Department of Energy & Climate Change

NATIONAL NUCLEAR LABORATORY

SMR Techno-Economic Assessment

Project 3: SMRs Emerging Technology

Assessment of Emerging SMR Technologies
Summary Report

For The Department of Energy and Climate Change

15th March 2016

Notice

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Date of assessment was March 2016.

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Acronyms and Definitions

Acronym	Name	Definition
CF	Capacity Factor	The capacity factor is the actual power produced over a period of time expressed as a percentage of the power that may have been produced if the station was running at full power for that period
CAPEX	Capital Expenditure	Capital expenditures (CAPEX) are expenditures either to buy fixed assets or to add to the value of existing fixed assets.
CHP	Combined Heat and Power	Combined Heat and Power (CHP) refers to the use of a plant to provide both power to generate electricity and useful heat for industrial applications. Operation to produce both heat and power may occur simultaneously or independently.
	Commercial Deployment	Commercial deployment is the putting into service by the generation of electricity or distribution of heat as export(s) on a revenue-earning basis. This could include a FOAK as long as it was revenue-earning.
DECC	Department of Energy & Climate Change	The Department of Energy & Climate Change (DECC) is a UK Government department with responsibility to make sure the UK has secure, clean, affordable energy supplies and promote international action to mitigate climate change.
DH	District Heating	District Heating is a system for distributing heat generated in a centralised location for residential and commercial heating requirements such as space heating and water heating.
ERPO	Extended Reduced Power Operation	In Extended Reduced Power Operation a unit is required to run a multiple number of consecutive hours at reduced power
ESME	Energy System Modelling Environment	ETI's whole energy modelling tool; Energy System Modelling Environment. This is used to populate the SESO model delivered by ETI to DECC and Project 1, informing Project 3
ETI	Energy Technologies Institute	The Energy Technologies Institute (ETI) is a public-private partnership between global energy and engineering companies and the UK Government. The role of ETI is to act as a conduit between academia, industry and the government to accelerate the development of low carbon technologies.
FOAK	First Of A Kind	First Of A Kind (FOAK) implies that the item or generation of items is new or novel. Used in engineering economics with the understanding that FOAK can cost significantly more than later items.
	Flexibility Factor	The flexibility factor of a power plant refers to the rate that an electricity generation plant can follow the load requirements of the consuming grid.
FR	Fast Reactor	Nuclear reactor technology in which the fission chain reaction is sustained by fast neutrons (instead of moderated thermal-neutrons) and thus does not require a neutron moderator. Also referred to as a 'Fast Neutron Reactor' or 'Fast Spectrum Reactor'.

Acronym	Name	Definition
GCR	Gas-Cooled Reactor	Nuclear reactor technology that uses graphite as a neutron moderator and carbon dioxide or helium as coolant. Alternative reactor designs that use gas to remove heat from the fuel but do not use a graphite moderator are excluded from this definition. The UK civil nuclear industry has utilised this technology with a fleet of Magnox reactors followed by Advanced Gas-Cooled Reactors (AGRs).
GDA	Generic Design Assessment	Used by UK regulators to assess the safety, security and environmental implications of new nuclear reactor designs separately from applications to build them at specific sites.
GDF	Geological Disposal Facility (GDF)	A Geological Disposal Facility (GDF) is a is a highly-engineered facility capable of isolating radioactive waste within multiple protective barriers, deep underground, to ensure that no harmful quantities of radioactivity ever reach the surface environment.
	Generic Small Modular Reactor	A Generic SMR is a PWR having a capacity of less than 300MWe. It should be capable of being deployed in multiple units, is based on currently PWR technology and uses pumped cooling.
GEN IV	Generation IV	Reactor designs studied by the Generation IV International Forum (GIF). Their designs include thermal and fast neutron spectra cores, closed and open fuel cycles. The reactors range in size from very small to very large. Depending on their respective degree of technical maturity, the first Generation IV systems are expected to be deployed commercially around 2030-2040.
GFA	Generic Feasibility Assessment	Assessment tool developed by National Nuclear Laboratory, The University of Manchester's Dalton Nuclear Institute and Integrated Decision Management Ltd to help assess the possible roles of different nuclear systems in the UK.
GIF	Generation IV International Forum	An international body that studies advanced reactor designs (see GEN IV)
GWd	Gigawatt days	The power generated by a 1 gigawatt generator in a day
GWd/tHM	Gigawatt days per tonne heavy metal	The power in gigawatts generated a tonne of heavy metal (generally uranium and/or plutonium) in a reactor
GWe	Gigawatt electrical	The electrical power generated in gigawatts (1000,000,000 watts)
GWth	Gigawatt thermal	The thermal power generated in gigawatts (1000,000,000 watts)
HTGR	High Temperature Gas Reactor	High temperature gas-cooled reactor is a Generation IV reactor concept that uses a graphite-moderated nuclear reactor with a once-through uranium fuel cycle.
IAEA	International Atomic Energy Agency	The International Atomic Energy Agency (IAEA) is an international organisation that serves as an intergovernmental forum for scientific and technical cooperation in the peaceful use of nuclear technology and nuclear power worldwide.
LFR	Lead Cooled Fast Reactor	Fast reactor systems that utilise lead as the coolant at temperatures less than or approximately equal to 550°C. Lead-bismuth eutectic is also used as a coolant

Acronym	Name	Definition
LCOE	Levelised Cost of Electricity	The Levelised Cost of Electricity (LCOE) represents the unit cost (per-kilowatt hour) in real value of building and operating a power plant over an assumed financial life and duty cycle.
	Load Factor	The load factor is the ratio of the average load to the peak load during a period of time
	Load Following	A load following power plant adjusts its power output in response to fluctuations in demand for electricity.
LOLE	Loss Of Load Expectation	Loss Of Load Expectation (LOLE) represents the number of hours per annum in which, over the long-term, it is statistically expected that supply will not meet demand.
LWR	Light Water Reactor	Nuclear reactor technology that uses normal water, (H_20) as opposed to heavy water (D_20), as both the coolant and neutron moderator.
LWGR	Light Water Graphite Reactor	The light water graphite reactor (LWGR) is a pressurised water-cooled reactor with individual fuel channels and using graphite as its moderator. The Soviet-designed RBMK is only reactor technology to utilise graphite moderator with water coolant. The RBMK was the design involved in the 1986 Chernobyl disaster.
MEL	Maximum Export Limit	The Maximum Export Limit is the maximum power output ; expressed in MWe
MOX	Mixed Oxide Fuel	Mixed Oxide Fuel (MOX) refers to nuclear fuel containing more than fissile oxide material. Generally this consists of a combination of Plutonium oxides and uranium oxides.
MSR	Molten Salt Reactor	A molten salt reactor (MSR) is a class of nuclear fission reactors in which the primary coolant, and in some designs even the fuel itself, is a molten fluoride salt mixture. The early concepts and many current ones rely on nuclear fuel dissolved in the molten fluoride salt as uranium tetrafluoride (UF_4) or thorium tetrafluoride (ThF_4). The fluid would reach criticality by flowing into a graphite core which would also serve as the moderator.
MSFR	Molten Salt Fast Reactor	A molten salt reactor (MSR) which does not use a moderator and operates with neutrons in the fast spectrum range
MSThR	Molten Salt Thermal Reactor	A molten salt reactor (MSR) which does uses a moderator and uses neutrons in the thermal spectrum range
NOAK	Nth of a Kind	Used in engineering economics to identify the Nth item or generation of items following on from the FOAK.
NPV	Net Present Value	Net Present Value (NPV) is a calculation that compares the amount invested today to the present value of the future cash receipts from the investment.
O&M	Operations and Maintenance	Operations and Maintenance (O&M) costs is a term typically used in the power generation industry to describe the cost of running and conducting routine maintenance on the plant.
OCC	Overnight Capital Cost	Overnight capital cost is a term typically used in the power generation industry to describe the cost of building a power plant overnight. The overnight capital cost does not take into account financing costs or escalation, and hence is not an actual estimate of construction cost.

Acronym	Name	Definition
OPEX	Operating Expenses	Operating Expenses (OPEX) are expenditures incurred during the ongoing operation of a plant. The term is used interchangeably with Operating Expenditure, Operational Expense and Operational Expenditure. It is alternatively referred to as Operating Costs.
PBR	Pebble Bed Reactor	The pebble-bed reactor (PBR) is a graphite-moderated, gas-cooled nuclear reactor. The basic design of pebble-bed reactors features spherical fuel elements called pebbles, made of pyrolytic graphite (which acts as the moderator) and contain thousands of micro-fuel particles. The uranium, thorium or plutonium nuclear fuels are in the form of a ceramic (usually oxides or carbides).
PCI	Pellet-Clad Interaction	The mechanical interaction of LWR fuel pellets and cladding, typically during power up-rates, which can stress the clad and ultimately contribute to clad failure.
PRPP	Proliferation Resistance and Physical Protection	Proliferation Resistance and Physical Protection (PRPP) is a combination of Proliferation Resistance 'that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by States in order to acquire nuclear weapons or other nuclear explosive devices' [1] and Physical Protection, which 'refers to those features of the nuclear system that provide intrinsic protective barriers that help prevent nuclear materials being accessed by a terrorist group' [2].
PWR	Pressurised Water Reactor	Pressurised water reactors (PWRs) are a type of light water reactor (LWR). In a PWR, the primary coolant (water) is pumped under high pressure that prevents boiling, to the reactor core where it is heated by nuclear fission reactions. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator.
R&D	Research and Development	Research and Development (R&D) refers to any activities in connection with innovation or the development of new products or procedures
SAPs	Safety Assessment Principles	Safety Assessment Principles (SAPs) are applied by the ONR to the assessment of safety at existing or proposed nuclear facilities to establish safety cases.
SEL	Stable Export Limit	The Stable Export Limit is the minimum available power output when running ; expressed in MWe
SFR	Sodium Fast Reactor	The sodium-cooled fast reactor (SFR) is a Gen IV reactor project to design an advanced fast neutron reactor utilising sodium as the coolant at temperatures less than or approximately equal to 550ºC.

Acronym	Name	Definition
SMR	Small Modular Reactor	Advanced reactor that produce electric power of less than 300 MWe, designed to be built in factories and shipped to utilities for installation as demand rises. The Parsons Brinckerhoff (PB) Specification [3] defines Small Modular Reactors as reactors below 300 MWe designed for off-site fabrication. The International Atomic Energy Agency (IAEA) official definition of SMRs is advanced reactors that produce electric power up to 300 MWe, designed to be built in factories and shipped to utilities for installation as demand arises [4]. These definitions do not make a distinction regarding technology, safety systems or reactor generation. Accordingly, an SMR can be a proven technology downscaled to produce less than 300 MWe, but also a revolutionary design using fuel or safety systems that have never been tested before for the commercial production of electricity.
SM-HTGR	Small Modular High Temperature Gas Reactor	Small (<300 MWe) Modular High Temperature Gas-cooled Reactor (see HTGR)
SM-LFR	Small Modular Lead Fast Reactor	Small (<300 MWe) Modular Lead-cooled Fast Reactor (see LFR)
SM-MSFR	Small Modular Molten Salt Fast Reactor	Small (<300 MWe) Modular Molten Salt Fast Reactor (see MSFR)
SM-MSThR	Small Modular Molten Salt Thermal Reactor	Small (<300 MWe) Modular Molten Salt Thermal Reactor (see MSThR)
SM-PWR	Small Modular Pressurised Water Reactor	Small (<300 MWe) Modular Pressurised Water Reactor includes the Generic SMR as defined together with variants using natural rather than pumped circulation of the coolant
SM-SFR	Small Modular Sodium Cooled Fast Reactor	Small (<300 MWe) Modular Sodium Cooled Fast Reactor (see SFR)
TEA	Techno-Economic Assessment	The techno-economic assessment (TEA) is a study with the objective of delivering the necessary evidence base to inform a policy decision on whether the UK Government should support the development and deployment of SMRs within the UK.
TRL	Technology Readiness Level	Technology Readiness Levels (TRLs) are a method of estimating technology maturity of critical technology. TRLs are based on a scale from 1 to 9, with 9 being the most mature technology

Executive summary

The Department of Energy and Climate Change (DECC) commissioned a detailed Techno-economic assessment (TEA) into Small Modular Reactor (SMR) designs, aiming to deliver the necessary evidence base to underpin a policy decision on the development and deployment of SMRs in the UK. This report examines the potential suitability of Emerging SMR Technologies, defined as ‘those SMR systems not considered to be available for deployment in the UK by 2030.’

The examination methodology employed was based upon the Generic Feasibility Assessment (GFA) technique developed for DECC by the National Nuclear Laboratory (NNL), the Dalton Nuclear Institute of the University of Manchester (Dalton) and Integrated Decision Management Limited (IDM). The GFA methodology provides the Benefits and Challenges offered by the Emerging Technologies against 12 Attributes which have an audit trail back to internationally recognised evaluations of advanced nuclear reactor systems. The GFA technique is particularly suited to the examination of Emerging Technologies since it is based upon public domain information and referenced sources. This allows an open and transparent evaluation of technologies which do not have the technical maturity to be examined at the level required for them to be licensed in the short to medium term.

Over 40 SMR concepts were reviewed from available literature and web-based searches and 6 SMR technology groups were derived, namely:

1. Small Modular Pressurised Water Reactors (SM-PWR)
2. Small Modular Sodium-cooled Fast Reactors (SM-SFR)
3. Small Modular Lead-cooled Fast Reactors (SM-LFR)
4. Small Modular Molten Salt Fast Reactors (SM-MSFR)
5. Small Modular Thermal Neutron Molten Salt Reactors (SM-MSThR)
6. Small Modular High Temperature Gas-cooled Reactors (SM-HTGR)

It is believed that these concepts and groups cover the totality of the SMR technologies which have commercial interest in their continued development and deployment. The Emerging Technologies were examined against timescales of (a) deployment by around 2030 and/or (b) the ability to contribute materially to the UK’s 2050 decarbonisation commitment of an 80% reduction relative to 1990 levels.

In order to provide a baseline, the SM-PWR was compared with a Gigawatt-sized Pressurised Water Reactor. The Emerging Technologies could then be assessed against this agreed Generic SM-PWR as the Reference case to obtain a review of their relative Benefits and Challenges in relation to the 12 Attributes.

The Benefits and Challenges were then evaluated against:

- The operational requirements for SMRs in a UK energy mix – notably the requirement to operate flexibly, especially in ‘electricity futures’ with a high penetration of intermittent renewable generation and/or a low penetration of gas generation with carbon capture and storage.
- The ability to provide fuel and radioactive waste management for the various Emerging Technologies.
- The importance of each Attribute to the economics of electricity generation by considering the components of the Levelised Cost of Energy (LCOE) in international studies of nuclear energy.
- The potential for non-electricity generation roles for SMRs, for example the provision of high temperature process heat for helping to decarbonise industrial processes and transport operations.

The results of these examinations were:

Electricity Generation Requirements for SMR Deployment

A decarbonised UK electricity generation system will need to accommodate a significant volume of intermittent output from renewable sources. This will place a requirement on dispatchable low-carbon generation to operate flexibly. The flexibility required from SMRs in a variety of energy futures was examined, and found to be significant, particularly where gas generation with carbon capture and storage was limited or absent. However, when operated flexibly, SMRs generate less electricity while their generation costs remain essentially fixed. A commercial framework would have to be developed which would allow SMRs to operate under these conditions.

Observations on GFAs of Emerging Technologies

All the Emerging Systems offer benefits on some of the assessed GFA Attributes, for example:

- The fast reactor systems (SM-SFR, SM-LFR, SM-MSFR) offer a very much reduced requirement for uranium, and could essentially remove the dependence of power generation on the security of uranium supply. However, uranium supply/price is not viewed as a major driver in the short to medium term.
- Systems using recycling (e.g. fast reactors) can offer waste disposal advantages, but this is, in most cases, combined with the requirement to develop novel treatment routes for challenging wastes.
- When deployed as low-capacity (<<1GWe) groups, SMRs can have siting Benefits because of lower cooling water and grid connectivity requirements. The level of Challenge will increase as site capacity rises or elements of the back end of the fuel cycle are required to be co-located on the reactor site.
- All the Emerging Technology groups were potentially more flexible in operation than SM-PWRs, but not by a sufficient margin to be a ‘game changer’.

A combination of a lack of technical maturity, together with the likely time and effort for licensing and deployment indicates that all Emerging Technologies except SM-HTGR are at least significantly challenged on ‘Time and Cost to Deployment’ relative to SM-PWRs.

Levelised Cost of Electricity (LCOE)

A review of the Levelised Cost of Energy (LCOE) has allowed a balanced view of the likely economic importance of the Benefits and Challenges of the Emerging Technologies. The cost components making up the LCOE reveal:

- An overriding importance of capital and financing costs, including discount rate (50% to 80% of LCOE as discount rate varies from 3% to 10%)
- A comparatively small dependence on fuel cycle costs (20% to 10% of LCOE as discount rate varies from 3% to 10%)
- A small effect of waste treatment and disposal costs (5% to 2%)
- A minuscule effect of decommissioning costs (1.0% to 0.1%)

In this light, few of the benefits identified for Emerging Technologies can be judged to be significant to electricity generation costs. This leads to the conclusion that none of the Emerging Technologies are likely to generate electricity cheaper than SM-PWRs, at least up to 2050.

Nuclear Futures

SM-PWRs represent the least cost generation option for SMR technologies, and can provide low grade heat for district heating and some industrial processes. However, Emerging Technologies can offer other advantages in UK energy futures where high temperature process heat is used directly to decarbonise industrial and/or transport activities. For such futures, for example using process heat in support of hydrogen as an energy vector, Emerging Technologies offer higher temperatures than SM-PWRs, with the SM-HTGR technology offering the highest temperatures and the least challenges on timescale and cost grounds.

Learning Points

The application of the Generic Feasibility Assessment methodology proved to be effective in clarifying the Benefits and Challenges of the different Emerging Technologies across a large range of technical maturity and development. Reliance upon public domain information backed up by professional technical judgement may overstate Challenges in cases where proprietary information is available to proponents of Technologies. A GFA offers the opportunity for technology proponents to substantiate a change in the assessment thereby increasing confidence in the credibility and robustness of the technology and specific design.

The examination of GFA Attributes across the five Emerging Technologies and the Generic SM-PWR Reference was instructive in comparing the relative Benefits and Challenges between the Technologies, and also acted as a check on the consistency of the assessments.

Applying the concept of the Lifecycle Cost of Energy provided insights into the likely economic weight to be attributed to various Attributes. The Discount Rate to be applied in technology assessment was seen to be particularly relevant. However, the question of the appropriate discount rates to be applied over the timescales of Project 3 (e.g. Technology Readiness Level 2, timescale for deployment 2070) was not addressed. The influence of discount rate on LCOE needs to be treated as a more transparent parameter in economic assessments.

It could be assumed that the greater the technical certainty, the lower the discount rate that could be applied, and the power of the discount rate in affecting LCOE will make the choice of discount rate very important.

The study was primarily focussed on electricity generation with the conclusion that none of the emerging technologies were likely to provide economic advantages to the SM-PWR in the short or medium term. However the extent that high temperature heat is required for decabonisation, emerging technologies could have a role with SM-HTGR best positioned. The system drivers which might favour SM-HTGR's were not examined in such detail that would enable a decision whether to support development of the system in and for the UK. We gratefully acknowledge the assistance, including peer-review, provided by Atkins, EDF Energy R&D UK and the University of Manchester.

1. Introduction

1.1. Introduction and Background

The Department of Energy and Climate Change (DECC) has commissioned a detailed techno-economic assessment (TEA) into Small Modular Reactor (SMR) designs. The TEA is designed to deliver the necessary evidence base to inform a policy decision on whether the Government should support the development and deployment of SMRs within the UK and identify solutions to any challenges highlighted. DECC wishes to understand how SMR deployment could fit within existing UK capabilities and strengths throughout the technical assessment.

There are a total of seven projects that make up the programme of work, which include:

Project 1 – SMRs: Comprehensive Analysis and Assessment

Project 2 – SMRs: Systems Optimisation Modelling

Project 3 – SMRs: Emerging Technologies

Project 4 – SMRs: UK Regulatory Regime

Project 5 –SMRs: Advanced Manufacturing

Project 6 – SMRs: Advanced assembly, modularisation and construction

Project 7 – SMRs: Control, operation and electric systems

1.2. Project 3 Description

Paragraph 15 of the Invitation to Tender (ITT) issued by DECC defines the requirements of Project 3 as:

"This study is expected to deliver a strategic assessment system, including market assessment, for emerging technologies and apply this system to the future nuclear industry".

For the purposes of this study, Emerging Technologies are defined as those SMR systems which are considered not to be available for deployment in the UK by 2030 and in which a commercial interest in development and deployment has been shown.

In delivering the required strategic assessment of Emerging Technologies, Project 3 has drawn upon the Generic Feasibility Assessment (GFA) methodology, developed for DECC by the National Nuclear Laboratory (NNL), The Dalton Nuclear Institute of the University of Manchester, and Integrated Decision Management Ltd (IDM). The GFA methodology is described more fully in Section 2.

Using the GFA approach allowed Project 3 to assess Emerging Technologies using only public domain information on the various technologies augmented by professional knowledge and judgement of the Project Partners.[1]

[1] NNL, IDM, EDF Energy R&D UK Centre and University of Manchester

2. Generic Feasibility Assessment

2.1. Generic Feasibility Assessment – What it is and what it isn't?

The Generic Feasibility Assessment methodology provides a high level method of assessing the different nuclear reactor and fuel cycle systems which the UK might want to consider for the future.

The GFA concept seeks to answer the high level strategic question:

"What are the attributes of a nuclear energy system which would justify investment in its future development with view to deployment in the UK?"

For this strategic analysis, the GFA concept starts from the recognition that, in the UK context, safety, environmental and proliferation/security attributes are all covered by well-developed regulatory regimes – so that reactor system deployment is not about "how safe, secure, and environmentally benign" a system is – but rather how much time and effort must be expended to allow the system to conform with these tried and tested regulatory frameworks.

The GFA methodology sets up a number of Attributes (supported by more detailed Sub-Attributes and Metrics) against which to assess a candidate system. The conventional approach would then be to subject the data to Multi-Attribute Decision Analysis (MADA), where, each system would be given a 'score' on each of the Metrics, Sub Attributes and Attributes (i.e. How much? How long? How many?). The Metrics, Sub Attributes and Attributes are then given 'weights' reflecting how important each is thought to be, and scores are then multiplied by the weights and the system acquires an overall rating.

It was successfully argued that, even with a modest number of Metrics, the 'score-weight combination MADA process' becomes complex and can be very opaque. The GFA methodology seeks to address the complex assessment of nuclear energy systems in a way which makes the results assessable and transparently underpinned by detailed information. GFA uses paired comparisons (with for example, the 'new system' compared with the 'current system') and with 'scores' replaced by a limited number of levels of either 'benefits' or 'challenges' offered by the 'new system' compared with the 'current system'. Each assessed 'benefit' or 'challenge' is backed up by a short explanation and, where available, by references. The output of the GFA is a hyperlinked pdf document which allows easy navigation throughout the Metric/Sub Attribute/Attribute 'tree', with a visual presentation of the level of challenge or benefit on charts such as the one shown in Figure 1.

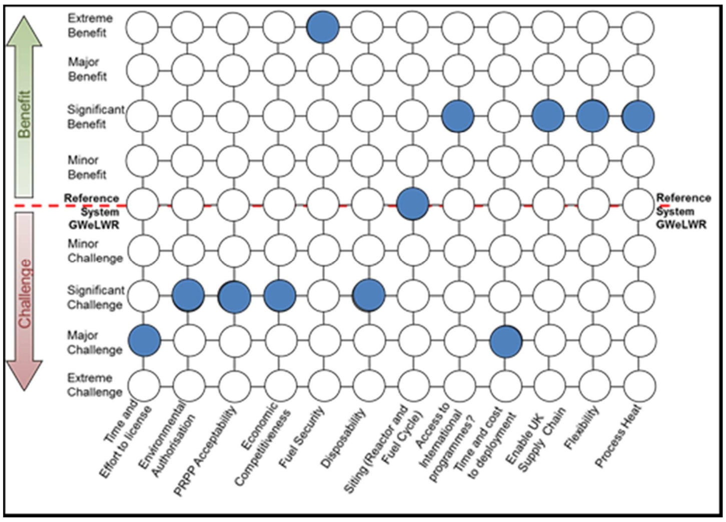


Figure 1: Comparison View for System Attributes compared to a Reference System (in this case a comparison of the Gen IV International Forum (GIF) Molten Salt Fast Reactor with a GWe-sized LWR) [5]

Very importantly, all the information used in undertaking a GFA is taken from public domain sources. In effect, GFA replaces an opaque mathematical combination methodology with a series of reasoned arguments based on a commonly available data set. In using public domain information, GFA says 'given what we know, these are the benefits and detriments'. If more information is made available, the assessment can change; it is a 'work in progress', and is itself intended to be made available in the public domain.

As mentioned, GFA is based on paired comparisons, and conventionally the 'base case' is termed the 'Reference System', with the 'proposed case' being termed the 'Subject System'. By building up a data set of 'A to B', 'A to C' etc comparisons, the assessment of 'B to C' etc cases becomes progressively easier. A fuller explanation of the GFA methodology is available on the Dalton Nuclear Institute Website (see Ref. [6]).

In Summary, GFA can:

- Identify strategically significant factors
- Highlight the difficult questions and uncertainties (Challenges) relating to a system,
- Show the conditions under which each system might be successfully deployed and the Benefits that might accrue.
- Identify information gaps which need to be filled.
- Help prioritise research needs;
- Provide a focus on innovation opportunities;

However, GFA operates within well-defined constraints:

- GFA **helps** decisions, it doesn't seek to **make** them
- It examines **relative** Challenges and Benefits – it is not directly trackable to monetary values or exact timescales
- It clarifies the issues and assesses the 'fit' of systems into UK energy futures, it does not determine what those futures should be.

2.2. GFA Attributes

The GFA methodology has developed 12 Strategic Attributes derived from reports produced by NNL for DECC, a body of work dating from 2012 to the present [7**,**8**,**9**,**10**,**11**], underpinned by a series of Attributes and Metrics, the Metrics being ultimately traceable back to assessment methods used in the Generation IV International Forum [**12**].**

Table 1 provides a summary of the Strategic Attributes, Attributes and Metrics.

Table 1: GFA - summary of the Strategic Attributes, Attributes and Metrics

No	Strategic Attribute (SA)	At. No	Attributes	Metrics identified in NNL Reports
Regulatory Challenges and Timescales				
1a	Safety, Licenseability	1a.1	Effort to satisfy ONR Safety Assessment Principles (SAPs)	12. Safety 13. Reactivity control 14. Decay heat removal 15. Low uncertainties on dominant phenomena 16. Fuel thermal response 18. Source term 19. Energy release mechanisms 20. System response times 21. Effective holdup 34. Benefits or risks for security
		1a.2	Timescale required to demonstrate SAPs can be satisfied	
		1a.3	Ability to meet radiological regulations	11. Worker exposures
1b	Environmental Authorisation	1b.1	Ability to meet environmental regulations	06. Environmental impact
1c	PRPP acceptability	1c.1	Does the fuel cycle involve the production of high grade fissile materials at any stage?	07. Separated Materials 37. Proliferation resistance
		1c.2	Are the nuclear materials in the fuel cycle in a form that provides inherent self-protection against theft or dispersal?	08. Spent fuel characteristics 09. Sabotage resistance
Economic Competitiveness				
2a	Economic Competitiveness	2a.1	Overnight construction cost	22. Overnight Construction Costs 24. Construction duration 29. Scaleability 38. Ease of Construction
		2a.2	Operating and maintenance cost	10. Reliability 23. Production costs (O&M)
		2a.3	Fuel cycle cost - fuel cycle cost (front-end and back-end combined)	

No	Strategic Attribute (SA)	At. No	Attributes	Metrics identified in NNL Reports
		2a.4	Decommissioning cost	41. Decommissioning Cost
		2a.5	R&D cost (feed from HLD1)	17. Integral experiment scaleability 26. R&D costs
Deployment				
3a	Fuel Security	3a.1	Ability to Deploy - Fissile material availability	
		3a.2	Spent fuel characteristics - Is the spent fuel compatible with existing reprocessing technology?	
		3a.3	Uranium dependence	01. Fuel utilisation 39. Sustainability
3b	Waste Storage and Disposability	3b.1	Waste Forms - are the waste forms compatible with existing waste management and disposal routes?	
		3b.2	GDF disposal impact - Waste incorporation rate	33. Waste arisings – volumes of HLW, ILW, LLW
		3b.3	GDF disposal impact - Long term decay heat	04. Long term heat output 27. Plutonium and minor actinide management
		3b.4	GDF disposal impact - Long term radiotoxicity	02. Spent Fuel Mass 03. VHLW volume 05. Long term radiotoxicity
		3b5	Isotopes driving safety case	To be developed
3c	Siting	3c.1	Siting - number and size of reactors c/f likely site availability	32. Flexibility of location 35. Number and size of reactors needed
		3c.2	Siting – associated fuel cycle plants	36. Fuel cycle plants
Development Route and Timescale				
4a	Access to International Programmes	4a.1	Re-engagement in international programmes	
4b	Time and cost to deployment	4b.1	Commercial availability - Deployment time – plus in-feed from 1 and 2a	25. Development costs 30. Timescales to deployment
		4b.2	Technology Readiness Level	31. Technology Reference Level
4c	Meet market and enable supply chain	4c.1	Market Failure (To be developed)	
		4c.2	Supply chain opportunities	
Market Matching				
5a	Meets Energy Requirements - Load-follow capability	5a.1	Load-follow capability	28. Load follow capability
5b	Meets Energy Requirements – Process Heat	5b.1	Industrial process heat – potential to drive thermal processes	40. Potential to drive thermal processes 42. Primary purpose

This summary table has been developed through use, and provides the technical basis for the GFA template.

Many of the roles being considered for Small Modular Reactors, particularly those classed as 'Emerging Technologies' have a higher focus on their ability to meet non-baseload energy requirements than previous assessments. This reflects the fact that, as higher proportions of intermittent renewable generation is added to the grid, there is an imperative to provide variable dispatchable power to balance the system. There is a need to understand how nuclear generation, particularly from SMRs, can contribute to this balancing. Additional work has therefore been incorporated in Project 3 to increase the understanding and analysis of the requirements and capability of the Flexibility Attribute (5a in the

Table 1). Section 6 discusses the flexibility that SMRs would need to contribute to the generation system, and the technical requirements under various generation futures are given in a separate study [**13**].

3. Defining Options

3.1. 'Emerging Technologies' Methodology

The stages adopted in the Project 3 assessment of the suitability of Emerging Technologies are given in Table 2.

Table 2: Methodology for assessing Emerging Technology SMRs

Stage No	Stage	Description	Section Number
i	Derive GFA Template.	GFA methodology described in Section 2.	2
ii	Define methodology for assessing Emerging Technologies.	As detailed in Table 2.	3.1
iii	Define Generic SMR.	Defines Reference Case against which emerging systems will be assessed.	3.2
iv	Define Technology Groups for Emerging Technologies.	Groupings based on Gen-IV reactor type definitions, level of commercial interest, technical challenges and fuel cycle properties. See 0.	3.3
v	Produce Technical Reviews of Emerging Technology Groups using public domain information.	General review of Emerging Technologies in 3.3.	3.3
vi	Compare Generic SMR against a Reference Case of a 1 GWe LWR.	Will clarify the challenges faced by Generic SMRs in gaining market share from GWe-sized LWRs.	4.2
vii	Compare of Emerging Technology Groups with Generic SMR as the Reference Case – produce GFAs and GFA summaries with Comparisons across Technology Groups.	Outlines benefits and challenges of Emerging Technology Groups when compared with the Generic SMR, and cross-comparisons between emerging technologies based on GFA Attributes.	4.3 – 4.8
viii	Clarify the factors contributing to the Levelised Cost of Energy for nuclear (LCOE).	Examine the importance of the various economic factors in the buildup of Levelised Cost of Energy for nuclear (LCOE).	5.1
ix	Examine Possible nuclear constraints (U availability, disposal etc) c/f GFA results.	Which GFA benefits and challenges are likely to develop into economic drivers for reactor choices?	5.2

Stage No	Stage	Description	Section Number
x	Define a range of UK Energy Futures in which SMRs could operate, and examine SM technology assessments from (vi) to (viii) to determine possible/likely uses and the factors favouring such uses.	Examining factors associated with UK energy usage and how it can be decarbonised, the timing/technology of nuclear decarbonisation opportunities.	6.1
xi	Future flexibility – define the range of flexibility required for future generation systems, and the ability of SMR technologies to provide this.	Examining the operational requirements for nuclear electricity generation in various UK energy futures.	6.2

3.2. Defining a Generic SMR

For the purposes of this Project, the following definition was agreed:

> A Generic SMR is a PWR having a capacity of less than 300 MWe. It should be capable of being deployed in multiple units, is based on current PWR technology and uses pumped cooling.
>
> This Generic SMR will be adopted as the baseline against which SMRs using other LWR technologies could be assessed, for example PWRs using natural convection cooling. However, such technologies should have development and deployment schedules such that a second of a kind commercial plant, benefitting from operation and refuelling demonstration from a First of a Kind (FOAK) anywhere in the world, could be built, commissioned and operating in the UK from 2030 or soon thereafter.

The maximum of less than 300 MWe conforms to the current IAEA definition of a Small or Medium Reactor [**4**], here refined to define a Small Modular Reactor. The 2030 deployment date was derived from work by ETI and accepted by all participants in the Project, including DECC. The timescale in this definition – “built, commissioned and operating in the UK from 2030 or soon thereafter” – is shorter than the 2032 date estimated for ETI [**18**], and might be taken to preclude the inclusion of any non-LWR-based technology as a ‘Generic SMR’.

3.3. SMR Technology Groups

To consolidate the number of GFA assessments which needed to be performed, a web search and literature review was carried out to scope various designs of SMRs which had been proposed. The list obtained is included in Appendix A. A large majority of the proposed designs could be consolidated into six Technology Groups with summary descriptions given below. A Technical Review Paper [**14**] has been prepared outlining the key aspects of the reactor technologies and their fuel cycles.

Group 1. Small Modular Pressurised Water Reactors (SM-PWRs)

Includes the Generic SMR as defined above together with variants using natural rather than pumped circulation of the coolant. This variation in cooling does give some significant differences in reactor operations and control, which are summarised in the Technical Review [**14**].

Group 2. Small Modular Sodium-cooled Fast Reactors (SM-SFRs)

A Small Modular pool configuration Sodium Fast Reactor with an electrical generation capacity of less than 300 MWe. The SM-SFR is assumed to operate with a self-sufficient breeding cycle with U and U-Pu fuels. The SM-SFR outlet temperature is limited to 550°C.

Group 3. Small Modular Lead-cooled Fast Reactors (SM-LFRs)

An SM-LFR with an electrical generation capacity of less than 300 MWe. The SM-LFR is assumed to operate with Lead Bismuth Eutectic or molten lead coolant and use either uranium dioxide (UO_2) or Uranium Nitride (UN) fuel. The SM-LFR outlet temperature is limited to 550°C.

Group 4. Small Modular Molten Salt Fast Reactors (SM-MSFRs)

Molten Salt Fast Reactors use similar concepts to Group 5, but dispense with the moderator. The fuel normally consists of fissile and fertile material (typically as chlorides or fluorides) dissolved in molten salt which also serves as the primary coolant. Temperatures are limited to approximately 700°C. The SM-MSFR is assumed to require a secondary salt circuit.

SM-MSFRs can operate with a uranium-plutonium (U-Pu) or a thorium-uranium (Th-U-233) fuel cycle and is assumed to operate with full on-line recycle, with removal of fission products and separation of fissile materials.

A variant within SM-MSFR is a system which uses molten salt fuel materials enclosed in tubes, rather than mixed with the coolant. The current design in the open literature is for a GWe sized reactor, and as the data is limited, any SMR application could be judged by examination of the Group 4 assessment.

Group 5. Small Modular Thermal Neutron Molten Salt Reactors (SM-MSThRs)

Thermal Neutron Molten Salt Reactors use graphite as the moderator. The fuel consists of fissile material (typically as fluorides) dissolved in molten salt [2] which also serves as the primary coolant. SM-MSThRs have been partially demonstrated at prototype level in the Oak Ridge Molten Salt Reactor Experiment (MSRE).

Group 6. High Temperature Gas-cooled Reactors (SM-HTGR)

The SM-HTGR design has a thermal output limited to around100 MWth and employs TRISO fuel containing either UO_2 or uranium oxycarbide (UCO) fuel kernels. The SM-HTGR definition encompasses pebble-bed and prismatic core designs. The baseline energy conversion system is a steam (Rankine) cycle, with outlet temperatures limited to approximately 800°C.

The thermal output restraint is included since: 1) the low volumetric power density of HTGRs makes these systems relatively large and at higher power outputs it is difficult to envisage how a HTGR design could retain the benefits attributable to Small Modular systems; and 2) many of the safety features SM-HTGR designs aim to employ necessitate limiting thermal output to significantly lower levels than in the other reactor groupings listed above.

[2] Various salts are proposed, including NaF, KF, BeF_2, and ZrF_4.

4. Results of Generic Feasibility Assessment on Emerging SMR Technology Groups

4.1. Introduction

GFAs were carried out as detailed in Section 3, and the full Visualisations are available to accompany this report. In the following sections these assessments are summarised for each technology group, with subsequent examination of key Attributes which might be expected to contribute towards the suitability of the different Emerging Technologies for further study and/or development.

4.2. Generic SMR with GWe LWR Reference

This assessment compares the Generic (PWR) SMR with a GWe-sized LWR as the Reference System. The high level Assessment Matrix is shown in Figure 2.

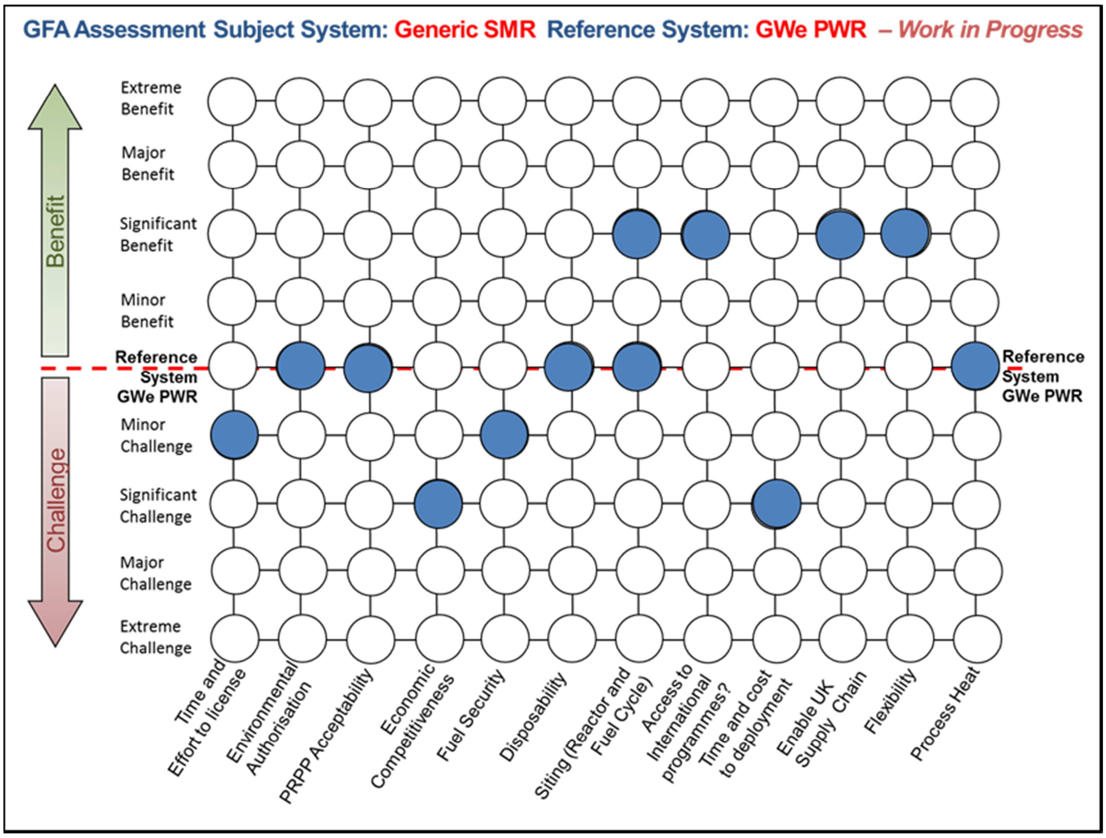


Figure 2: GFA of Generic SMR with GWe LWR Reference

Time and Effort to License – assessed as 'Minor Challenge'

There is relatively little to distinguish SMRs from large scale plants with respect to demonstrating overall safety, though individual SMR units may need to achieve more stringent limits when installed as multiple units to meet the same overall safety performance for the entire site.

Environmental Authorisation – assessed as 'Reference'

Essentially same as large scale PWRs, but details of environmental impacts will be design specific, and will vary with the number of units on a site, and the site location, particularly if a distributed network of SMRs is envisaged.

PRPP Acceptability – assessed as ‘Reference’

The once-through PWR fuel cycle is internationally recognised as the reference system for PRPP assessments. Small modular PWRs are essentially the same, with any differences (in elements such as initial enrichments; discharge burnups; spent fuel mass per gigawatt year (GWy) and fuel assembly mass) being very minor and in terms of PRPP largely inconsequential.

Economic Competitiveness – assessed as ‘Significant Challenge’

Although SMRs have the theoretical potential to improve economic competitiveness, there are some significant challenges that will need to be addressed. SMRs are likely be penalised by historic scaling laws that favour large plants [**15**] and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges. The analysis of these factors is the primary purpose of the Techno-Economic Assessment being carried out in Lot 1 of this study.

Fuel Security – assessed as ‘Minor Challenge’

Essentially same as large scale PWRs for SM-PWRs using batch refuelling. Designs using single batch (i.e. whole core) refuelling will incur a significant penalty in uranium usage.

Disposability – assessed as ‘Reference’

Largely equivalent to large scale PWR, but with details which are design dependent. Fuel volume will vary with the refuelling patterns used, but the heat equivalent per TWh will be essentially constant.

Siting - assessed as ‘Significant Benefit’ (dispersed network) to ‘Reference’ (GWe-sized groupings)

There is a range of potential SMR siting scenarios from a dispersed network of low capacity (one or a few SMR plants) to GWe-sized groupings. There is a tension between dispersed siting (lower demands on cooling water and grid connections) and economics (with dispersed siting likely to involve more manpower for both operations and site security for GWe installed, at least initially). Both extremes have been assessed for this Attribute, and also for overall economics.

Access to International Programmes – assessed as ‘Significant Benefit’

A strong potential for international collaboration, as demonstrated by the IRIS[3] consortium. UK engagement in small modular PWR design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

Time and Cost to Deployment – assessed as ‘Significant Challenge’

The defined Generic SMR (PWR with forced circulation) is judged to be at TRL 7, and is estimated to have an estimated 10 year minimum ‘time to licensing complete’ (2025+). Assuming a FOAK build time of 5 years gives an ‘earliest on the bars’ date from 2030. This represents a Significant Challenge when compared to the GWE-sized Gen III+ LWR designs currently undergoing (or in the case of EPR having passed) GDA and either building or operational in other parts of the world.

Enable UK Supply Chain – assessed as ‘Significant Benefit’

The Generic SMR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification. By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

[3] The **I**nternational **R**eactor **I**nnovative & **S**ecure (IRIS) system is nominally a 335 MWe modular reactor (with variants as low as 100 MWe) which, whilst led by the US company Westinghouse, involved collaboration between a number of countries during its development [**16**].

Flexibility – Load Follow Capability – assessed as 'Significant Benefit'

SM-PWRs have a number of attributes which are favourable with respect to load following. SM-PWRs generally have low power densities (relative to large PWRs) which is likely to result in less restrictive power manoeuvrability limits in SM-PWRs in comparison with large PWRs. Furthermore, some SM-PWRs operate without soluble boron, which is normally used to aid reactivity control in large PWRs; by operating without soluble boron, limits associated with the rate at which soluble boron can be removed from the coolant are eliminated and improvements in power manoeuvrability can be obtained. Finally, large PWRs can be susceptible to variations in fission product inventories complicating reactivity control; this can result in restrictions during power manoeuvres. For SM-PWRs with sufficiently short fuel rods (<~2.5 m) this problem can be removed.

Nuclear reactors in the UK do not currently load follow. However, nuclear plants that can load follow may become important in future scenarios involving strong nuclear growth, high intermittent renewable generation and/or dispersed nuclear siting. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load follow capability helps support the grid system.

Process Heat – assessed as 'Reference'

The Generic SMR as defined is capable of supplying only low grade heat. This would have limited application when deployed in GWe-sized groupings, but would have possible applications in district energy supply, and other processes requiring low-grade heat, if dispersed siting is contemplated.

4.3. SM-SFR with Generic SM-PWR Reference

This assessment compares the SM Sodium-cooled Fast Reactor (SM-SFR) with the Generic SM-PWR as the Reference System. The SM-SFR is assumed to be a pool configuration sodium fast reactor with an electric capacity of less than 300 MWe; in addition, it is assumed to operate with a self-sufficient breeding cycle with U and U-Pu fuels. The high level Assessment Matrix is shown in Figure 3.

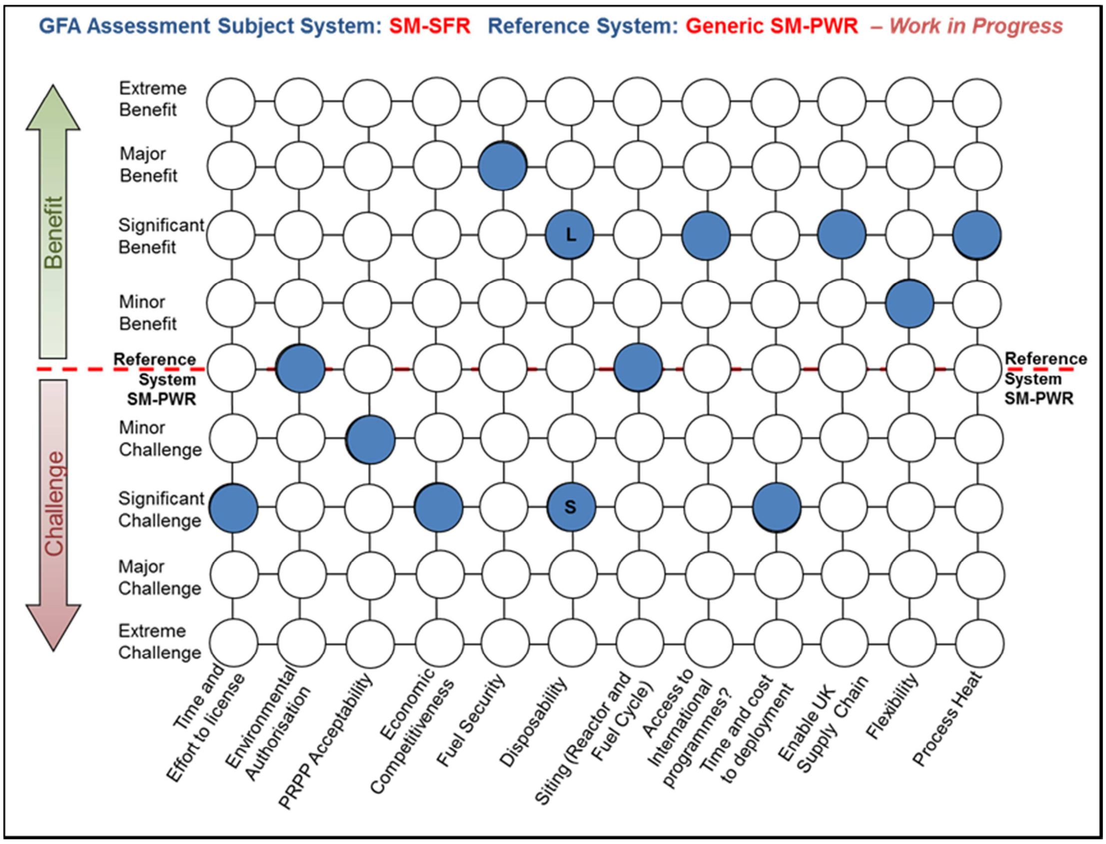


Figure 3: GFA of SM Sodium Cooled Fast Reactor with Generic SM-PWR Reference

Time and Effort to License – assessed as 'Significant Challenge'

The overall assessment is that SM-SFR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer. However, the timescales are likely to be shorter than most other emerging systems because of substantial experience with demonstration reactors at an appropriate size. Taking these considerations into account it is judged that a development programme lasting at least 15 years will be necessary to address technical and regulatory challenges before being ready for GDA. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2040.

Environmental Authorisation – assessed as 'Reference'

SM-SFRs will require further design and development in order to be able to satisfy environmental permitting requirements. However, SFRs have some favourable characteristics on radiological performance and the work required is likely to be similar to that for the reference SMR-PWR.

PRPP Acceptability – assessed as 'Minor Challenge'

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the spent fuel from SM-SFR will be reprocessed, there is the potential for the inherent PRPP performance to be less favourable (this applies even if the reprocessing flowsheet avoids the separation of pure plutonium). Overall, the security and safeguards will be designed to offer adequate protection and inherent PRPP is seen as posing a Minor Challenge.

Economic Competitiveness – assessed as 'Significant Challenge'

SM-SFRs have the theoretical potential to improve economic competitiveness, in that they have the potential to be more compact than SM-PWR and operate at low pressure that could give savings on steel and concrete. However, there are some significant challenges that will need to be addressed. SM-SFR is likely be penalised by historic scaling laws that favour large plants and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges. In the absence of evidence to the contrary, SM-SFR is assumed subject to the same scaling laws as the SM-PWR reference system, but to be economically disadvantaged by requiring a secondary sodium circuit, and a demanding fuel cycle, which under current conditions would not be compensated for by the reduction in uranium usage. SM-SFR is assessed as Significant Challenge.

Fuel Security – assessed as 'Major Benefit'

With a closed fuel cycle SM-SFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. SM-SFR could also have a role in managing existing or future plutonium stocks.

Disposability – assessed as 'Significant Benefit' to 'Significant Challenge'

The spent fuel characteristics of SM-SFR are considerably more challenging than for the SM-PWR Reference Systems, especially if the fuel is reprocessed at short cooling times. There are aspects which may pose a Major Challenge and others which are assessed as giving a Significant Benefit. Overall assessment ranging between Significant Challenge for short cooling time requirement to Significant Benefit if there if long cooling times are allowed[4].

Fuel reprocessing and waste management is more challenging for fast reactor spent fuel than it is for thermal reactors, especially if short cooling times are required. Current PUREX[5] reprocessing plants and their associated waste management plants are optimised to process thermal reactor spent fuels that typically have a lower discharge burnup (< 50 GWd/tHM[6]) and longer cooling times (>5 years). The design of reprocessing and waste management plants for fast reactor fuels will need to take account of the higher

[4] The relatively limited economic significance of waste treatment and disposal is discussed in Section 5.1
[5] **P**lutonium **U**ranium **R**edox **EX**traction
[6] Gigawatt-Days per Tonne of Heavy Metal

burnup of fast reactor fuels (typically ~100 GWd/tHM) and short cooling times (as low as 5 years), which results in higher decay heat loads and higher neutron emissions. It cannot be assumed that current reprocessing and waste management plant designs can be simply adapted to meet the specifications for fast reactor spent fuel and significant R&D will likely be required, even for PUREX reprocessing. In particular, for a reprocessing scheme producing Vitrified High Level Waste (VHLW) is likely to pose major challenges with waste incorporation rates.

Siting - assessed as 'Reference'

The Benefits or Challenges associated with the deployment of all SMRs vary depending on whether they are deployed singly or in groups, potentially of up to GWe capacity[7]. SM-SFR is assessed to be equivalent to the SM-PWR Reference System with respect to siting, based on the assumption that reprocessing of SM-SFR spent fuel is carried out in a centralised facility. If the reprocessing facility were co-located with the reactor(s) it would complicate the time and effort required for licensing, environmental authorisation and PRPP acceptability, and this would alter the assessment to Significant Challenge.

Access to International Programmes – assessed as 'Significant Benefit'

SM-SFR offers strong potential for international collaboration, because further development work is required and designs are not fully developed. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

Time and Cost to Deployment – assessed as 'Significant Challenge'

SM-SFR is assessed to be between TRL 3 and TRL 7 depending on the fuel type and energy conversion system and is estimated to have an earliest deployment not before 2040. This represents a Significant Challenge when compared to the SM-PWR Reference System.

Enable UK Supply Chain – assessed as 'Significant Benefit'

SM-SFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification. By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Flexibility – Load Follow Capability – assessed as 'Minor Benefit'

The impact of power cycling on the SM-SFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in the same way as PWRs. Metal fuel systems will have some PCI but it will not include stress concentrations from pellet cracking. PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xenon (Xe) poisoning effect that places restrictions on low power operation and start-up after trips.

Process Heat – assessed as 'Significant Benefit'

SM-SFR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat.

4.4. SM-LFR with Generic SM-PWR Reference

This assessment compares the SM Lead-Cooled Fast Reactor with the Generic (PWR) SMR as the Reference System. The high level Assessment Matrix is shown in Figure 4.

[7] This is discussed further in Section 4.8.8 and Appendix B.

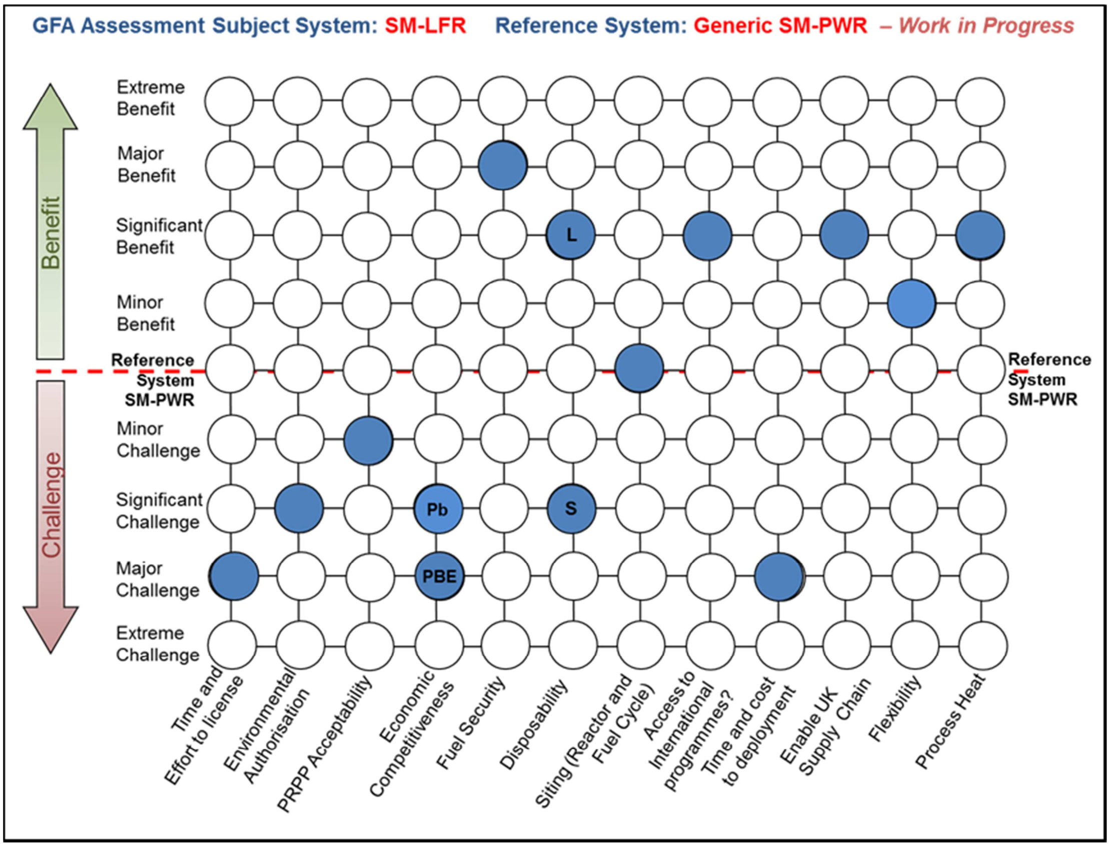


Figure 4: GFA of SM Lead Cooled Fast Reactor with Generic SM-PWR Reference

Time and Effort to License – assessed as 'Major Challenge'

The overall assessment is that SM-LFR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer. Significant R&D is required regarding the development and testing of computer codes, materials and numerous reactor systems (e.g. chemistry control and reactor instrumentation). The development programme is judged to take at least 25 years until a prototype LFR could be constructed. Historically, prototype fast reactors have operated for around 10 years until subsequent reactor iterations have been constructed. Therefore, assuming a 5 year GDA process and a 5 FOAK build time, deployment before 2060 is deemed unlikely.

Environmental Authorisation – assessed as 'Significant Challenge'

SM-LFR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements and this would be further complicated if on-site reprocessing were contemplated.

PRPP Acceptability – assessed as 'Minor Challenge'

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the spent fuel from SM-LFR will be reprocessed, there is the potential for the inherent PRPP performance to be less favourable (this applies even if the reprocessing flowsheet avoids the separation of pure plutonium). Overall, the security and safeguards will be designed to offer adequate protection and inherent PRPP is seen as posing a Minor Challenge.

Economic Competitiveness – assessed as 'Significant Challenge' for Pb cooled system and 'Major Challenge' for LBE cooled system

There are Major Challenges that must be overcome to demonstrate the economic competitiveness of SM-LFRs. R&D costs and operation and maintenance costs are likely to be considerably higher than those associated with SM-PWRs. For Pb-cooled SM-LFRs there are challenges associated with the increased complexity of instrumentation, control and chemical systems; in addition the need for sufficient redundancy to reduce the likelihood of coolant freezing. For LBE-cooled reactors the expense of bismuth considerably degrades the economic performance of the reactor system.

It is expected that the SM-LFR closed fuel cycle will be prove more expensive than the once-through SM-PWR fuel cycle due to the extra complexity and the technically demanding nature of closed fuel cycles.

Fuel Security – assessed as 'Major Benefit'

With a closed fuel cycle SM-LFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independently of the world uranium market, which is beneficial for fuel security.

Disposability – assessed as 'Significant Benefit' to 'Significant Challenge'

The spent fuel characteristics of SM-LFR are considerably more challenging than for the SM-PWR Reference Systems, especially if the fuel is reprocessed at short cooling times. Furthermore, there are complications associated with elevated C-14 concentrations for the waste from a uranium nitride fuelled LFR.

Overall assessment regarding disposability ranges from Significant Challenge, for short cooling time requirement using UN fuel, to Significant Benefit if long cooling times are allowed and UO_2 fuel is utilised.

Siting - assessed as 'Reference'

The Benefits or Challenges associated with the deployment of all SMRs vary depending on whether they are deployed singly or in groups, potentially of up to GWe capacity[8]. SM-LFR is assessed to be equivalent to the SM-PWR Reference System with respect to siting, based on the assumption that reprocessing of SM-LFR spent fuel is carried out in a centralised facility. If the reprocessing facility were co-located with the reactor(s) it would complicate the time and effort required for licensing, environmental authorisation and PRPP acceptability, and this would alter the assessment to Significant Challenge.

Access to International Programmes – assessed as 'Significant Benefit'

SM-LFR offers strong potential for international collaboration due to the significant cross-over with Sodium Fast Reactor technology (for which there is significant research ongoing in a number of countries) and currently there is significant R&D investigating advanced material options for LFR systems. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

Time and Cost to Deployment – assessed as 'Major Challenge'

Significant R&D is required regarding the development and testing of computer codes, materials and numerous reactor systems (e.g. chemistry control and reactor instrumentation). The development programme is judged to take at least 25 years until a prototype LFR could be constructed. Historically, prototype fast reactors have operated for around 10 years until subsequent reactor iterations have been constructed. Adding 5 years for GDA and 5 years build time gives 2060 as an earliest deployment date.

Enable UK Supply Chain – assessed as 'Significant Benefit'

SM-LFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification. By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise contributing to developing component designs from the beginning thereby adding higher UK economic value.

[8] This is discussed further in Section 4.8.8 and Appendix B.

Flexibility – Load Follow Capability – assessed as 'Minor Benefit'

The impact of power cycling on the SM-LFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in a similar way to PWRs. PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xe poisoning effect that places restrictions on low power operation and start-up after trips.

Process Heat – assessed as 'Significant Benefit'

SM-LFR is expected to operate at significantly higher working temperatures (~550ºC) than the SM-PWR Reference System (~300°C), which is capable of supplying only low grade heat.

4.5. SM-MSFR with Generic SM-PWR Reference

This assessment compares the SM Molten Salt Fast Reactor with the Generic (PWR) SMR as the Reference System. The high level Assessment Matrix is shown in Figure 5.

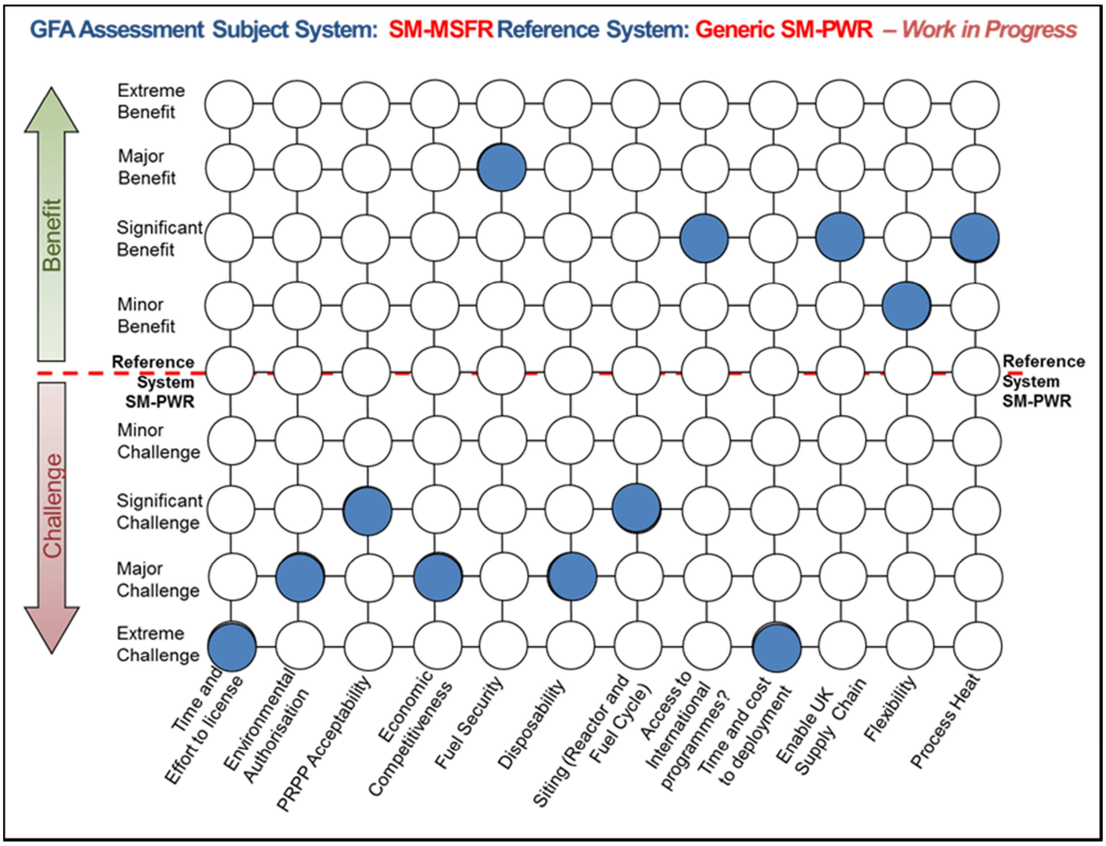


Figure 5: GFA of SM Molten Salt Fast Reactor with Generic SM-PWR Reference

Time and Effort to License – assessed as 'Extreme Challenge'

The approach to constructing a safety case for SM-MSFR will necessarily be very different to that for a conventional solid fuel reactor. This is dictated by the fact that in an MSR the normal operating condition is with the fuel melted and therefore some of the barriers to release of fission products, actinides and activation products in a solid fuel reactor no longer apply. Although MSR designs are typically characterised by strong negative temperature feedback coefficients, un-pressurised systems, tolerance of high temperatures and passive decay heat removal, these features per se may not necessarily make the safety case easy to demonstrate. There will need to be extensive experimental test data available that will substantiate all aspects of the safety case. At present this database does not exist.

Current designs of SM-MSFR are judged to require at least 35 years research and development before a prototype could begin operation. A prototype would likely need to operate for around 10 years needed to build-up operating experience. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would indicate SM-MSFR reactors being operational around 2070, in agreement with the timescale estimated by international studies [17].

Environmental Authorisation – assessed as 'Major Challenge'

SM-MSFR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements.

PRPP Acceptability – assessed as 'Significant Challenge'

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. As the SM-MSFR utilises a liquid fuel and nominally operates with extensive on-line reprocessing, the barriers to accessing fissile material and other radioactive materials are potentially reduced relative to spent fuel from solid fuel reactors. Hence, there is the potential for the inherent PRPP performance to be less favourable.

Depending on the fuel cycle adopted, SM-MSFR may produce separated U-233. Although the U-233 would be expected to be contaminated with U-232, the daughter products of which produce, in due course, a strong gamma emitter. However, the radiation field so produced, although too intense to allow unshielded handling in a licensed fuel cycle plant, would be insufficient to result in rapid incapacitation in a scenario where a sub-national group attempted to acquire fissile material without shielding measures.

Economic Competitiveness – assessed as 'Major Challenge'

Although SM-MSFR has an unpressurised primary circuit vessel, the vessel will nevertheless need to meet a very high standard of containment, which may require a second vessel. There will need to be robust barriers in place anywhere fuel/coolant could escape throughout the reactor system. Incorporating an on-line reprocessing system will almost inevitably increase plant capital costs relative to systems that utilise a centralised reprocessing system. Furthermore, whilst fuel costs are expected to be low for SM-MSFRs, these will likely be offset by higher operational and maintenance costs associated with working with a corrosive, highly active coolant. The SM-MSFR is further penalised due to its low maturity and therefore very high R&D costs, which leads to an overall assessment as Major Challenge.

Fuel Security – assessed as 'Major Benefit'

With a U-Pu or Th-232/U-233 fuel cycle SM-MSFR could in principle operate with a breeding cycle. In this instance, the system could operate independently of the world uranium market, which is beneficial for fuel security. Also, the fuel form does not require fuel assembly fabrication and so is less tied to specific fuel vendors.

Disposability – assessed as 'Major Challenge'

The spent fuel characteristics of SM-MSFR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF. Although there are aspects which would give a Significant Benefit, the overall assessment is dominated by the Extreme Challenge posed by the waste form.

Siting - assessed as 'Significant Challenge'

The Benefits or Challenges associated with the deployment of all SMRs vary depending on whether they are deployed singly or in groups, potentially of up to GWe capacity[9]. SM-MSFR is assessed as a 'Significant Challenge' compared to SM-PWR with respect to siting as SM-MSFR is assumed to require extensive on-line reprocessing (i.e. separation of fission products and fissile material). This implies the co-location of a reprocessing plant on each reactor site. Reprocessing operations will have an impact on radiological release in normal operation and in accident conditions and will also introduce a new aspect to the safety case increasing the time and effort required for licensing, environmental authorisation, and will add complexity to PRPP requirements.

Access to International Programmes – assessed as 'Significant Benefit'

SM-MSFR offers strong potential for international collaboration, on account of its low TRL. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

[9] This is discussed further in Section 4.8.8 and Appendix B.

Time and Cost to Deployment – assessed as ‘Extreme Challenge’

SM-MSFR is judged to be at TRL 2-3 and is estimated to have an earliest deployment date of 2070.

Enable UK Supply Chain – assessed as ‘Significant Benefit’

SM-MSFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification. By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Flexibility – Load Follow Capability – assessed as ‘Minor Benefit’

SM-MSFR is not limited in load-follow operation by fuel thermal limits. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. By utilising a fast spectrum the reactor will be less sensitive to the build-up of fission products. Furthermore, the use of a liquid fuel/coolant removes issues regarding the mechanical interactions between solid fuel and metallic cladding that affects other reactor systems.

Process Heat – assessed as ‘Significant Benefit’

SM-MSFR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat. Therefore SM-MSFR is assessed as offering a Significant Benefit.

4.6. SM-MSThR with Generic SM-PWR Reference

This assessment compares the SM Molten Salt Thermal Reactor with the Generic (PWR) SMR as the Reference System. The high level Assessment Matrix is shown in Figure 6.

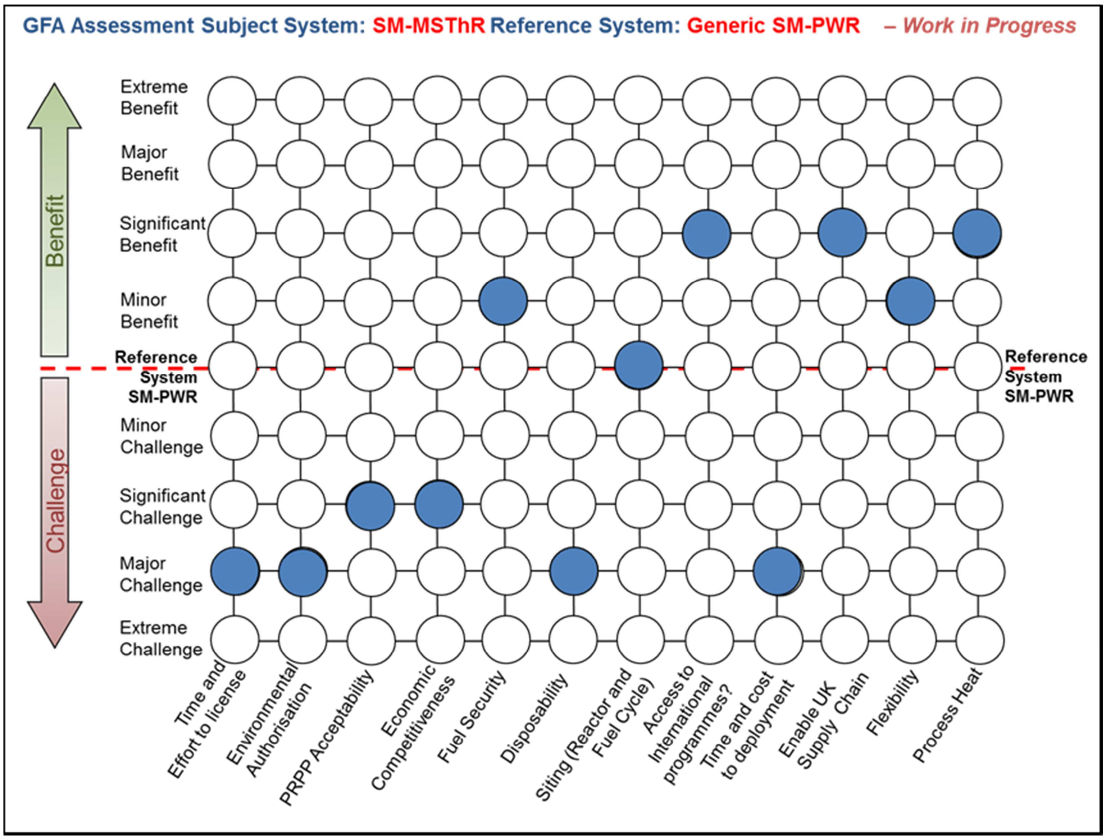


Figure 6: GFA of SM Molten Salt Thermal Reactor with Generic SM-PWR Reference

Time and Effort to License – assessed as 'Major Challenge'

The approach to constructing a safety case for SM-MSThR will necessarily be very different to those for a conventional solid fuel reactor. This is dictated by the fact that in an MSR the normal operating condition is with the fuel melted and therefore some of the barriers to release of fission products, actinides and activation products in a solid fuel reactor no longer apply. Although MSR designs are typically characterised by strong negative temperature feedback coefficients, un-pressurised systems, tolerance of high temperatures and passive decay heat removal, these features per se may not necessarily make the safety case easy to demonstrate. There will need to be extensive experimental test data available that will substantiate all aspects of the safety case. At present this database does not exist and it is arguable whether the historic experience gained with MSRE will count for much beyond having demonstrated initial proof of concept.

Environmental Authorisation – assessed as 'Major Challenge'

SM-MSThR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements. In particular, molten salt technology represents a major departure from current experience of solid fuelled reactors and the environmental discharge routes for gases are not sufficiently defined at present.

PRPP Acceptability – assessed as 'Significant Challenge'

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Whilst the SM-MSThR does not nominally operate with extensive on-line reprocessing, it still utilises a liquid fuel, thereby potentially reducing the number of barriers to accessing fissile material and other radioactive materials relative to spent fuel from solid fuel reactors. Hence, there is the potential for the inherent PRPP performance to be less favourable.

Depending on the fuel cycle adopted, SM-MSFR may produce separated U-233, although the U-233 would be expected to be contaminated with U-232, the daughter products of which produce a strong gamma emitter. However, the radiation field so produced, although too intense to allow unshielded handling in a licensed fuel cycle plant, would be insufficient to result in rapid incapacitation in a scenario where a sub-national group attempted to acquire fissile material without shielding measures.

Economic Competitiveness – assessed as 'Significant Challenge'

Whilst the SM-MSThR operates at low pressure, does not nominally incorporate an extensive on-line reprocessing system and a number of candidate materials have been identified, significant R&D must be expended to achieve commercialisation. Furthermore, the highly active, corrosive nature of the coolant will necessitate robust barriers to contain the coolant which will penalise its economic performance. Finally, whilst fuel costs are expected to be low for SM-MSFRs, these will likely be offset by higher operational and maintenance costs associated with working with a corrosive, highly active coolant.

Fuel Security – assessed as 'Minor Benefit'

If utilising a Th/U233 fuel cycle, SM-MSThR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. Also, the fuel form does not require fuel assembly fabrication and so is less tied to specific fuel vendors. SM-MSThR can operate with a U-Pu or a Th-U fuel cycle. However SMThR is assessed as only a Minor Benefit because the reference system is specified as not having full reprocessing.

Disposability – assessed as 'Major Challenge'

The spent fuel characteristics of SM-MSThR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF. Although there are aspects which would give a Significant Benefit, the overall assessment is dominated by the Extreme Challenge posed by the waste form.

Siting - assessed as 'Reference'

The Benefits or Challenges associated with the deployment of all SMRs vary depending on whether they are deployed singly or in groups, potentially of up to GWe capacity[10]**.** SM-MSThR is assessed to be equivalent to the SM-PWR Reference System with respect to siting, assuming that there is minimum scope for on-site reprocessing. This avoids the siting issues associated with a co-located reprocessing plant.

[10] This is discussed further in Section 4.8.8 and Appendix B.

Access to International Programmes – assessed as 'Significant Benefit'
SM-MSThR offers strong potential for international collaboration, on account of its low TRL. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

Time and Cost to Deployment – assessed as 'Major Challenge'
SM-MSThR is judged to be at TRL 5. Current designs of SM-MSThR are judged to be at least 35 years from being ready for GDA, once factoring in necessary R&D required to allow for operation of a prototype system. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2060.

Enable UK Supply Chain – assessed as 'Significant Benefit'
SM-MSThR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Flexibility – Load Follow Capability – assessed as 'Minor Benefit'
SM-MSThR is not limited in load-follow operation by fuel thermal limits. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. Overall assessment as Minor Benefit.

Process Heat – assessed as 'Significant Benefit'
SM-MSThR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat.

4.7. SM-HTGR with Generic SM-PWR Reference

This assessment compares the SM High Temperature Gas-cooled Reactor with the Generic (PWR) SMR as the Reference System. The high level Assessment Matrix is shown in Figure 7.

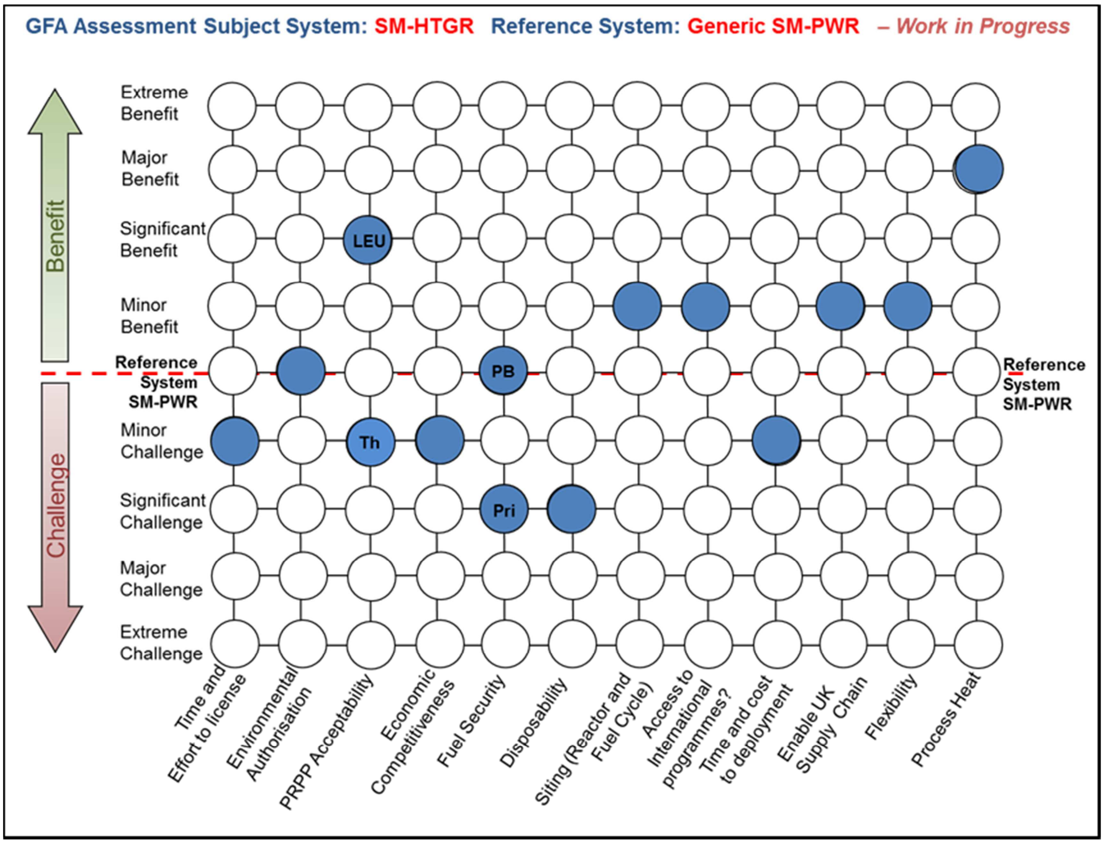


Figure 7: GFA of SM High Temperature Gas-cooled Reactor with Generic SM-PWR Reference

Time and Effort to License – assessed as 'Minor Challenge'

The overall assessment is that SM-HTGR will require slightly more effort than the SM-PWR Reference System to progress through licensing due to uncertainties surrounding material performance of the chosen graphite grade, uncertainties in the amount of graphite dust that could be released in a major fault and barriers to obtaining large quantities of TRISO based fuel from a commercial supplier.

Environmental Authorisation – assessed as 'Reference

No more challenging than SM-PWRs, but details of environmental impacts will be design specific, and will vary with the number of units on a site, and the site location, particularly if a distributed network of SMRs is envisaged.

PRPP Acceptability – assessed as 'Significant Benefit' to 'Minor Challenge'

SM-HTGRs operated with a once-through cycle and using LEU fuel, avoid the production of weapons usable materials but use fuel of a significantly higher enrichment to the SM-PWRs. SM-HTGRs further improve PRPP due to the highly robust nature of HTGR fuel and very low uranium concentrations in fuel elements (for instance in a pebble bed reactor, each pebble contains only ~6 g of uranium). However, if thorium based fuels (e.g. thorium mixed with Pu) are used, the production of the fissile U233 isotope leads to a change in assessment to Minor Challenge.

Economic Competitiveness – assessed as 'Minor Challenge'

SM-HTGRs will not only have to overcome scaling laws that favour large plants (perhaps by relying on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges) but SM-HTGR cores are also quite large for a given power output and utilise a more complex, and therefore expensive, fuel form. SM-HTGRs will have to demonstrate that their safety performance advantages and/or the benefits associated with process heat can overcome these economic penalties.

Fuel Security – assessed as 'Reference' to 'Significant Challenge'

SM-HTGRs typically operate with uranium fuel and utilise LEU. Given the current availability of uranium, there is no reason to suspect fuel security issues will arise during SM-HTGR's operational lives. The energy produced per unit of uranium feed for pebble-bed SM-HTGRs is comparable to SM-PWRs. However, prismatic cores have higher uranium feed requirements as they utilise fuel less efficiently than pebble-bed cores, which leads to the alternative assessment as ‘Significant Challenge’.

Disposability – assessed as ‘Significant Challenge’

The ability of TRISO particles to effectively retain fission products is a favourable characteristic for direct disposal. However, there are significant uncertainties surrounding the necessary preconditioning processes for irradiated graphite and limited experience with disposing of TRISO fuel. Moreover, the low power density of HTR cores results in large volumes of waste that requires storage and eventual disposal relative to SM-PWR spent fuel.

Siting - assessed as ‘Minor Benefit’

SM-PWRs already offer significant benefits attached to lower demands on cooling water and grid connections if the aim is to deploy a dispersed network. SM-HTGRs are able to replicate the benefits attached to SM-PWRs in addition to being able to offer process heat to a greater number of industrial customers.

Most SM-HTGR concepts are projected to operate at the lower end of SMR system thermal outputs (less than or approximately equal to 100 MWth) and the concepts do not envisage deploying many units at one site to achieve the equivalent electrical output from a single large PWR. This leads to an assessment of Minor Benefit for SM-HTGR.

Access to International Programmes – assessed as ‘Minor Benefit’

SM-PWRs offers strong potential for international collaboration. HTGRs, being less mature, further expand the benefits attached to access to international programmes. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise and knowledge transfer, and would also help provide a positive focus for UK nuclear R&D.

Time and Cost to Deployment – assessed as ‘Minor Challenge’

HTGR technology is relatively mature with a number of small prototype HTGRs operated in recent years. Furthermore, significant R&D has been on going to qualify the performance of TRISO fuel, which HTGRs are dependent on to achieve many of their stated benefits. However, there are currently no commercial suppliers of TRISO fuel and any SM-HTGR project will need to ensure they have all of the material test data to prove that the specified graphite grade will operate within design limits. Furthermore, there may be issues (such as graphite oxidation and/or graphite dust production) that require experimentation/modelling to provide data to support licensing.

It is judged that over a 10 year period, with sufficient resources dedicated, the above issues could be addressed. This would give time for regulators to become more informed regarding HTGR technology. Then a standard 5 year GDA process and 5 year FOAK build is assumed. Hence, current designs of SM-HTGRs therefore are unlikely to achieve commercial deployment until at least around 2035.

Enable UK Supply Chain – assessed as ‘Minor Benefit’

SM-HTGRs present increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. Commercial suppliers of HTGR fuel are currently very limited, and given that the UK has expertise in fuel manufacturing, establishing a TRISO fuel manufacturing facility in the UK should be assessed.

Flexibility – Load Follow Capability – assessed as ‘Minor Benefit’

SM-HTGRs as thermal reactors have similar limitations on power as the Reference SM-PWR because of Xe poisoning. However, SM-HTGRs have some advantage in that they are not susceptible to pellet clad interactions on power rises, which are most damaging after operation for lengthy periods at lower power. The TRISO fuel is very resilient to power changes and should be able to load follow within reactivity constraints.

Process Heat – assessed as ‘Major Benefit’

As currently configured, SM-HTGR has a reactor outlet temperature of 800°C, which is adequate for some, but not all, industrial processes. However, there are a number of key industries (such as cement and steel) that require temperatures significantly above 800°C in their production processes, and the production of hydrogen using thermo-chemical processes ideally requires outlet temperatures around 1000°C. Current technology would involve temperature 'boosts', using heat pumps for example, to raise outlet temperatures.

HTGRs capable of producing hydrogen could have a role in future energy mixes that utilise hydrogen for industrial processes, for maintaining grid stability and/or helping to decarbonise transport.

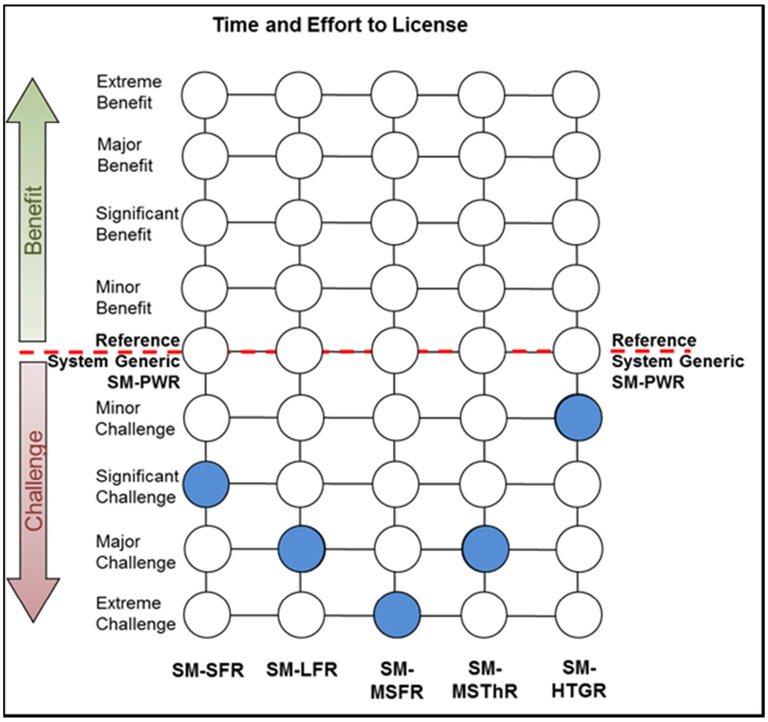
4.8. Attribute Comparisons across Systems

4.8.1. Introduction

The comparison by GFA of a number of nuclear technologies on any given attribute should involve a succession of one-to-one assessments where 'A' is compared with 'B', then 'B' with 'C' and so on. This is because the 'benefits and 'challenges' are essentially subjective, so there is no guarantee that a 'Significant Benefit' for 'A' over 'B' would be of the same magnitude as a 'Significant benefit' for 'A' over 'C'. However, accepting this limitation, it is instructive to examine the GFA results on the range of technical Attributes. The Attributes relating to 'Access to International Programmes' and 'Enable UK Supply Chain' have not been examined as these are more appropriately addressed by policy makers. The relative economic importance of the Attributes is examined in Section 5.1.

4.8.2. Time and Effort to License

The assessment of 'Time and Effort to License' for the five Emerging Technologies is given in Figure 8.



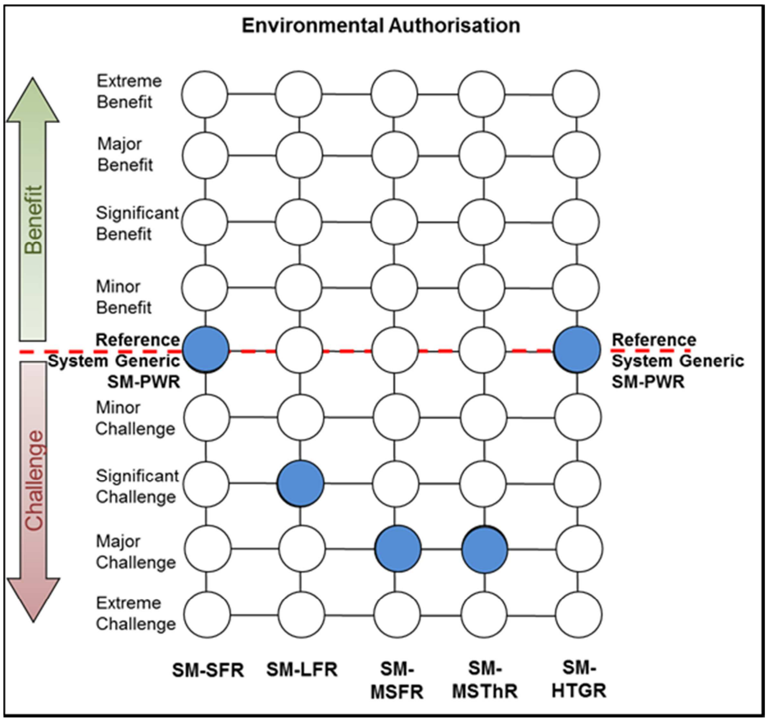
Note: A Generic SM-PWR is assessed as 'Minor Challenge' on 'Time and Effort to License' in comparison to a GWe-sized PWR

Figure 8: Time and Effort to License from GFAs

The Time and Effort to License reflects the current level of knowledge of the Emerging Technologies, in particular in the area of novel systems and fuel cycles that will pose new questions for regulators.

4.8.3. Environmental Authorisation

The assessment of 'Environmental Authorisation' for the five Emerging Technologies is given in Figure 9.



Note: A Generic SM-PWR is assessed as 'Reference' on 'Environmental Authorisation' in comparison to a GWe-sized PWR

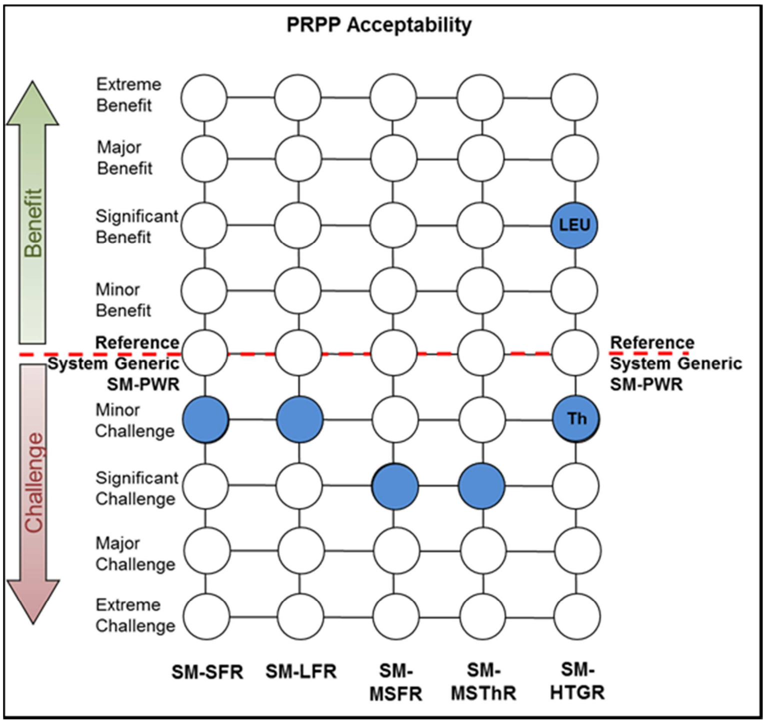
Figure 9: Environmental Authorisation from GFAs

The relative degree of challenge associated with the SM-LFR is due to the high level of development needed, and in addition to this, some of the SM-MSThR and all of the SM-MSFR technologies can involve siting of back-end fuel cycle activities which will require specific discharge authorisations.

4.8.4. PRPP Acceptability

The assessment of 'PRPP Acceptability' for the five Emerging Technologies is given in Figure 10.

The relative degree of challenge associated with the Emerging Technologies is linked to the level of recycle and separation of fissile materials, especially where U-233 is separated during thorium fuel cycles. The Significant Benefit indicated for SM-HTGR systems with LEU fuel reflects the extreme inaccessibility of the fissile material in TRISO fuels.



Note: A Generic SM-PWR is assessed as 'Reference' on 'PRPP Acceptability' in comparison to a GWe-sized PWR

Figure 10: PRPP Acceptability from GFAs

4.8.5. Economic Competitiveness

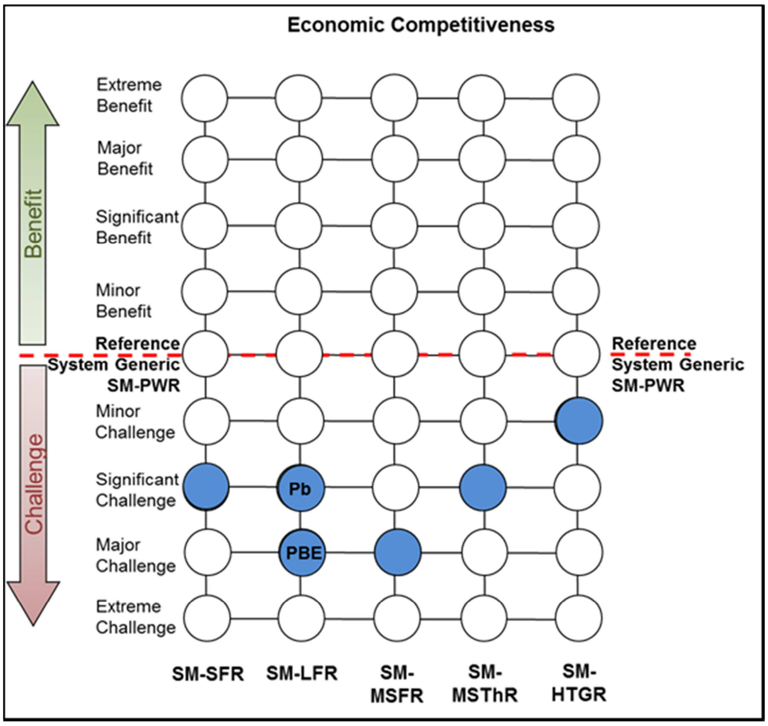
Two GFA stages are relevant to Economic Competiveness:

- The overall Economic Competitiveness attribute which assesses the entire cost from 'now' to deployment
- The Overnight Capital Cost, which will have the greatest bearing on the decision to invest (or not) once the system is ready for market.

These assessments are given in Figure 11 and Figure 12 below.

It is notable that all systems are assessed as representing a challenge in comparison to an SM-PWR, which itself represents a Significant Challenge in comparison to a GWe-sized PWR. Note that overall the SM-HTGR is seen as representing the least challenge, and the SM-MSFR the most.

This assessment suggests that none of the systems could gain a place in the market solely on the basis of their capital cost, and would need to rely on advantages in other areas to overcome their capital cost challenge.



Note: A Generic SM-PWR is assessed as a 'Significant Challenge' on 'Economic Competitiveness' in comparison to a GWe-sized PWR

Figure 11: Economic Competitiveness from GFAs

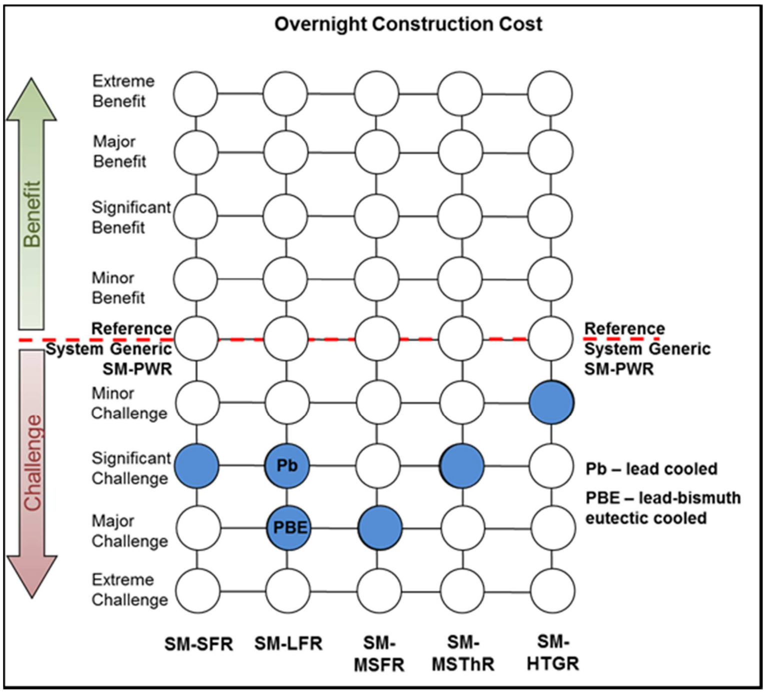
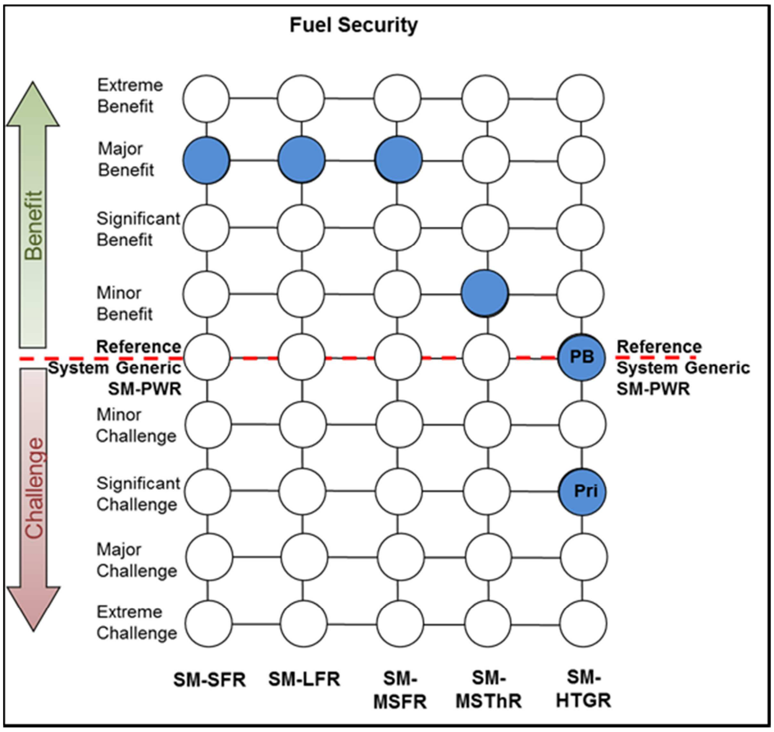


Figure 12: Overnight Construction Cost from GFAs

4.8.6. Fuel Security

The achievement of fuel security – principally by reducing the amount of mined uranium required per TWh of generated electricity – is much quoted as a major driver in the choice of reactor systems. However, as discussed in Section 5.2, the cost of the fuel cycle is not likely to become an important discriminator unless uranium is very scarce and/or extremely expensive. However, the differences in uranium use are extreme, covering a factor of at least 50. The GFA assessments are seen in Figure 13 below.



Note: A Generic SM-PWR is assessed as a 'Minor Challenge' on 'Fuel Security' in comparison to a GWe-sized PWR

Figure 13: Fuel Security from GFAs

Note that only the HTGR systems represent a challenge in comparison to the Generic SM-PWR. All the Emerging fast reactor technologies, when at equilibrium, offer self-sufficiency in fissile isotopes, consuming only fertile U-238 or thorium. This can also be achieved in SM-MSThR systems using the thorium cycle.

4.8.7. Disposability

The disposability Attribute has two key Sub-Attributes (see Figure 15 and Figure 16):

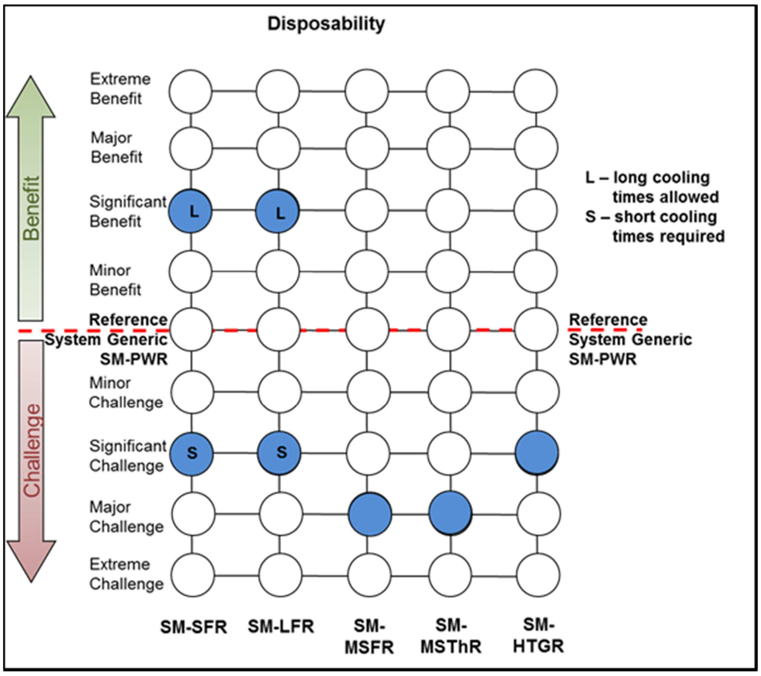
The number and type of wasteforms, and their compatibility with current waste processes.

Fuel reprocessing and waste management is more challenging for fast reactor spent fuel than it is for thermal reactors, especially if short cooling times are required. Current PUREX reprocessing plants and their associated waste management plants are optimised to process thermal reactor spent fuels that typically have a lower discharge burnup (< 50 GWd/tHM) and longer cooling times (>5 years). The design of reprocessing and waste management plants for fast reactor fuels will need to take account of the higher burnup of fast reactor fuels (typically ~100 GWd/tHM) and short cooling times (as low as 5 years), which results in higher decay heat loads and higher neutron emissions. It cannot be assumed that current reprocessing and waste management plant designs can be simply adapted to meet the specifications for fast reactor spent fuel and significant R&D will likely be required, even for PUREX reprocessing. In particular, for a reprocessing scheme producing Vitrified High Level Waste (VHLW) is likely to pose major challenges with waste incorporation rates.

The long term heat generation from the waste.

This impacts upon the design of the GDF, increasing the spacing of waste containers, and potentially increasing the difficulty of making a safety case.

In general, there are benefits to be had from lower heat generation (except in SM-HTGR), but challenges to produce the wasteforms to achieve this.



Note: A Generic SM-PWR is assessed as 'Reference' on 'Disposability' in comparison to a GWe-sized PWR

Figure 14: Disposability from GFAs

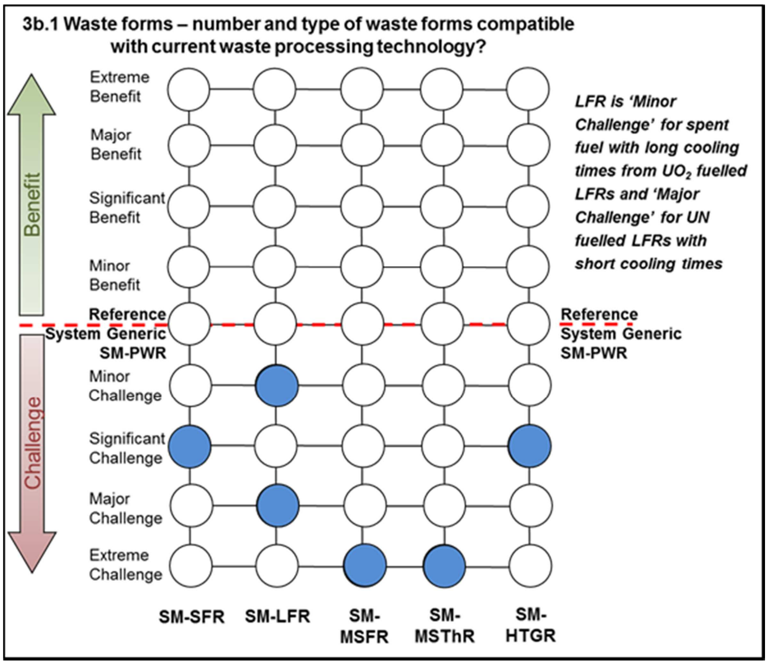


Figure 15: Wasteform Compatibility from GFAs

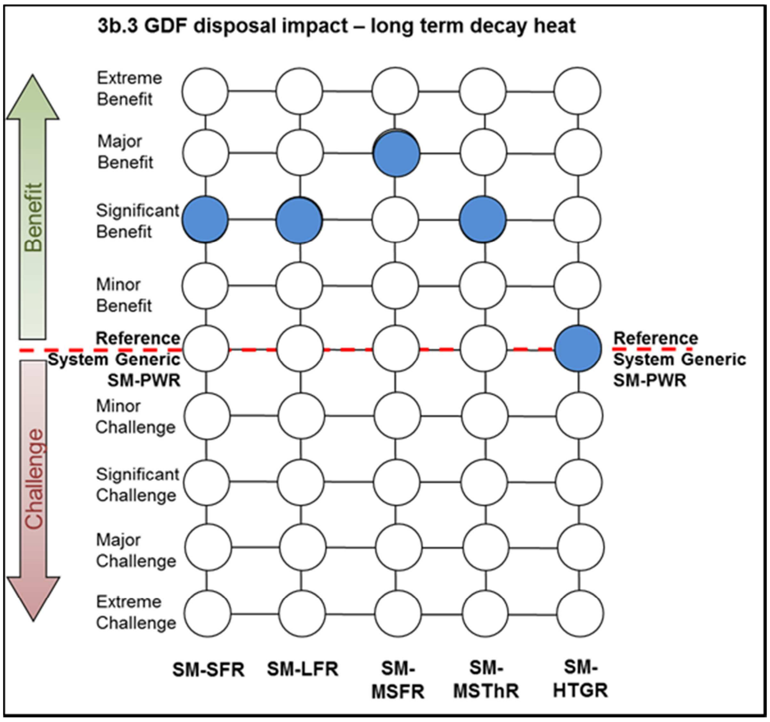


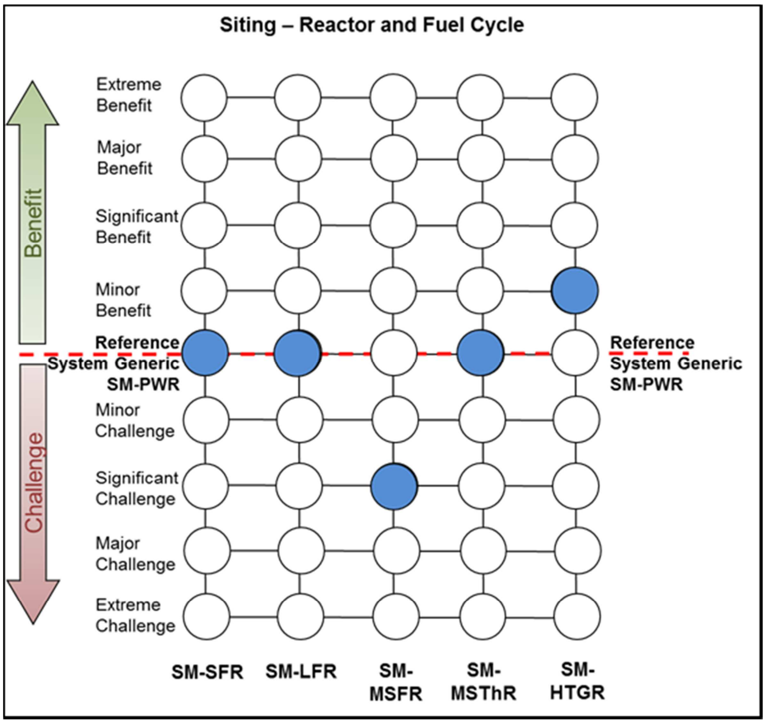
Figure 16: Long Term Decay Heat Impacts from GFAs

4.8.8. Siting – Reactor and Fuel Cycle

The Benefits or Challenges associated with the deployment of all SMRs vary depending on whether they are deployed singly or in groups, potentially of up to GWe capacity. In small capacity installations, there will be Benefits in smaller cooling water requirements and grid connectivity demands, whereas, if deployed in larger groups, the infrastructure required could approach that of a GWe-sized reactor.

Most SM-HTGR concepts are projected to operate at the lower end of SMR system thermal outputs (less than or approximately equal to 100 MWth) and the concepts do not envisage deploying many units at one site to achieve the equivalent electrical output from a single large PWR. This leads to an assessment of Minor Benefit for SM-HTGR.

For other Emerging Technologies, a key factor for defining siting challenges is whether there is a need to provide elements of the back end of the fuel cycle on the reactor site. For SM-SFR and SM-LFR technologies, co-location of spent fuel reprocessing on the reactor sites would change the level of Challenge away from the Reference level to Significant Challenge. At the current state of knowledge, on-site reprocessing would seem almost inevitable for SM-MSFR technologies, but it is assumed that such activities can be minimised for SM-MSThR systems that attempt to replicate historic experience with Thermal Neutron Molten Salt Reactors [**14**].



Note: A Generic SM-PWR, when compared with to a GWE-sized PWR, is assessed as 'Reference' when deployed in GWe-sized groupings and 'Significant Benefit' when deployed as a dispersed network

Figure 17: Siting – Reactor and Fuel Cycle from GFAs

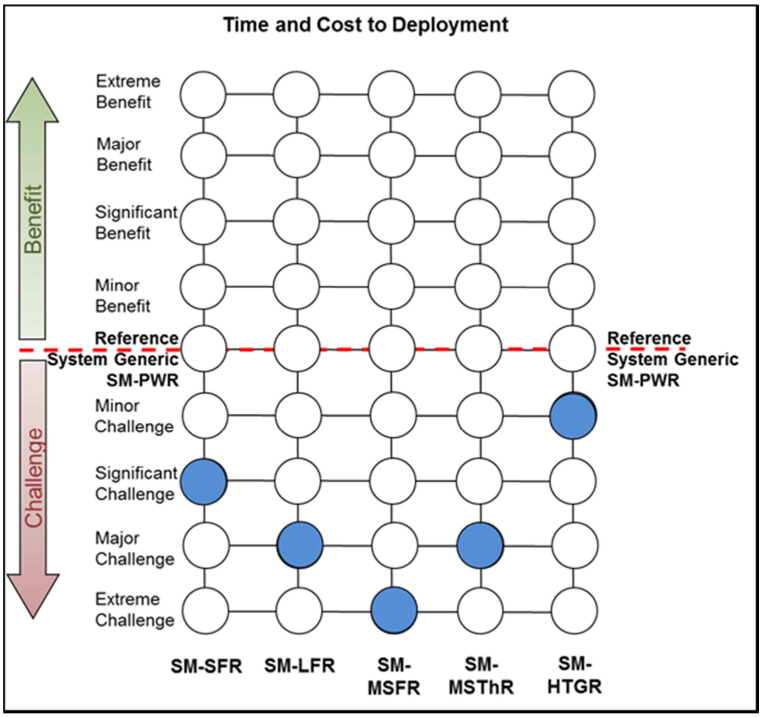
The small electrical (and potentially heat) output of SMRs can have a significant effect on the availability of suitable sites and a distributed network could give benefits. This is discussed in more detail in Appendix B.

4.8.9. Time and Cost to Deployment

Time to Deployment is important, to the extent that the consideration of roles for nuclear power is directed at the reduction of the UK's carbon emissions by 80% of their 1990 level by 2050. If the 2050 commitment is to be achieved, then the deployment of Emerging Technologies available on this or later timescales could be restricted to replacement of the nuclear power stations then in operation. If a first on-line date for GWe-sized PWRs of 2025 with a 60-year lifespan is realised, the replacement market might not materialise until after 2085.

Within GFA, Time and Cost to Deployment is assessed after considering:

- The Technology Readiness Level (TRL) – an estimate of the maturity of critical technology
- An estimate of the likely time before being able to submit for licensing
- The time to license, and
- The likely build time.



Note: A Generic SM-PWR is assessed as 'Significant Challenge' on 'Time and Cost to Deployment' in comparison to a GWE-sized PWR

Approximate First Operation in the UK:

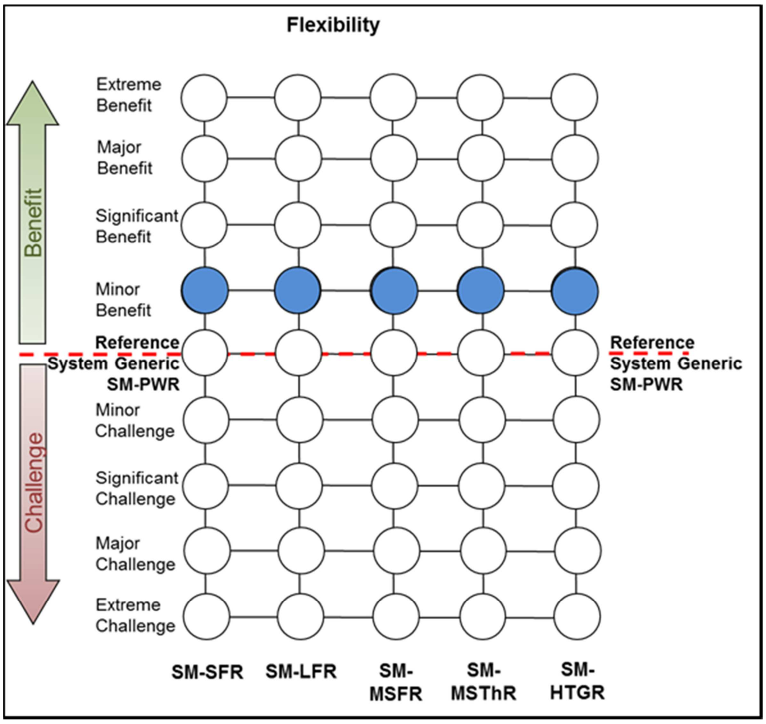
SM-PWR	2030
SM-HTGR	2035
SM-SFR	2040
SM-LFR	2060
SM-MSThR	2060
SM-MSFR	2070

Figure 18: Time and Cost to Deployment from GFAs

The assessed timescale for first operation in the UK is given in the GFAs and accompanying text in Figure 18. This, and the GFA assessment, indicates that all the Emerging Technologies, with the possible exception of HTGR, will be challenged to achieve a significant deployment before 2050.

4.8.10. Flexibility

All the Emerging Technologies are assessed to give a 'Minor Benefit' in comparison to the Generic SM-PWR, as shown in Figure 19.



Note: A Generic SM-PWR is assessed as 'Significant Benefit' on 'Flexibility' in comparison with a GWe-sized PWR

Figure 19: Flexibility from GFAs

4.8.11. Process Heat

All the Emerging Technologies can produce higher temperature process heat than SM-PWRs (seeFigure 20). The currently assumed available temperatures are given the text box below. SM-HTGR offers the highest temperature and, particularly when combined with its 'Minor Benefit' on 'Siting', is probably the system most likely to be targeted for high temperature process heat applications.

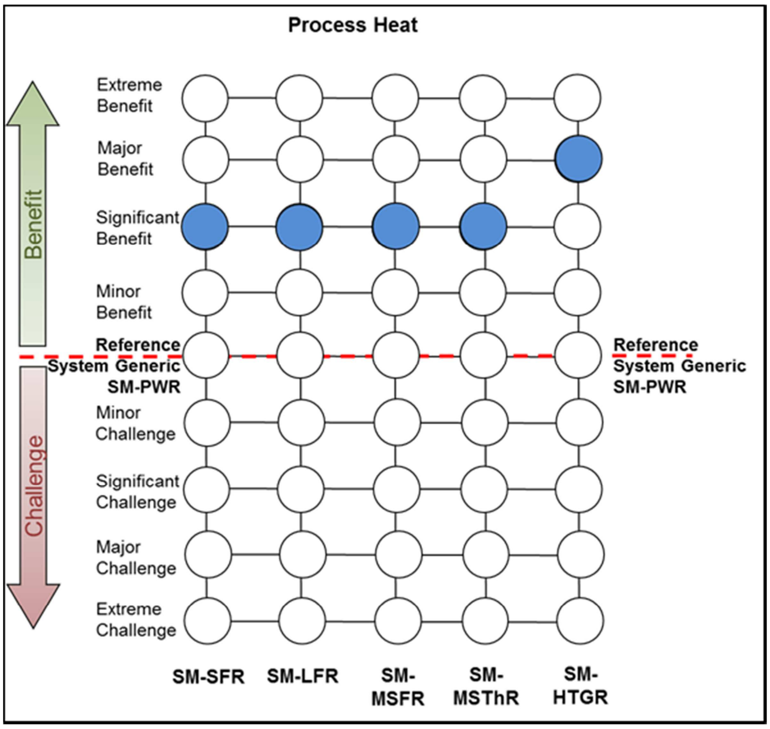


Figure 20: Process Heat from GFAs

Note: A Generic SM-PWR is assessed as 'Reference' on 'Process Heat' in comparison with a GWe-sized PWR

Process Heat – temperatures available:

SM-SFR	~550ºC
SM-LFR	~550ºC
SM-MSFR	~700ºC
SM-MSThR	~700ºC
SM-HTGR	~800ºC

5. Levelised Cost of Electricity and Nuclear Externalities

5.1. Levelised Cost of Electricity (LCOE)

The Levelised Cost of Electricity (LCOE) analyses the cost of the various economic components of nuclear power generation over a reactor's lifetime at assumed financial discount rates. LCOE can be used in conjunction with GFA, helping to provide an economic context for Benefits and Challenges on particular Attributes. The principal source used here is a 2015 analysis of LCOE for GWe-sized LWRs performed by International Energy Agency and Nuclear Energy Agency [**19**]. The figures below are derived from Table 3.11 of the reference, and give the costs of the various elements of LCOE at three discount rates – 3%, 7% and 10%. These give only the broad 'Fuel Cycle' costs, but the split assumed between 'front end of fuel cycle' and 'back end of fuel cycle' is stated, and this allows the 'Front End' to be further sub-divided into 'uranium', enrichment, and 'conversion/fabrication'. This additional breakdown is seen in Table 3 below.

Table 3: LCOE buildup for GWe LWR Reactors[11]

Discount Rate	**LCOE (USD/MWh)**	**Investment cost (USD/MWh)**	**O&M costs (USD/MWh)**	**Refurbishment and decommissioning costs (USD/MWh)**	**Fuel and waste costs (USD/MWh)**	**Back End (25%)**	**Front End (75%)**	***Uranium***	***Enrichment***	***Conversion + Fabrication***
3%	**51.45**	26.99	13.55	0.46	10.25	2.56	7.69	*3.84*	*2.69*	*1.15*
% of LCOE		52.46%	26.34%	0.89%	19.92%	4.98%	14.94%	*7.47%*	*5.23%*	*2.24%*
7%	**80.53**	55.43	13.55	0.29	10.25	2.56	7.69	*3.84*	*2.69*	*1.15*
% of LCOE		68.83%	16.83%	0.36%	12.73%	3.18%	9.55%	*4.77%*	*3.34%*	*1.43%*
10%	**109.32**	84.37	13.55	0.14	10.25	2.56	7.69	*3.84*	*2.69*	*1.15*
% of LCOE		77.18%	12.39%	0.13%	9.38%	2.34%	7.03%	*3.52%*	*2.46%*	*1.05%*

This LCOE build-up is illustrated for the 10% discount rate in Figure 21.

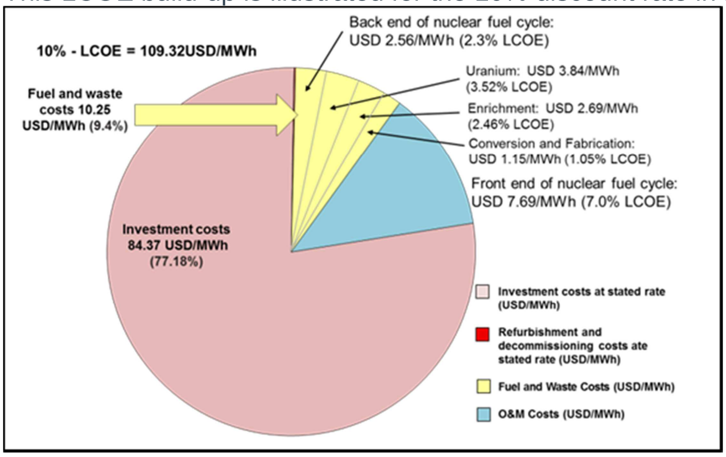


Figure 21: LCOE breakdown at 10% Discount Rate

[11] Reactors were modelled with nationally-nominated Capacity Factors for commissioning after 2020. This would typically be around 90%.

Though it should always be remembered that these are discounted dollars, the observations from Table 3 and Figure 21 include:

- Savings in fuel costs will, at current prices, constitute a relatively small saving in terms of percentage of LCOE
- In particular, uranium costs vary with discount rate from 3.5% to 7.5% of LCOE, and so even complete removal of uranium costs will have only a modest effect at current prices, and, as a corollary, very severe increases in uranium prices (or major limitations in supply) would be necessary to make uranium costs a strong economic driver for reactor choice.
- The entire back end of the fuel cycle (storage and disposal) accounts for some 2.3% - 5.0% of LCOE, so here again major changes in storage/disposal costs or their availability would be required to drive economic reactor choice.
- Similarly, the decommissioning costs of 0.1% - 0.9% of LCOE will offer little incentive to make choices based on these costs, though this is the classic case of a very expensive operation appearing economically insignificant because it will take place many decades in the future.

The particular significance of these observations for each reactor group will be included in conjunction with the overall analysis of the GFA results.

The other major observation from these figures is the very large variation in LCOE with assumed Discount Rate. This is illustrated in Figure 22.

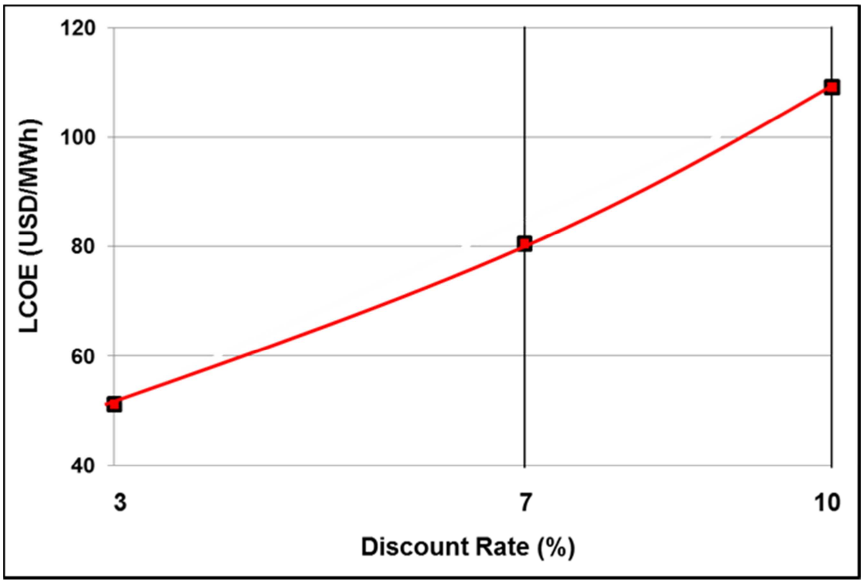


Figure 22: Variation in LCOE with Discount Rate

As seen here and in Table 3, the assessed LCOE changes by more than a factor of two as the Discount Rate is varied between 3% and 10%. A 1% increase in Discount Rate increases nuclear LCOE by 7.5-10 USD/MWh, in contrast to the entire fuel cycle element of the LCOE, which is 10.25 USD/MWh. It is thus crucially important that there is clarity over the Discount Rate assumed in any analysis, and the reasons for the assumption.

Another factor which will strongly affect LCOE is the length of time for which the financing operates, which in turn is affected by the time taken to build the reactor. SMRs could benefit here, as ‘factory build, deliver to site and install’ should give a shorter build time. This should be effective once the SMRs in question are ‘rolling off the production line’ – or very much ‘Nth of a kind’. However, during the initial period during which the ‘production line’ is being set up and proved, the first units would be expected to take longer between ‘hardware ordering’ and ‘delivery to site’ thus eroding the ‘build time’ advantage. The overcoming of this initial cost ‘spike’ will be part of the overall evaluation and decision making for any series build of SMRs.

5.2. Nuclear Energy 'Externalities'

Emerging nuclear technologies will, as assessed by GFA, have Benefits and Challenges, many of which will become major drivers in only a sub-set of possible futures. For example, 'Fuel Security' may be extremely important in a future where uranium supplies are greatly restricted and/or very expensive. Similarly, the Metrics making up 'Disposability' may become very significant if there is a restriction on the volume, radioactive content or heat output of the waste produced.

Preliminary studies for DECC [**20**] failed to find convincing evidence of imminent (i.e. this century) shortages of uranium at any credible world LWR build rate. Though more work is needed, it can be said that the onus is on those asserting shortages to show how, when and why these might occur. In the absence of uranium shortages many of the 'Fuel Security' benefits of fast reactor and thorium systems may not translate into economic drivers for these systems.

Disposability is also an area requiring clarification of how, when and why GFA Benefits would translate into economic drivers. For example, many studies treat reduced radiotoxicity[12] as a benefit, while the most radiotoxic species (mainly actinides) are generally not mobile in geological settings and do not become limiting in Geological Disposal Facility (GDF) safety cases. In fact, most disposal safety cases are driven by the occurrence and abundance of long-lived mobile fission products, which could be expected to be approximately the same for a similar power output of any fission system[13].

On the other hand, heat output could be expected to affect the spacing of waste in a repository, and thus the cost of disposal. However, the relatively small contribution of the fuel cycle 'Back End' to LCOE (see Section 5.1) would require a very large change in back end costs before these would become an important overall driver. One obvious 'tipping point' would be if the increased waste spacing, and hence repository footprint, led to a particular body of rock to be insufficiently large to take the UK inventory. This would potentially mean a shift from one to two repositories, with very large extra spend, but it is unclear how the likelihood of such a 'tipping point' occurring could be assessed.

So, though more work is needed, it is not immediately obvious that 'Benefits' involving several GFA Attributes could evolve into significant drivers in a decision-making regime relying on discounted money.

5.3. Nuclear Energy 'Externalities' – fit with Technology Groupings

As outlined in Sections 5.1 and 5.2, the Levelised Cost of Energy (LCOE) has been used to provide a context for assessing the significance of the benefits of each of the 6 Technology Groupings in different 'nuclear energy futures'. The sections below place the GFA results into this economic perspective.

5.3.1. Scarce/Expensive Uranium Future

The benefits of systems which use less mined uranium will become significant if uranium becomes scarce or very expensive. The dependence on uranium is reflected in the 'Fuel Security' Attribute, and the results for the five Technology Groups are given in Figure 23 below.

[12] See for example IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Methodology [**21**].
[13] Currently the subject of a PhD at the University of Manchester in partnership with NNL.

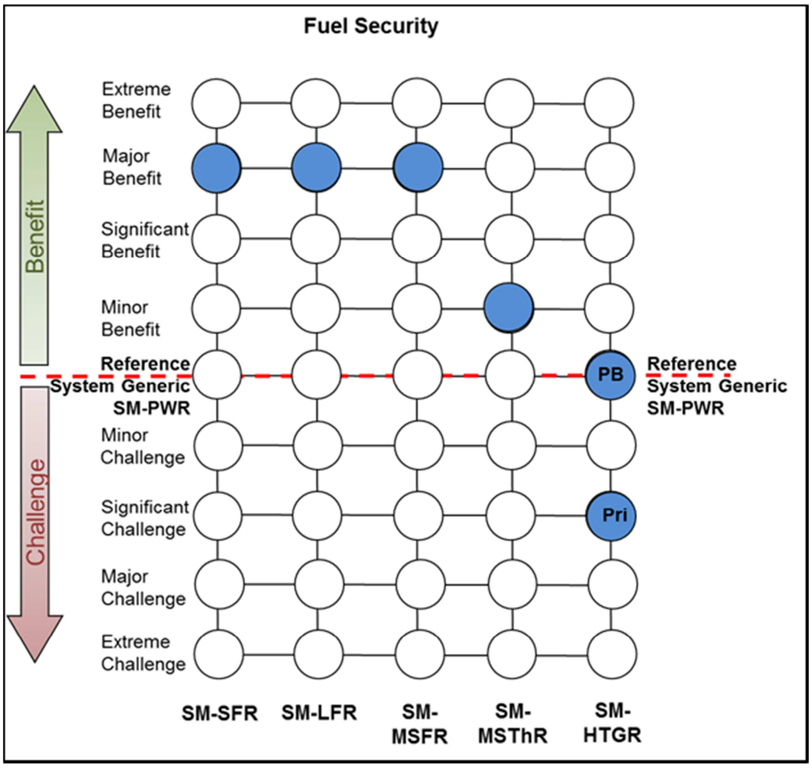


Figure 23: Assessment of Fuel Security for Technology Groups

This shows that the three fast reactor systems show a major benefit in fuel security, and are, when at equilibrium, dependent only on supplies of fertile, rather than fissile material. These systems would thus become favoured if supplies of uranium were threatened. As previously discussed, though further work is needed, it is not currently thought likely that a major uranium shortage will materialise this century. Also, as discussed in Sections 5.1 and 5.2, uranium price rises would need to be extreme to have a significant effect on LCOE. Perhaps the most likely effect of uranium supply would be if there was a market perception that U supplies might be limited. This might lead to pressure from investors to buy any reactor's lifetime U supplies 'up front', with consequent considerable effects on the installed cost/KWe, and hence on the LCOE.

Overall, however, it is difficult to see the 'uranium driver' becoming a significant factor in near term (several decades) decision making.

5.3.2. Disposal Limited Future

As previously discussed, it is not immediately obvious how advantages in waste volumes, isotopic makeup and heat output would become a major driver for one system compared to another. In the GFA analysis, the outcome is complicated by the fact that before disposing of the waste, the spent fuel or reprocessing wastes must be conditioned into a form which will retard radioisotope release sufficiently to allow a GDF safety case to be met. In many of the Emerging Technology systems examined, the definition of the wasteforms is at a very early stage, and though disposal may ultimately be easier, there is a large conditioning hurdle to be surmounted first. The results of the 'Disposability' Attribute for the five Technology Groups are given in Figure 24 below.

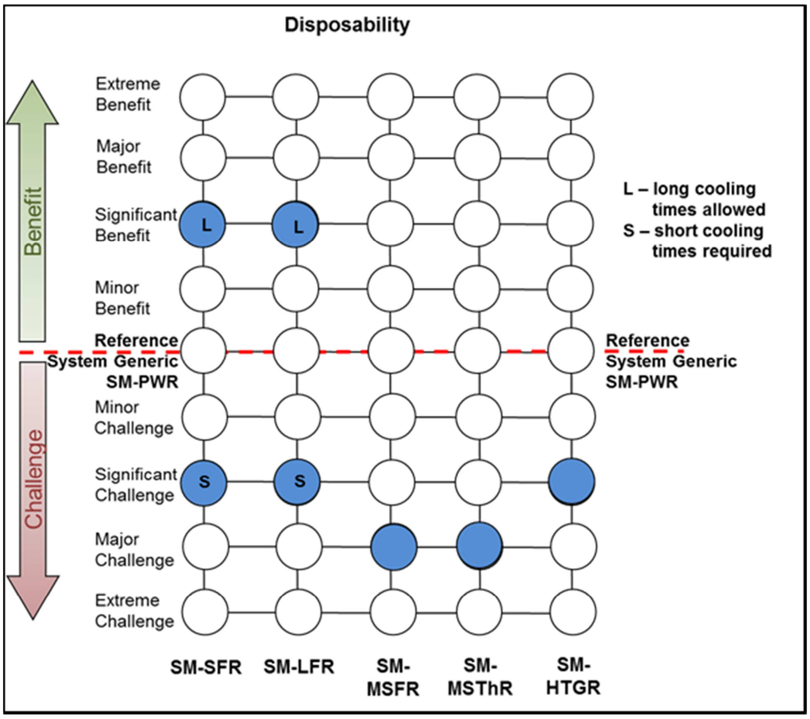


Figure 24: Assessment of Disposability for Technology Groups

As discussed in Section 5.2, even if the difficulties of achieving adequate wasteforms are discounted, there is no obvious route by which disposability would become a major economic driver. In fact, it could be suggested that it is the achievement of geological disposal per se which is the key step, with consideration of ‘what is to be disposed’ as a very secondary factor.

In summary, it is not easy to anticipate a ‘nuclear future’ in which advantages in uranium usage or waste disposability could promote either attribute as a significant economic factor in a choice between nuclear fission technologies.

6. Possible Roles for SMR Technologies in UK Energy Futures

6.1. UK Energy Futures

6.1.1. UK Energy Usage

SMRs have a potential role in the nuclear power portion of UK energy futures. A prime role of nuclear is to contribute to the economic decarbonisation of energy production in the low carbon UK future now enshrined in legislation.

Total final consumption of UK energy products can be divided into four sectors – transport, domestic, industrial and services. Only 10% of the primary energy is delivered as electricity [**22**]. The consumption for these sectors in 2013, excluding fuel use in electricity generation, is summarised in the Table 4 below. Note the extremely large electrical capacities needed to directly replace 'heat by fuels' with 'heat by electricity', though this can be mitigated to some extent by the use of higher efficiency systems such as heat pumps and improvement in the thermal efficiency of homes and industrial processes.

Table 4: UK Energy Consumption in 2013 [23**].**

End Use	Domestic	Services	Industry	Transport	Total te oil eq[b]	%	TWh	GWy at 85%CF[a]
Space heating	28,728	10,084	3,109	-	41,922	30.6%	487.6	65.4
Water heating	7,494	1,953	-	-	9,447	6.9%	109.9	14.7
Process use	-	-	9,082	-	9,082	6.6%	105.6	14.2
Cooking/catering	1,108	2,042	-	-	3,150	2.3%	36.6	4.9
Drying/separation	-	-	1,762	-	1,762	1.3%	20.5	2.8
Heat total	37,330	14,079	13,954	-	65,363	47.8%	760.2	102.0
Transport				53,418	53,418	39.1%	621.3	83.4
Other Non-heat uses	6,464	6,006	5,535		11,541	8.4%	134.2	18.0
Total	43,794	20,085	19,489	53,418	136,786	100.0%	1590.	213.5
Total TWh	509.3	233.6	226.7	621.3				
%	32.0%	14.7%	14.2%	39.1%	100.0%			

Notes: [a]1GWe at 85% Annual Capacity Factor = 7.45 TWh. [b]1,000te oil equivalent = 0.01163TWh. It should be noted that the GWy figures would equate to the number of 1 GWe reactors if the energy was delivered via electricity, but only around one third of the number of reactors if the energy was delivered via heat.

To meet the Government's decarbonisation targets it will be essential to achieve substantial decarbonisation in these four sectors, together with decarbonising the electricity supply. These targets provide some indicators as to the range of energy 'futures' which the Government would wish to address and the drivers and issues associated with fulfilling such futures. The key questions for this Project are therefore 'what role could/should nuclear perform' and 'within this, what role could/should SMRs perform' in each sector. Electricity and the four energy sectors are now examined in turn.

6.1.2. Decarbonising Electricity

All the nuclear technologies examined produce electricity with very low carbon emissions. The extent to which these technologies are used to decarbonise the UK's electricity will be determined by:

- Their perceived economics in comparison to other low carbon electricity sources, within the constraints placed by requiring a network which delivers power with high reliability, and

- The ability to find sites for the number of nuclear power stations required.

The role of SMRs within this will be determined by:

- Their economic performance: scaling factors would favour larger (GWe-sized) reactors, while modularisation and 'factory build' would seem to favour SMRs

- The ability to find sites, with SMRs generally being considered less constrained in their choice of site as, individually, they have less stringent cooling water and grid connection requirements.

These are in fact the questions that are being posed by Project 1 of the Technical-Economic Assessment, and the conclusions reached on current technologies should provide a benchmark against which emerging technologies can be assessed.

6.1.3. Decarbonising Space Heating (30.6% of usage) and Water Heating (6.9% of usage)

Nuclear power can play a role in decarbonising domestic heating by a number of routes, with various vectors being utilised to deliver the heat to its required domestic destination, as discussed in the following sections.

Electricity

Electricity is produced by all the nuclear technologies examined and can directly replace fossil fuels to provide space or water heating. The level to which this occurs will be determined by the relative economics of heating by 'nuclear electricity' compared with other means. The economic position of SMRs in electricity generation will be determined as for 'Decarbonising Electricity'.

Low grade heat

Low grade heat can be produced as water at around 80ºC by most if not all of the technologies examined (and in particular by PWRs), and this temperature is sufficient for virtually all domestic heating requirements, and a portion of the water heating needs. The heat production entails some reduction in the electricity produced, and the consequent reduction in electrical sales income needs to be compensated by the price obtained for the heat. The hot water needs to be fed into a district heating network, so the overall economics of 'heat production plus delivery network' will determine the desirability of the route. Clearly the installation of heat networks in new domestic developments would be easier than for established communities. Here, the ability to site the reactor(s) closer to the heat demand would be expected to favour SMRs over GWe-sized reactors.

Hydrogen

Hydrogen would essentially be used as a substitute for natural gas, and is a candidate for decarbonising domestic heating, provided that it can be produced using a low carbon source of power. Hydrogen cannot be a direct substitute for natural gas in the existing gas network, though much experience from the time of 'town gas'[14] (~50% hydrogen) will be relevant. The requirement for hydrogen would also be expected to fluctuate, so a viable network would need to be combined with storage. For nuclear to be relevant, it would have to produce hydrogen at a price which was economic when considered together with the costs of the storage distribution network.

As all nuclear technologies can produce electricity, all can produce low carbon hydrogen by the electrolysis of water. This is process has low efficiency, and is unlikely to be economic unless the marginal cost of power is very low, though niche uses of the process have already been established [**24**]. Higher efficiencies require the use of low carbon high temperature process heat, which some of the reactor technologies examined may be able to provide. At present, most hydrogen production methods require temperatures in excess of 900ºC, which is currently a challenge for nuclear systems. The storage and distribution considerations of hydrogen as a vector would favour generation near point of storage and/or usage, and this may favour SMRs.

[14] Before the advent of natural gas in the 1970s, virtually all fuel and lighting gas in the UK was made from coal ('town' or 'coal' gas, ~50% hydrogen) and was supplied by municipal networks.

6.1.4. Decarbonising Cooking and Catering (2.3% of usage)

Cooking and catering will require a mixture of low grade heat for preparation and cleaning, and higher grade heat for hobs, ovens and the like, together with electricity for lighting and appliances. It is highly unlikely that any higher grade heat use would be large enough to justify nuclear heat, so decarbonising cooking and catering is liable to lie with electricity and low grade heat, together with hydrogen if this were to be substituted for natural gas in the future.

6.1.5. Decarbonising Process Use (6.6% of usage) and Drying/separation (1.3% of usage)

Industrial heat from fossil fuels can be replaced by low carbon electricity subject to the same economic considerations as in 'Decarbonising Electricity'. It is assumed that most of the heat use processes, drying and separation, are likely to require higher temperature heat than hot water can provide on its own.

Higher temperature heat

As mentioned under 'hydrogen production' above, several of the reactor technologies can provide low carbon process heat at higher temperatures than LWRs, and these could be considered for industrial process heat. Here the proximity of heat generation to heat use would be very important, and this would be expected to favour SMRs.

Hydrogen

The considerations surrounding hydrogen use for industry are essentially those already discussed for the use of hydrogen in decarbonising domestic heating, with the temperature required for hydrogen production currently a challenge, and with distribution and storage considerations tending to favour SMRs.

6.1.6. Decarbonising Transport (39.1% of usage)

Here low grade heat is not relevant, and the potential for decarbonisation is restricted to:

- Electricity – with the transport function supplied by
  - Connections (overhead or ground level conductors for trains, trams and subways),
  - Batteries, which whilst significant improvements in technical and economic performance have been made in recent years, further improvements are required to achieve widespread use, or
- Fuels which can be converted to electricity in fuel cells, with hydrogen the main candidate.
- Low carbon fuels which mimic fossil fuels for use in internal combustion, jet engines or gas turbines. These can consist of:
  - Hydrogen – requiring high temperatures for efficient production
  - Synthetic fuel (including methane, and substitutes for petrol, diesel oil, and kerosene) produced from the hydrogenation of carbon dioxide by low carbon energy. The temperatures required are in the region of 200–300°C, and so could be provided by several of the nuclear technologies being examined, though the hydrogen supply will require high temperatures as already mentioned.

For a nuclear role in decarbonisation, all of these options require economic nuclear power, some of them require medium- or high-temperature process heat, and some of them would benefit from the power/heat source being small and local, thus favouring SMRs.

6.1.7. Scale of Nuclear Opportunities to 2050

DECC is currently examining nuclear capacities up to 75GWe by 2050 [**25**][15]: "The 75 GW from nuclear energy is part of a scenario where total installed capacity in the UK is around 160 GW by 2050". Studies for ETI have demonstrated that this magnitude of (GWe-sized) nuclear programme is capable of being sited [**26**].

[15] Note that '2050 Pathways Analysis, HMG, July 2011' examined nuclear programmes up to 130 GWe.

Credible scenarios which use significant nuclear capacity are exemplified by the 'Clockwork' scenario which has been extensively examined by the Energy Technologies Institute (ETI) [**27**]. This requires 40 GWe of nuclear capacity by 2050[16]. Subsequently, ETI's study on SMRs has examined up to 21 GWe of SMR deployment [**28**], combining a dispersed siting of SMRs with provision of district heating using 80ºC water from the SMRs as the vector. 80ºC water could be abstracted from all the technologies examined, both PWR and 'emerging', but the low temperature limits this vector to replacing other sources of low temperature heat, and will find application in the Domestic and Services sectors, which currently make up nearly 50% of the market, as seen in Table 5 below. This table also indicates the vectors which can be used to decarbonise the sectors, as discussed above in Sections 6.1.2 – 6.1.6.

Table 5: Energy usage by sector, 2013[17]. * Remainder for 'non-heat uses'

Sector	Vector(s) to decarbonise	Sector usage TWh	% usage TWh	Cumulative %
Domestic	Electricity, Low Temperature Heat, Hydrogen	509	32	32
Services	Electricity, Low Temperature Heat, Hydrogen	234	15	47
Industry	Electricity, Low Temperature Heat, High Temperature Heat, Hydrogen	227	14	61
Transport	Electricity, Hydrogen, Synthetic Fuels	621	39	100

Table 5 indicates that access to the remaining 50% of the heat market (vis Industry and transport) will require additional energy vectors, either to directly substitute for fossil fuels (e.g. electricity for industrial process heat) or to create carbon-neutral fuels which can be used as vectors (e.g. hydrogen, synthetic fuels). For nuclear to access the 'carbon-neutral fuel' options process heat is needed at temperatures well in excess of that available from LWR technology, and in essence the amount of this heat market which can be accessed will increase as the temperature of the available process heat increases.

Table 6: Process heat temperatures for SMR Technology Groupings from GFAs

Small Modular Technology	Process Heat Temperature (ºC)
Pressurised Water Reactors	<320
Sodium Cooled Fast Reactor	~550
Lead Cooled Fast Reactor	~550
Molten Salt Fast Reactor	~700
Molten Salt Thermal Reactor	~700
High Temperature Reactor	~800

[16] Note that this study pre-dates the consideration of SMRs, so all the 40 GWe consists of GWe-sized reactors.
[17] Derived from Table 4.

The only system with which it is currently feasible to achieve temperatures near 900°C is the SM-HTGR. Even here the present technology would require some extra heat input to bridge the gap between the 800ºC currently expected and the 900ºC required for hydrogen production.

6.1.8. Timing of Nuclear Decarbonisation Opportunities

The above analysis indicates that, to the extent that decarbonisation can economically be achieved using electricity as the vector, then GWe-sized LWR stations with SM-PWRs would be the credible nuclear candidates. However, for decarbonisation using process heat, the higher temperatures required for at least some of the industry and transport sectors would favour emerging technologies, notably SM-HTGR.

If a 2050 decarbonisation target is to be met, this could achieved by:

- a combination of ‘electricity plus low temperature heat’ using GWe LWRs and SM-PWRs deployable by 2030, together with
- ‘higher temperature heat’ using SM-HTGR technology from circa 2035 onwards.

6.2. Future Flexibility

One central element of the market assessment is the analysis of the role that SMR technology could play within the power system and the benefits (and eventually the drawbacks) that this technology could bring to the operability of the electrical system and thus the revenue streams that could be generated as a counter part of those benefits.

It is important in such analysis to adopt an hourly modelling of the operation of the UK power system. This will highlight not only the seasonal intermittency of some generation technologies but also the short term variability that may have a significant impact on the system and SMR operability.

In summary, the analysis showed that the “flexibility” (or lack of flexibility) property of an SMR design is one of the major impacting features facilitating (or preventing) the integration of the technology within the UK Power Mix[18]. The full analysis is provided in an accompanying paper.

SMR flexibility is highlighted when high intermittent generation capacity is present within the UK mix and exacerbated by periods of low electricity demand. During these events:

- SMRs could reduce renewable curtailment allowing renewable technologies to generate more.
- Technically, SMRs could contribute to the system response provision, preventing fossil fuelled units from starting up only to provide response.
- SMRs could provide upward flexibility to the system operation.

In contrast to these benefits, these flexibilities would lead to SMRs being run at lower capacity factors. Assuming export capacity from the UK system could allow an increase the SMR capacity factor and positively contribute to the UK commercial balance. Having “low variable cost” energy mix with renewable generation and nuclear could contribute to UK power generation competitiveness with regard to continental Europe. This could offer more opportunities for SMRs and could allow them to operate at higher capacity factors.

Energy storage technologies would also play a significant role both in helping intermittent generators to increase their generation and avoid curtailment, and for nuclear generation, to avoid de-loading and shutdowns for load-following. This happens by shifting the usages from peak hours to non-peak ones, thus

[18] These assumptions rely on SMRs demonstrating improved flexibility and lower financing costs than large nuclear technologies.

flattening the load curve. As pumped hydro storages sites are limited in the UK, chemical storage (batteries) and thermal[19] storage will play a significant role.

The capability of SMR to leverage the generated heat through high temperature processes may also add another revenue stream to their operation. For instance, it may be used to produce hydrogen that can be stored and used in H2 turbines to produce electricity in peak periods. Though, generating heat could constrain SMR flexibility as the heat process often needs a steady heat provision.

Flexible SMR would also face important operation constraints, when high intermittent renewable energy share is present within the energy mix. The SMR number of shutdowns for load following may increase together with the number of hours operating at reduced output[20]. This needs to be considered for flexible SMR designs.

The main technical constraints that SMR flexible operation may face are:

- The small size of SMRs would have an advantage during unplanned outages events. If we assume the same outage rate for a 200 MW SMR unit and for 1000MW unit, the probability of having 1GW of SMRs in outage at the same time would be far smaller than the probability of one of the large 1000MW being in outage. In a system with an integrated fleet of SMRs, there would be more unit outages, but less of the UK capacity off-line at any one time. Note, however, that site-effect outages (outages that affect all the units on the same site) may be a disadvantage for SMRs in multi-unit deployment.

- The number of shutdowns and changes in the operating regime of an SMR unit will impact the vessel fatigue. This also highlights the importance of designs with a low Stable Export Limit (SEL) as it will allow the SMR unit to de-load instead of shutting down. Note that from the system operation point of view, the system operator may choose to shut down some units and run the others at full load or de-load the whole fleet. This would be decided from a technical and cost optimisation point of view and would probably result in a de-load of the whole fleet as it would spare the additional start-up costs. Thus, the larger the fleet of SMRs, the lower will be the constraints on the flexible operation.

- Also, the flexibility of SMR designs with added Boron evolves during the cycle (between two refuelling shutdowns). In fact the Stable Export Limit is lower at the start of the cycle and increases as the cycle advances, increasing the likelihood of shutdowns for load following. Boron-free designs would be, in that sense, more flexible.

- The other important impact of flexible operation on an SMR unit is the Extended Reduced Power Operation (ERPO) when the unit is required to run a multiple number of consecutive hours at reduced power. This may result in a high risk of fuel failure due to pellet-cladding interaction (PCI). Initially the pellets will shrink because of thermal contraction as the reactor power decreases, causing the pellet-clad gap to reopen. Then, if sufficient time passes the shrinking of the pellets is followed by clad creep-down. The cladding will then be in a state where a sustained period of rapid pellet expansion as power is raised will result in considerable stress imposed on the cladding[21].

[19] Electricity is stored when it is used for space and water heating and electricity demand is reduced (instead of electricity generated) when stopping the heating.
[20] It will generally be preferable to operate at low power for as long as possible rather than shut down the reactor, as once shut down, the reactor cannot be called upon for generation for around 24 hours, thereby reducing grid resilience. However, periods of severe overcapacity (e.g. high wind/low demand) will still require shutdown to be available.
[21] Detailed conditions of ERPO and PCI will depend strongly on recent core history, with public domain information available in Ref. [**29**].

7. Conclusions and Observations

7.1. Effectiveness of GFA for assessment of Emerging SMR Technologies

The GFA approach, using public domain information and professional judgement, proved to be an effective strategic assessment tool especially since it 'asks all the questions' which Emerging SMR Technologies, being at an early stage of development, may not have addressed.

The original GFA methodology was augmented by undertaking cross-system comparisons by single Attribute and allowed observations to be made on the relative 'fit' of each SMR technology to the various possible UK energy futures. The cross-system comparisons also provided an additional test, in that the relative scale of 'Benefit' and 'Challenge' was 'normalised' across the Emerging Technologies examined.

7.2. Range of Emerging SMR Technologies Reviewed

Over 40 potential SMR concepts were reviewed on the basis of the public domain information available. The Project classified these into six technology groups:

7. Small Modular Pressurised Water Reactors (SM-PWR)
8. Small Modular Sodium-cooled Fast Reactors (SM-SFR)
9. Small Modular Lead-cooled Fast Reactors (SM-LFR)
10. Small Modular Molten Salt Fast Reactors (SM-MSFR)
11. Small Modular Thermal Neutron Molten Salt Reactors (SM-MSThR)
12. Small Modular High Temperature Gas-cooled Reactors (SM-HTGR)

It is believed that these concepts and groups cover the totality of the SMR technologies which have commercial interest in their continued development and deployment. The Emerging Technologies were examined against timescales of (a) deployment by around 2030 and/or (b) the ability to contribute materially to the UK's 2050 decarbonisation commitment of an 80% reduction relative to 1990 levels.

7.3. Electricity Generation Requirements for SMR Deployment

A decarbonised UK electricity generation system will need to accommodate a significant volume of intermittent output from renewable sources. This will place a requirement on dispatchable low-carbon generation to operate flexibly. The flexibility required from SMRs in a variety of energy futures was examined, and found to be significant, particularly where gas generation with carbon capture and storage was limited or absent. However, when operated flexibly, SMRs achieve reduced capacity factors and a suitable commercial framework would have to be developed.

7.4. Observations on GFAs of Emerging Technologies

All the Emerging Systems offer benefits on some of the assessed GFA Attributes, for example:

- The fast reactor systems (SM-SFR, SM-LFR, SM-MSFR) offer a very much reduced requirement for uranium, and could essentially remove the dependence of power generation on the security of uranium supply.
- Systems using recycling (e.g. fast reactors) can offer waste disposal advantages, but this is, in most cases, combined with the requirement to develop novel treatment routes for challenging wastes.

- When deployed as low-capacity (<<1GWe) groups, SMRs can have siting Benefits because of lower cooling water and grid connectivity requirements. The level of Challenge will increase as site capacity rises or elements of the back end of the fuel cycle are required to be co-located on the reactor site.

- All the Emerging Technology groups were potentially more flexible in operation than SM-PWRs, but not by a sufficient margin to be a 'game changer'.

A combination of a lack of technical maturity, together with the likely time and effort for licensing and deployment indicates that all Emerging Technologies except SM-HTGR are at least significantly challenged on 'Time and Cost to Deployment' relative to SM-PWRs.

7.5. Levelised Cost of Electricity (LCOE)

A review of the Levelised Cost of Energy (LCOE) has allowed a balanced view of the likely economic importance of the Benefits and Challenges of the Emerging Technologies. The cost components making up the LCOE reveal:

- An overriding importance of capital and financing costs, including discount rate (50-80%)

- A comparatively small dependence on fuel cycle costs (10-20%)

- A small effect of waste treatment and disposal costs (2-5%)

- A minuscule effect of decommissioning costs (0.1-1.0%)

The Emerging Technologies studied offer potential Benefits in areas such as fuel cycle and waste treatment costs, but all appear to offer Challenges in capital cost, which LCOE indicates is the biggest electricity cost driver. This leads to the conclusion that none of the Emerging Technologies are likely to generate electricity cheaper than SM-PWRs.

7.6. Nuclear Futures

If SM-PWRs do represent the least cost generation option for SMRs, Emerging Technologies can offer other Benefits in UK energy futures where high temperature process heat is used directly to decarbonise industrial and/or transport activities. For such futures, for example using process heat in support of hydrogen as an energy vector, Emerging Technologies offer higher temperatures than SM-PWRs, with the SM-HTGR technology offering the highest temperatures and the least challenges on timescale and cost grounds.

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Appendices

Appendix A. Non-exhaustive Review of SMRs from the Literature

Note that though the reactors listed here are all 'small' (<300 MWe) or at least vendors state that 'small' variants of their designs exist, many of them will not be 'modular' and so strictly not classed as SMRs.

SMR Name	Company	Country	MWe net (Max)	Type	Fuel	Coolant
CNP-300	Shanghai Nuclear Engineering Research and Design Institute (SNERDI)	China	300	PWR pumped	<5% enriched UO_2	Light Water
VBER-300	OKBM Afrikantov	Russia	295	PWR pumped	<5% enriched UO_2	Light Water
ABV-6M	OKBM Afrikantov	Russia	10	PWR pumped	<20% enriched UO_2	Light Water
ACP100	China National Nuclear Corporation (CNNC)	China	150	PWR pumped	<5% enriched UO_2	Light Water
IRIS - International Reactor Innovative and Secure	Westinghouse-led - 19 organizations from 10 countries	USA, Croatia etc	335	PWR pumped	<5% enriched UO_2	Light Water
KLT-40S	OKBM Afrikantov	Russia	35	PWR pumped	<20% enriched UO_2	Light Water
mPower	B&W Company and Bechtel Power Corporation	USA	180	PWR pumped	<5% enriched UO_2	Light Water
RADIX	Radix Power and Energy Corporation	USA	50	PWR pumped	TRIGA' <20% enriched U-zirconium-hydride (UZrH)	Light Water
RITM-200	OKBM Afrikantov	Russia	50	PWR pumped	<20% enriched UO_2	Light Water
SMART	Korea Atomic Energy Research Institute (KAERI)	South Korea	100	PWR pumped	4.8% enriched UO_2	Light Water

SMR Name	Company	Country	MWe net (Max)	Type	Fuel	Coolant
Westinghouse SMR	Westinghouse	USA	225	PWR pumped	<5% enriched UO_2	Light Water
CAREM	Comision Nacional de Energia Atomica	Argentina	25	PWR Natural	3.5% enriched UO_2	Light Water
SMR-160	Holtec International	USA	160	PWR Natural	5% enriched UO_2	Light Water
NHR-200	Institute of Nuclear Energy and New Technology (INET) at Tsinghua University	China	65	PWR Natural	3% enriched UO_2	Light Water
NuScale	NuScale Power Inc., Fluor	USA	50	PWR Natural	<5% enriched UO_2	Light Water
4S	Toshiba	Japan	10	SFR	19.9% enriched U-10% Zr alloy	Sodium
ARC-100	Advanced Reactor Concepts, LLC	USA	100	SFR	<17% U-Zr alloy	Sodium
PRISM	General Electric-Hitachi	USA	311	SFR	U, Pu,Zr alloy	Sodium
Rapid	Japanese Central Research Institute of Electric Power Industry (CRIEPI)	Japan	1	SFR	UO_2	Sodium
Travelling Wave Reactor	TerraPower, LLC	USA	300	SFR	<20% enriched U-Zr alloy	Sodium
SVBR-100	AKME Engineering	Russia	100	LBEFR	16.5% enriched UO_2	Lead-bismuth eutectic
G4M (HPM)	Gen4 Energy, Inc. (Hyperion Power Generation)	USA	25	LBEFR	19.75% enriched UN	Lead-bismuth eutectic
ENHS	LLNL	USA	50	LBEFR	~12% Pu U-Pu-Zr	Lead-bismuth eutectic
LSPR	Tokyo Institute of Technology	Japan	53	LBEFR	10-12.5% enriched UN	Lead-bismuth eutectic
SEALER - the Swedish Advanced Lead Reactor	LeadCold, spin-off from Royal Institute of Technology (KTH), Stockholm	Sweden	10	LFR	<20% enriched UO_2	Lead
BREST-OD-300	N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET)	Russia	300	LFR	U,PuN	Lead
Moltex SMR	Moltex	UK	Unknown	MSFR	LEU	Molten Salt

SMR Name	Company	Country	MWe net (Max)	Type	Fuel	Coolant
MCFR Molten Chloride Fast Reactor	Southern Company Services Molten Chloride Fast Reactor (MCFR)	USA	Unknown	MSFR	Unknown	Molten Salt
Molten Salt Reactor	Terrestrial Energy	USA	~240	MSThR	NaF-RbF-UF_4 or NaF-BeF-UF_4	Molten Salt
FUJI	International Thorium Energy & Molten-Salt Technology (Japan)	Japan / Czech Republic	200	MSThR	Thorium	Molten Salt
Integral Molten Salt Reactor	Terrestrial Energy	USA	~240	MSThR	NaF-RbF-UF_4 or NaF-BeF-UF_4	Molten Salt
ThorCon	ThorCon 550MWth Molten Salt	USA	250	MSThR	Na, Be, U and Th fluorides	Molten Salt
LFTR	Flibe	USA	Unknown	MSThR	(Th,U) salt	Molten Salt
NC21	Nuclear Cogeneration Industrial Initiative NC2I	European	Unknown	HTGR	Unknown	Helium
Xe-100 Pebble Bed Advanced Reactor	Xe-100 Pebble Bed Advanced Reactor	USA	45	HTGR - Pebble	UCO fuel in TRISO	Helium
HTMR100	Steenkampskraal Thorium Limited	South Africa	35	HTGR Pebble	$(Th,U)O_2$ fuel in TRISO	Helium
HTR-PM	Institute of Nuclear Energy and New Technology (INET) at Tsinghua University & Huaneng Shandong Shidaowan Nuclear Power Company (HSSNPC)	China	200	HTGR Pebble	8.5% enriched UO_2 in TRISO	Helium
Hydromine	Hydromine Inc	USA	35	HTGR Pebble	Pebbles, Thorium	Helium
GT-MHR (Gas-Turbine Modular Helium Reactor)	National Project Management Corporation (NPMC)	USA/South Africa	165	HTGR Pebble	Triso pebble bed	Helium
GTHTR	Japan Atomic Energy Agency (JAEA)	Japan	275	HTGR Pins	14% enriched TRISO in pins	Helium
NGNP	NGNP Industry Alliance	International	~250	HTGR Prismatic	Prismatic Triso	Helium
SC-HTGR (Antares)	Areva	France	250	HTGR prismatic	TRISO	Helium

SMR Name	Company	Country	MWe net (Max)	Type	Fuel	Coolant
U-Battery	Reactor Institute Delft - University of Manchester	UK-Netherlands	4	HTGR Prismatic	S triso-prismatic-fuelled HTR. 20% enriched UO_2	Helium
VK-300	NIKIET, Moscow	Russia	250	BWR natural circ	Unknown	Light Water
EM2 (Energy Multiplier Module)	General Atomics	USA	240	HTFR	12% enriched 'starter' then DU or REPU.	Helium
GT-MHR (Gas-Turbine Modular Helium Reactor)	General Atomics, OKBM Afrikantov	USA-Russia	285	HTFR	Enriched 'starter' then DU or REPU.	Helium
EGP-6	Teploelectroproekt	Russia	11	BWR graphite moderated	Unknown	Light water
AHWR	Babha Atomic Research Center (BARC)	India	284	PHWR	LEU/ThO_2	Light water
IPHWR	Babha Atomic Research Center (BARC)	India	236	PHWR	Natural U	Heavy Water

Appendix B. Siting Considerations

The low power output from SMR systems may allow for significant benefits with respect to the fewer restrictions on siting. There will be fewer restrictions regarding:

- Cooling water availability – low power outputs reduces water requirements for cooling, thereby permitting the location of power plants in areas where water restrictions forbid the location of plants with higher power outputs that utilise direct cooling or necessitate the alternative coolant methods[22].

- Ultimate Heat Sink – there must always be sufficient coolant to ensure the removal of decay heat, the associated demands on the ultimate heat sink decrease with decreasing power output.

- Grid Connection – there is an economic preference (due to the grid payment system) to locate power systems near areas of high electricity demand. This may be difficult for systems with high power outputs where infrastructure requirements (such as cooling) forbid locating plants near areas of high electricity demand.

- Transmission infrastructure – for power plants with low power outputs it may be possible to transmit electricity using the available transmission infrastructure that was designed for older plants with outputs < 1 GWe.

All SMRs benefit from the above. However, as SMR systems are located together (in order to provide higher power output) the above benefits begin to reduce. The reference SM-PWR system offered was judged to offer significant benefits with respect to siting relative to a 1 GWe PWR system when SM-PWRs were not co-located. In the event, SM-PWRs are co-located with combined outputs ~1 GWe then these benefits are reduced to the extent where siting characteristics are considered to be effectively the same as a 1 GWe PWR.

For systems that rely on on-site reprocessing systems (e.g. the generic SM-MSFR) there may be challenges associated with having to obtain authorisation for any discharges relating to operation of the co-located reprocessing system. Hence, the SM-MSFR was judged to offer significant challenges with respect to siting relative to the reference SM-PWR system.

For the SM-HTGR, which offers the greatest extent of process heat applications, there is likely to be an increased benefit with respect to siting as the system is capable of being employed for industrial uses above those capable with SM-PWRs. Furthermore, the safety performance advantages of SM-HTRs (low power density and robust fuel) arguably make co-locating SM-HTRs near an industrial consumer easier than with other SMR systems. Hence, the SM-HTR was judged to offer a minor benefit with respect to siting relative to the reference SM-PWR system.

The remaining Emerging SMR Technologies (SM-SFR, SM-LFR and SM-MSThR) were considered to offer the same benefits as SM-PWRs.

[22] Alternative cooling methods to direct cooling (heat transfer based solely on water) are available, namely: indirect cooling (heat transfer via evaporation using cooling towers) or dry cooling (heat transfer via air cooling). Whilst both of these alternative methods can be utilised with nuclear power plants they are generally less economical than the conventional direct cooling method used in UK nuclear power plants, this is especially true for dry cooling.