Emerging Nuclear Reactor Technology for Mid Term Commercial Deployment

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***Abstract*—Gen IV nuclear energy systems are likely to become an important base load power source in the low-carbon generation mix by 2030. There are currently six key designs that are the subject of international effort to bring to commercial readiness. However, the path to deployment is complex and requires the resolution of technical, social, environmental, political and economic factors. This paper provides an insight to the motivation for Gen IV technology, a background of the designs and a summary of current R&D progress. A multi-attribute utility analysis of the technology has been performed to understand the commercial viability of each design. It has been found that the Very High Temperature Reactor and Sodium cooled Fast Reactor are the most likely to reach commercial deployment, although it is noted that any conclusions at this early stage of development are subject to change. A list of terms used in this paper is provided in Appendix A.**

I. Introduction

ENERGY security, sustainability and affordability are key challenges confronting global energy policy. 2050 electricity demand is expected to increase by a minimum of 27% compared to 2010. This is due to the electrification of transport and heating in developed countries and increasing demand in developing countries [1]. This insatiable demand for more energy must be reconciled with combating climate change, and has led to renewed investment in nuclear energy [2].

Generating electricity from nuclear fission is a well established science and has been used to supply low-carbon power in commercial quantities since Calder Hall opened in October 1956 [3]. Most of the worlds' reactors were built between 1965 and 1975 with the peak number of grid connections in 1984 [2], just prior to the Chernobyl catastrophe in 1986. Nuclear capacity was in decline by the end of the 1980s [2].

While a full scale "nuclear renaissance" was thwarted by the multi-reactor incident at Fukushima in 2011 [4], nuclear energy remains an important base-load resource in the low-carbon energy mix. In 2012, 437 nuclear fission reactors generated 10.3% of the worlds' electricity[1]. A further 67 reactors were under construction [5], more than at any point since 1988 [2]. With the outlook for new nuclear build becoming increasingly optimistic, this paper considers revolutionary new reactor designs that could transform the nuclear energy sector.

II. Evolution of Reactor Technology

Nuclear energy systems are split into four generations of technology. The first experimental and prototype systems were built between 1950 and 1970 [7] and are referred to as Generation I or Gen I. These include examples of PWR, BWR, Magnox and fast reactor technologies [8] [9].

[1]Calculated from IAEA nuclear total generation [5] of 2,346TWh and Enerdata total electricity production value of 22,619TWh [6].

TABLE I: Gen IV Technology Summary [7]

Reactor System	Spectrum	Fuel Cycle
Sodium Cooled Fast Reactor (SFR)	Fast	Closed
Very High Temperature Reactor (VHTR)	Thermal	Open
Supercritical Water Cooled Reactor (SCWR)	Thermal or Fast	Open or Closed
Gas Cooled Fast Reactor (GFR)	Fast	Closed
Lead Cooled Fast Reactor (LFR)	Fast	Closed
Molten Salt Reactor (MSR)	Thermal	Closed

Gen II systems are reactors that were deployed between 1970 and 1990 motivated by the OPEC-oil crisis in 1974 [9]. These commercial sized systems form the bulk of the reactors operating today. The majority of Gen II systems use PWR technology, although there are a significant number of BWRs, and a minority of AGR, VVER and CANDU reactors [5]. These reactors are claimed to have exemplary safety records and commercial performance [7]–[10] despite the incidents at Chernobyl, Three Mile Island and Fukushima all involving this generation of technology.

Many of the 67 reactors currently under construction will be Gen III or III+ designs [5], representing evolutionary improvements over Gen II reactor designs [11]. Such improvements include the standardisation of designs for licensing purposes, simpler modular designs, the greater use of passive safety systems and reduced core melt frequency [2], [11]. Key Gen III designs include the Areva EPR; under construction at Flamanville in France, Olkiluoto in Finland and Hinkley Point in the UK, and the Westinghouse AP1000; under construction at Sanmen and Haiyang in China and considered for the Moorside development in the UK [5]. These systems are expected to continue to dominate the new build market for the coming decade [11].

This paper is concerned with the future Gen IV designs. Gen IV technology has four goals; to improve the sustainability, economics, safety performance and proliferation resistance of nuclear energy systems [7]. These designs are likely to be available for commercial deployment beyond 2030, when most of the world's current reactors will reach the end of their operational life [2]. The Generation IV International Forum (GIF) was established in 2001 to coordinate the research required to realise next generation reactor designs [7]. Six key emerging technologies are highlighted by the Gen IV International Forum [7] and are introduced in Table I.

All of these technologies have been previously studied in various levels of detail prior to the formation of the GIF [11]. However, there is a marked removal from past approaches. Three of the six Gen IV technologies are fast reactors as opposed to the thermal reactor designs dominating past generations. Fast reactors are able to convert unconventional fertile material into fissile reactor fuel within a reactor by using unmoderated neutrons. This can increase uranium efficiency by around 50 times [10]. Four of the six technologies use a closed fuel cycle as opposed to the once-through cycle for current LWRs. Closing the fuel cycle presents significant societal benefits, namely the reduction of nuclear waste through better actinide management [7], [9]. Gen IV systems will achieve much higher operating temperatures than current designs, promoting the use of nuclear energy for co-generation [9].

In this article, sections III to VIII contain an overview of the state-of-the-art technology and ongoing research is collated and presented, and an evaluation as to the commercial readiness of the technology performed in section IX.

III. Sodium Cooled Fast Reactor

SFRs are one of the most mature Gen IV technologies [11]. Worldwide investment in the development and demonstration of SFRs already exceeds US $50billion [12]. By utilising fast-spectrum neutrons and closed fuel recycling, SFRs present significant improvements in fuel utilisation and are one of the nearer term options for managing plutonium and minor actinide waste [13].

Liquid sodium is an excellent reactor coolant. It is inexpensive, liquid within a wide operating range $93^oC - 883^oC$ and undergoes very little activation [14]. Sodium is chemically compatible with stainless steel when closed within the reactor, but reacts violently with air and water [14], causing several fires at SFR experimental facilities. Although none of these fires have caused any radiological leakage [12], there is a continuous effort to reduce leak occurrence and mitigate the fire risk. The Gen IV forum is actively addressing safety concerns such as these [7].

There are several potential configurations of the SFR. The layout could be chosen to be a pool-design as experimentally proven at EBR-II in the US, or a loop design as first proven at BR-10 in Russia [12]. The JSFR is a 3570MWth SFR project in Japan and will use a loop configuration. Prior to construction starting, the two layouts were compared against criteria such as construction cost, technical feasibility, in service inspection & repair (ISIR) and potential for cost reduction [14]. The pool layout presented advantages including the reduction in leakage probability due to a fully enclosed primary circuit, higher thermal inertia which is beneficial in an accident scenario and is the most experimented design. However, the loop layout was chosen due to economic competitiveness [10]. The loop design has scope for cost savings through changes to the secondary loop, including the reduction in piping length and the integration of the intermediate heat exchanger and primary circulation pump [14]. Other SFR projects such as KALIMER in Korea and the BN-800 currently under construction in Russia and China adopt a pool design. Despite the Japanese claims, the pool layout also presents opportunities for cost efficiency by reducing piping length and adopting innovative core internals [10]. It remains to be seen which of these designs prevails, and will largely depend on the combined construction and operational costs of these demonstration projects.

Another key design decision is the size of the reactor. While it is necessary to consider the economies of scale, not all SFR designs are large commercial power reactors greater than 1000MWth. There are several small modular reactor (SMR) designs utilising sodium as coolant. The Toshiba 4S is one example of a pool design of just 10MWe [10]. The PRISM reactor offered by GE Hitachi is another pool type SFR of 311MWe output [10]. The NDA is considering deploying a PRISM reactor in the UK to deal with the 140 tonne stockpile of civil plutonium [15]. The design is based on the EBR-II reactor in the USA, and this experience-based design combined with a small unit size means the licensing and construction time combined is just 14-18 years [15].

There remains several performance related challenges to overcome before the SFR can be deployed commercially. SFRs have been built and operated successfully in France, Germany, India, Japan, Russia, the UK and the USA meaning a considerable amount of construction and operating experience has already been gained [12]. The GIF has organised the remaining challenges into several working groups [13]:

- System Integration and Assessment Project - to track and integrate global R&D approaches and experience.
- Safety and Operations Project - to continue model development, experimental programs and assessment of safety systems. Also to integrate decommissioning feedback, ISIR techniques and under-sodium viewing techniques.
- Advanced Fuel Project - to design high burn-up minor actinide bearing fuels, as well as associated cladding.
- Component Design and Balance-of-Plant Project - to enhance the economics of the SFR.
- Gloabal Actinide Cycle International Demonstration Project - to demonstrate on an industrial scale actinide management by fast reactors.

IV. Very High Temperature Reactor

The VHTR concept is a helium gas cooled, graphite moderated reactor planned for an open fuel cycle [11]. The main purpose of this reactor is to achieve extremely high core outlet temperatures. The Gen IV forum target for this technology is to reach over 1000^oC [7] as opposed to 320^oC for current LWRs and around $500^oC - 700^oC$ for Gen IV SFRs and MSRs [9]. The increased core outlet temperature improves the thermodynamic efficiency of the system. The GT-MHR developed by General Atomics is expected to reach efficiencies of 47% operating at 850^oC [11] compared to around 30% for current LWR designs. More importantly, the high outlet temperature increases the potential for co-generation. Process heat is currently used in oil refining, metallurgic processes and synthetic hydrocarbon production. Temperatures in excess of 750^oC are required for hydrogen production.Hydrogen could partially replace refined hydrocarbons as the energy vector of choice in the future. The VHTR is one of the few clean technologies that could be used to create abundant quantities of hydrogen [9].

The VHTR could use either a pebble bed core or a prismatic block core. The HTTR in Japan started operating in 2004 with a prismatic core, while the Chinese HTR-10 uses a pebble bed core [16]. There are some trade-offs between the designs. The pebble bed core has a lower operating temperature allowing the use of a conventional steel pressure vessel and has an increased capacity factor due to online refuelling. However, the prismatic core has a higher power density making it economically superior [10]. The technology readiness level of both core designs is relatively high due to these experimental projects [16]. Regardless of the core design, a significantly different fuel design is used. Tri-isotropic (TRISO) layered particles are 1mm diameter spheres containing a fuel kernel at the centre. The kernel is covered in three layers of carbon and a layer of silicon carbide. This fuel design is required to withstand the high temperatures, and also improves proliferation resistance of the system by encapsulating all fuel inside the particle [11].

There remains some significant challenges to the commercial deployment of the VHTR. The GIF coordinate four paths of global research [13]. The identification of high temperature materials for pipework, gas circulators, heat exchangers and other core internals is of critical importance. Data are currently being gathered on the performance of several alloys at very high temperature for collation by ASME, expected to be complete in the next four years [16]. The TRISO fuel is also a subject of a GIF working group, which aims to establish the best practice for TRISO fuel fabrication, undertake irradiation experiments [16] and to understand how to reprocess spent fuel [13]. The hydrogen production group examine both thermo-chemical and high-temperature electrolysis hydrogen production methods [13]. Despite this being a longer term goal, the future potential of a large scale hydrogen economy warrants the research effort. Current work focusses on producing a $50-200l/h$ laboratory scale hydrogen production demonstration with the thermo-chemical method [16]. The final working group involves computational modelling for verification and benchmarking for licensing and design improvement [13].

The HTR-PM is a commercial evolution of the HTR-10 reactor up-scaled to 210MWe using a pebble bed core and is being built in Shidaowan, China [10]. Although commercial deployment of VHTRs is not expected until 2020 [7], construction of the HTR-PM is expected to be complete in 2017 [16]. The VHTR design presents some significant design challenges, but as one of the more realistic options for large scale hydrogen production, this design could be deployed widely in the future. The 2025 target deployment date set by the GIF [7] is attainable provided commercial partnerships are developed to capitalise on the current research [16].

V. Gas Cooled Fast Reactor

Following on from the VHTR, the GFR is another gas cooled, high temperature design. A helium coolant is used but no moderator is required due to the use of the fast neutron spectrum. This allows the use of a closed fuel cycle for full actinide management and the use of both fissile and fertile fuels. This is expected to deliver fuel efficiencies two orders of magnitude greater than current LWR designs [7]. It will operate at similar temperatures to the VHTR of around 850^oC, which provides opportunities for cogeneration [9].

The reference GFR design is 2400MWth in an attempt to exploit economies of scale [10]. The system uses a helium coolant in a primary circuit, which is used to heat a secondary helium-nitrogen mixture through a heat exchanger. This secondary circuit gas operates on a closed helium Brayton cycle. Waste heat from the gas turbine is recovered through a conventional steam Rankine cycle [13].

The use of helium as a coolant has some significant advantages. It is single phase, chemically inert, non-corrosive, transparent to neutrons and optically transparent [12]. This means that directly coupled Brayton cycles can be used without specialist equipment to isolate the coolant or for fire protection. ISIR techniques are simplified through direct observation [10]. However, helium does not have the same heat transfer properties as sodium or metal coolants and must be pressurised. Additionally, the GFR has no graphite moderator which enhances the thermal inertia of the core under and accident scenario in the VHTR. There is some significant R&D required to identify passive cooling and pressurisation techniques for accident scenarios [12].

The GFR and VHTR have some synergistic research areas, particularly high temperature materials, the development of helium turbomachinery and the development of advanced nuclear fuel [10]. The 75MWth ALLEGRO experimental reactor is a key enabler of GFR research and critical to achieve demonstration of many key aspects [12]. Commissioning is planned for 2026 [10]. The aim of ALLEGRO is to demonstrate commercial viability of GFRs, demonstrate safe core operation with appropriate instrumentation, establish an operational safety framework and to gain operating experience [12]. Current research for ALLEGRO focuses on fuel design and reactor modelling for safety system development [13].

The target commercial deployment date for the GFR was 2025 when the GIF produced the 2002 Gen IV roadmap [7]. However, with ALLEGRO not planned for commissioning until 2026, it is highly unlikely this target will be met. France and Japan have taken a lead role in developing the GFR. Since Fukushima, France has refocussed on the more developed SFR concept and Japan has also slowed research [13]. The GFR is more likely to be deployed as an evolution of the VHTR thermal reactor design further into the future.

VI. Supercritical Water Cooled Reactor

The main design aim of the SCWR is to increase the efficiency of current LWR reactor designs by operating at high temperatures and pressures, above the thermodynamic critical point of water [7]. The SCWR concept has been inspired by state-of-the-art coal-fired power stations that have successfully increased net efficiency while decreasing the capital cost required per unit electricity. Supercritical coal plants are expected to reach efficiencies of 50% in the near future while current LWR designs are only around 30% efficient and have not improved since the 1970s [13]. The target efficiency for the SCWR is 44% [11].

Operating at supercritical pressures presents opportunities for large cost savings and safety improvements. Water can only exist in a single homogeneous phase above the thermodynamic critical point. Current BWR designs have a number of in-core devices to handle the phase change of water as it circulates [11]. SCWRs do not require devices such as steam dryers, separators, recirculation pumps or steam generators, which vastly simplifies the design. This results in estimated savings of 50% in specific capital cost and 35% of O&M costs over the BWR [7]. This also has a positive impact on the safety performance of the reactor due to the simpler design alongside the elimination of core dry out events by the continuous heat transfer regime provided by a single phase coolant [7].

The technology base for SCWRs is broad. Supercritical coal-fired stations have operational experience involving turbogenerators, piping and other balance-of-plant equipment [7]. The reactor design could be either a pressure vessel similar to Gen III ABWRs, or a pressure tube design similar to the CANDU reactor [9]. The pressure vessel concept is being progressed in the Japanese Super LWR and European HPLWR projects. These are thermal designs optimised for electricity production expected for deployment is 2020 and 2035 respectively [10]. Additionally there is a variant on the Super LWR being developed for the fast neutron spectrum [10]. The pressure tube design is being developed in the Canadian-SCWR project, and could use a closed thorium fuel cycle [10].

Unlike other Gen IV designs, the SCWR design has never been built. This significantly delays the deployment of any SCWR designs for demonstration purposes [13]. One of the main areas of research is into materials for both in and outside the reactor core. Extreme materials are required to withstand the high temperatures and pressures, radiation and the highly corrosive environment due to the supercritical water [13]. The next milestone for SCWR research is to conduct in-pile tests of a fuel assembly under supercritical conditions [13]. The Gen IV target for deployment of 2025 remains ambitious.

VII. Lead Cooled Fast Reactor

The LFR refers to a fast reactor design cooled by one of two different liquid heavy metals. Lead (Pb) itself is one option and a lead-bismuth eutectic (LBE) composed of 45% lead and 55% bismuth the alternative [12]. Both coolants are high temperature, low-pressure, chemically inert and feature good thermodynamic properties [13]. Using a fast reactor with a closed fuel cycle means the LFR can be used as a burner to consume minor actinide waste or as a breeder using thorium matrices [13]. Some believe that LFR designs can increase the safety of reactor systems while being economically competitive with LWRs [12].

A pure Pb coolant is the preferred option since PB is inexpensive and abundant, while bismuth is a rare earth element. Pb is also less corrosive at high temperatures than a LBE [10]. However, the LBE has a melting point of 125^oC compared to pure Pb at 327^oC and therefore reduces the risk of core freezing during transient events [10]. Techniques for maintenance at high temperature are required in order to use a pure Pb coolant [12]. A further advantage of Pb is that bismuth undergoes activation in high neutron flux. Using LBE produces ^{210}Po which requires a complex and expensive scrubbing process for removal [12].

The LFR has further advantages besides those shared with all fast reactor designs. Pb and LBE do not react with air or water meaning a secondary circuit is not a necessary safety requirement. Many designs feature the steam generators immersed in the reactor pool core [7]. This reduces the capital cost of the plant and increases reliability when compared with SFRs. Pb has a high atmospheric boiling temperature of 1740^oC eliminating core boiling events [14]. It also permits high temperature operation to the limit of core materials, between $550^oC - 850^oC$, which increases the efficiency of attached thermodynamic cycles [11] .

There are several reference designs for the LFR concept. The ELSY design is a 600MWe design with the aim to deploy a competitive fast reactor in the EU energy market [10]. It has a pool type core, 40% efficiency and operates at a relatively low maximum temperature of 550^oC to cater for current fuel cladding material technology [12]. The project started in 2006 as a consortium of 20 organisations, however there is no expected deployment date for the system [13]. The SSTAR project is a 20MWe SMR designed for easy transportation [13]. The core is designed to last for 15-30 years without refueling and relies on natural convection for both operational and emergency heat removal scenarios [12]. SSTAR could serve developing nations or remote communities with an integrally safe and reliable electricity supply while offering very high proliferation resistance [12].

There remains some significant research required to meet the GIF target deployment date of 2025 [7]. The high melting point of Pb requires the system to be maintained at a high enough temperature to prevent solidification. This presents a challenge during repair and maintenance [13]. Pb is opaque, a property shared with sodium, and requires advanced ISIR techniques to be developed [13]. Lead coolants become increasingly corrosive to structural materials at high temperatures and flow rates. Potential solutions include limiting flow rates below $1m/s$ or forming layers of protective oxide [12]. Special materials must be developed for high velocity machinery parts, such as the internals of pumps. Materials such as Ti_3SiC_2 are currently being tested for corrosion resistance for these purposes [12]. A final challenge is presented by the natural toxicity of lead. Regulations for construction workers have been developed which do not impede start-up or operation of experimental facilities [12], but the disposal of such a coolant remains an ecological challenge that must be resolved [10].

VIII. Molten Salt Reactor

The uniquity of the MSR is that the fuel is dissolved in a molten mixture of fluoride salts [7]. Instead of holding the fuel in a solid phase encased in cladding, uranium and plutonium are dissolved in sodium or zirconium fluorides [11]. The first MSR was experimentally operated at Oak Ridge in the USA in the 60s [11]. This operated on the thermal spectrum with a graphite moderator. Most research since 2005 has focussed on developing a fast spectrum MSR to combine the benefits of fast reactors and molten salt coolants and fuels [13].

The advantages of this innovative fuel design is the elimination of fuel fabrication. This vastly reduces fuel cycle costs [10]. The liquid fuel is spread throughout the core which eliminates any formation of hot spots associated with solid fuels [10]. It also allows the adoption of a number of fuel cycles from burning LWR waste to breeding fissile ^{233}U from thorium [13]. Additionally, the coolant is optically transparent allowing traditional ISIR techniques to be employed [9]. Molten salts are thermally stable to a very high temperature, so the MSR can be operated up to 800^oC for cogeneration applications [11].

There are several worldwide projects looking to implement MSR technology. The French MSFR project is a fast reactor design exploiting the ^{232}Th-^{233}U breeder fuel cycle [13] to produce 1300MWe [10]. The full design is yet to be finalised with multiple thermodynamic cycles for the secondary circuit under consideration, including the helium Brayton cycle and the supercritical Rankine cycle [10]. The project aims to build a prototype by 2020 and a commercial reactor by 2040 [10]. The Russian MOSART project is another fast reactor design but with a focus on actinide waste management. The key advantages of this design aside from waste management, is the ability to operate for up to 50 years without refueling by using a mixture of thorium and actinide waste fuels [13].

The use of a liquid fuel alongside a liquid coolant poses some unique issues [14]. The common aim of current GIF R&D is to propose a single optimal system configuration from physical, chemical and material studies. Initial physical studies indicate MSR designs have a very high negative temperature coefficient, which is beneficial in accident scenarios and absent in many Gen IV designs. Safety considerations are paramount, and the negative temperature coefficient combined with the high thermal inertia of molten salts led to safe shutdown in major accident simulations [13]. However, the passive safety of the design is yet to be established [10]. The salt coolant also poses other issues, including the development of a reprocessing strategy for a coolant/fuel mix and the understanding of the thermodynamic properties of molten salts [13]. Material technology must also progress. Materials must be found that can withstand the corrosive, high temperature and high neutron flux conditions in the MSR core [13].

The MSR poses some considerable design challenges. The GIF target for commercial deployment of the MSR is 2025 [7] which is very optimistic given the earliest planned project is 2040 [10].

IX. Challenges to Deployment

Having considered the technology presented in each Gen IV reactor design, an assessment of the commercial readiness can be undertaken. Ultimately, the commercial viability of each design is dictated by the ability of Gen IV technology to resolve the issues facing global energy supply for a given cost.

A. Technology Assessment

The UK nuclear R&D partnership National Nuclear Laboratory has reviewed the six Gen IV reactor technologies in a UK deployment context. A multi-attribute utility analysis was performed for each of the technologies against a set of performance metrics covering factors such as safety, economics and technology development. A subset of these metrics has been selected and is presented in table II. The same analysis was performed for current Gen III LWR technology as a baseline for comparison.

TABLE II: Gen IV Technology Aggregate Scores [17] (out of 4, 4 being best)

Metric	SFR	GFR	LFR	VHTR	SCWR	MSR	LWR
Fuel Utilisation	4	4	4	1	1	4	1
VHLW volume	3	3	3	1	2	3	2
Long term radiotoxicity	3	3	3	2	2	3	2
Environmental impact	4	4	4	3	3	4	3
Reliability	3	3	3	4	3	2	3
Safety	2	2	2	4	3	2	3
Reactivity control	2	2	2	3	2	3	2
Decay heat removal	2	2	2	4	2	3	2
Fuel thermal response	3	1	3	4	1	3	1
Scale of demonstration	3	1	2	3	1	1	4
Capital costs	1	1	1	2	2	2	2
Production costs	2	2	2	2	2	1	2
Construction duration	2	2	2	3	2	2	2
Development costs	2	1	2	3	1	1	4
R&D costs	2	1	2	3	1	1	4
Waste management	3	3	3	3	2	4	2
Load follow capability	2	2	2	3	2	3	2
Scalability	2	2	2	3	2	3	2
Timescales to deployment	3	1	2	2	1	1	4
Technology Readiness Level	3	1	2	3	1	1	4
Security	2	2	2	4	2	2	2
Associated fuel cycle	1	1	1	1	3	1	4
Proliferation resistance	2	2	2	4	3	2	3
Ease of construction	1	1	1	3	2	1	2
Sustainability	4	4	4	1	1	4	1
Cogeneration	2	3	2	4	2	3	1
Decommissioning costs	2	2	2	3	3	2	3
Primary purpose	3	3	3	4	2	3	1
Total	**68**	**59**	**65**	**80**	**54**	**65**	**68**

There are severe limitations to this type of analysis. Efforts have been made to remove subjective bias from the analysis by incorporating reviewers' comments. Additionally, there is no attempt to weight the corresponding factors according to importance. Therefore the values given in table II should be used only as a basis for general comparison.

The analysis shows a clear preference for the VHTR, while the SFR, LFR and MSR are all approximately comparable to current LWR technology. Fast reactor technology has advantages in terms of fuel sustainability and waste minimisation, but suffer in the analysis due to technological feasibility. The SFR is the most proven design and it could be argued that this system is the most technologically feasible of all the fast reactor designs. The VHTR benefits from a wide network of support within the GIF, partly due to the prospect of commercial scale hydrogen production. This combined with operating prototype designs makes the VHTR a prime candidate for deployment.

B. Needs Assessment

The deployment of Gen IV technology is not dependent solely on the technology offering. It must also resolve a number of social, economic, political and sustainability issues.

While other renewable technologies face a degree of social opposition, nuclear technology is often the most emotive.

A fundamental mistrust of the industry alongside a misunderstanding of technology and safety makes it difficult to deploy any nuclear technology. The social issue is particularly apparent in discussions involving waste and safety, where technical risk assessments often have very little impact on public opinion [11]. Companies hoping to deploy Gen IV technology must carefully engage with the public in order to gain a level of acceptance.

Gen IV R&D progress is suffering due to the poor economic climate [17]. Additionally, there are issues in gaining the necessary investment to bring Gen IV concepts to a commercially deployable state [9]. The economics of mega-projects must also be understood. The deployment of Areva EPR technology at Flamanville and Olkilhuoto illustrates some of the issues with large technology projects. First-of-a-kind issues and poor forecasting have lead to inflated budgets [10]. Any Gen IV construction project must learn from these experiences.

Nuclear technology is a long-term commitment which poses a significant investment risk in a short-term political landscape. The varied response to Fukushima is a particular example of this. Germany has decided to phase out nuclear power by 2022, alongside the Swiss response not to renew any of its nuclear capacity [2]. It is right to re-assess the safety framework of an industry following a severe incident. However, the political response remains fragmented and unpredictable. Politics poses a risk to long-term investment decisions, particularly for Gen IV technology where there remains a significant time until the technology becomes profitable.

Nuclear energy has environmental benefits in the reduction of greenhouse gas emissions, which is a key driver of the recent renewal of nuclear deployment. However, the current nuclear fuel cycle is not sustainable, with known reserves forecast to last just 80 years with current consumption levels [11]. One of the major benefits of Gen IV technology is the ability to close the fuel cycle or to breed fissile fuel from unconventional nuclear fuel sources. This will enable the efficient use of current uranium reserves and promote the use of more available fuels. An additional environmental benefit offered by Gen IV technology is the waste handling capability, vastly cutting the volume and longevity of high level nuclear waste [7].

X. Conclusion

This paper has examined the technology offering of different Gen IV concepts in the light of future energy issues. Clearly, there are significant benefits that warrant the further development of Gen IV technology. It remains to be seen what the whole cost to develop these technologies will be, and whether they will be commercially viable. There remains many unresolved factors which make any conclusions regarding the deployment of technology highly likely to change. Given the current state of technology and an appreciation of the challenges facing energy policy, it would seem likely that one or two technologies become successful. Particularly, the SFR may be deployed to manage waste, while the VHTR may present significant opportunities as hydrocarbons become increasingly expensive. What is clear is that innovation and entrepreneurship will be required to bring these concepts to a deployable state in order to transform the nuclear energy sector for the better.

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APPENDIX A
LIST OF TERMS

4S Super Safe, Small and Simple
ABWR Advanced Boiling Water Reactor
ASME American Society of Mechanical Engineers
BWR Boiling Water Reactor
CANDU CANadian Deuterium Uranium
EBR Experimental Breeder Reactor
ELSY European Lead-cooled SYstem
EPR European Pressurised Reactor
ES-BWR Economic Simplified Boiling Water Reactor
GE General Electric
GFR Gas Cooled Fast Reactor
GIF Generation IV International Forum
GT-MHR Gas Turbine Modular Helium Reactor
HTR High Temperature Reactor
HTR-PM High Temperature Reactor Pebble bed Modular
HTTR High Temperature Test Reactor
IAEA International Atomic Energy Agency
ISIR In Service Inspection and Repair
JSFR Japan atomic energy agency Sodium cooled Fast Reactor
KALIMER Korea Advanced Liquid MEtal Reactor
LBE Lead Bismuth Eutectic
LFR Lead Cooled Fast Reactor
LWR Light Water Reactor
Magnox Magnesium Non-Oxidising
MOSART MOlten Salt Actinide Recycler and Transmuter
MSFR Molten Salt Fast Reactor
MSR Molten Salt Reactor
OPEC Organization of the Petroleum Exporting Countries
PRISM Power Reactor Innovative Small Module
PWR Pressurised Water Reactor
SCWR Supercritical Water Cooled Reactor
SFR Sodium Cooled Fast Reactor
SMR Small Modular Reactor
SSTAR Small Secure Transportable Autonomous Reactor
TRISO Tri-isotropic
VHTR Very High Temperature Reactor
VVER Vodo-Vodyanoi Energetichesky Reactor