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# Navigating the Path of Least Resistance to Sustainable, Widespread Adoption of Nuclear Power

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**Abstract:** With climate change rapidly accelerating, we must seriously reconsider our inconsistent and, at times, disjointed approach to energy grid decarbonisation by applying extant low-carbon technologies rapidly and at scale rather than continuing to rely on fossil fuel generation. In contrast to more transient renewables such as wind and solar energy, nuclear power is capable of reliably generating large quantities of baseload low-carbon energy. Despite this advantage, however, deployment has stagnated due to a combination of high costs, safety concerns, and an unwillingness of political authorities to commit to a large-scale, publicly funded program. The focus on private sector leadership in R&D has resulted in a smorgasbord of under-developed and conceptual reactor and fuel cycle technologies, many of which are a decade or more from commercial viability. Meanwhile, the aforementioned political issues have prevented the necessary long-term funding, incentivisation, or provision of the necessary market structures for the significant construction of actual generating plants. With this in mind, we present a potential path to a long-term sustainable approach to the nuclear fuel cycle, highlighting key reactor and fuel cycle technologies and providing an overview of how these should be implemented. Additionally, we discuss the industrial, political, and societal changes needed to achieve this through the comprehensive management of both waste and resources.

**Keywords:** nuclear fuel cycle; reactor; reprocessing; waste management; sustainability; resource management; circular economy; climate change; Net Zero; decarbonisation



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## 1. Introduction

The widespread adoption of nuclear fission is hindered by excessively high costs [1], concerns over environmental impacts and radioactive waste [2], persistent negative perceptions surrounding safety [3], and proliferation [2] in both the public and political fields. This is despite the often-highlighted promise of this technology as a cornerstone of the Net Zero transition [4,5], in combination with renewables and storage [6], to achieve grid decarbonisation. As early as the 1970s, it was recognised that renewables alone might struggle to meet the exponentially increasing demands from the developed and developing world and that nuclear should be a major contributor to future energy generation [7]. However, a lack of cohesive energy strategy across most of the globe [8] means that the technology's potential as the ideal baseload to complement more transient renewables is not being realised despite the challenge of [9] rapidly accelerating anthropogenic climate change. This is despite evidence that the inclusion of nuclear power in future energy scenarios will improve social, environmental, techno-economic, resource consumption, and energy security outcomes [10]. The problem is further compounded by the notoriously conservative attitudes prevalent within the nuclear industry [11] and its political proponents, including a lack of forward-thinking when considering the long-term sustainability of the nuclear fuel cycle (NFC) [12,13]. The latter, fuel cycle, issue will become increasingly important if installed capacity is to increase over the coming decades [14]. While there has been an increase in interest in civil nuclear marine propulsion as a means to offset the ~3.2% total carbon emissions that arise from civil marine transport [15], and a commitment by several nations to the construction of nuclear-powered military submarines, the discussion of both of these is beyond the scope of this work.

In this paper, we present a concise overview of current and in-development nuclear power technologies and discuss how these could best be employed over the next several decades to allow for a transition to a more sustainable, holistic, and cradle-to-grave approach to the NFC. This process would be undertaken in three or perhaps four stages, with the best usage cases for all natural and produced fertile and fissile resources being highlighted and contextualised in each stage. At the core of this approach is the comprehensive recycling (or reprocessing) of spent nuclear fuel (SNF), which is presently viewed by many nations as a waste rather than the resource it represents, and the application of the most developed technologies in the most appropriate role. This would naturally be within the context of a safety-oriented, proliferation-resistant [16] approach to nuclear power with comprehensive and responsible waste management and would help to guarantee energy security in times of increasingly unstable climate and geopolitical tension. The security of scarce natural resources beyond the actinides could be afforded if these are extracted from SNF during reprocessing or recycling, as discussed later [17].

We note that the many and varied current and legacy types of radioactive waste remain a significant and ongoing challenge for the nuclear industry, and new approaches to handling these are being implemented in the significantly more responsible and risk-conscious culture that exists nowadays compared to that of the earlier years in the 1940–1960s [18]. Whilst the destruction of radioactive materials cannot be accelerated, save through transmutation in a fast reactor [19], there remains substantial scope for improvements in management relative to present practices in that target species, which can be effectively partitioned and better managed than is currently achieved. Strategies such as the partitioning and transmutation or fission of the minor actinides (MAs: Np, Am, Cm, Bk, Cm, Es, and Fm) would serve to eliminate the bulk of long-lived radioactivity [16]. Minor actinide nuclei destroyed through fission additionally generates useful energy in a reactor or similar system. Such concepts have been developed over the previous several decades and will likely be implemented in next-generation fuel cycles. Nevertheless, it may be possible to hasten this development, as will be discussed later.

Please note that the technological assessments presented here are cursory and expanded on only when relevant to the discussion; we would encourage readers to see the many excellent in-depth assessments of fuel cycle technologies published recently [16,20]. This will be especially necessary as grid demands increase with the advancing quality of life across the world and the increased electrification of vehicles [21] and shift away from fossil fuel heating to electrical energy, including heat pumps [22].

As a preface to the following discussion, the core of this concept is to fully exploit the incremental advancement for reactor performance and safety developed over the past several decades. These include concepts such as advanced technology fuels (ATFs), including alternative cladding materials and fuel ceramics, which could be achieved if these are at a sufficient state of development and would not be detrimental to fuel cycle operations [23,24]. Another core part of achieving the greatest efficiency in the nuclear fuel cycle is employing the inherent "value of neutrons", i.e., attaining the greatest neutron economy for the simultaneous production of fissile isotopes via breeding and the generation of energy, given the finite nature of naturally occurring $^{235}U$ [25]. Finally, at the core of this principle must be the organic linking of all aspects of the fuel cycle for increased efficiency and to reduce barriers to implementation [26].

## 2. Stage One: Short-Term Expansion and Establishment of Sustainability—The Present to Two Decades

The current approach to nuclear power in the developed and developing world can be described as somewhat scattergun and piecemeal in nature [8]; additionally characterised by the leadership of commercial enterprises and the free market in research, development, and deployment of new build. Furthermore, government involvement has been sporadic and has often involved little in the way of funding, direction, and oversight [27]. This has resulted in vast sums of both public and private money being, in essence, wasted on the development and, in some cases, implementation of unproven technologies [28] rather than incremental improvements on or the miniaturisation of known designs and concepts. This is combined with a lack of political will to commit the necessary funds to new nuclear projects, many of which have experienced extensive delays and eye-watering cost overruns during construction, particularly for some Gen III(+) reactor designs [29]. Addressing this is imperative given the aging nature of the large Gen II reactor fleets operating in several notable states, including the USA, UK, Japan, Russia, and France. These Gen II reactor types were direct or indirect causes of incidents such as Chernobyl, Three Mile Island, and Fukushima, the safety margins of which have been vastly exceeded in newer Gen III(+) designs. Indeed, this is one of the driving factors behind incremental technological advancements, and as such, we can assume that the incident rate for these newer reactor designs, alongside their supporting fuel cycle facilities, is at least two or three orders of magnitude higher than the units they will replace in order to maintain generating capacity. Any further assessment of the safety of our proposed scheme is beyond the scope of this initial overview but is evidenced by the purported increases in core-damage frequencies from Gen II reactors (1 in 10,000-1 million core-years) to Gen III(+) reactors (1 in 10 million and more) [30]. Newer SNF reprocessing and recycling facilities, in addition to other supporting fuel cycle infrastructure, would similarly be built to increased safety and risk mitigation standards compared to current- and previous-generation plants [18].

Themanifold scaled-down reactor designs, such as the plethora of small modular reactor concepts (SMR, typically defined as $\leq$300 MWe or $\leq$1000 MWth)) [5,20,31] potentially promise, based on manufacturer claims, to reduce capital and operational costs and construction times (both by at least half for the nth unit as claimed by various companies), and have greater flexibility of operation and in potential sites due to lower plant sizes [5]. These reactors suffer from marginally (5–10%) decreased overall operational efficiency and increased waste outputs relative to large reactors [20,32] and, in any case, none of these are yet operational or even past the licensing stage for most designs at the time of writing [5,33], being partially restrained by the more onerous regulatory requirements placed on large reactor designs for which the licensing process was designed [5]. Indeed, some proposed plants have been cancelled before ground has even been broken [34]. Larger-scale production of traditional, large-scale reactors could similarly reduce costs if commonality of design and best practice in construction were employed [35], especially through learning from previous experience and mistakes [36].

Currently, this is lacking: at the time of writing, there are 57 reactors under construction globally of 17 different designs [37]. This illustrates the fact that the industry is not exploiting the economic benefits that arise from repeated 'nth-of-a-kind' construction but instead consistently exposes itself to the expense of first-, second- or third-of-a-kind construction.

A conceptual implementation of the two-stage approach outlined in this work is presented in Figure 1. This was, in part, inspired by the proposed Indian three-stage nuclear power concept [38] but has been adapted for the greater amounts of U available outside of that nation [39], essentially merging stages 2 and 3 (SFR and MSR) of the Indian proposal into a single second stage with the two complementary reactor types operating in parallel rather than the second feeding into the third. The second stage of our concept is discussed later.

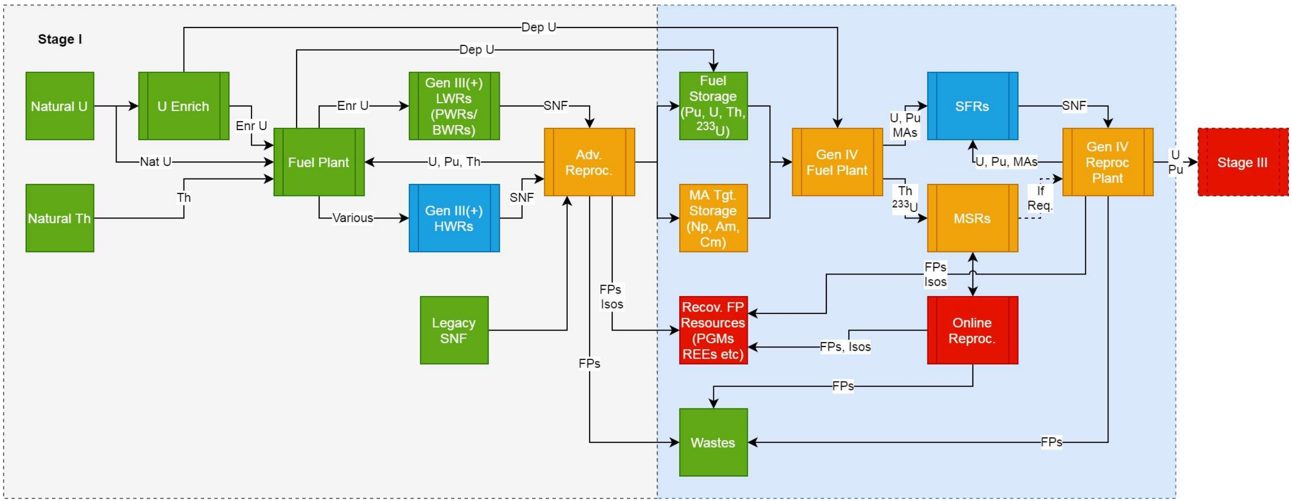


**Figure 1.** Schematic summary of Stages I and II of this proposed concept indicating the simplified routing of fissile and fertile materials through processes and reactor types, and the state of development of each of the required technologies: **green** = well-developed and operational commercially; **blue** = prototypes demonstrated and operating at the time of writing; **orange** = limited prototypes in a previous run or low-medium state of development; and **red** = conceptual or very low state of development. Please note this is not an exhaustive diagram of the possible uses and routing of isotopes and materials. Key abbreviations: Enr. U = enriched U; Nat. U = natural U; Dep U = depleted U.; enrich. = enrichment; SNF = spent nuclear fuel; Adv. Reproc = advanced reprocessing; MA Tgt. = minor actinide target; Recov. = recovered; PGMs = platinum group metals; REEs = rare earth elements; FPs =fission products; Isos = isotopes.

To simultaneously address the necessity to decarbonise power grids partly using nuclear fission to provide energy security and improve the sustainability of energy generation generally, we propose a number of actions to be taken and concepts and technologies to be implemented.

Firstly, a unified approach to reactor construction, licensing, and legislation at a national or even supra-national (e.g., EU (European Union) or US (United States) Federal) level is strongly preferred, if not required, using the latest established reliable Gen III(+) designs capable of flexible operation (i.e., capable of running on Pu MOX (mixed-oxide) for a closed fuel cycle) with increased efficiency and safety [40]. Such standardisation would allow for rapid, at-scale construction of generating plants using identical units to reduce costs and construction times in a manner similar to that often proposed for SMRs without surrendering the economic advantage of large reactors. [32,41]. In addition to Gen III(+) LWRs (light water reactors—PWRs (pressurised water reactors) and BWRs (boiling water reactors)), a number of modern HWRs (heavy water reactors [42]) should also be constructed to allow for additional fuel cycle flexibility and to prepare for Stage 2, as these reactors can operate on non-conventional fuel sources. The fuelling options for modern HWRs include natural uranium, low Pu MOX, reprocessed uranium, repackaged spent LWR fuel ('DUPIC'), as well as $^{233}$U-Th breeder cycles. Furthermore, most HWR designs are capable of online refuelling, meaning that potentially achievable capacity factors are higher as the typical LWR refuelling outages are eliminated. Although some breeding occurs in LWRs—producing as much as 50% of the power from in situ bred Pu—the neutron economy is nearly always insufficient in commercial power reactors to "break even"; Th can also be partially bred to $^{233}$U [43,44], but again, this often does not produce more fissile material than is consumed. The most likely use of such material would be in the "starter cores" of new reactors, where the grid matrix of variably enriched fuels is used to maintain even power generation across the core, with a proportion replaced after each refuelling outage; the lowest enriched "bred" fissile materials could then be recovered during reprocessing after cooling. These reactors could be funded by the diversion of funds away from the development of the aforementioned unproven technologies, with the increased taxation of carbon-producing entities, including fossil fuel (coal, oil, gas) energy generation [45], and ceasing the construction and cancellation of overpriced and poorly implemented political "vanity projects" [46]. This would allow for the simultaneous expansion of nuclear fleets and the replacement of aging reactors as they reach the ends of their useful lives and should begin immediately, given the long (8–10 y) construction times of most large reactor designs and the necessity to decommission operational plants within many nuclear nations over the next few decades.

Secondly, a commitment to closing the NFC is essential to its long-term sustainability. Natural fissile ($^{235}$U) and fertile ($^{238}$U and $^{232}$Th) resources are finite in nature and non-renewable, with the present U-based fuel cycle extracting <1% of the potential energy present in natural U when enrichment is taken into account. The single recycle and reuse of the generated Pu as MOX reduces demand on natural U by about 20% when recycled once [47], with most modern reactors likely capable of running on multi-recycled Pu to increase this further [12,13]. The addition of advanced technologies to reprocessing could allow for the recycling of shorter-cooled fuel (e.g., 5 rather than 10 years), thereby increasing the fissile content of recovered Pu, as greater concentrations of $^{241}$Pu ($t_{0.5}$ = 14.1 y) would be present. This would require expansion of reprocessing capacity to both meet current SNF output (~7–11,000 t/y) and likely exceed this to allow for the recovery of U and Pu from legacy SNF stored beyond the ~25–33% capability currently extant [16]. Although Pu is bred from U more effectively in fast reactors, Th can be bred to $^{233}$U in some thermal reactor designs and will form an important feedstock for later stages of the proposed sustainable nuclear fuel cycle. Th-U or Th-Pu MOX fuel can be reprocessed using an adapted PUREX (plutonium and uranium reduction extraction) process (i.e., THOREX (thorium extraction)) in the same plants as conventional $UO_2$ fuels [48]. New reprocessing facilities would also likely include some mechanism to partition the MAs for later transmutation in fast reactors, which serves to reduce waste volumes and radiation levels for [16] the future, thereby reducing intergenerational burdens and inequalities. MA separation processes (e.g., SANEX (selective actinide extraction), GANEX (grouped actinide extraction)) are not in commercial operation at the time of writing but are at high levels of development (TRL (technology readiness level) 6–7) [16]. This would require separated MAs to be stored until such a time as suitable reactors for transmuting them (i.e., SFRs, see below) can be brought online, though extended burning in thermal-spectrum reactors could sufficiently lower the concentrations of these species [49,50] at the expense of reduced neutron economy [51]. The recovery or recycling of other valuable resources present in SNF, such as strategic elements (PGMs: Ru, Rh, Pd, Ag; REEs: Y, La-Dy; NGs: He, Kr, Xe), useful isotopes [17,25,52,53], and high-purity zircalloy cladding has been proposed over the years but not implemented as of yet [54]. This would serve to increase the efficiency of the NFC by recovering unconventional or presently untapped resources, potentially offsetting or even eliminating the high costs of reprocessing and other fuel cycle costs, and reducing waste volumes for final disposals, though technological and regulatory hurdles may not be surmountable in the short time frames necessary for the construction of new SNF reprocessing plants, given the essential impossibility of retrofitting such operations [55]. This concept requires a stockpile of fissile and fertile materials to support the second stage of the operations; this would have to be conducted in a proliferation-resistant manner with all appropriate nuclear safeguards for such material applied [56]. It may furthermore be apt to segregate $^{233}$U and Th-based materials from the more common U and Pu operations despite the potential to operate both within the same reactors, reprocessing facilities, and other supporting infrastructure. Closing the NFC inherently reduces waste volumes relative to the direct disposal of SNF and is, thus, highly beneficial as it reduces the demand on geological disposal facilities by at least a factor of 20 for even the simple PUREX process. The further separation and removal of valuable fission product resources and useful isotopes would decrease these volumes for disposal even more than this [17]. The waste arising from fuel cycle operations would, as discussed in the introduction, be subject to modern, responsible treatment and handling approaches for better risk mitigation [18]. We would not seek to significantly change the methods and means of radioactive waste management and disposal in this concept, as these are established and well-functioning aspects of the NFC that have seen significant development since the early days of the nuclear fuel cycle. Notwithstanding efforts to reduce waste volumes through partition, transmutation, and the recovery of valuable materials, significant highly active wastes will likely remain. These would be disposed of by currently proposed deep geological or borehole disposal methods [57]. The high costs of these facilities would be naturally lowered by reduced overall waste volumes.

Thirdly, the augmentation of the large reactor fleet with SMRs based on established technology (i.e., LWRs [20,33]) should begin in earnest. This would incorporate expedited licensing procedures for these designs, which are often tailored far more toward large plants [58] and, thus, are not necessarily fit for an SMR assessment. The purported shortened construction times of SMRs [32] could, if the necessary paperwork is completed quickly enough, allow for the commercial operation of SMRs within the same timeframe as large plants. By using established LWR technology, the SNF from these reactors would also be compatible with reprocessing, and most designs should, with minimal modifications, be capable of operation on MOX fuel as their larger brethren are [12,41].

The application of ATF concepts to existing and new build reactors would also aid in increasing the margins of safety and efficiency in the NFC [23]. A coordinated system between nuclear-generating nations to share essential data on the preparation and irradiation performance of such novel cladding materials and/or fuel ceramics would aid in their development and speed adoption. This could likely be achieved through the same cohesive regulatory frameworks that would cover reactor types, as outlined above. The specific drivers to adopt such technologies, however, would ultimatelyy remain with the operator of each reactor in question.

The first stage, as outlined, would serve as the seed for a self-sustaining second (and possibly third) stage NFC, with the more resource-intensive Gen III(+) reactors retired at the end of their useful lives and replaced by the now-established Gen IV designs outlined below [26]. Such an approach is noted as a necessity by Adamov and coworkers, who outline a similar, if somewhat more concise approach, in their work [26], which analyses the resource demands of both stages in greater detail.

## 3. Stage Two: Medium-Term Expansion and Advancement—One to Three Decades

Once stage one has been established and is generating low-carbon energy commercially, resources should be released and devoted to the development of the second stage of this concept, involving the transition to targeted Gen IV reactor designs to further expand nuclear capacity and advance the sustainability of the NFC for long-term (centuries) operation. A concise summary of the six Gen IV reactor concepts, alongside their current state of development, advantages, and drawbacks, is provided here as this impacts the choice of design(s) for the second stage of our concept, as follows:

- The sodium-cooled fast reactor (SFR) is the only design sufficiently developed for short-term (5–10 year) deployment [59] with several examples, including one large-scale reactor (BN-800, 800 MWe, Russia), operating at the time of writing, in addition to operational experience in the USA, UK, France, Japan, and others. The advantages of this design include the ability to transmute (fission) the MAs and non-fissile Pu isotopes, use Np as part of their driver fuel [60], potentially transmute long-lived (e.g., $^{99}$Tc and $^{129}$I) or highly active fission products (e.g., $^{90}$Sr and $^{137}$Cs) into more stable derivatives [19], breed $^{238}$U into $^{239}$Pu effectively [61], are passively safe in the event of a power outage [62], do not require high-pressure reactor vessels, and operate at higher temperatures and, thus, higher thermal efficiencies than LWRs. Disadvantages include the requirement for a high concentration of fissile material to operate and a coolant, which is highly reactive with both air and water.

- Molten salt reactors (MSRs) are a diverse class of primarily liquid-cooled reactors (Fredrickson et al., 2018) with respect to neutron spectrum and salt chemistry. The most notable proposals include thermal-spectrum (graphite moderated) reactors using fluoride salts (e.g., FLiBe) or fast-spectrum implementations using chloride salts, with the fissile (and fertile) material normally dissolved in the salt in both of these cases, though there are exceptions to this. Thermal-spectrum molten-salt fluoride reactors (MSFRs) are particularly notable as being able to breed thorium effectively into $^{233}U$ [63]. These designs are further capable of incorporating online reprocessing for the continuous removal of neutron poisons to maximise neutron efficiency, though this technology is in its infancy at the time of writing [64]. Fast-spectrum designs could effectively fission the MAs in the same manner as SFRs. The primary advantages of MSRs include a high degree of passive safety, higher operating temperature, and efficiency than Gen III(+) designs, ambient-pressure core operation, and a high degree of fuel cycle flexibility, but conversely, they are not well developed, their operating experience relative to SFRs [63] is far lower, challenges persist around structural material corrosion arising from the harsh environment in the reactor, and large volumes of additional waste (graphite) are generated at the end of life for thermal-spectrum MSRs.
- High-temperature gas-cooled reactors (HTGRs) use a graphite-moderated core, TRISO (tri-iso-structural) fuel, and He coolant, with an operating temperature of potentially up to 900 °C or higher. This represents the primary advantage of these reactors, and as such, they have been considered by some nations [65] as a means of chemically producing hydrogen via high-temperature catalytic methods for energy storage as a means that is more efficient than electrolysis. The thermal efficiency is also the highest of all proposed reactor designs at ~50%. The disadvantages include limited operation experience to date, historically low capacity factors [66], challenging fuel processing at either end of the fuel cycle (effectively negating a close fuel cycle) [67,68], and the generation of large volumes of additional active waste (graphite) at the end of plant life [69].
- The lead-cooled fast reactor (LFR) [70,71] is similar in concept to the SFR but instead uses molten lead, or a lead-bismuth eutectic, as the coolant. These possess much the same advantages as the SFR, with the addition of lead being an excellent radiation shield, unreactive with air and water, and of low susceptibility to neutron activation at the expense of a very dense and, thus, heavy reactor material corrosion challenges, and negligible operating experience. The only lead-cooled reactors constructed to date, at least to our knowledge, operated on Soviet submarines during the Cold War but were likely constructed with a Be moderator and demonstrated a somewhat alarming tendency to suffer operational problems resulting in the loss or extreme contamination of several vessels [72]. Several concepts utilise what is, in essence, a lead-cooled fast reactor with a sub-critical core, where the reaction is driven by an external particle accelerator which generates a neutron beam to make the core assembly critical; for example, the EU MYRRHA (multi-purpose hybrid research reactor for high-tech applications) project [73], in addition to SMR concepts being developed by start-up companies, seek to address the challenges experienced in operation so far [74].
- Gas-cooled fast reactors (GFRs) use a compact core with a high content of fissile material and a He coolant, which is, in essence, the fast-spectrum parallel to the GCFR, allowing for similar high-temperature operation. To date, no GFR has been built or operated, and, as such, these designs remain purely conceptual at the time of writing.
- Supercritical water reactors (SCWRs) can be viewed as an extension of LWR technology operating at higher pressures and temperatures, allowing for the (light or heavy) water coolant to exceed the critical point (phase change, not the nuclear term) in turn, provide higher thermal efficiencies (~45%) over standard LWRs. These reactors can be configured in a number of ways to provide harder neutron spectra than conventional LWRs, potentially allowing for the burning of MAs. Due to material challenges,

amongst other factors, no SCWR has yet been built or operated, and these designs remain purely conceptual at the time of writing.

In addition to being used for energy generation in a conventional manner, all Gen IV reactors operate at higher temperatures (450–800 °C) than Gen III(+) designs and, as such, there is significant potential to utilise their heat output to drive thermally-demanding drive chemical processes such as hydrogen production (e.g., via the S-I cycle) [75]. All Gen IV designs fall short of the temperatures required by steam cracking (1000 °C) and blast furnaces (1500 °C), and as such, other technologies will be required to drive these operations, or the less efficient use of nuclear-produced electricity where a proportion of gross heat output is lost to turbine and genset losses.

The future scale of the market for $H_2$ is uncertain [76], given advancing electrical transmission and storage technologies [77], and is, in any case, subject to competition with low-temperature electrolysis using surplus or off-peak electricity. As the future market for $H_2$ as an energy storage medium is uncertain in light of advancing grid-scale battery storage and other factors, we will primarily consider the merits of Gen IV reactors based on their potential to generate electrical energy, with additional uses as secondary targets. Accounting for the above and fissile and fertile resources readily available to us from the existing nuclear fleet, two complementary Gen IV reactor designs would form the cornerstone of the second stage of our fully-closed, sustainable fuel cycle concept: the SFR and the MSR.

As many current nuclear nations have past or present experience in constructing and operating SFRs, a standardised design process for these should begin in earnest for deployment to begin within the next two decades. These reactors would be fuelled by MOX prepared from existing reprocessed Pu and U initially, setting up a self-sustaining, fully-closed U breeder cycle once a sufficient number of reactors and the necessary supporting infrastructure have been built. Adaption to MA burning would follow once the fleet is established. As Gen IV reactors are of significantly lower maturity than their Gen III(+) counterparts, construction and commissioning times would inherently be longer (perhaps by 50% more, i.e., 9–15 years vs. 6–10) as any teething troubles in the technology are ironed out. Once these have been addressed with the first few units, these times would naturally decrease.

In parallel to this, the development of thermal-spectrum, core-blanket MSRs with online reprocessing to establish a complimentary Th breeder cycle should be initiated. As MSRs have a somewhat greater list of technical and regulatory challenges to address, a longer lead-time is necessary before these can become operational. MSRs can be fuelled by a range of fissile materials in the same manner as CANDU reactors drawn from the first stage of this proposal. However, the success of an MSR programme is not essential to the implementation of the remainder of this plan, although it is expected that it would be highly beneficial.

As of now, we believe that research efforts should be devoted to these two reactor types and their supporting fuel cycle infrastructure (reprocessing, etc.). This would allow for a gradual (50+ year) transition to these two reactor types, which are capable of effectively utilising all natural and generated fissile and fertile resources between them. Combined with robust, advanced reprocessing and waste management [78–81], and the recovery and recycling of other resources in the fuel cycle, this would grant a sustainable, cradle-to-grave approach to nuclear energy, implementing holistic, circular economic principles for minimised costs and environmental impacts with maximised efficiency. See Figure 1 for a diagrammatic overview of this proposed concept.

## 4. Stages Three and Perhaps Four: The Far Future—Two Decades and Beyond

Beyond the establishment of the first two stages of this concept, the way forward is a little more speculative. The four remaining Gen IV reactor concepts possess merits (including higher thermal efficiencies) of their own but require such levels of further development as to only warrant significant attention once a sizable fleet of SFRs is operational, the operational niggles with MSRs have been ironed out, and commercial operation is viable. Once any challenges with GFRs, LFRs, SCWRs, and HTGRs have been addressed, these could then join their SFR and MSR peers as part of the operational fleet, with any such fuel cycle incorporating sufficient flexibility to allow for their seamless integration.

We state a “perhaps” to the fourth stage of this concept with respect to fusion. Although proposed since the 1950s as the panacea to all of mankind’s energy needs, the commercial, grid-scale operation of this technology has always been “20/30/40/50 years away” [7]. Demonstrators at the time of writing are able to briefly break even with energy input but are far from being able to produce overall net power, let alone run for days, weeks, months, or years without break as fission reactors can [82]. At the time of writing, fusion is one of the technologies receiving vast sums of money [82] from many sources, including recent commitments by the USA and partners at COP28 to accelerate its funding as part of decarbonisation efforts [83]. This funding would, in our opinion, be better diverted toward the construction of new, viable fission plants of existing and workable designs, given the urgency to decarbonise power grids. Fusion should, thus, at least for the next few decades or even half a century, be left by the wayside to allow for functional low-carbon fission to be built up to a much larger proportion of energy grids before any significant effort is devoted to its development. The presence of a sustainable breeder cycle for U, using fast reactors, and Th, using thermal reactors, could potentially negate the need for fusion entirely, at least for several centuries if not for tens of millennia [7], assuming that we can ever get fusion to work properly in the first place [84].

## 5. Other Challenges and How to Overcome Them

The above presents the technological hurdles necessary to achieve a sustainable, long-term NFC, but there are many other social, environmental, and economic challenges that must be overcome in order for this to be achievable. The most significant of these, alongside possible mitigations, are presented below.

- Nuclear facilities are often affected by NIMBYism (not in my backyard-ism) [85,86] arising from the negative public perception of the technology generally, applying to both reactors and other fuel cycle facilities. This is despite the many high-paying jobs created by such facilities and the support these provide to local economies [87], many of which are heavily dependent, if not totally reliant, on the presence of the nuclear industry in their area [88]. Opposition such as this may be driven by the psychology of place attachment and identity and feelings of externally imposed change; therefore, proponents should seek to demonstrate how these new facilities enhance rather than disrupt the local area and its distinctiveness as well as the agency of the affected people [89]. This might include an emphasis on skills development, career opportunities, improved infrastructure, and minimised environmental impacts (e.g., $gCO_2eq/kWh$), among others. Given this difficulty, it may also be advisable to develop the available sites with the greatest output achievable from a suitably compact site footprint and with available cooling resources. Maximising achievable output would reduce the number of sites that must be developed and, thus, the total effort required to overcome opposition [41].
- As previously highlighted, a lack of political will to invest the necessary cash to build new reactors and associated fuel cycle facilities means that wide-scale construction is slow and at a far smaller scale than necessary for grid decarbonisation, relying more instead on significant private or even international investment to ensure the go-ahead of such projects. Reliance on such private investment ultimately increases the long-term costs of such projects compared to public ownership, as governments can often borrow at far lower interest rates than commercial entities. This would lower the relative capital expenditure of new-build nuclear plants and, thus, decrease the end cost of the energy generated. Governments must, thus, be willing to commit the necessary public money to build new reactors and supporting infrastructure, which would, at the scale necessary for grid decarbonisation and, with a concerted effort

internationally, bring down overall unit costs. If increased funding is required to achieve this, the approaches outlined above could be used to raise the additional necessary revenue.

- Another factor limiting nuclear uptake is political short-termism and a lack of general agility, arising from the normal 5–10 yearly change in governments within democratic nations, resulting in a lack of long-term commitment to invest in technologies that require it [90], such as nuclear power. Addressing this will rely on a multilateral approach within countries and could be aided by greater international cohesion in the implementation of nuclear technology.
- Parallel to these are the over-reliance on market forces and a general lack of technical direction with respect to national fuel cycle implementation in some nations. In some cases, such as France, these are managed at the national level through state-owned enterprises, resulting in the cohesive management of the power sector while in others, such as the UK, the privatised power grid, market-driven approach, and lack of long-term planning have resulted in vastly higher overall energy prices [91] and a slower-than-necessary commitment to new nuclear builds and supporting infrastructure maintenance due to a lack of political direction and an over-reliance on foreign investment [92]. This is similarly reflected in the manyfold private enterprises developing numerous and varied SMR designs, a large proportion of which are reliant on undeveloped or unproven technology and, as such, detract from the concept outlined here [20,28]. A more focused and unified top-down management of the fuel cycle on a national or, more preferably, supra-national level would mitigate this.
- Nuclear incidents such as Chernobyl and Fukushima have often been followed by a kneejerk political insistence on divestment from nuclear energy as rapidly as possible [93] despite the inherent safety of more modern reactors over those legacy designs that suffered the aforementioned accidents or incidents. This has resulted in, for example, the legally mandated cessation of nuclear generation in Germany during the time of the highest global fossil fuel and energy prices in recent years; these six mothballed reactors [94] could be brought back online with minimal cost and effort to provide >6 GWe of low-carbon power, which would provide ~10% of the nation's use at the time of writing. Similarly, reactors constructed but never commissioned in Austria [95] and the Philippines [96] could be brought online, and supporting infrastructure, such as the THORP (thermal oxide reprocessing plant) facility at Sellafield in the UK could have been kept operational rather than being prematurely decommissioned, or never operated in the first place [97].

## 6. Conclusions

This work presents a conceptual approach to increasing the capacity and long-term sustainability of the nuclear fuel cycle, primarily focusing on technical and technological aspects but also highlighting some prevalent and persistent socio-economic challenges which hinder this. A possible timeline for the implementation of our proposed concept is presented in Figure 2. This assumes a 60-year life for the Stage 1 reactors and facilities with ongoing use for all technologies in Stages 2 and 3.

As anthropogenic climate change is rapidly accelerating at the time of writing and the necessity to reach Net Zero as soon as possible has never been clearer, the current approach to nuclear power must change with the utmost priority, preferably in a coordinated, international manner. In this respect, socio-economic and cultural hurdles are the biggest hindrance to wider nuclear adoption than any technological or environmental one. The potential of introducing a circular economy around the NFC would provide a great many benefits beyond those outlined, though these are beyond the scope of this overview piece.

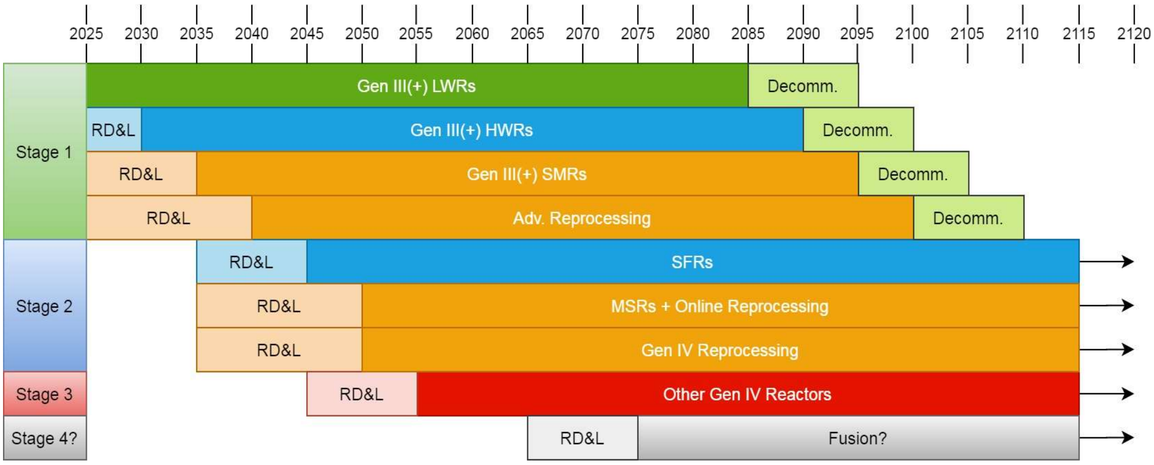


**Figure 2.** Possible timeline for the implementation of the 3- or 4-stage concepts presented in this work. The approximate state of development of each technology is presented in the same scheme as **Figure 1**: **green** = well-developed and commercially operational; **blue** = prototypes demonstrated and operating at the time of writing; **orange** = limited prototypes in a previous run or low-medium state of development; and **red** = conceptual or very low state of development. RD&L = research, development, and licensing; Decomm. = decommissioning; other acronyms are the same as the main text.

Nonetheless, we hope this work will provide a technical framework for a more sustainable nuclear fuel cycle, promote discussion and collaboration between necessary political, regulatory, and technological parties, and spur more rapid action to cement nuclear energy as the cornerstone of Net Zero that it should be.

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