be related to personnel costs. A smaller generation capacity on that site, coupled with an increase in reactor units will dictate a higher cost burden per MW of output. A single 1200MW NPP will today require a single operating team for normal operations. The requirements for a multi-reactor SMR are less clear. The current regulatory requirement may mandate an operating team per module, which would have a negative impact upon the OPEX per MW of output, but a different approach could have a radical effect on the operating costs

- Construction Costs

SMRs are designed to be road/rail portable with a reduced requirement for onsite assembly. The requirement for transport infrastructure and onsite accommodation for the construction team could be reduced significantly so it would be realistic to expect a significant reduction in the upfront site preparation costs.

The site preparation and civil engineering required for the actual construction of a conventional NPP are a significant component of build cost. A smaller outer-containment coupled with the reduced plant footprint required for an SMR, could give a significant benefit to plant construction cost on a per MW basis.

All these benefits should have a positive impact on the build time duration for the SMR. This in turn will reduce the project management and site overhead costs of projects whilst having a positive impact on the risk profile and finance related costs.

- Wider Benefits to the consumer

The reduced capital requirement and lower cost of capital referred to above mean that SMRs could increase the number of developers in the market and reduce the reliance on Government support mechanisms to encourage investment.

By maximising nuclear capacity the impact of significant gas price inflation and security of gas supply is reduced by the deployment of SMR technology to replace gas fired power stations when they reach the end of their operational life. Furthermore there would be a reduction on reliance on more costly low carbon alternatives – the levelised cost of energy from other low carbon options that will be required to meet the UK's 2050 emission targets are potentially significantly higher than electricity produced by SMRs.

Cogeneration such as CHP and desalination are viable opportunities to derive additional cost benefits from SMR technology. In the UK this opportunity may be limited by the cost of district heating networks, the proximity of the power station to the heat end user, and the potential public resistance to nuclear power being constructed on sites that are not currently nuclear sites. However there is a stronger case in countries such as in the Middle East where cogeneration desalination is seen as economically beneficial and there is little or no public resistance to the deployment of nuclear power.

Finally there may be the possibility to avoid costs of strengthening the Grid. The capacity and security of the power distribution grid is a key cost factor for large nuclear plants and for renewable forms of generation. SMRs have a lower power output and so there is no requirement to upgrade the grid when replacing existing NPPs or fossil powered plants. Destabilising of the Grid is a particular issue in countries with smaller power distribution grids and infrastructure that is less well developed.

- Financing

As noted above, one of the biggest barriers to investment in large reactors is the pure size of the required capital. According to Moody's Investor Service this level of investment concentrated in a single project represents a '"bet the farm" endeavour for most companies, due to the size of the investment and the length of time needed to build a nuclear power facility."[23] A more analytical 2008 paper by Moody's concedes that whilst it does not expect 'near term rating or rating outlook changes associated solely with the decision to pursue new nuclear generating capacity", a utility that "builds a new nuclear power plant may experience an approximately 25-30% deterioration in cash-flow related credit metrics, effectively reducing the ratio of cash-flow from operations as a percentage of debt from roughly 25% to the mid-teens."[24] The long-term implications for the utility are that it may need to: curtail its future dividend, reduce baseline capital expenditures, seek equity partners or pursue Government loan guarantees. Of these the dividend option is not attractive to shareholders, the reduction in capital expenditure is hard to achieve with a fleet of operating assets that will require ongoing maintenance and investment and the creation of a special purpose investment vehicle will be hard to structure off the balance sheet due to the size and risk of the investment. This leaves the utility reliant upon government subsidy: As Moody's note, "Most of the utilities currently contemplating new nuclear generation are basing their decisions, in part, on the availability of federal government subsidies and/ or other federal incentives."[25]

The issues outlined are reflected for the UK and wider European market. It can be seen in Figure 26 that in most cases raising the additional debt to cover the costs of a single 1600MWe unit would materially increase the overall debt to levels very close to, and even above, the Market Capitalisation.[26],[27] This suggests that the project would be almost impossible to finance without partnering to spread the risk.

[23] Page 6, 'Small Modular Reactors- Key to Future Nuclear Power Generation in the US', Rosner and Goldberg, Energy Policy Institute at Chicago, 14 July 2011

[24] Page 2, 'New Nuclear Generation Capacity, Potential Credit Implications for U.S. Investor Owned Utilities', Moody's Corporate Finance, May 2008

[25] Page 13, 'New Nuclear Generation Capacity, Potential Credit Implications for U.S. Investor Owned Utilities', Moody's Corporate Finance, May 2008

[26] Assume 1 plant at 4,800 Euro / KW and 1,600 MW = Euro 7.6 billion,

[27] CapitalIQ as on September 2, 2014; Net Debt as per last filing

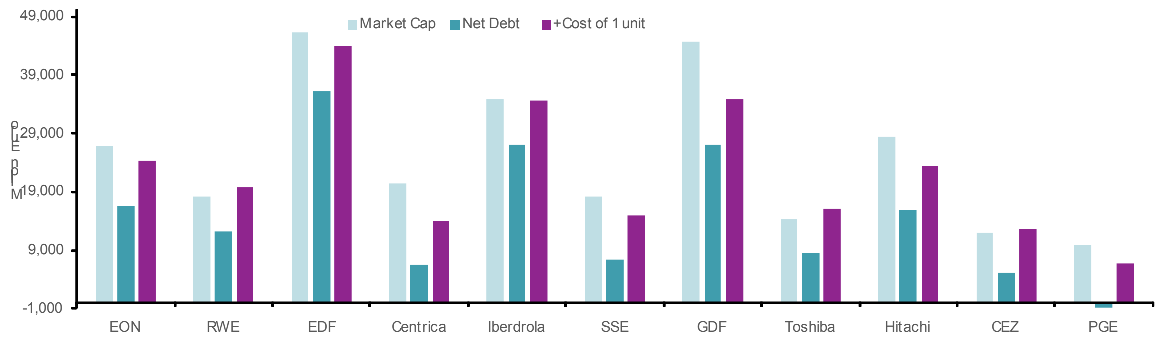

Figure 26 - Market Cap vs. Debt – investment in large Reactors

This is in comparison to SMRs, which depending on the reactor and configuration chosen is likely to require a capital outlay more in the £1bn - £2bn range which is actually comparable with a large off shore wind farm and only 15% of annual revenues (see above). Looking at the European utilities again, Figure 27[28] shows the vastly reduced impact of the additional debt requirement on the financial metrics of the companies.

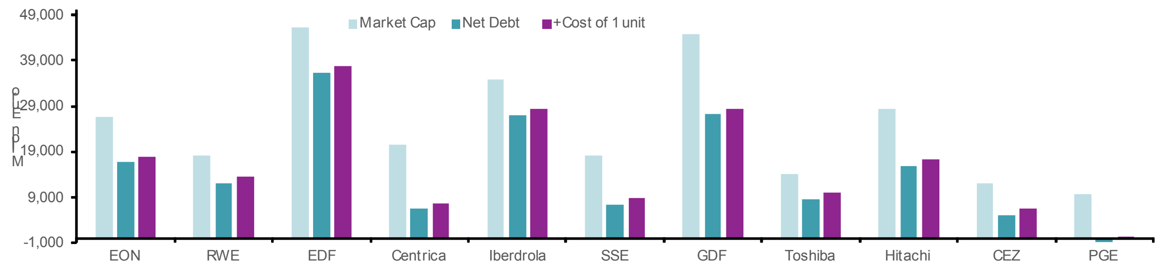

Figure 27 - Market Cap vs. Debt – investment in SMRs

It may be argued that the actual cost of capital itself (interest rate) may not be significantly reduced for an SMR compared to a GW reactor, until at least some of the FOAK assumed risks have been driven out or shown to be unfounded. Although, clearly, the reduced level of debt in comparison to the overall company value, the reduction of total interest payments, and the ability to manage costs overruns etc, will be key.

Furthermore the construction time to first “bars on the grid” reduces by up to a 1/3 permitting re-cycling of investments for the next build (again much like phased wind farm construction) reducing the risk of inflation and escalation and providing for multiple investment decision points and hence keeping capital free until absolutely required.

So while the actual cost of capital may not be differentiating factor the significantly reduced quantum of capital requirement (and hence impact on company metrics) and the ability to re-cycle capital over a shorter time frame means that SMRs have a real advantage over large reactors when it comes to financing.

[28] Assume 1 plant at 4,800 Euro / KW and 300 MW = Euro 1.4 billion

5.7 Conclusions

- The results represent the limited financial information received at this stage. More detailed analysis is required in conjunction with assessment of the various designs against the UK's specific requirements if a higher degree of accuracy is required.

- Current estimates suggest that the Overnight Capital Cost of SMRs is broadly in line with current market estimates for FOAK Large Scale Nuclear projects in the UK. With the potential for being comparable with NOAK costs for Large Scale Nuclear projects in the UK.

- Current estimates suggest that the LCOE of SMRs are broadly in line, if not slightly cheaper that the CfD Strike Price that has been announced for Hinkley Point C at circa £84/MWh. An assumption of 15 or more reactors and a programme to maximize the quantity of factory produced items has the potential to reduce the cost of electricity from SMR significantly below those anticipated for large reactors, with a conservative estimate currently being £67/MWh.

- The smaller capacity and shorter construction duration of SMRs means that revenue is generated quicker; there is less exposure to inflation and escalation risk during construction; plant size can be build to more closely match demand curves and smaller investment decisions can be made, freeing up capital.

- Costs can become more predictable and repeatable through the modularisation and factory production of a significant proportion of the reactor.

- The smaller "ticket size" and ability to re-cycle capital over shorter periods of time make the raising of debt capital a far more realistic option for SMRs.

6 UK Commercial Assessment (Government Involvement Options)

Financial involvement by the UK Government in the UK Nuclear Industry is a significant decision but consistent with the requirement to deliver the strategy laid out in the "UK Nuclear Future" paper, which has among its objectives:

- *<u>Being a 'top table' nuclear nation</u>, working in international partnerships leading the direction of future technology advances across the fuel cycle.*
- *To be a <u>key partner of choice in commercialising Generation III+, IV and SMR technologies</u> worldwide.*

An assessment has been carried out into why the UK should be involved in the design and development of SMR reactors. This also describes why UK industry is today indicating that the risks of involvement are too great and hence there is a need for Government involvement.

Involvement can be divided into two distinct steps.

1. Development of the engineering knowledge necessary to be an equal partner in an SMR design and development through financial involvement in R&D. This work can be generic and applicable to all of the SMRs considered in depth in this report. This work could be competed amongst UK companies, or led by the National Nuclear Laboratory (NNL) where the NNL involves capabilities from appropriate UK companies. Through such a programme the UK can develop the basic building blocks that can enable commercialisation of the resulting capabilities. This step will not happen without Government intervention.
2. Exploitation of the results of step 1. It would be necessary to establish a reactor vendor partnership that has the capabilities to exploit the results of the R&D work. An international partnership with an existing reactor vendor could at this stage be established via a competition considering a number of different criteria including but not exclusively:
    - The price (per MW) of the resulting power
    - Utilisation of the UK R&D developed knowledge
    - UK Supply Chain opportunities
    - Scope for International development
    - Technical assessment of the design including time to market
    - Commitment by a Utility to the partnership

    The study has considered a number of different mechanisms for step 2 however it is not clear at this stage whether or not market forces alone would be sufficient to ensure exploitation of the results of the R&D. This step is likely to be a competitive environment and there are significant complexities with respect to the need to involve an appropriate Utility, the CfD mechanism, implications of an EU assessment, the requirement to find a suitable site, site licensing and the GDA process etc. As a consequence this report is not attempting to define exactly how Step 2 should be taken or whether or not the Government would need to be financially involved. However a number of different mechanisms for Government involvement have been identified that could, at the appropriate point be considered.

<u>The UK opportunity</u>

The market study has shown that there is potentially a significant global market for SMRs. This could amount to 65-85GW of power over the next 20 years. Russia, Korea, China and Argentina are all preparing for construction of their designs and the USA has granted both mPower and Nuscale over $200M (approx £127M) each in support of their development programmes as part of a $452M (approx £287M) SMR support programme.

These reactors are (in various stages of their development) being designed, manufactured, and constructed in a number of countries today. However, only significant UK involvement in the development of a reactor is likely to result in skilled jobs in design and manufacturing in this country, serving a global market.

The financial section of this paper shows that there is a good chance that SMRs can produce electricity at least as cheaply as large Nuclear and considering learner curve theory, modularisation and value engineering potentially significantly cheaper.

The UK has a skilled nuclear workforce seen by vendors as credible in helping solve the challenges facing the SMRs in development. The known technical challenges for SMR designs are such that if we were prepared to actively work to address them, the possibility of securing a significant role throughout the supply chain, is very real. The UK currently has a nuclear industry of 60-70,000 people[29], built upon the historical ownership of nuclear reactor and fuel cycle facility design and intellectual property originating in BNFL and the CEGB. British engineers designed MAGNOX and Advanced Gas Cooled reactors; a UK company holds the design information for Sizewell B (under licence from Westinghouse) and Rolls-Royce has designed and delivered 27 complete reactors for the UK submarine programme. This has resulted in a nuclear supply chain, that now delivers support to nuclear industries around the world. The aim would be to replicate this capability for SMRs.

Barriers to private investment

In spite of these very positive signals UK companies continue to signal that the risk of investing in this market without government support is too great. This is not inconsistent with other parts of the energy sector or the nuclear industry in the USA where both Nuscale and mPower have entered into co-operative agreements with the DoE as part of the US Governments efforts to support their nuclear industry long term.

Large Nuclear has struggled to get launched in spite of relatively few technical hurdles. Site concerns, planning obligations, the events at Fukushima, GDA timescales, waste strategy, CfD negotiations, EU investigations, and funding, have all contributed to significant delays. None of these issues are technical, so for the SMR market, where the engineering hurdles are added to these other factors, shareholders perceive too many impediments; the risks are considered too great.

Government support for the fundamental R&D that SMRs still require would change the UK Nuclear industries perception of the overall risks for the SMR market. It is more likely that shareholders would be prepared to stand behind their organisations if they see a change to the risk to reward equation. There are many other areas where Government signalling its determination to support an SMR industry would also be seen as a positive sign, like suitably licensed sites, but without financial support for the R&D engineering in the short term these initiatives alone will not be sufficient.

There is every possibility of industry changing its position if a national programme can address some of the challenges. Furthermore governmental commitment to an R&D programme would convince industry that their interest is ultimately focussed on affordable electricity and therefore there is the potential for UK industry to make money for their shareholders in the long term.

- **Technical Maturity**

To date SMRs remain unproven technology, although the signs are positive there are a number of significant technical hurdles to overcome. The reactor vendors that have entered into detailed technical discussions as part of this feasibility study all have a number of problems to solve, some common and some unique to their

[29] NIA Jobs Map 2013 (Nuclear Industry Association)

particular designs. Technology Readiness Level (TRL) assessments have ranged the technical maturity from 3 to 7 (where 10 represents a fully mature technology). It is not certain how expensive it will be to resolve these issues and critically if they can be solved without fundamentally changing the economic analysis of the cost of electricity.

- **Regulatory Concerns**

Most of the operating models produced by the reactor vendors make assumptions about the eventual regulatory position both in terms of required changes to ensure acceptance in the UK through the GDA process but also in terms of the plant operations. The proposed assumptions are not at all unreasonable but cannot be taken for granted and if incorrect have the potential to significantly alter the timescales for deployment and the economic out turn.

- **Competing Energy Sources**

National commitments to climate change targets remain strong at the strategic level but potentially weak in the short term if alternative energy sources are, or become available. The significant fall in the price of gas in the USA with the productionisation of shale gas sources has given utilities alternative energy sources and has, as a consequence, weakened the demand for new conventional or SMR nuclear power.

From the point of view of a utility that exists to generate and sell electricity on the wholesale market, there is no shortage of technologies for power generation. National governments can create incentives to encourage use of clean technologies or disincentives for polluting technologies but this approach has not, to date, been adopted globally, even though this has been a key part of the UK Governments energy strategy.

However, the position of nuclear energy within this dynamic market remains uncertain, there are alternative low-carbon generation technologies. Given the development time of SMRs, or large-scale nuclear plants investors and shareholders will look at the global market with a healthy degree of scepticism

Even though nuclear power currently provides perhaps the only viable on demand low-carbon source of power, its position and acceptance within the global market remains uncertain. Many countries consider that there are viable alternatives. Given the development time of SMRs, or large-scale nuclear plants investors and shareholders will look at the global market with a healthy degree of scepticism

- **Public Perception**

  Whilst public perception of nuclear remains rational and pragmatic at the present this is not a position that can be guaranteed. Today there is a broad acceptability of nuclear power as a source of electricity within a balanced energy mix (a DECC public attitudes tracker survey March 2014 shows support for nuclear at 42% with 34% neutral).

  Public perception of nuclear energy in general and SMR technology in particular, will continue to be important to ensure the political mandate to take forward a strategy for this technology. Whilst the public are largely favourably disposed towards new nuclear build replacing existing nuclear generating capacity in the UK as part of a wider energy mix, it will be important to engage effectively with the public in areas such as SMR technology that might see nuclear energy as a greater proportion of the UK energy mix, and nuclear generation on power generating sites that have not, to date, hosted nuclear facilities. This will require an effective public engagement strategy at both national and local level that listens to local issues and addresses these in an open and transparent manner.

The Nuclear Industry Council report, "In the Public Eye: Nuclear Energy and Society" sets out a high level strategy for the effective engagement of the public on nuclear energy. This includes the recommendation to follow four best practice principles within a public engagement strategy on SMR technology:

- Ensure clarity in communications to enhance an appreciation of energy matters, recognising the social, economic and environmental benefit of nuclear energy and SMR technology;
- Build trust in those who communicate to enhance understanding of nuclear matters, recognising the need for respect, openness and transparency;
- Enable dialogue with the public to provide opportunities to listen and address those issues which are in the public mind, recognising the value of challenge; and
- Facilitate consultation with local stakeholders and those who may have influence on nuclear energy matters, recognising the need to be a good neighbour.

To help ensure clarity in all public engagement it will be important that particular elements of the key messages associated with SMR technology, e.g. that SMRs provide an effective and cost effective route for the production of secure low carbon energy, are developed into a clear and concise strategic narrative that provides a touchstone fort all communications are clear and consistent. It will be important that such a narrative recognises and addresses public views on nuclear and SMR technology in an open, honest and transparent way. The only way such views can be understood is by creating space to listen, and it will therefore be critically important to facilitate dialogue with the public in a manner that respects opinion and addresses priority issues in a clear and honest manner. It will be particularly important that those living close to potential SMR sites—whether these be existing nuclear sites or not—have the opportunity to engage in meaningful consultation, e.g. through local stakeholder groups. Consultation will need to address how nuclear/SMR technology can best be deployed in a manner that provides local benefit to those most affected by the development.

The Economic case for UK Government involvement in SMR Development

The economic case for Government involvement in the Research and Development has not been fully developed as part of this study. It is fully recognised that the development of a full business case using the Green Book Five Case model including a detailed economic case will be required in due course. However an overall stepped approach has been identified:

1. Government involvement in the generic R&D of SMRs
2. An international reactor vendor partnership is established through competition exploiting the results of the generic R&D.
3. The resulting deal in terms of electricity prices and economic impact justifies the original investment

This process is not entirely dissimilar to the current CCS Commercialisation programme, where upfront FEED (Front End Engineering and Design) contracts have been awarded to gain a more mature offering as part of an overall deal which includes significant grant funding. The key difference with the proposed SMR approach is that the major investment is in the R&D programme and so the Government will benefit from retaining intellectual rights that will provide for returns for the tax payer and other economic benefits even if there is not further investment in a partnership. Consideration will also need to be given to the implications on Government budgets and spending limits. Clearly a number of options will raise issues from an EU perspective including procurement limitations and an assessment of the Market Economy Investor Principle (MEIP). It is recommended that this be investigated further.

The successful development and commercialisation of an SMR industry in the UK, has the potential to deliver a significant number of benefits as outlined elsewhere in this report. However the market is not mature enough for private enterprise to take the risk and make a significant capital investment at this moment in time. To facilitate the UK Nuclear industry the broader government perspective can consider the longer-term wealth creation from an industry involved in New Nuclear, in a way not possible on the new large reactor as well as ultimately an economic source of green electricity.