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Generic Feasibility Assessment: Helping to Choose the Nuclear Piece of the Net Zero Jigsaw

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Abstract: The United Kingdom has declared a climate change policy of 100% reduction in carbon dioxide emissions by 2050. Efforts thus far have been limited solely to electricity generation methods. While progress has been admirable, effort now must be directed at the nation's non-electrical energy use. Nuclear energy is an essential part of any energy future, since it is low-carbon, firm and supplies synchronous electricity; however the nation's nuclear strategy to date has been erratic, costly and lacking in strategic oversight. A multitude of reactor designs are on offer for potential uptake, and decision-makers must have clarity of vision on what these systems must deliver before forming a strategy. Choosing between these systems, given the uncharted energy future faced by the UK is a daunting prospect. Generic feasibility assessment offers a tool for decision-makers to assist them in selecting the most suitable nuclear system for chosen future conditions. Generic feasibility assessment offers an alternative to traditional multi-attribute decision analyses, which can be confusing to even committed stakeholders when large numbers of attributes are weighted and compiled. Generic feasibility assessment forms part of a toolkit which will be of utility in achieving net zero by 2050, given the short time that remains.

Keywords: nuclear; reactor; choice; net zero; policy

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1. Introduction

The 60+ year history of nuclear energy in the United Kingdom has been characterised by the installation of reactors of three main technology branches: the first generation Magnox plants [1]; the successor advanced gas-cooled reactor (AGR) designs [2,3]; and finally, one pressurised water reactor (PWR) [4]. One main reason for the sub-optimal performance of the nuclear sector in the UK is that almost all of the plants built have been of unique design, built by different consortia (in pursuit of competition) [5], and with little evidence of series development and installation. This contrasts with, for example, the French energy policy over the same period, which committed to a PWR system [6] and thus reaped the benefits yielded by series-build. Only two examples of UK nuclear systems were ever exported, and both were the early Magnox designs [7]: Latina in Italy, which generated from 1963 until 1987; and Tokai Mura, from 1965 until 1998 in Japan. Despite export potential forming part of the political motivation for developing the AGRs, none were ever exported.

The last reactor to be delivered in the UK was a Westinghouse-derived PWR built at Sizewell [8]. This was initially intended as one of four identical plants but all subsequent plants were cancelled in 1990, again losing any opportunity for savings resulting from series-build.

Never has the UK's nuclear system selection featured a methodology which could compare the various attributes of the competing systems and their fit into the UK's energy future. Such a methodology is essential to avoid replicating the mistakes made in the past; and one such methodology is proposed in this paper to fulfil this role.

Since Sizewell B, proposed new nuclear stations in the UK were:

- Horizon; 5.7 GW from four advanced boiling water reactors at Oldbury and Wylfa;
- NuGeneration; 3.4 GW from three AP1000 PWRs at Moorside in Cumbria;
- EDF Energy and China General Nuclear Power Group (CGN); 6.4 GW from four European pressurised water reactors (EPRs) at Hinkley Point and Sizewell;
- CGN and EDF Energy; 2.2 GW from two HPR1000 PWRs at Bradwell-on-Sea.

The NuGeneration project was cancelled in late 2018 [9] due to lack of financing options, and Horizon was shelved in early 2019 [10] for similar reasons. The HPR1000 reactor is currently undergoing generic design assessment (GDA) by the UK Office for Nuclear Regulation (ONR) [11]. Only the EPRs are making substantive progress, with Hinkley Point C beginning construction in 2018 [12], and construction of an identical EPR at Sizewell [13] anticipated to begin in 2021.

Meanwhile, the 2019 amendment to the 2008 Climate Change Act, has changed the UK's target carbon emissions from the original "at least 80% lower than the 1990 baseline" by 2050 to achieving "net zero" (i.e., 100% lower than the 1990 baseline) by 2050 [14]. If the original target was ambitious; eradicating the final 20% is an enormous challenge. While low-carbon electricity generation methods such as nuclear, carbon capture and storage (CCS) or renewables emit less carbon dioxide than fossil fuel combustion, they still have some carbon debit [15]. These challenges become even more substantial when attempting to decarbonise transport (aviation, maritime, road and rail) and domestic and industrial heating; the focus on electricity generation, rather than energy consumption has led to the challenge of net zero often being understated. Figure 1 highlights the difference between these two measures. Figure 1B shows the share of electricity supplied across the whole of 2018, and while this is now generated mostly from low-carbon sources, this must be viewed in context of the entire UK energy consumption (Figure 1A), of which electricity use comprises less than one fifth of all energy used. Of the non-electric consumption in the UK, almost all derives from fossil fuels for heating, industry and transport [16]. When viewed in terms of energy rather than electricity, the true extent of the challenge still to be achieved with decarbonisation is revealed.

The 2050 target has however focused minds; with this target, the process can now be envisaged as a jigsaw with each low-carbon energy mechanism contributing an essential part of the eventual net zero solution. Omitting technologies from consideration must be robustly justified, and without undefined steps being required to achieve the 2050 goal in absence of the offending technology.

To displace existing fossil fuels with renewables for example would require an enormous expansion of generation capacity, with considerable spare capacity and an as-yet unavailable storage solution to accommodate the intermittency. Balancing intermittent generation methods with "firm" methods (i.e., those that are reliably available) [17], reduces the amount of redundancy that would be required. The remote nature of existing and prospective wind farms also raises concerns regarding expanding network transmission infrastructure, which prefers high density generation nearer to population centres. The matter of the raw materials requirements needed for a move to a primarily wind and solar network also has not received much attention in public discussion.

Beyond vastly expanding capacity, a high proportion of renewables in the energy mix has consequences for the electrical grid. Thermal generation relies on heat to rotate generators which themselves provide a stabilising effect on the system frequency of the national grid. Wind and solar are asynchronous and do not provide such a benefit, and the network relies on its thermal generation sources to provide stability. As more power proportionally comes from wind and solar, and less from synchronous sources, stability lessens. Sizeable thermal generation alongside future renewables is therefore of considerable utility; as fossil fuel generators come offline, in the absence of effective CCS, biomass or nuclear are the only thermal options available to fulfil this role. In order to make judgements on the roles for generation methods for the future of the nation's energy, a "level playing field" attitude to all available technologies must be adopted if the challenge of achieving net zero is going to be met.

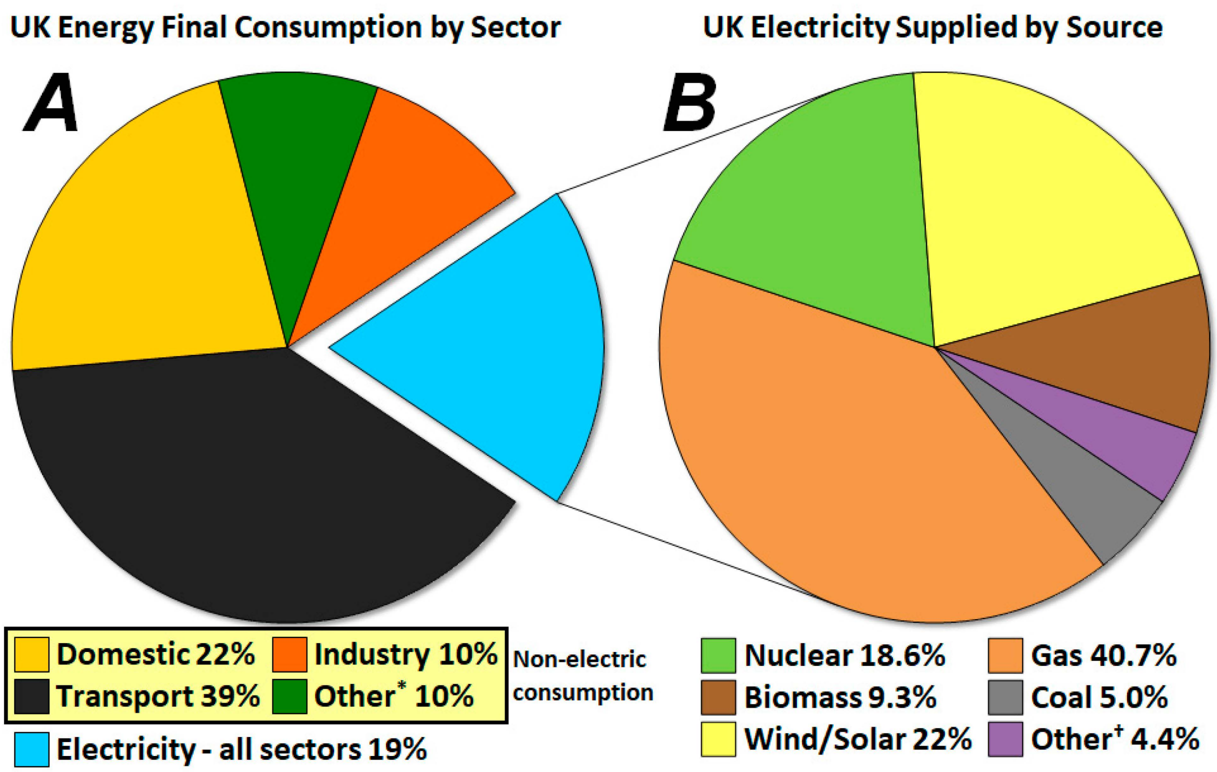

Figure 1. (**A**) UK proportional final energy consumption by sector in 2018. Domestic, industry, transport and other consumption only include non-electric energy consumption; the blue segment comprises the electricity use by all sectors ([16], pp. 11–30; Table 1.1). (**B**) The electricity supply by source in the UK in 2018 ([16], pp. 80–107; Tables 5.6 & 5.1.3). 47% of final energy consumption is petroleum products; 29% is natural gas (not including natural gas used in electricity generation). * "Other" sectors comprise administrative, commercial, agricultural and miscellaneous consumption. † "Other" electricity sources comprise hydroelectric generation and, pumped storage and oil combustion.

The firm and specific 2050 target should presage a period where UK energy policy is part of a culture of continuing development over several decades. This is particularly so for nuclear, as the time constant for nuclear system development and deployment is measured in decades [18]. In contrast, UK energy strategy over the last half-century has often been conducted with decisions which appear to have been taken with considerations spanning only years or even months [5]. Nuclear is not alone with tough time constraints however, CCS is facing similar difficulties [19–21].

As evidenced at Moorside [9] and Wylfa [10], the main challenge to nuclear new build is the high up-front capital cost; a consequence of lengthy construction times combined with sub-optimal financing conditions. The reluctance of governments ([22], p. 12) since electricity privatisation to become involved in the new-build process has the result of raising the cost of borrowing for nuclear projects, which are sensitive to the lending rate. The extent of this effect can be illustrated by the fact that for Hinkley Point C, a 2% rather than 9% rate would have halved the cost ([23], p. 72). In response to this, the Government issued a consultation on a new method of financing—the "regulated asset base" (RAB) [24]. The nuclear industry responded to the challenge of high nuclear capital costs by striking a Nuclear Sector Deal [25] which, inter alia, offered to deliver a 30% reduction in the cost of new build projects by 2030.

The UK's energy troubles come at a time when a range of nuclear systems are being proposed; the proposed systems are typically grouped into three categories. The first are light water reactors (LWRs); systems moderated by light water with a power output of the order of GWe. These make up the overwhelming majority of systems worldwide, but have the downside of being stick-built, which raises costs. The second category are small modular reactors (SMRs), which are generally considered as LWRs with a power output below 300 MWe. The attraction of SMRs is the potential for incorporating factory-built modules, which would reduce construction costs. Finally, advanced modular reactors (AMRs) have been defined as being distinct from SMRs in that while they are small in size and modular in construction, they are not of the traditional light water moderated variety, making them a more exotic proposition with potential benefits beyond just electricity generation. One such benefit is process heat, which has been recognised as a candidate to decarbonise both high and low temperature thermal processes as diverse as district heating and hydrogen generation. Efficiencies in producing hydrogen through electrolysis is low, whereas thermochemical processes utilising heat from a high temperature AMR could achieve efficiencies of ~50% ([26], p. 4). The possible roles for nuclear in net zero by 2050 are therefore far broader than they have been historically, where they had been limited to the role of base-load electricity generation. This broadening of potential roles demands a more holistic evaluation mechanism, not just for nuclear, but also for all other carbon-reducing technologies.

The economics of any new nuclear systems depend on delivering large numbers of reactors of a standardised design ("economy of number"). This contrasts with the approach attempted in the past, which pursued economic benefits through increased reactor output; seeking to reduce the costs of siting, construction and operation in terms of cost per MWe installed (termed "economy of size"). It should be clear that the UK's programmes involving small numbers of multiple different designs [27] will not deliver improved economics. Even with large reactors, economies of number are more likely to reduce costs than economies of size. Previously, the UK has relied on (in fact, attempted to foster artificially) competition, at the expense of a single design and the repetition that follows [5]. Based on this experience, the concept of backing a single SMR design, and its production in large numbers should be compelling to the UK.

Nuclear in the UK supplies 59.1 TWh (18.6%) ([16], pp. 80–107; Tables 5.6 & 5.1.3) of the nation's electricity from 15 reactors at seven sites. Current expectations are that the 14 AGRs will all cease production by 2030, with a near-zero prospect of further life extensions; whereas the PWR at Sizewell B is expected to generate until 2035 and, based on performance of similar plant internationally, will likely receive life extensions.

In summary, the combined challenges of:

- An obligation to implement severe emissions reductions;
- The lack of an economically viable, firm, low-carbon alternative;
- The imminent closure of almost all existing nuclear plant;
- Decarbonising heating and vehicles;

suggest that there is a significant role for nuclear to play, particularly for AMRs which are those best placed to address all four of the above. However, many of the new reactor systems on offer are at an early stage of development, yet are generally presented by vendors and enthusiasts as self-evidently safe, cheap and available. This situation, combined with the net zero imperative, brings with it an essential need to be able to objectively assess the suitability of a range of very different systems.

Nuclear's Possible Contribution to Net Zero

Historically, electricity supply and demand has exhibited the concept of base-load power; a residual minimum level of demand which is required at all times of the year, and at all times of day. Nuclear generation has been well-suited to providing this kind of electricity because of its reliability and low fuel costs, with combined cycle gas turbine (CCGT) generators accommodating extra demand as it peaks over a 24 h cycle. Nuclear power has previously proved ill-suited to supplying varying demand, as its high capital costs require constant operation in order to fulfil its economic obligations over a plant's lifetime. Nuclear plant have therefore been designed to fulfil an "always-on" role, and their lack of potential for variable electricity production is often wrongly attributed as a fundamental technical limitation, rather than an economic one.

As energy becomes more networked (as is anticipated), and electricity, vehicles and heating become incorporated into an energy network, the potential for nuclear flexibility becomes possible. Energy storage technologies, which are essential in enabling renewables to begin to shoulder a larger proportion of energy generation, can equally be used by nuclear generators to flatten demand curves, thus giving nuclear stations the ability to contribute to demands beyond base-load.

In addition, nuclear power is a thermal generator. The heat produced is likely to be of utility in the future, thus enabling it to contribute to a complex future energy landscape. Recent studies [28–31] have highlighted opportunities for nuclear generation in the provision of heat, and it should be readily appreciated that the economic provision of low-carbon heat covering the spectrum from domestic heating, via industrial heat to heat for the synthesis of low carbon transport fuels could make a very large contribution to overall decarbonisation. In particular, the provision of heat from SMRs could support district heating; whereas AMRs (which have higher operating temperatures), could provide higher temperature heat for industrial processes including hydrogen generation, which could have widespread use in an updated natural gas network. Therefore, in order to compare the potential for the available energy generation technologies available, the contributions from process heat must be considered (in addition to the limitations from other low-carbon sources).

One problem from this added complexity is that between different future nuclear technology options, there are large differences in the end-products; the potential for heat for example ranges from 100 °C for some LWR systems to over 800 °C for some AMRs. The key to nuclear's level playing field contribution must incorporate all of these options. Decision-makers need to ensure that the right technology to meet the energy demands of the future is pursued, and be confident it can be built on the required timescale—and at the right price.

Figure 2 shows the broad breakdown of the levelised cost of electricity (LCOE) for a traditional LWR nuclear energy system. A future nuclear technology impacts 33% of the LCOE price; this will obviously contribute to the cost and temperature of heat which can be generated/sold. Crucially, as is better illustrated in Figure 3, the overall levelised cost (i.e., the remaining 67%) will be very largely determined by the cost of borrowing. Much of this cost will depend on the specifics of the lender, and under what mechanism the money is lent; but the other major underlying factor will be the level of technological risk. This is particularly relevant for the advanced systems, where parts of the reactor systems and/or fuel cycle are not yet fully developed to the same extent as the major nuclear technology in use (i.e., LWRs for baseload electricity).

There is thus a real need for a tool which can provide an assessment of the capabilities of the plethora of nuclear systems currently being developed; and a means to compare these with current nuclear technologies (i.e., LWRs), the economics of which (and the challenges faced), are well understood.

In the nuclear field, the study of AMRs reveals many areas where difficulties have been ignored, and a cursory study reveals a similar lack of acknowledgment of engineering challenges may exist in other low-carbon energy methodologies. Net zero however, requires a genuinely holistic approach, across all technologies and systems. Generic feasibility assessment (GFA) is a tool which points out the advantages and challenges across the range of nuclear systems. The general fields such as provision of materials, actual (rather than idealised/assumed) carbon detriments, interaction with grids, and distribution and siting are common to all carbon reduction methods and require a similar holistic treatment. A GFA approach therefore has utility beyond nuclear energy, in any sphere where technologies are being compared. One such example would be energy more generally; today's policymakers are required to make difficult decisions over what energy generation mix should be pursued to reduce carbon emissions without suffering excessive economic damage. As an example, the consequences from abandonment of firm fossil fuel generation in favour of intermittent renewables on grid stability, storage and transmission infrastructure are generally poorly understood outside the field; decision makers could thus benefit from a similar tool on energy more broadly.

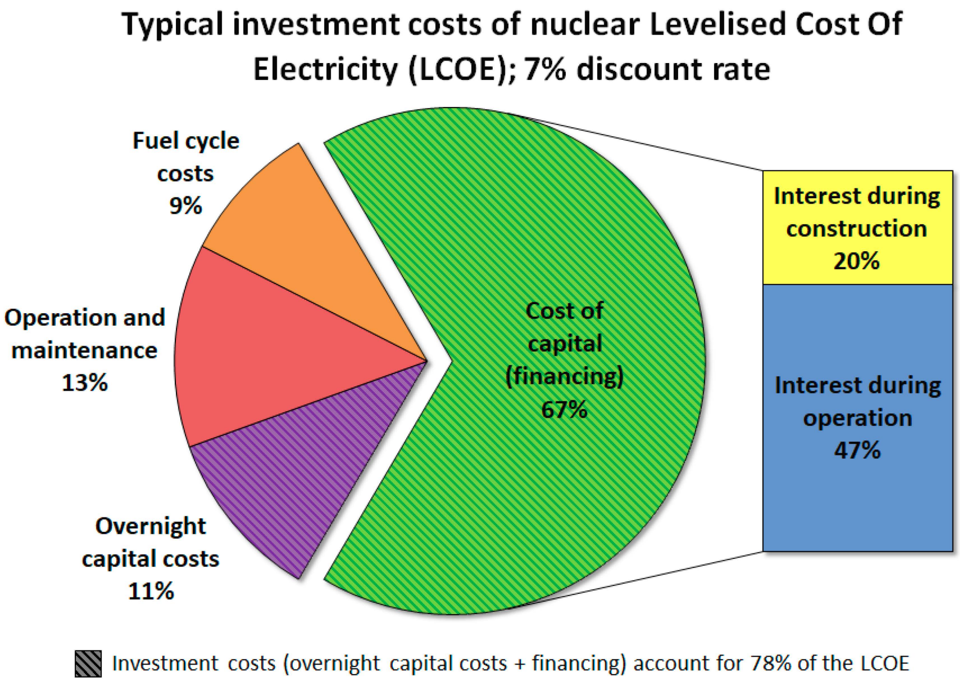

Figure 2. The extent to which up-front capital costs dominate (78%) in the construction of LWR nuclear power plants. 67% of the LCOE for nuclear power can be attributed to the cost of borrowing. Any attempts to reduce nuclear's LCOE should therefore be focused on the cost of borrowing. Reproduced from [32], NEA: 2020.

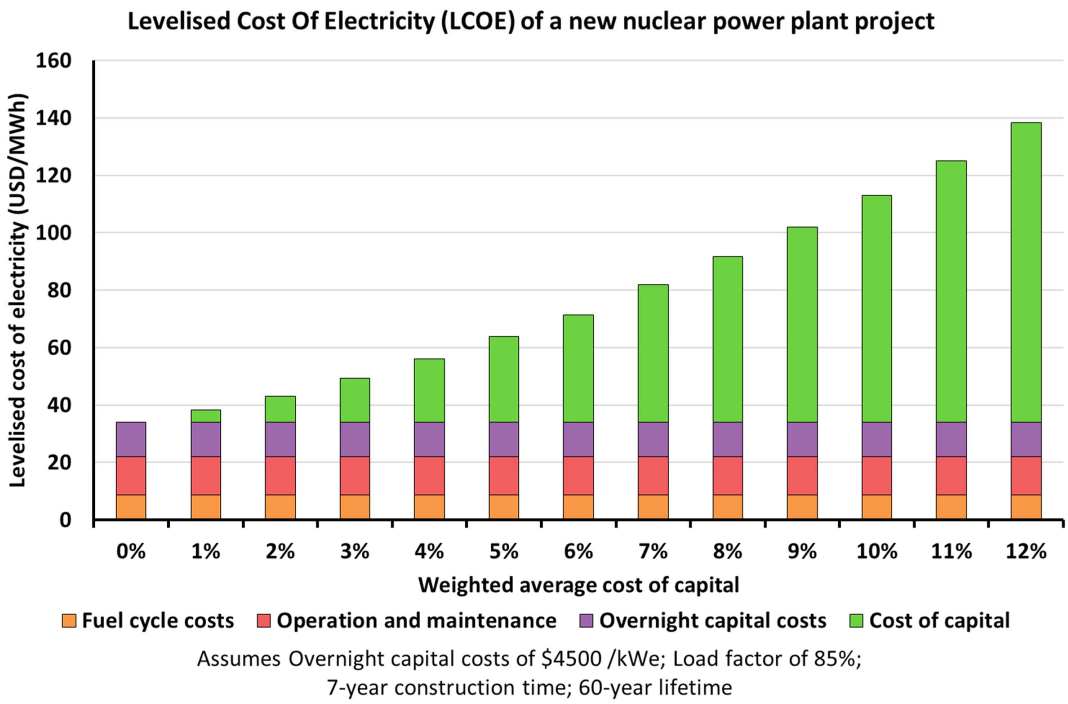

Figure 3. The effect of borrowing costs on the LCOE. Reducing the cost of capital from 8% to 2% halves the LCOE. Reproduced from [32], NEA: 2020.

2. Generic Feasibility Assessment: A Nuclear System Selection Tool

It has been more than half a century since a new nuclear power system became a major player in the world market. Now though, driven by the need for carbon-free energy, a very wide spectrum of systems is being developed, and are at a variety of stages from concepts to demonstration reactors. The UK must be in the market for a broad spectrum of low carbon energy systems, and it must pursue this need against the background of its most recent nuclear reactor (Sizewell B), which started generation over 25 years ago.

As discussed, nuclear energy can fulfil a variety of future roles in the UK and elsewhere, but like every other energy system, it will have to balance a variety of factors if it is to succeed in any realistic energy future. These can be summed up by the following considerations:

(1) The UK has a well-developed regulatory system for nuclear activities, so any system must conform to stringent safety, environmental and security standards before any installation is contemplated;
(2) A system must be economically competitive. Since the initial capital cost and interest makes up a large part of the cost of producing energy, the costs of building the reactors and any dedicated parts of the fuel cycle must compete with other low-carbon energy sources, as well as existing nuclear systems;
(3) The system must have a fuel supply which is adequately assured for the lifetime of the reactor;
(4) The waste produced by the system and its fuel cycle must be capable of being stored and disposed of within the context of the existing UK nuclear policies;
(5) The reactors and (where relevant) the UK-based parts of their fuel cycles, must be capable of being sited in the UK in accordance with the various stringent siting standards and regulations;
(6) The system must be ready in time to satisfy the future needs of the UK. This has been particularly brought into prominence by the net zero by 2050 policy, since 30 years is certainly not a long timescale in the nuclear field to proceed from the early stages of research and development (R&D) to plant installation;
(7) The system must be clear on the roles it can fulfil in UK energy futures. This should include consideration of:
    (a) Economic baseload electricity;
    (b) Variable electricity generation;
    (c) Low temperature heat provision for, inter alia, building and district heating;
    (d) High temperature heat provision for, inter alia, chemical processes such as hydrogen generation and the production of low carbon synthetic fuels.

As the diversity of AMR and SMR nuclear technologies has grown, these considerations showed that there was a clear need for a methodology for evaluating the claims of new reactor systems at a strategic level; to ensure that the "good" features claimed of the systems are not solely considered, while ignoring the "bad". This should extend to examining which are the energy futures which will extract value from any given system's characteristics, and which futures will reduce or remove a system's attributes as drivers for deployment.

The common method of comparing complex systems is to use multi-attribute decision analysis (MADA). In this method a group of attributes are defined to cover the main parameters of the systems, and scores are allocated depending on how well or badly a system performs. For example, a fast reactor system might score highly on "uranium usage", while a once-through LWR regime would score badly. Not all parameters will be deemed to carry the same importance however, so the scores which have been compiled are weighted by a set of weighting values. The weighted scores are compiled to provide an overall consolidated score for the particular system.

In 2012-2013, the National Nuclear Laboratory (NNL) developed a MADA system to examine nuclear power systems [33] based on 42 metrics derived from those used by the Generation IV International Forum (GIF). These were subsequently divided into seven groups and used to assess advanced reactor systems: Cost, Proliferation Resistance and Physical Protection (PRPP), Safety, Strategic, Deployability, Sustainability, and Waste [34]. The scores from these analyses defined "winners" and "losers", but the approach suffered from two main disadvantages:

(1) The use of a MADA with a large number of metrics makes the result very difficult to communicate meaningfully, even to committed stakeholders. There is often a shared understanding by those present for the analysis, which fails to be transferable to others;
(2) The suitability of a reactor system depends on the world in which it must operate. For example, high scores for uranium economy (e.g., fast reactors) should be highly weighted in a "uranium scarce" future, but will not feature in a "uranium plentiful" (and therefore cheap) future

In March 2012, a stakeholder workshop reviewed the NNL work and addressed the problem of "decision opacity" caused by the use of MADA [35]. Subsequently, joint working by the Dalton Nuclear Institute, Integrated Decision Management (IDM) and NNL addressed this weakness. A key change was the recognition that in the UK and other states with well-established nuclear programmes, safety, environmental and proliferation/security attributes are all covered by well-developed regulatory regimes. 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 this tried and tested regulatory framework.

This was found to lead to five further questions which any system seeking entry into an energy market must answer:

(1) How much time and effort will be required to achieve regulatory approvals needed to deploy this nuclear energy system?
(2) Is it likely that the nuclear energy system is capable of being economically competitive with a well-defined reference system?
(3) Is there a credible path between state-led R&D investment now, and private sector deployment in the future (a.k.a. "the valley of death")?
(4) If this system was deployed, what are the fuel supply, waste disposal and reactor/fuel cycle siting issues?
(5) Can it meet market demands (e.g., flexibility, or high temperature heat)?

In what became the GFA methodology, the system data from the complex NNL analyses are utilised, but they are accumulated into a more useable number (originally 11) high level discriminators, and are assessed by pairwise comparison to a reference system. This reference system has been assumed to be a contemporary gigawatt-scale PWR with a once-through fuel cycle operating under the current regulatory regime, and for which many of the parameters are already well-known (Sizewell B in the UK would be a specific example). The comparisons made are based on published data which can be referenced, linked and made publicly available. The result is an analysis which relies on easily assimilated graphics and words, rather than complex and opaque marking systems.

It is primarily MADA's potential for opacity which GFA attempts to tackle. While MADA is a valuable technique for clarifying the scores and weights (or crudely, facts and opinion respectively) for the selection of any particular option, it is very difficult to communicate the reasoning behind the output decision by simple written communication. The result is often that those involved in the development of the MADA are well-versed in the analytics; however those not involved (often this includes the policy makers) are exposed to the result only, with little appreciation of either the scores or weighting criteria applied in the process. As the landscape inevitably changes with time, it may be difficult for decision makers to realise how the MADA output would be affected.

GFA is therefore not intended to replace MADA; the former provides clear representations on the challenges and benefits to given systems, but in no way seeks to make a decision in the way the latter does—that decision (including any scoring and weighting process) is left to the user. Different individuals with different value systems are therefore free to weight the GFA data to their own priorities. In addition, the relative importance of the discriminators may change with time, in recent months in the UK for example, awareness of the importance of high temperature heat for activities such as hydrogen and synthetic fuel production has been increasing; it is likely that the weighting applied by decision makers to that specific metric will have increased as a result.

As shown in Figure 4, the 11 high level discriminators (here safety and licenseability is exemplified) are divided into a number of strategic attributes, each of which incorporates a proportion of the original 42 Gen-IV metrics.

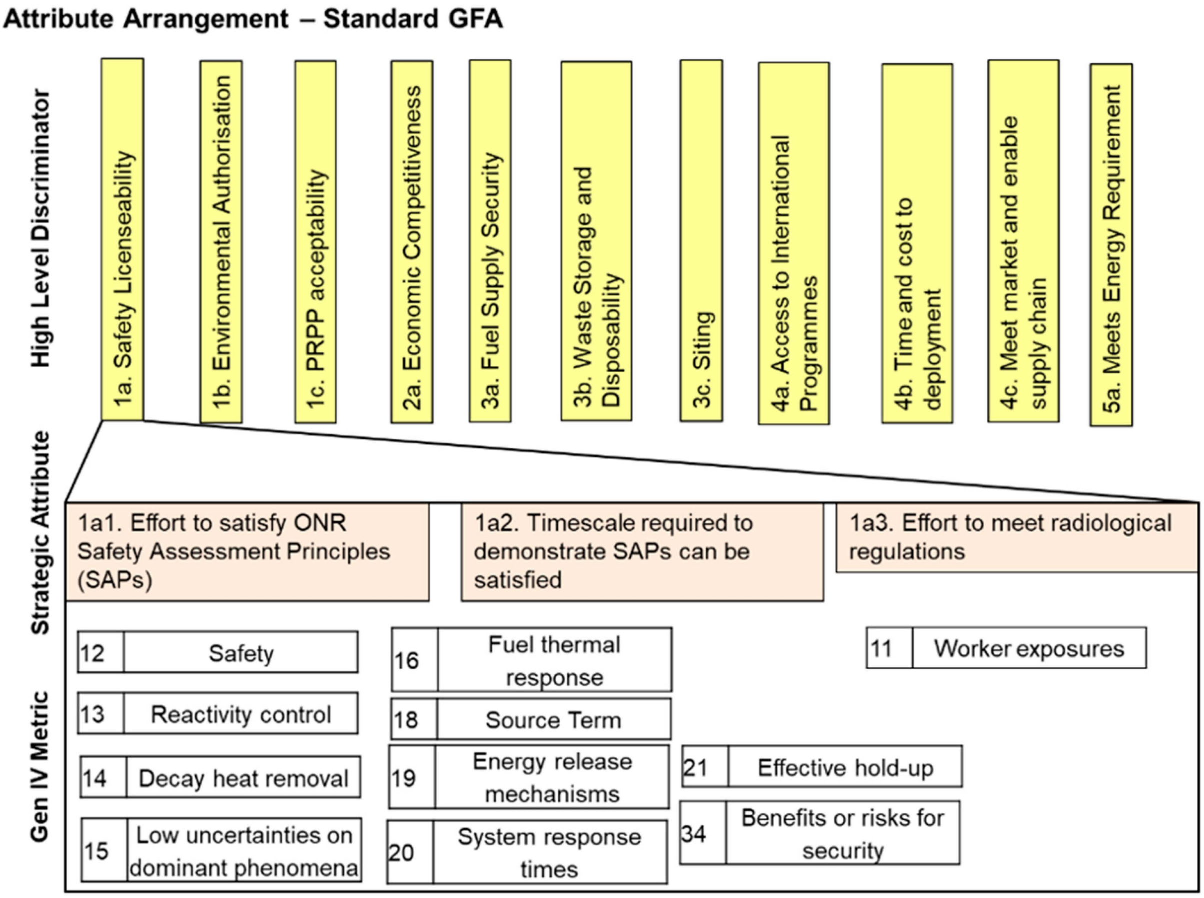

Figure 4. Attribute Chain from Gen-IV metric to High Level Discriminator (Safety and Licenseability example).

In the example shown in Figure 5, the time and effort to license for the system being assessed offers a minor challenge (to become compliant with the current licensing standards) when compared with the once-through PWR reference system, but a significant benefit in terms of access to international programmes. In the completed assessments, the “buttons” (the shaded circular indicators within the grid) for each high level discriminator are linked to the strategic attribute level and thence to the Gen-IV metrics, with written assessments at each level. This means that the decision tree that led to the high level assessment can be easily appreciated.

Note that some of the high level discriminators can have more than one button. This is because the reactor system has variants leading down different assessment paths. The two buttons seen in Figure 5 for siting (reactor and fuel cycle) are because SMR projects will be easier to site as single reactors, but this benefit may disappear if multiple-unit sitings are proposed.

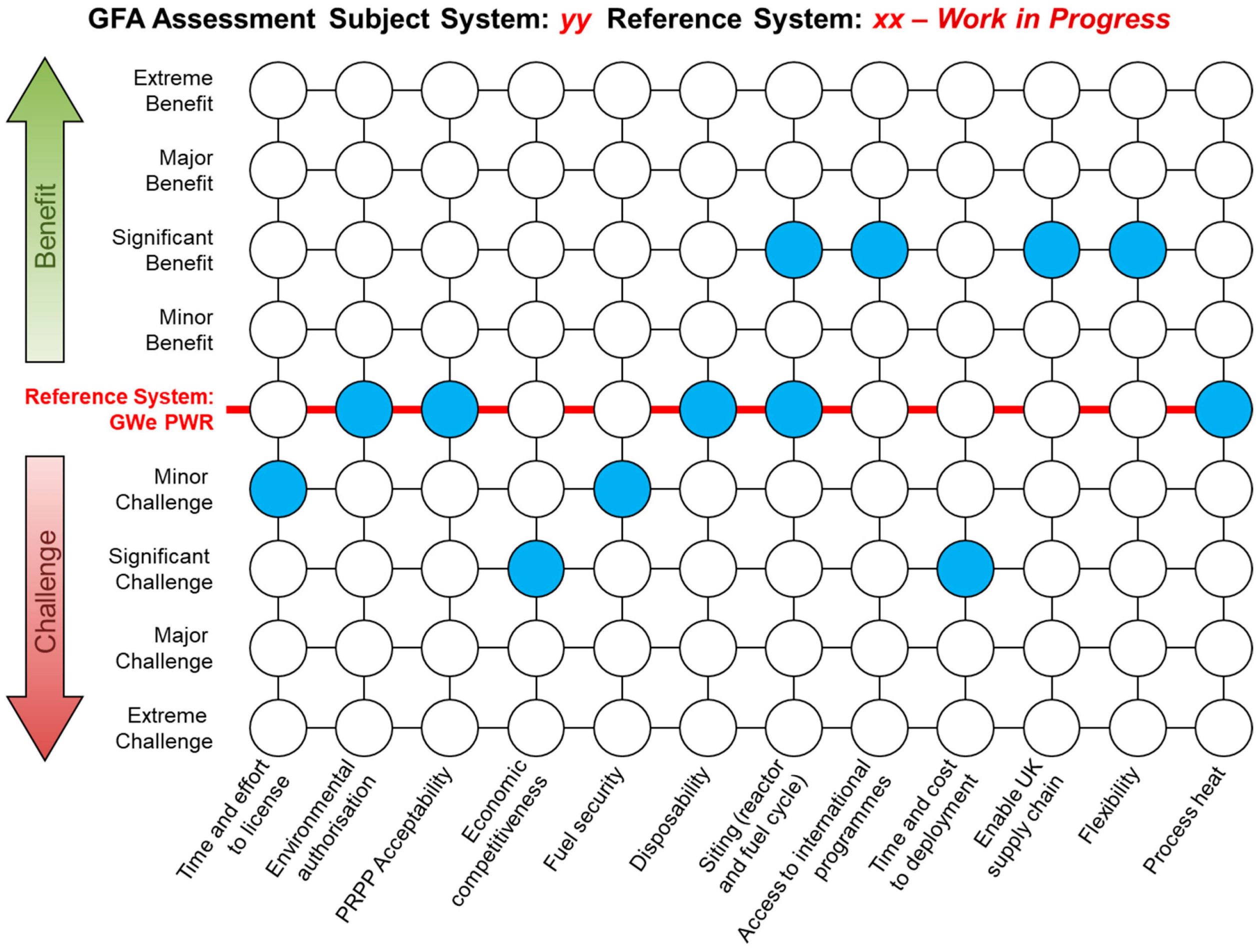

Figure 5. GFA Assessment Template Version 14, 2020.

The completed GFAs provide policy makers with insights into the capabilities of each system (including, but not limited to: baseload power, flexible generation, high/low temperature process heat, economic hurdles to be overcome, timescale of a system's likely availability and the energy futures in which it is likely to contribute). GFA examines reactor and fuel cycle systems, not individual designs, so it asks the questions which need to be asked; but when actual adoption of a reactor is contemplated, the answers must be offered by the proposer. If the proposer's submission is in stark contrast to the GFA however, detailed examination of the evidence should have been prompted.

3. Results

In 2015-2016, NNL, IDM and the Dalton Nuclear Institute carried out GFAs of six systems of SMR reactors for the Department for Energy and Climate Change (DECC; now BEIS—Business, Energy and Industrial Strategy):

(1) Small modular PWR (SM-PWR) versus a GWe PWR standard;
(2) Small modular sodium-cooled fast reactor (SM-SFR);
(3) Small modular lead-cooled fast reactor (SM-LFR);
(4) High temperature gas-cooled reactor (SM-HTGR);
(5) Molten salt-cooled thermal reactor (SM-MSThR);
(6) Molten salt-cooled fast reactor (SM-MSFR).

Systems 2–6 above were rated versus an SM-PWR reference system. The report on the resulting GFAs and the literature on which the assessments were based are currently on the BEIS website [35,36]. Some results are provided, together with their implications.

The time and effort to licence (Figure 6) is understandably more challenging for all systems when compared with a SM-PWR, with the challenge becoming more severe as world and UK reactor and fuel cycle experience reduces. Since these assessments, considerable work has been performed on technology reference levels (TRLs; ranked 1–9 with 9 being highest readiness), with a greater appreciation that the on-power date of a reactor represents the end of the critical path leading all R&D areas to TRL9. Table 1 provides a list of estimates for various systems to come online. These estimates have gained a far greater importance since the UK Government committed to net zero by 2050. Taken at face value, the assessments mean that only the SM-HTGR and the SM-SFR would be available early enough to contribute to the UK's 2050 target.

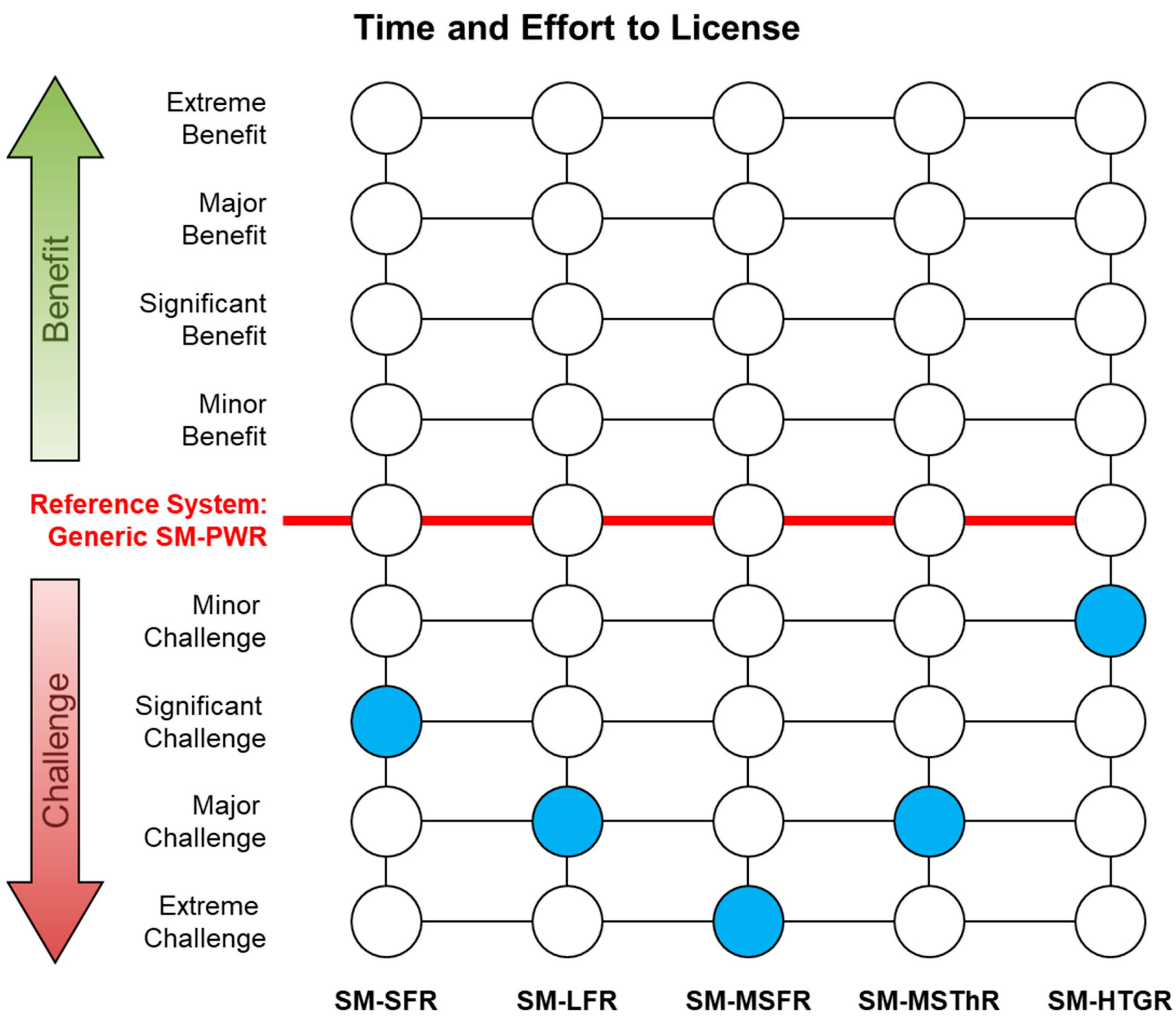

Figure 6. Time and Effort to License from GFAs.

Table 1. On-line dates for the various systems as estimated by GFA.

System	Estimated Online Date
SM-PWR	2030
SM-HTGR	2035
SM-SFR	2040
SM-LFR	2060
SM-MSThR	2060
SM-MSFR	2070

The assessments of economic competitiveness are seen in Figure 7, and reflect the rather obvious conclusion that, when judged by success in the marketplace, LWRs are found to succeed when subjected to many different versions of economic examination.

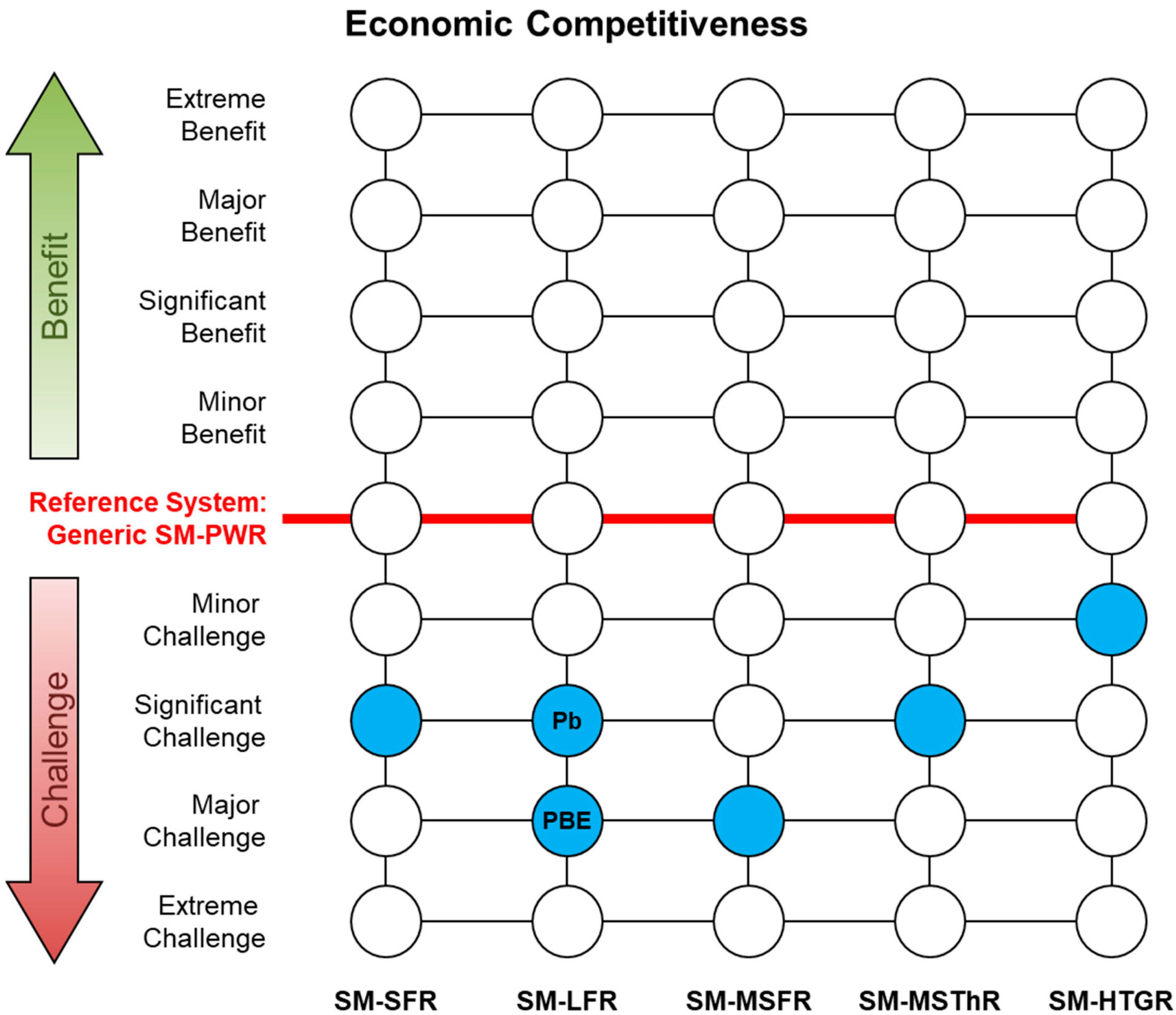

Figure 7. Economic Competitiveness from GFAs. Note that the SM-LFR has two ratings, referring to the use of either lead or lead-bismuth eutectic (PBE) as coolant.

These assessments reflect the background of nuclear in its role for delivering baseload electricity, as, while the supply of heat was assessed, the analysis went little further than considering the temperatures which could be supplied by the various systems (Table 2).

Table 2. Potential temperatures supplied by various systems, in contrast to LWRs which are generally only considered in terms of district heating at ~100 °C.

System	Approximate Potential Temperature Supplied
SM-SFR	550 °C
SM-LFR	550 °C
SM-MSFR	700 °C
SM-MSThR	700 °C
SM-HTGR	800 °C

In both the previous examples (for "time and effort to license" and "economic competitiveness" respectively), the more exotic reactor systems have shown no benefits at present over the reference light water reactor system, owing to their comparative technological immaturity. It should be stated that this is not the case for all metrics; one noteworthy example is that of fuel security, shown in Figure 8. Here, fast reactors have a clear advantage over their thermal counterparts. How important this is depends on factors such as the present or anticipated price of uranium. In an energy future of expensive uranium, this metric would rise in importance.

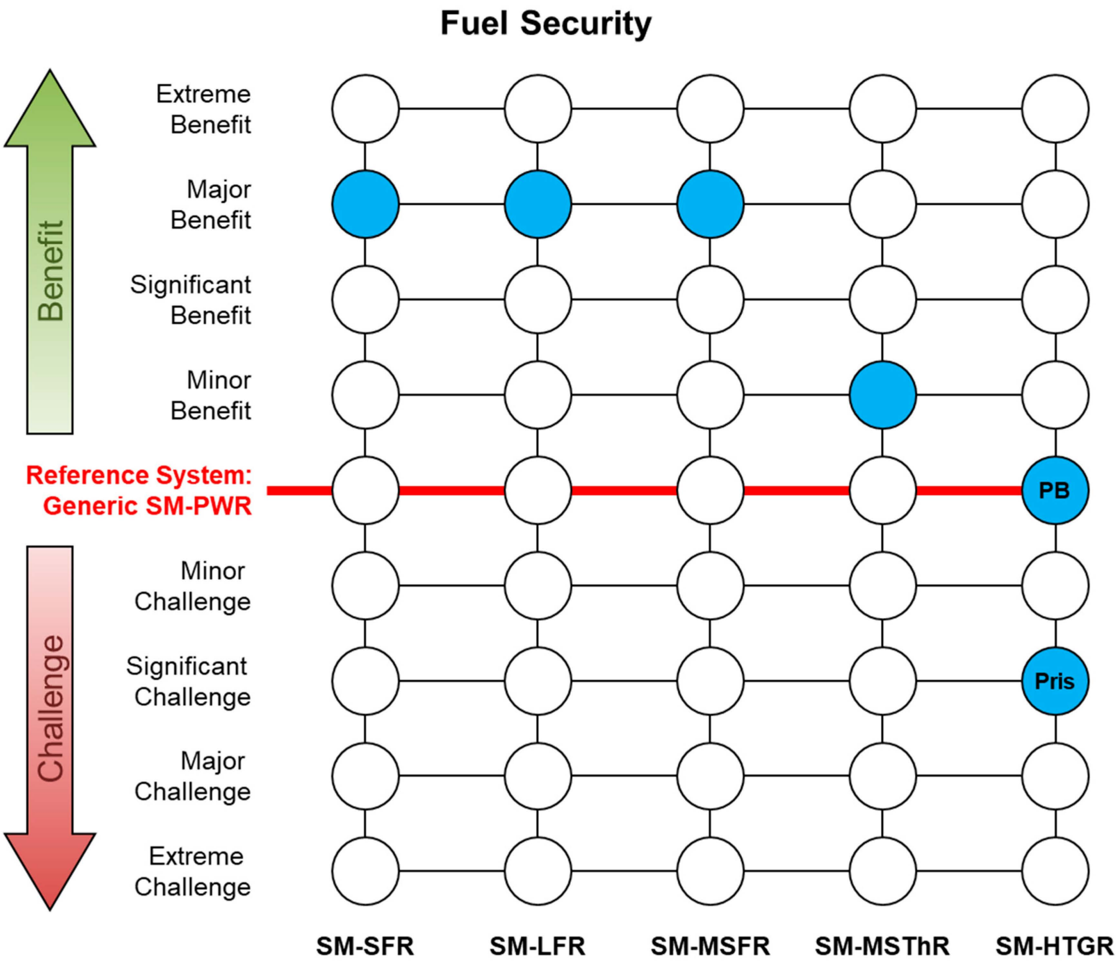

Figure 8. Fuel Security from GFAs. SM-HTGR has two ratings in this example, depending on whether a Pebble Bed (PB) or Prismatic block core is adopted.

Developments for Net Zero

When viewed against the needs of a net zero future, the GFA methodology is challenged to be developed to provide firmer comparisons in the areas of:

(1) SMR economics against the background of progress of GWe LWR systems aimed at reducing capital costs, reducing perceived project risks, and obtaining less expensive sources of finance. In the absence of these improvements, the risk is that GFA could be mounting a comparison against a reference system that is itself too expensive to succeed in the market;
(2) AMR economics on a "whole-system" basis. Various systems which have been examined have areas where challenges remain and where processes are unspecified. This is particularly true in some areas of the fuel cycle, where early pioneering experiments did not deal with reprocessing technology or waste treatment, and where

elements of waste treatment are sometimes sited with the reactors, thus becoming part of the overall capital cost. Such uncertainties are completely at odds with obtaining a licence under the UK system, and the unaddressed risks must act against the availability of low financing rates;

(3) The economics of both SMR and AMR systems have been compared at a "peer reviewed professional judgement" level on a whole-system basis. This analysis could be improved by making more detailed comparisons at sub-system level. This should be aided by the fact that the capital costs of GWe-sized LWRs have become much better critiqued and investigated in recent years, as well as being subjected to many studies aimed at allowing costs to be reduced [37];

(4) Heat generation. The costs, temperature and practicality of heat supply need much more study to address the use of nuclear heat for the temperature spectrum from 100 °C for commercial and domestic heating, to 800 °C or higher for the generation of hydrogen and/or synthetic fuels for transport uses.

The fact that, at least in the UK, the area of heat generation has only recently been addressed with any real priority, means that the whole spectrum of temperature, availability, unit size and "user plant interface" is currently at an early stage of development. Developments in this field need to be encouraged by, and incorporated into, the GFA methodology; and into the engineering efforts of those proposing nuclear heat systems for adoption in the market. Examination of even the high level figures (see Figures 2 and 3) could well support a view that the useable heat energy from nuclear could be envisaged to approach or even exceed the amount of nuclear electricity which could be involved in an economic net zero future for the UK.

Unsurprisingly, the systems examined for the UK Government represent only a cross-section of the technologies being offered today and, with the acceptance of a wider selection of roles for nuclear energy, a much more comprehensive coverage of technologies is justified. It is also true that GFA, as well as representing a challenge for reactor developers, is a very thorough examination of the likely market applicability, and of the degree to which more information will be essential before any given system is thought ready to present to the UK regulators. GFA will point out areas requiring more study, and the current licensing procedure, beginning with GDA [38–40] requires a far higher and more detailed level of knowledge, and UK regulators have proved very unlikely to respond well to "it went well in a lab in USA in 1984"!

4. Conclusions and Policy Implications

The UK has suffered from a lack of attention to scientific, economic or national drivers regarding nuclear energy. Nuclear energy is now much more widely analysed, and is available via a plethora of systems with differing challenges and benefits for the provision of electricity, and heat at a large range of temperatures. The adoption of net zero by 2050 gives a clear need for a long term holistic UK energy strategy, covering both electricity and the supply of heat at a range of temperatures, to span the next 30 years. Certainly, the challenge demands a clear appreciation of the possible pieces of the "net zero jigsaw", and GFA is a valuable methodology with which to define the range of possible jigsaw pieces which can be filled by nuclear options. GFA, if used appropriately, will enable policy-makers to effectively evaluate the nuclear systems on offer and their possible roles, and to compare these with their low-carbon, non-nuclear alternatives.

In defining both the challenges and the benefits of nuclear systems, GFA should also play a role in focusing attention on areas where challenges are not being met, or where defined benefits are not materialising. It also provides a means for non-technical decision-makers to examine energy alternatives, particularly by highlighting areas where current knowledge is lacking for given systems and further focus is required. This is especially important in an area where regulation is necessarily stringent.

A lot can happen in three decades, and knowing the basis of the current nuclear policy via its GFA profile can enable changes in the "optimum future" to be easily tracked, and the fit of developing systems can be examined against new circumstances. It would also be easy to justify the development and use of a GFA-type analysis for all low carbon energy possibilities (i.e., beyond just nuclear systems), to clarify, follow and allow steering of the possible range of level playing field solutions to what is possibly the most taxing peacetime policy commitment the UK has ever committed to.

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