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Review

A Review of Environmental and Economic Implications of Closing the Nuclear Fuel Cycle—Part Two: Economic Impacts

Robin Taylor [1,*], William Bodel [2,*] and Gregg Butler [2]

[1] National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale CA20 1PG, UK
[2] Dalton Nuclear Institute, The University of Manchester, Manchester M13 9PL, UK; gregg.butler@btinternet.com
* Correspondence: robin.j.taylor@uknnl.com (R.T.); william.bodel@manchester.ac.uk (W.B.)

Abstract: Globally, around half a million tonnes of spent nuclear fuel (SNF) will be in dry or wet storage by around 2050. Continued storage is not sustainable and this SNF must eventually either be disposed (the open nuclear fuel cycle) or recycled (the closed fuel cycle). Many international studies have addressed the advantages and disadvantages of these options which can be considered now in the framework of sustainable development and the three pillars of: economic, environmental and societal impacts. To inform this debate, a detailed survey of the available literature related to economic assessments of closed and open cycles has been undertaken—this complements an earlier review on environmental impacts. Results of economic assessments showing how the management of spent fuels in the open and closed cycles impacts the costs of the nuclear fuel cycle, are usually presented in terms of the levelised cost of electricity (LCOE). It is clear that the costs of the back end of the fuel cycle are a relatively minor component of the LCOE and that there is significant overlap between calculations on open and closed fuel cycles.

Keywords: radioactive waste; spent nuclear fuel; sustainability; nuclear fuel cycle; closed fuel cycle; open fuel cycle; levelised cost of electricity

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1. Introduction

The role of nuclear energy in contributing towards meeting "Net Zero" carbon emissions targets by 2050 is under consideration in the UK and globally [1–3]. In these considerations the full nuclear system must be analysed; that is the nuclear fuel cycle as well as the nuclear reactors themselves. One of the key concerns to the public is the management of radioactive wastes, and particularly the used or "spent" nuclear fuels (SNF) discharged from the reactor [4]. Spent fuel management is either through the storage and disposal of SNF in a waste repository (the "open" or "once-through" cycle); or by reprocessing and recycling the uranium (U) and plutonium (Pu) into new fuel, with disposal of a reduced volume of immobilised high level (i.e., heat generating) waste (HLW) for disposal (the "closed cycle" [4]). There are many variations on these two options for the "back end" of the nuclear fuel cycle [5] but as of today most SNF is in interim storage pending the implementation of final disposition routes with only around 20% of SNF currently reprocessed for (mono-)recycling of fissile uranium and plutonium as mixed oxide (MOX) fuel (see data in [6]). The multiple recycling (multi-recycling) of nuclear materials has only been demonstrated at the semi-industrial scale [7]. Some countries are committed to the open cycle and, whilst there are presently none in operation, both Finland and Sweden are likely to have deep geological repositories (DGR) for their SNF available in the late 2020s and 2030s [8–11]. Many countries adopt a strategy of long term interim storage prior to the expected disposal of SNF in a DGR in the future [4]. Whilst many studies confirm that nuclear energy per se is comparable to renewable [12] energies, the choice of the nuclear fuel cycle is a secondary but important question that also needs to be analysed under the framework of "sustainability", i.e., the confluence of economic, environmental and societal impacts [13].

The environmental impacts, including waste generation and impacts on the DGR from open and closed fuel cycles, were discussed in our preceding paper [6]. The beneficial impacts of closed cycles on the environmental footprint of nuclear energy and the reductions in waste volumes, DGR size and long-term radiotoxicity of wastes were described. A key benefit from closed cycles is also better utilisation of natural uranium resources; this was also discussed previously. However, as noted above, environmental impacts are only one component of sustainability and, therefore, this review now addresses the second pillar of economic impacts.

Clearly, one of the key challenges to address in deploying current and future nuclear systems is cost. Nuclear-generated energy, whether for electricity, heat, hydrogen or synthetic fuels, needs to be competitive with other forms of low-carbon energy, whichever reactor system or fuel cycle is selected, thus economic studies are a key factor in decision making. However, estimating costs of future nuclear systems and fuel cycles, as with other energy generation technologies, is difficult due to uncertainties in factors such as the technology readiness, future availability (thus price) of resources (uranium), timescales to deployment, discount rates, etc. Nevertheless, there is a significant body of literature describing economic assessments of closed versus open fuel cycles. Such studies are necessarily theoretical and the outputs of fuel cycle modelling obviously depend on the assumptions made and the input data behind the calculations. Moreover, these scenario analyses are often country-specific and results may not be transferable to other countries with differing nuclear energy infrastructure or policy. Therefore, there is a need to look at this from a fundamental viewpoint to understand the differences between fuel cycles which can then be supplemented by country-specific data to inform the findings or provide context.

It is the aim of this paper to survey the available literature for studies that provide economic assessments of open versus closed fuel cycles. It will provide a critical review of the respective approaches in order to determine whether any generic conclusions on fuel cycle costs can be drawn, despite the many limitations noted above. Given the continually changing nature of economics, this paper restricts its focus to literature published after 2000 (and especially since 2010) in order to ensure meaningful conclusions.

Finally, this paper will draw the two parts of the review together by placing the economic costs of closing the fuel cycle in the context of the environmental and waste management benefits that can accrue from recycle and reuse of materials.

The paper is structured as follows: Section 2 summarises some of the key background elements that were described in more detail in Part 1 [6]. Section 3 focuses on the potential economic impacts of open versus closed fuel cycles by reviewing the literature on fuel cycle economics covering UK, US and other international studies. Section 4 will bring conclusions from both parts of the review together to integrate the environmental with the economic issues.

2. Summary

Section 1 of this review considered the wastes and environmental impacts of closing the nuclear fuel cycle [6]. This paper also introduced some key concepts which will be summarised very briefly here. For further details the reader should refer to the preceding paper.

2.1. Nuclear Fuel Cycles

The nuclear fuel cycle encompasses the range of steps needed to manufacture fuel for nuclear reactors and to safely process the used or "spent" nuclear fuels (SNF) and wastes [14]. There are a range of fuel cycle options available and the choice of fuel cycle can significantly affect the sustainability of nuclear power generation by potential impacts on, inter alia, the economics, environment, waste generation and disposal, non-proliferation and security risks and public acceptability [4,15,16]. At the back end of the fuel cycle, i.e., after the fuel is discharged from a nuclear reactor, there are two basic options: treat spent fuel as waste and dispose directly or recycle useful components and dispose of a smaller amount of waste. A period of interim storage is required for cooling and radioactive decay before either option is pursued. However, there are many variations on open and closed cycles and also the choice of the back-end fuel cycle affects the front-end fuel cycle; particularly in terms of how much uranium resources are needed and the facilities required for fuel manufacturing [5].

In this and the previous paper [6] the common forms of the nuclear fuel cycle discussed most frequently are:

- The open or once-through cycle (OTC), where spent uranium oxide (UOX) fuels are stored before direct disposal in a DGR, also known as a geological disposal facility (GDF) in the UK.
- The partially-closed, thermal recycle or twice-through cycle (TTC), based on reprocessing SNF to recover fissile material (i.e., uranium and plutonium) which is then recycled as MOX fuel, sometimes referred to as plutonium mono-recycling.
- The fully-closed cycle (FCC), in which SNF is reprocessed and fissile materials are usually recycled in a fast reactor (FR) multiple times to maximise the energy value of the fuel components, also referred to as plutonium multi-recycling. There are a number of variations on this concept, such as transition scenarios where light water reactors (LWRs) and FRs operate together, or a fleet comprised only of FRs. FRs can be configured to either burn or breed plutonium depending on the nuclear fuel cycle strategy to be followed.
- The partitioning and transmutation (P&T) scenario where minor actinides (MAs) are also recycled for burning (usually) in fast reactors or accelerator driven systems (ADS). This is aimed at minimising the MA waste burden to the DGR, rather than for their energy value.

2.2. Benefits of New Systems and Sustainability

The potential benefits of, or drivers for, introducing advanced nuclear technologies (including fuel cycles) are usually recognised to be [17]:

1. Sustainability, including more efficient use of natural resources.
2. Reduction in either volume, heat load, or in combination, of waste.
3. Reduction in the radiotoxicity of waste.
4. Economics.
5. Enhanced proliferation resistance, inherent physical protection or both.
6. Plutonium management.
7. Improved public acceptability.

The previous paper [6] considered topics 1–3 in the list above. This paper extends the review now to cover the economic impacts (costs) of fuel cycle options as this is often seen as a major challenge in deploying advanced nuclear technologies (ANT) and fuel cycles. Economic benefits, such as job creation and revenue generation, are outside the scope of this review.

Sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [18], and is based on meeting a combination of economic, societal and environmental requirements [13]. As with the previous paper, this paper considers the economic impacts within the overall framework of sustainability as applied to nuclear energy and fuel cycles.

2.3. Spent Nuclear Fuel Arisings and Fuel Cycle Models

Around 11,500 tHM of SNF is estimated to be generated per year [19], most of which is stored (the unit tHM denotes "tonnes of heavy metal", a mass unit commonly used to quantify materials such as uranium and plutonium and their derivatives). Reprocessing capacity (for spent fuel recycling) is around 2500 t/a (tonnes per annum) [6] which would lead to around half a million tonnes of SNF in storage by 2050 [20]. Ultimately, this SNF must be either disposed of in a DGR or recycled. The first DGRs for SNF are likely to be operational in the 2030s (Sweden, Finland) but most countries do not plan to have DGRs ready before 2050. Countries that reprocess and recycle must also dispose of vitrified HLW and higher volumes of ILW as well as any residual fuels that are not recycled.

Fuel cycle models are probably the most important tools available to analyse the impacts of various fuel cycle options at the macro-scale over timescales of decades or even centuries. Whilst results from various fuel cycle models are contained within this report further details about their applications are available in [6].

2.4. Summary of Conclusions

Conclusions of Section 1 described the results of life cycle analyses (LCA) of different nuclear fuel cycles [6]. LCA is a recognised method for making quantitative evaluations based on concepts of sustainability [12]. Whilst LCA shows that nuclear energy, even operating with the OTC, already has an environmental footprint that is competitive with renewable energy sources, it is clear that closed fuel cycles always perform significantly better than the open cycle against the key environmental indicators [13,21–26]. This is mainly due to recycling of materials and, therefore, reduced need for uranium mining, conversion and enrichment. Recycling also conserves natural resources and whilst a single recycle as MOX fuel only saves 10–25% uranium resources, multiplying recycling materials can extend the uranium resources massively [15]. However, most studies do not consider economic uranium resources to be a limiting factor for the duration of this century [27,28].

Whilst there are variations between studies, it is clear that actinide recycling can reduce the size (both surface footprint and volume) of the DGR by socially, if not geologically, significant factors of 2–10, or even higher if the heat generating fission products (Cs, Sr) are separated for decay storage [15,23,29–32]. The precise outputs of these calculations are dependent on the scenarios modelled. Actinide recycling can also reduce the longevity of the waste in the DGR (usually measured as the time required for the radiotoxicity to return to that of natural uranium ore) to historical (hundreds to a few thousand years) rather than geological (few hundred thousand to a million years) time-scales [33]. Whilst this may not benefit the repository safety assessments which are dominated by mobile radionuclides (notably ^{129}I) [34,35], the reduced repository size, complexity and waste radiotoxicity, plus increased durability of engineered wasteforms for HLW, can be beneficial to the overall sustainability arguments for nuclear.

3. Economic Assessments of Fuel Cycles

This section reviews the literature related to economic assessments of open versus closed fuel cycle options. As noted above, the focus is placed on literature published after 2000 and particularly since 2010 in order to ensure that up to date conclusions can be drawn. Furthermore, because these economic studies can be influenced by national issues (e.g., policies, regulations, infrastructure, markets, etc.), it is divided in subsections based on geography, i.e., Section 3.2 United Kingdom based studies; Section 3.3 studies from the United States; Section 3.4 international studies from (i) multinational organisations such as the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD-NEA) (Section 3.4.1) and (ii) other national or regional studies, e.g., Asia (Section 3.4.2).

3.1. Introduction

Operating nuclear power plants deliver low-carbon, stable, predictable baseload electricity at relatively low costs with typical plant lifetimes of 40–60 years. There is only a low dependence on the price of the raw material (uranium) and sources of uranium are widespread and quite robust to international tensions. However, capital costs of new nuclear reactors are high and the uncertainty in the estimates leads to high costs of financing the investments [36]. Concerns about the costs of nuclear energy are, therefore, one of the main barriers to low-carbon nuclear energy making a full contribution towards tackling climate change. Similar perceptions exist about the costs of the fuel cycle and this leads to many of the problems the industry faces in managing spent fuel arisings, nuclear materials and radioactive waste disposal.

This section focuses on costs of the back-end fuel cycle options, which are usually framed as variations of the closed cycle compared against the OTC as a baseline. Economic studies tend to follow similar formats with common ingredients, including fuel cycle models, a set of assumptions, cost variables and a number of exemplar fuel cycles. Most studies compare levelised costs of electricity (LCOE) to enable fair comparisons between different options, accounting for differing timescales of deployment by discounting costs to a net present value at a selected discount rate, and many calculate the uranium breakeven price as the point at which economics would switch in favour of the closed cycle option. Discounting is the process to calculate the present value of costs or income that will be paid or received in the future. This accounts for the decrease in value of money over time. A discount rate, usually quoted as a percentage, is used to calculate the net present value. The rate chosen can have a significant effect on the results and the conclusions drawn. Uranium prices and reprocessing costs used in various economic studies are compiled for reference in Tables 1 and 2, respectively, but these relate to reports published at different times with differing assumptions and justifications, thus direct comparisons should only be made cautiously and with reference to the original documents.

Table 1. Uranium prices used in economic studies of fuel cycle options.

Study	Low (USD/kg)	Nominal (USD/kg)	High (USD/kg)
Zhou (2014) [37]	30	80	360
Rodríguez (2014) [38]	EUR 40/kgU_3O_8	EUR 100	EUR 160
Shropshire (2009) [39]	30	70	85
Machiels (2010) [39]	104	169	520
OECD-NEA (2006) [39]	20	50	80
Choi (2014) [39]	50	100	300
Ko and Gao (2012) [40]	30	158	354

Table 2. Reprocessing costs used in economic studies of fuel cycle options.

Study	Low (USD/kgHM)	Nominal (USD/kgHM)	High (USD/kgHM)
Zhou (2014) [37]	700	1000	1600
Phathanapirom [41]		1370	
Rodríguez (2014) [38]	EUR 875/kg SF	1000	1125
Shropshire (2009) (PWR) [39]	1800	2300	2700
Shropshire (2009) (SFR) [39]	3000	6000	9000
OECD-NEA (2006) [39]	1000	2000	2500
KAERI (2010) [39]		5511	
Choi (2014) (PWR) [39]	727	832	2452
Choi (2014) (SFR) [39]	5267	5874	7831
Bunn (2003) [42]	500	1000	2000
Ko and Gao (2012) [40]	700	800	900
Peters/BCG (2005) [43]		520	

3.2. Results from UK Studies

Some data specific to the UK situation have been published. Hesketh et al. [44] present findings of a fuel cycle study using the ORION code which covers 18 different scenarios although the discussion focuses on the build up to a 75 GWe nuclear fleet with a transition to SFRs after 2040. In terms of uranium demand, the models show that for a UK FR fleet of 40 GWe or above, the reactor fleet only becomes independent of world uranium supplies by 2100. This is due to a shortage of plutonium for the fast reactor cores. The ORION models show that, in terms of fuel supplies, the FR fleet is best preceded by a thermal reactor fleet with reprocessing of SNF and that, as a guideline, a 1 GWe thermal reactor operated for 60 years will generate sufficient plutonium to support 1 GWe of fast reactor operation. The problem for the UK is, therefore, that nuclear energy peaked at around 16 GWe. These issues are not particularly sensitive to increased breeding ratio. For the deployment of FRs from 2040 onwards, reprocessing capacity is needed from 2045, even though the UK has a stockpile of ca. 130 t of separated plutonium already [45]. Indeed, it is concluded that the fuel supply for the FR fleet will be very dependent on the reliability of the reprocessing plant. The models assumed a six-year cooling period prior to reprocessing which means that the reprocessing plant will need to manage thermal fuel with heat loadings of 3 kW/tHM, whereas FR fuels were calculated to be 13.5 and 7 kW/tHM for two and five years cooling, respectively.

Butler [17] considered that uranium economics as a driver for more sustainable systems with SNF recycling as future global nuclear scenarios are likely to exceed the known supplies of uranium (6.3 Mt at USD 220/kg). Thermal recycling can increase uranium utilisation by 20% whilst fast reactor systems increase uranium utilisation by factors of 50–60. Butler challenges conclusions from the MIT study which stated: "Our analysis of uranium milling costs versus cumulative production in a world with ten times as many LWRs and each LWR operating for 100 years indicates a probable 50% increase in uranium costs. Such a modest increase in uranium costs would not significantly impact nuclear power economics." He cites issues with the cost methodology used by MIT and suggests that both cost and energy requirements of the mining and milling operations will affect the OTC viability much earlier at around 40 MtU total consumption with costs becoming prohibitive at 95 MtU. An interesting point is made concerning how increased mining needed to supply the expanded use of once-through nuclear energy could substantially increase carbon emissions from nuclear energy undermining its status as a low-carbon energy source.

Later work [46] calculating LCOE for reactors as well as front- and back-end fuel cycle operations exemplifies some of the key findings from economic studies. The reactor dominates the LCOE with only ~3% attributed to back-end fuel cycle costs (Figure 1). LCOE is most sensitive to capital costs, build times and discount rates assumed. Taking 20% as a significant difference in capital costs of a system and as roughly equivalent to savings in moving from the "first-of-a-kind" (FOAK) to the "nth-of-a-kind" (NOAK), uranium prices or fuel cycle costs have to increase by factors of 3–15 (Table 3). That is, from the perspective of the LCOE, even the uncertainty in the capital costs of building the reactor swamps any likely fluctuations in the fuel cycle costs. Furthermore, the whole fuel cycle costs have a smaller effect on the LCOE than changing the discount rates by ~1%. Investment/financing costs are a substantial component of the reactor cost; for example a 2% rate for Hinkley Point C new build in the UK would have halved the costs compared to the 9% rate [36]. However, the authors [46] caution that when in operation the fuel cycle costs become a significant proportion of running costs and tend to be judged against running costs rather than the overall costs or LCOE.

Dungan [47] analysed how the changes in disposal footprint [6] could impact the costs of disposal for five exemplar fuel cycles:

- SC1—OTC based on PWRs
- SC2—OTC based on high temperature reactors
- SC3—TTC based on PWRs
- SC4—as SC3 but spent MOX fuel is recycled in SFRs for burning TRU (Pu, Np, Am)
- SC5—closed cycle based on SFRs (iso-breeders, conversion ratio of 1)

As with previous studies she showed a substantial reduction in repository footprint with closed fuel cycles and increasing periods of decay storage even up to a factor of 70 for SC5 and 200 years cooling. However, it was found that whilst SC4 and SC5 scenarios might decease the footprint by over 80% the reduction in disposal costs was only 40 to 50% (excluding the fixed costs). Further it was shown that costs of disposal even for the most expensive option (SC1) were not a significant impact on the LCOE and that if even small discount rates were applied then the costs of disposal (50 or more years in the future) were further reduced and the impact of near-term investment costs increased (i.e., the reactor, but this would also apply to any fuel cycle facilities that were built in the near term rather than longer term). Any reductions in disposal costs would likely be offset by costs elsewhere in the fuel cycle (reprocessing and fuel manufacturing). It was concluded that the economics of disposal was not a clear driver for closing the fuel cycle.

Table 3. Changes in fuel cycle costs needed to cause a +20% increase in LCOE (assuming 7% discount rate) [46].

	Front End	Uranium	Enrichment	Conversion and Fabrication	Back End
% of LCOE	9.6	4.8	3.3	1.4	3.2
Cost multiple to equal 120% of LCOE	3.1	5.2	7.0	15.0	7.3

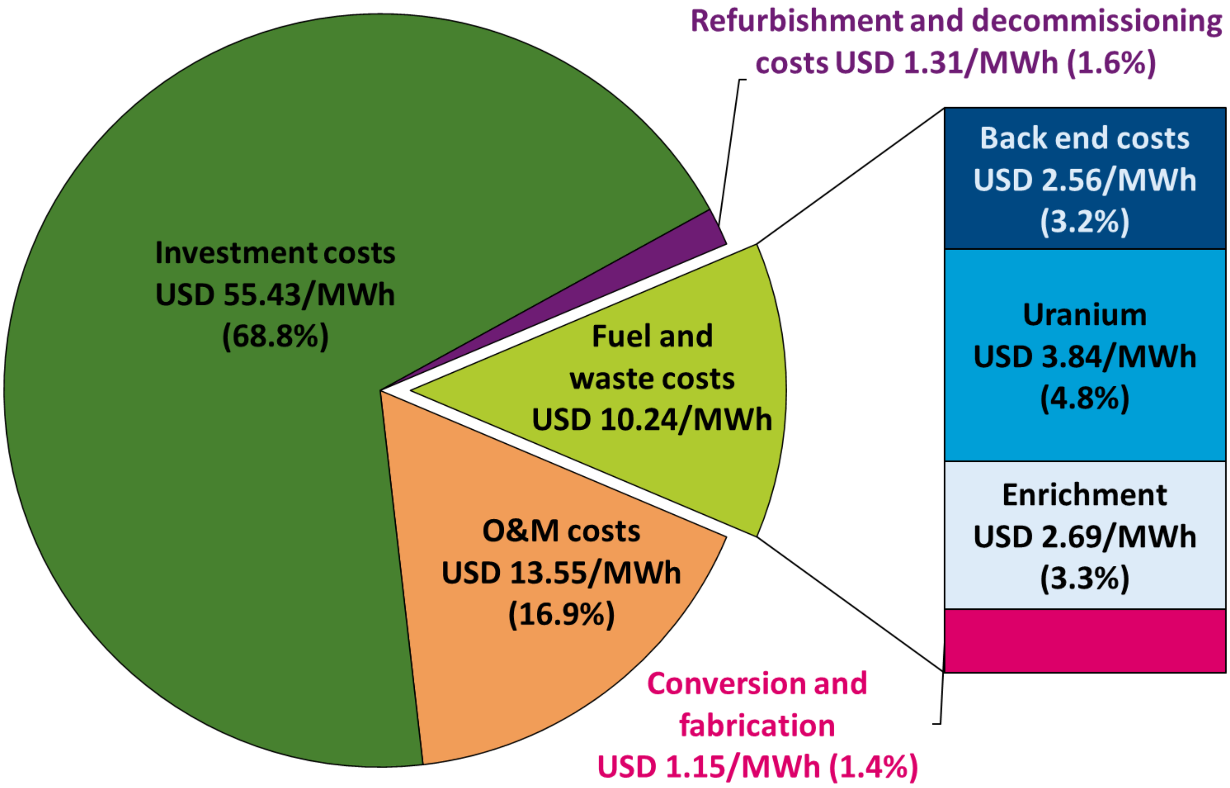

Figure 1. LCOE breakdown across the nuclear fuel cycle [46].

3.3. Results from US Studies

Some of the most influential economic studies originate from the United States, including reports from MIT [48], Harvard [42], the Boston Consulting Group [43] and USDOE [49]. The US has the world's largest nuclear fleet and an OTC policy, but no operational DGR as yet. The Yucca Mountain repository project has been controversial, with a number of set-backs [50], and this has stimulated studies of the merits of open versus closed fuel cycles, highly relevant to this review.

The 2003 MIT study on the future of nuclear power [48] was updated in 2009 [51]. The authors focused on how new nuclear plants could be economically built at a scale that would contribute towards mitigating climate change and, regarding the fuel cycle, advocated long term storage of SNF to create flexibility. Furthermore, they calculated that there are enough economic uranium reserves to fuel reactors for over 50 years in an OTC and no convincing waste management case for recycle given safety, security and environmental concerns. Regarding economics, their conclusion was that the costs of recycle were "unfavorable compared to a once-through cycle, but, the cost differential is small relative to the total cost of nuclear power generation". The authors argued against near-term reprocessing in the United States (as proposed by the GNEP (Global Nuclear Energy Programme) initiative at that time [52]), as it "sent the wrong message" on proliferation, but expressed support for fuel cycle services to be provided by G8 countries to newer users of nuclear power. Instead, nuclear system modelling was recommended to analyse costs, safety, wastes and proliferation characteristics of fuel cycle options. Moderate lab scale research into new separation technologies was proposed in the near term focused on approaches that reduce costs and enhance proliferation resistance and could be deployable in the latter half of the 21st century [48].

A more detailed analysis of the fuel cycle was subsequently undertaken by MIT in 2011 [28]. This study also concluded that sufficient uranium resources were available for most of this century and the OTC was the preferred economic option. However, it was recommended that fuel cycle options in the USA should be preserved by pursuing the OTC through (century long) SNF storage and development of the DGR, whilst researching alternative technologies that could meet a range of future nuclear scenarios. Indeed, they specifically stated that the "preservation of options for future fuel cycle choices has been undervalued in the debate about fuel cycle policy". A related recommendation was that waste management should be integrated into fuel cycle R&D to enable development of optimized solutions. Regarding future fuel cycles the authors warned that:

"The choices of nuclear fuel cycle (open, closed, or partially closed through limited SNF recycle) depend upon (1) the technologies we develop and (2) societal weighting of goals (safety, economics, waste management, and non-proliferation). . . . Today we do not have sufficient knowledge to make informed choices for the best cycles and associated technologies".

The long-term nature of closed fuel cycles (transition times of 50–100 years) was highlighted together with a proposal that a conversion ratio near unity is preferable in order to facilitate alternative closed fuel cycle pathways such as use of hard neutron spectrum reactors or start-up of fast reactors with low enriched uranium (LEU); these potentially being more economic or proliferation resistant options. An interesting suggestion is made with regards to the DGR; in that if it is sited before a closed cycle is deployed, co-location of the recycle (reprocessing and fuel fabrication) site with the DGR can be considered to improve both economics and security as well as repository performance through optimization of generated waste forms. The job creation and benefits thus compensating the local community hosting the DGR. In the OTC, fuel cycle costs are estimated to be ~10% of the LCOE with waste management costs about 10% of the fuel cycle costs (1–2% of the LCOE). The capital costs of the reactors thus dominate costs and thus will dictate decisions. Another interesting observation is that whereas ~7 t of LWR SF are needed produce 1 t of LWR MOX fuel, 1 t of spent FR fuel produces ~1 t of new FR fuel. Hence, reprocessing throughput (for the same electricity output) in a fast reactor cycle needs to be only 5–10% of that of an LWR cycle. This suggests scenarios where FR fuel recycle would be economic whilst LWR fuel recycle would not (the authors liken this to mining higher assay ores).

The MIT study used a fuel cycle simulation code CAFCA to model the OTC, TTC and multi-recycling, in both advanced burner (conversion ratio 0 to 1) and fast breeder reactors (conversion ratio of 1.23). LWR fuel burn up was assumed to be 50 GWd/t, five year cooled pre-reprocessing and two years post-reprocessing. The reprocessing plants have an assumed lifetime of 40 years with throughputs of 1000 tHM/y for LWR and 100–500 tHM/y for FR fuel reprocessing (for conversion ratios 0–1.2). The basis of their economic analysis and calculations of LCOE are described in detail in [53]. For fuel cycles with recycling, they calculate a total LCOE that is then decomposed into separate costs for each reactor cycle by determining a price for recycled elements. The LCOE is based on the decision to recycle and, as the prices for recycled elements (Pu or TRU) are negative (i.e., they are a liability), then it means the reactor burning recycled fuels must be compensated by the first reactor that burned the UOX fuel. Or put another way, this is essentially the cost of "disposal" of the spent fuel from the first reactor and the second reactor is being "paid" for this service. The economic analysis is summarised in Table 4 where it can be seen that:

Table 4. LCOE data for fuel cycle options calculated in the MIT fuel cycle study [28].

Fuel Cycle Stage	Unit *	OTC UOX	TTC MOX	AFC FR
Front-end fuel cycle	Mills/kWh	7.11	3.02	−15.66
Capital (reactor)	Mills/kWh	67.68	67.68	81.22
O&M costs (non-fuel)	Mills/kWh	7.72	7.72	9.26
Back-end fuel cycle	Mills/kWh	1.3	6.96	11.74
LCOE (total)	Mills/kWh	83.81	85.38	86.56
Relative cost (LCOE)	%	100.0%		
% Back end	%	1.6%	8.2%	4.7%

* One Mill is equal to 1/1000 of a US dollar. Mills/kWh are therefore equivalent to USD/MWh.

- The reactor dominates the LCOE, around 80% of the cost of electricity generation in the LWR cycles and over 90% for the fast reactor-based fuel cycle.
- The capital and operating costs of the fast reactor are assumed to be 20% higher than the LWR and this cost premium cannot be compensated for by savings in the fuel cycle or increases in uranium prices according to their modelling.
- Nevertheless, the total increase in LCOE is calculated to be only around 2–3% for fuel cycles involving recycle of fissile materials.
- Whatever fuel cycle is adopted, the back-end fuel cycle costs are a small percentage of the overall LCOE (1.6–4.7%).
- However, compared with the OTC, the overall fuel cycle costs have increased by 19 and 33% for the TTC and advanced fuel cycle (AFC) options. This mainly reflects the cost of reprocessing, the cost of MOX fuel disposal (in the TTC) and charges for the recovered TRUs. The premium for the recycling of SNF (the increase in total LCOE) is 21 and 112% for the TTC and AFC when calculated relative to the cost of direct disposal in the OTC (1.3 Mills/kWh).

Additionally, it was shown that the LCOE for the AFC increased with conversion ratio from 85.86 to 86.57 to 86.91 for conversion ratios of 0.5, 1 and 1.2, respectively. It is apparent that, since the LCOE increases only marginally, there are many trade-offs in the fuel cycle economics as the complexity of the fuel cycle increases. With recycle, savings can be made in front-end costs whilst back-end costs rise. Advanced reactors and use of MOX/TRU fuels also add costs.

DeRoo and Parsons [53] compare their methodology with others such as [42,54] who calculated costs based on equilibrium situations (where costs attributed to the recycled TRUs are avoided). Using the example of the AFC with FR fuel recycling it was shown that calculations based on this equilibrium approach would give higher values than the MIT methodology by 4–15% for conversion ratios of 0.5–1.23.

A major (although now dated) analysis of the economics of reprocessing versus direct disposal was carried out by Bunn et al. [42] in 2003. They draw on a wide range of sources to attribute costs across the full life cycle, including estimates of upper and lower bounds to each reference value. The basis of the component costs, including the costs allocated to reprocessing, MOX fuel fabrication, HLW disposal (including the savings over direct disposal of SNF) and price of uranium, are discussed in detail with reference to a wide base of source materials. They then primarily analyse the economics in terms of the uranium breakeven price, (i.e., the point at which reprocessing would be cheaper than disposal). For their reference uranium price (USD 50/kg), Table 5 indicates the changes to other costs that would be needed to reach the uranium breakeven price; for instance, it is calculated that reprocessing costs would need to be decreased to 42% of their reference cost or the price of fresh uranium would need to increase to around USD 370/kg.

Table 5. Changes to selected parameters (with respect to the reference cost) needed to reach the uranium breakeven price [42].

Parameter	Breakeven/Reference
Disposal	3.2
Interim SNF storage	3.9
Enrichment	12
Reprocessing	0.42
Uranium	7.4

Bunn et al. [54] also calculate the additional costs of reprocessing to be about 1 Mill/kWh for their reference reprocessing (USD 1000/kgHM) cost up to a uranium price of USD 130/kg. How this additional cost varies with uranium price for reprocessing costs between 50 and 200% of the reference value is illustrated in Figure 2. They estimate the back-end cost of the OTC is about 1.5 Mills/kWh, so the reference case suggests reprocessing increases the back-end costs by more than 80%. They conclude that given probable global uranium resources, and based on their analysis, that recycling is unlikely to be economically competitive with direct disposal (as indicated by the uranium breakeven price) for more than a century.

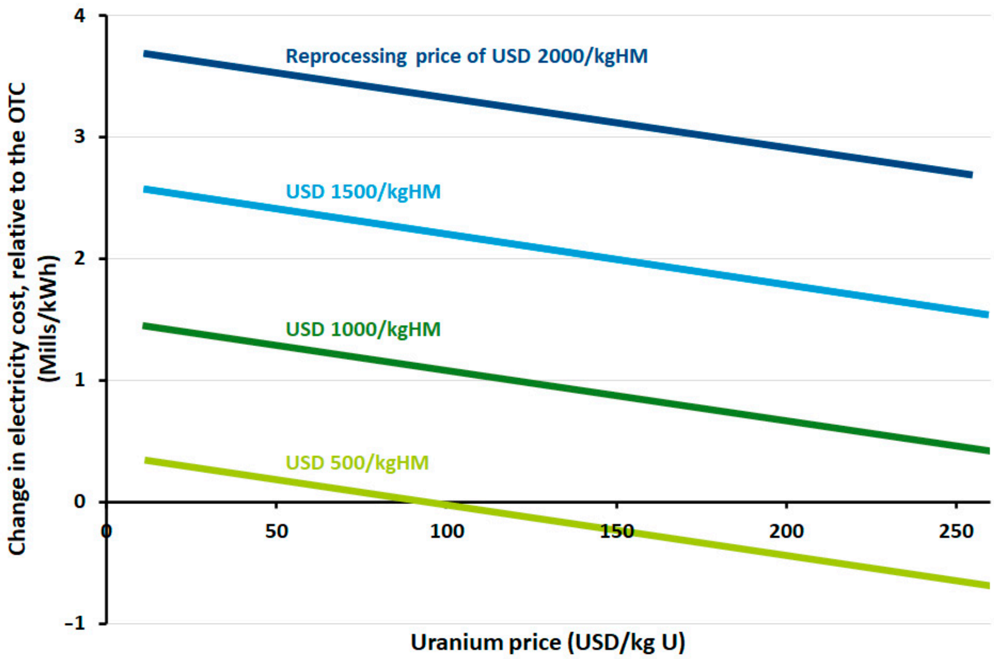

Figure 2. Additional cost of electricity for reprocessing and recycling of SNF (TTC) compared to the OTC for selected reprocessing costs as a function of the uranium price [55].

The Boston Consulting Group in 2006 arrived at different conclusions based on access to proprietary economic and operational data from reprocessing in France [43]. They analysed two scenarios for the United States:

- A generic greenfield approach with recycling (TTC) and a HLW repository versus an OTC with repository for all SNF.
- An implementation approach specific to the US scenario with recycling (TTC) and the Yucca Mountain repository for legacy fuel and HLW (the “portfolio” strategy), versus an OTC with an expanded Yucca Mountain capacity (120 ktHM) and second repository to meet demand over a 50-year period (2020–2070).

The greenfield approach enabled direct comparisons to be made for OTC and TTC in the US and comparisons with other studies. The implementation approach enabled analysis of what were considered at the time to be more realistic deployment scenarios for recycle and disposal in the USA. In the implementation approach with recycling, 125,000 tonnes of legacy and new SNFs are recycled and 50,000 tonnes of legacy SF disposed of in the Yucca Mountain DGR. Furthermore, 15,000 tonnes of MOX fuels are stored at reactor sites for future disposition (no end point). The recycle option assumed an integrated recycling plant incorporating a combined extraction (COEX) reprocessing plant, MOX fuel fabrication, vitrification, hulls waste management and interim storage of spent MOX and vitrified HLW.

The BCG analysis concluded that in the greenfield approach discounted costs of recycling (TTC) are within 10% of OTC costs (USD 520/kg compared with USD 500/kg in 2005). In the implementation approach costs were also very similar up to 2070 (net present costs of USD 48–53 bn for TTC compared to USD 47–50 bn for OTC), and in fact the total undiscounted life cycle cost for the portfolio strategy (TTC) is ~10% lower (USD 113 bn for TTC compared with USD 124–130 bn for OTC; see Figure 3.). Even when sensitivities to the uranium price and repository cost are analysed, both OTC and TTC strategies exhibit "comparable economics". One significant difference in the models was the cash-flow predictions with near term peak capital costs to build infrastructure for the portfolio TTC strategy and then a reducing demand compared with a mid-term bulge in the OTC due to operating the first repository whilst constructing the second repository around the mid-century (Figure 4). Some notable assumptions in their modelling include the assumption that space savings in the repository translate directly to cost savings, a nominal 25-year-decay period before SNF or HLW is emplaced in the repository for both OTC and TTC scenarios and interim storage of spent MOX (~300 t/y). The management of spent MOX fuel, in particular, is a key uncertainty in the proposed portfolio approach. The authors suggest multi-recycling in LWR or burning in fast reactors which may be available later this century and estimate this would increase the recycling costs by 10–15%. Disposal of spent MOX (assuming the nominal 25-year-decay period) is not favoured as it would negate the savings in repository footprint obtained by recycling UOX fuels and add up to 40% to the recycle costs. The other problem with MOX is that there is a "MOX acceptance cost" that is needed to address difficulties that utilities have in using MOX compared with standard fresh UOX fuel. The value of MOX, therefore, is calculated to be ~75% of the value of UOX fuel. De Roo and Parsons [53] criticise this approach as, in their opinion, it prevents the calculation of the LCOE for the full cycle. Nor does it reflect the market position whereby if there is an option of UOX fuel then an operator with only a UOX license can afford to refuse the use of MOX fuel; hence, any MOX discount would have to be very large to overcome the regulatory and stakeholder challenges of enabling the use of MOX. This would change, of course, if there is a national level strategy based on recycling. Certainly, the assumption of interim storage of spent MOX fuel without a specific costed disposition route leaves a major gap in the fuel cycle strategy.

Since 2003, the US Department of Energy Office of Nuclear Energy has published a regular in-depth review of advanced fuel cycle costs, with the latest edition published in 2017 [49], although it cautions that the data are best used for relative comparisons of options rather than accurate determinations of fuel cycle costs. Furthermore, that the results of models may vary due to user-defined parameters, such as users' individual treatment of cost escalations, learning effects, fuel cycle configurations, etc. The impacts of discount rates and accounting for future benefits to present values are discussed and how this leads to delays in adopting technologies; for instance, how this can lead to analyses whereby the cost of dry storage is always less than geological disposal even if packages degrade and require over-packing. The authors highlight that, whilst economics are important, other factors, such as sustainability, proliferation risks and adaptability to future scenarios, also need to be part of the evaluation process. Nonetheless, this work rigorously compiles and evaluates a broad range of cost data across the full future cycle, including assessing sensitivities and providing high and low estimates.

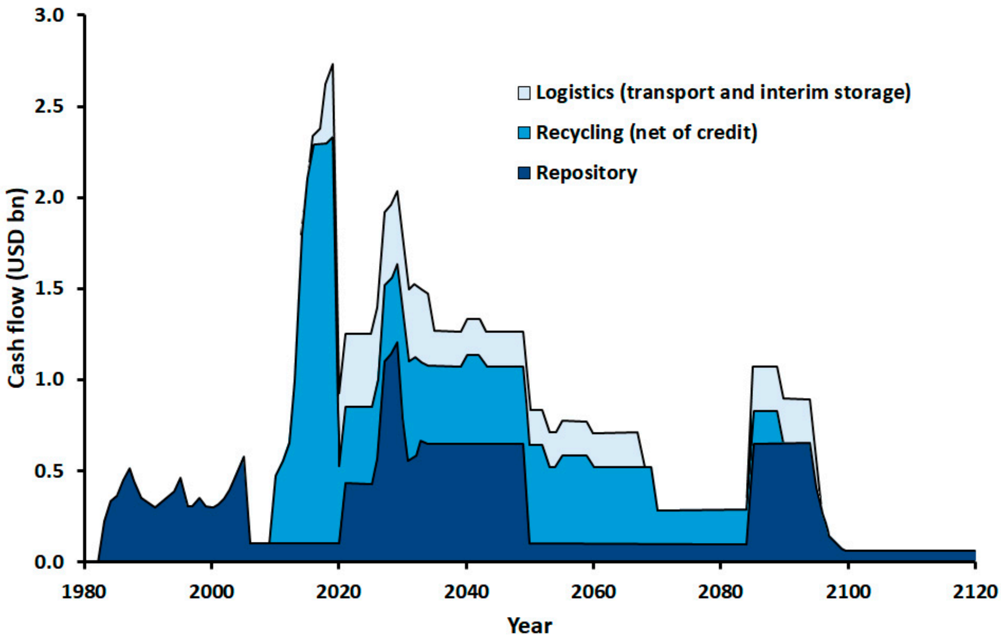

Figure 3. Cash flow profile for the TTC "portfolio" strategy (emplacement in Yucca Mountain in 2030, and acceptance of used fuel begins 2010–2020) [43].

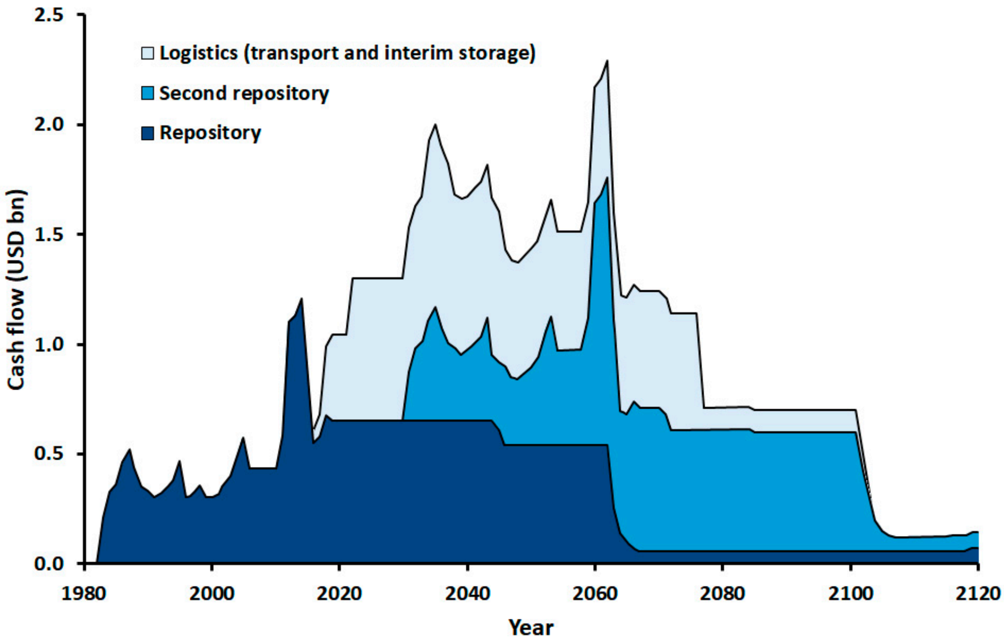

Figure 4. Cash flow profile for once-through strategy (acceptance of used fuel begins 2010–2020) [43].

The results of the reprocessing analysis are given in Table 6 for aqueous reprocessing using the French COEX process, UREX + 1a and UREX + 3a processes and a pyro-electrochemical process. A possible 24% reduction in UREX + 1a costs was noted but not implemented at this time (all reprocessing technologies could possibly be lowered in future). UREX is a modified PUREX process to prevent plutonium extraction, thus achieving waste volume reduction by removing the uranium. Variations of UREX (indicated by the suffixes) include additional separations to recover plutonium, MA and/or HHR, to save space in the DGR but with increased proliferation resistance by avoiding pure separate plutonium compared to the conventional PUREX process. Whilst COEX is a rather conventional PUREX process, adapted to produce a mixed U-Pu product, UREX+ involves sequential separations to recover U, Pu, minor actinides, high heat generating isotopes of caesium and strontium and zircaloy hulls [55,56]. Issues related to scaling are discussed in detail and it is considered that plant throughputs in the range of 1000–2000 tHM/y are probably near the minimum of the cost curve even if several lines are needed. FR reprocessing is considered at a lower scale (~300 t/y) where the effects of the relatively larger head end are not significant. For the United States, a plant of 2500 t/y and operating life of 40 years is said to be the most economical deployment. It is noted that the influence of line throughput and solvent extraction contactor type are not explicitly analysed and may have impacts. Interestingly, the head end, chemical separation and U/TRU storage facilities are said to account for nearly 60% of the reprocessing costs with head end (comprising fuel receipt and storage, shearing, dissolution, off gas management, hulls treatment and technetium alloying) being the most expensive facility area.

Table 6. AFC cost data for three aqueous reprocessing options (with and without waste conditioning and storage costs included), and electrochemical (pyro-) processing (with and without remote fuel fabrication costs) of spent fuel in 2017 USD [49].

	Low (USD/kgHM)	Mode (USD/kgHM)	Mean (USD/kgHM)	High (USD/kgHM)
COEX reprocessing	861	1055	1055	1250
COEX inc. WM and storage	1263	1562	1557	1846
UREX + 1a	1030	1277	1277	1526
UREX + 1a inc. WM and storage	1703	2109	2125 *	2523
UREX + 3a	1156	1482	1482	1776
UREX + 3a inc. WM and storage	1904	2371	2371	2836
Electrochemical	1000	1200		1400
Electrochemical inc. remote refabrication	2000	2600		3200

* Report specifies USD 21,125, but this is an error.

In the non-aqueous electrochemical processing of SNF [57], refabrication of fuel is an integral part of the process and must be a remote operation due to high residual activity of the reprocessed products. Cost estimates, therefore, included remote refabrication of fuel, although estimates were made of this activity alone in order to enable better comparisons with aqueous options (Table 6). Throughputs are generally low (20–300 tHM/y) as, at least in the United States, this technology is considered to be applied to FR fuel (usually metal) recycling either as part of an island site (the Integral Fast Reactor concept [58]) or servicing a group of FRs. Limitations are also posed by electrochemical processing being a batch process. The report notes that whilst a number of cost studies have been made they are all underpinned by only one practical implementation—the engineering scale facility at the Idaho National Laboratory that processed Experimental Breeder Reactor-II (EBR-II) fuel [57]. Whilst the report notes scopes for reductions in costs it also warns that costs associated with first of a kind (FOAK) implementation and lack of technology scale-up experience could be significant in this case.

Phathanapirom and Schneider [41] proposed a decision theory based model to strategise the transition from the OTC to FRs with plutonium and MA recycle given the costs of implementing FRs are unknown. The aim is to use stochastic modelling, in which the "regrets" from pursuing different pathways can be estimated, to develop a hedging strategy and help decision making. Costs are estimated as LCOE and the simulation is essentially for the United States with a 100 GWe fleet in 2015 assuming 1.25% growth per year up to 2100. The strategy is controlled by the availability of TRU; that is the amount of LWR reprocessing capacity and thus timings at which 500 tHM/y and then 3000 tHM/y reprocessing plants are installed. The study concludes that in all scenarios, partial transition to a closed cycle is advised. This involves deploying a pilot scale (500 t/y) reprocessing plant for LWR fuel and adjusting the strategy once build costs of FRs become clearer.

3.4. Results from Other International Studies

3.4.1. Multinational Studies

Cost estimates for example fuel cycles, from an OECD-NEA study in 2006, are illustrated in Figure 5, normalised to the OTC [59]. These show the dominating effect of the reactor and calculate only a marginal difference between the OTC and TTC. A more recent (2013) OECD-NEA inter-comparison of back end fuel cycle costs amongst interested member states [60] concluded that comparisons were difficult and variations could be quite large due to disparate factors, and uncertainties would be reduced only as global experience in SNF disposition increased. The study compared OTC, TTC and Pu multi-recycling scenarios with 0 and 3% discount rates, and system sizes of 25 TWh/y to 800 TWh/y. For all the strategies it was shown that back-end fuel cycle costs were a small proportion of the LCOE (e.g., 6.5% in France), but small fluctuations could still result in large absolute figures depending on the quantity of nuclear energy generated. The OTC was the lowest cost option but differences were within uncertainty bands, due to uncertainties in input data, initial assumptions including discount rates and trade-offs between front-end and back-end costs in recycle scenarios. Since some costs decrease with the size of the nuclear programme, sharing fuel cycle facilities between countries may have economic advantages. Further, sensitivity studies indicated a low sensitivity on the cost of the geological repository but, as elsewhere, a strong dependence on the price of uranium. However, they concluded it was difficult to estimate the breakeven price for recycling strategies but agree that large increases in uranium costs were required to make Pu multi-recycling in LWRs or FRs economically attractive, at least from this perspective. Depending on the scenario, the next highest sensitivities were to the cost of reprocessing and the FR cost premium. They also warn that "economics is only one of many factors influencing the decisions regarding SNF management options" and suggest that a multi-criteria approach is needed to evaluate a range of factors for a specific national situation.

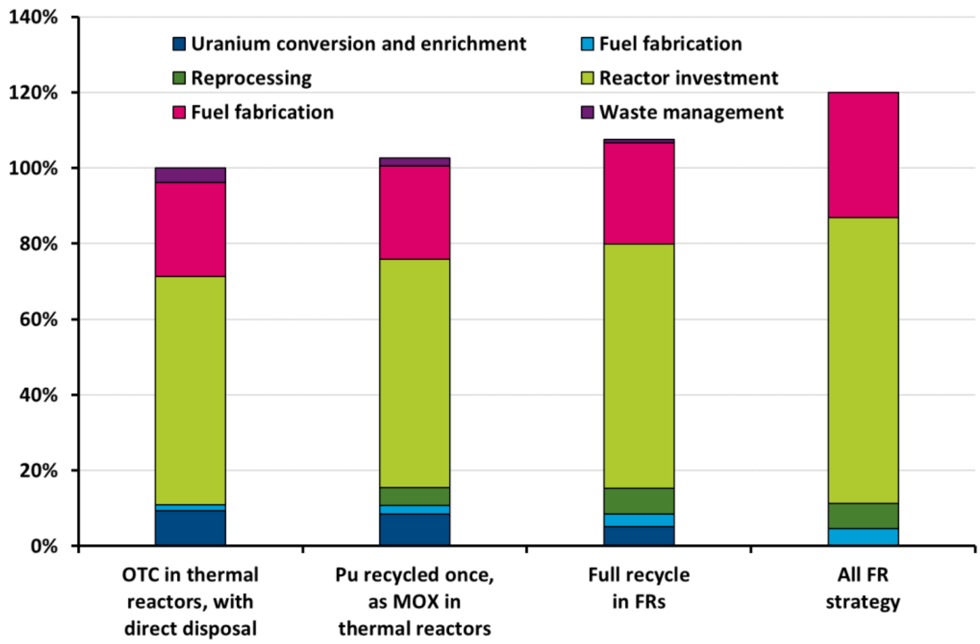

Figure 5. Cost estimates normalised to the OTC for various closed cycle options [4,59].

A review of international studies (MIT [48], De Roo [53], EPRI, BCG [43], OECD-NEA [61]) was made by Moratilla Soria et al. [62] in 2013. Their analysis contrasted trends in the cost estimates for the DGR and for the TTC (Figures 6 and 7)—costs were updated using the Chemical Engineering Plant Cost Index (CEPI). They concluded that costs of the DGR have increased with time whereas the costs of the TTC have decreased with time. They suggest that this is due to uncertainties in the DGR costs since no DGR has yet been fully implemented compared with the mature industrial experience in the TTC that is leading to cost reductions. However, they note that the two MIT-based studies [48,53] do not follow these trends. Whilst this is an interesting result, clearly further analysis would be needed to add credibility to the proposed trends, given that the preparation of the DGR is technologically simpler than closing the fuel cycle.

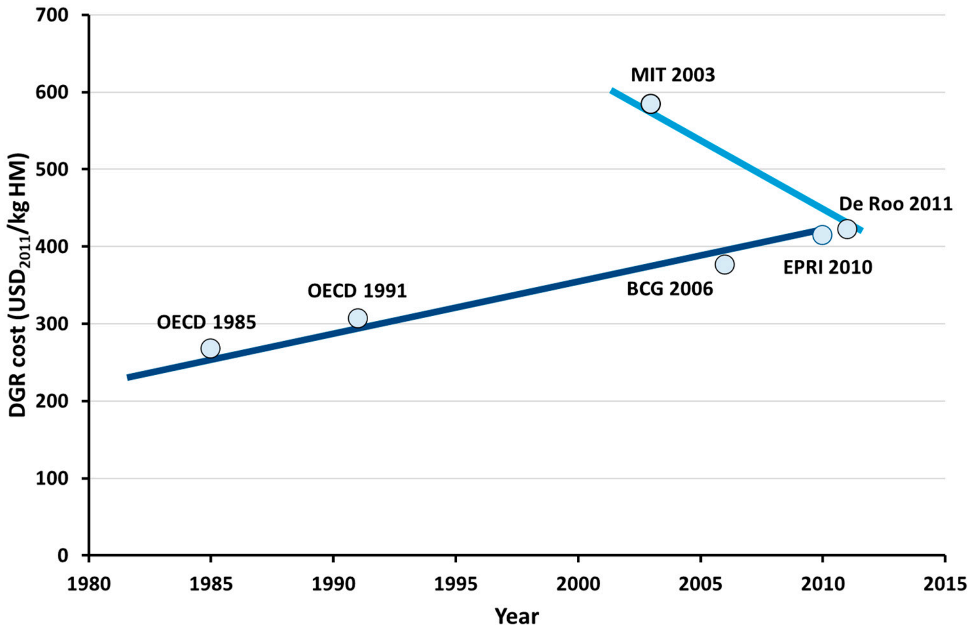

Figure 6. Cost trends for the DGR in the TTC based on analysis in [62].

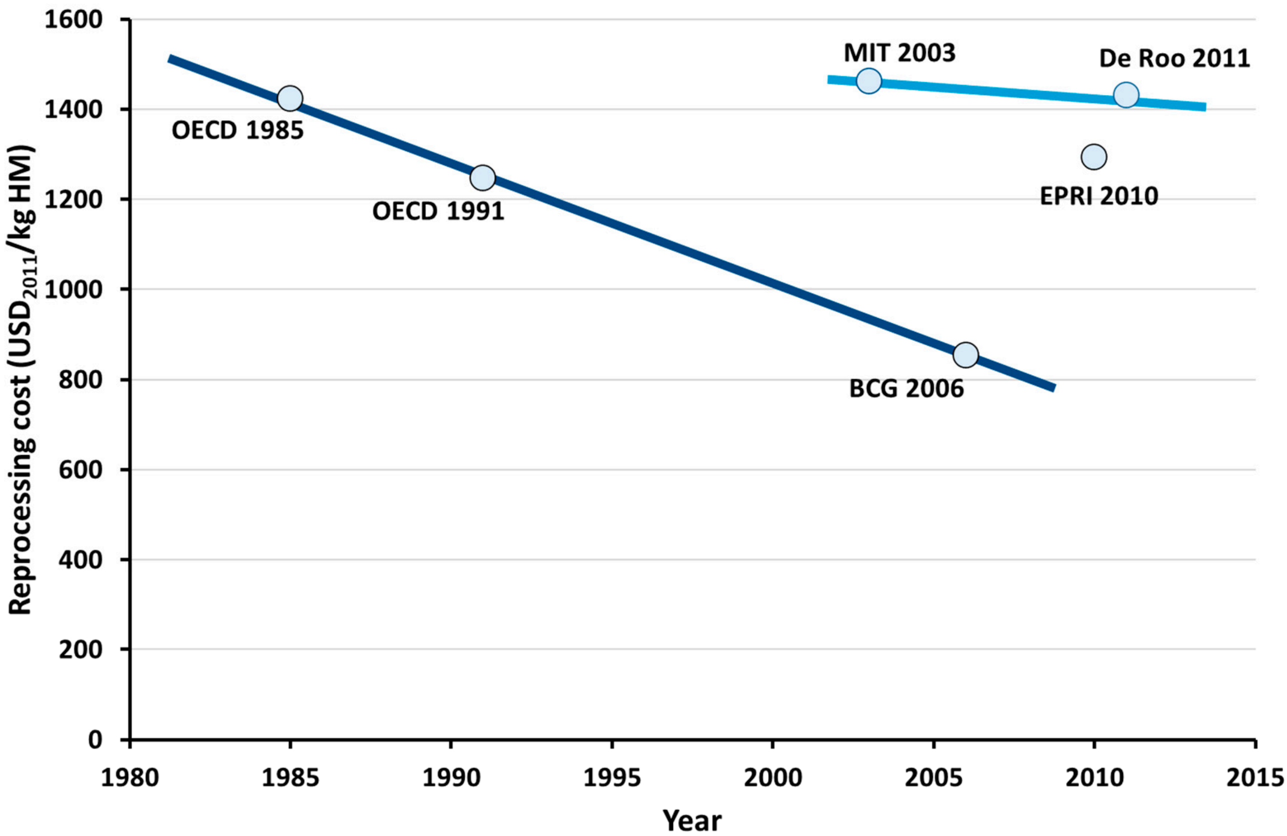

Figure 7. Reprocessing cost trends in the TTC based on analysis in [62].

3.4.2. Other International Reports

Gao et al. [63,64] published an economic assessment of fuel cycles options in China based on phased deployments (this was published in 2017. The recent announcement that China will aim for net zero emissions by 2060 is obviously a new factor). The initial study was focused on transition scenarios up to 2050 and looked at growth from 20 GW in 2014 to 58 GW by 2020, 200 GW by 2030 and 400 GW by 2050. Assumptions in this study included PHWR not being reprocessed and PHWRs phased out by 2043 and no costings for disposal in the DGR as these were beyond 2050. Four scenarios were analysed:

1. The OTC
2. The TTC
3. A delayed introduction of fast reactors with multi-recycling of SNF, thus recycle of plutonium as thermal MOX is still needed.
4. A prompt introduction of fast reactors such that use of PWR-MOX fuel is not required.

Minimum cooling periods of five and two years are assumed for PWR and FR fuels, respectively. In all scenarios, PWRs with UOX fuel remain the dominant supplier, providing 70–100% of nuclear electricity in 2050. With the OTC 141,000 tonnes of SNF are accumulated by 2050; this is reduced by 75–82% with recycling. Uranium savings are less (in the range of 8–18%) because PWRs with UOX fuel remain so prevalent in the nuclear energy mix by 2050. In their economic analysis, Gao et al. calculated LCOE with 5% discount rates (reprocessing costs are given in Table 2). The results are summarised in Table 7**.** As expected, the reactor costs account for >80% of the LCOE and the OTC is the lowest cost overall with increasing back-end fuel cycle complexity increasing costs. The interesting point here is that the percentage increases are only around 3–5%, relative to the OTC, and this does not account for the ultimate (post-2050) disposal cost which can be expected to be greater for the OTC. A second study defined phase 1 leading to 58 GWe in 2020 and phases 2 and 3 are based on respective projections of 400 GWe nuclear energy in 2050 and 1400 GWe in 2100; start-up of fast reactors is assumed in 2040. Scenarios analysed were:

1. The OTC.
2. Mono-recycling of MOX in PWRs.
3. Mono-recycled PWR MOX fuel is recycled in FRs.
4. PWR fuels recycled to fast reactors.

Table 7. Nuclear fuel cycle costs (LCOE in Mills/kWh based on 2014 USD) for Gao-defined China nuclear fuel cycle scenarios [63,64].

Scenario	1	2	3	4
Reference	**[63]**	**[63]**	**[63]**	**[63]**
Reactors	42.209	42.207	43.081	44.452
Front-end fuel cycle	8.250	7.566	6.888	6.349
Back-end fuel cycle	4.357	5.613	5.802	5.923
Total fuel cycle	54.816	55.386	55.771	56.724

The availability of reprocessing capacity is clearly critical with 800–1000 tHM/y throughput reprocessing plants assumed to be deployed every five years between 2020 and 2050, reducing to 400 tHM/y after this date. Fast reactor scenarios also require fast reactor fuel reprocessing capability that matches the spent fuel arisings. The economic assessment was based on the LCOE and used a probabilistic method. Discount rates were applied as either 5% of the deterministic value or used a probabilistic method. Over 75% of the LCOE is due to front-end costs. The three closed cycles were calculated to be up to 3.5% more expensive than the open cycle using the probabilistic method. This is due to reprocessing and refabrication costs outweighing savings in front-end costs of 8–23%. Deterministic calculations gave a larger margin in favour of the open cycle (up to 5.1%). Overall system costs are most sensitive to capital costs of the reactors but the factors that affect the cost difference between options were the uranium price, interim storage of PWR fuel, capital costs of reactors and reprocessing costs. The PWR MOX closed cycle options could be calculated to equal the open cycle (the breakeven cost) if the price of uranium was increased to 3.5 times the nominal value (USD 350/kgU), interim storage costs nearly doubled or PWR fuel reprocessing reduced by around 20–30%. The FR cycle offers a greater potential to break even due to potential reductions in costs of the fast reactor itself. From Table 7, it is apparent that Gao et al. estimate back-end costs to be around 10% of the overall system costs only and the closed cycle options to be only ~5% more expensive than the open cycle. However, this small net change is due to the trade-off between back end and front-end fuel cycle costs that occurs with recycle of SNF.

Baschwitz et al. [65] employ a similar approach to Gao et al. based on calculation of the LCOE. As with similar studies, they use the uranium price above in which recycling in LWRs or FRs becomes more cost effective than the OTC (the "uranium breakeven cost") as the single economic criterion. Time dependent natural uranium production curves are estimated by three models: (a) a pessimistic model based on known economic reserves, (b) a model in which limited quantities of new economic reserves are found and (c) an optimistic model where economic sources of uranium are always available. Their results, therefore, are founded on a basic assumption that the price of uranium will rise over the lifetime of the reactor and that studies which maintain a constant uranium price are extremely optimistic. The Gestion des Ressources en Uranium avec STELLA (translation: Management of Uranium Resources with STELLA; GRUS) model is used to predict the global nuclear reactor fleet and fuel demands. Reactors are generation II LWRs (i.e., the 2010 fleet), generation III LWRs that will be built after 2010 and generation IV FRs. Apart from the price of uranium, all costs are fixed over the time period considered which enables a comparison of relative competitiveness to be made between LWR and fast reactor technologies. How to cost plutonium is highlighted as a key issue and two different scenarios are explored: (a) countries which have reprocessing capacity already for LWR fuels and thus plutonium is available initially for the start-up of fast reactors (e.g., France) and (b) countries which do not (e.g., USA). For scenario b the costs of reprocessing the LWR fuels to generate plutonium for start-up are attributed to the FR. In this study, Baschwitz et al. [65] only draw qualitative conclusions with increased availability of uranium, any additional cost burden of fast reactor build and increased discount rates all strongly extending the date at which fast reactors can become competitive with LWRs. Factors strongly reducing the timescales were scenarios with limited uranium supplies, linked to the global electricity scenario applied, or countries having existing LWR reprocessing capacity. The authors state that future quantitative assessments using their methodology are to be expected.

Zhou et al. [37] reported a Monte Carlo-based economic assessment of the OTC and thermal reactor recycle fuel cycle options using the levelised fuel cycle cost (LFCC), along with a sensitivity analysis to calculate a breakeven uranium price at which recycle options become competitive with the OTC. The LFCC is the front-end and back-end fuel cycle cost (i.e., a fraction of the LCOE). The modelling assumes an equilibrium state; it does not include fuel cycle capital cost and operation and maintenance cost as they were considered to be fixed costs and, in the case of capital costs, the major cause of uncertainty. Uranium prices are given in Table 1**.** and reprocessing costs in Table 2. Discount rates were applied of between 5 and 10% with a nominal value of 7.6%. The results of their modelling were that the LFCC for the OTC was 3% lower than the recycle options and that this difference lies within the associated error bands (Figure 8). The breakeven uranium price was calculated to be USD 112/kgHM with the factors that affect this being the discount rate, reprocessing cost and MOX fuel fabrication cost; these factors can change the uranium breakeven price by over 30%. A 30% decrease in nominal reprocessing costs (to the low estimate) resulted in a reduction in the uranium breakeven price to USD 69/kgHM.

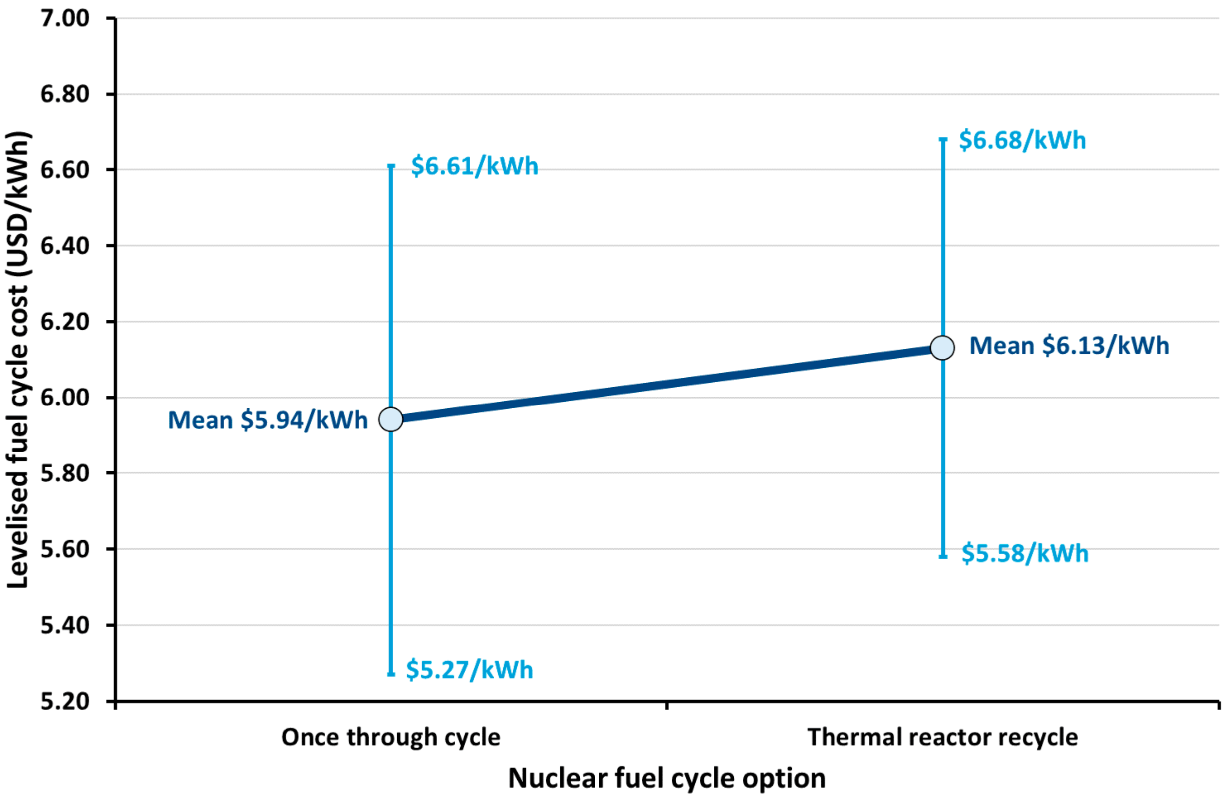

Figure 8. Comparison of LFCC of the OTC and TTC (TRR—thermal reactor recycle scenarios) from Zhou et al. [37].

In a similar fashion, Ko and Gao [40] calculated LFCC for the Korean options of a fuel cycle based on PWRs followed by the OTC, DUPIC recycling in CANDU, PUREX recycling as MOX fuel (TTC) and pyroprocessing with multi-recycling in SFRs (pyro-SFR). Costs (in 2010 USD) are listed in Table 9**,** where it can be seen that the DUPIC and TTC options are estimated to be about 20% more expensive than the OTC whilst the pyro-SFR option is only 5% more. This is an equilibrium study with 5% discount rates applied and reactor costs are not included (hence LFCC costs not LCOE). It is interesting that the Monte Carlo sensitivity analysis indicated uncertainties of 1.16–1.69 Mills/kWh, meaning that there was significant overlap between the probabilistic density functions of all options (Figure 9). The uranium breakeven price (Table 1) is calculated as USD 215/kgU for the pyro-SFR fuel cycle reducing to USD 125/kgU if the cost of pyroprocessing could be reduced to the same as the cost of PUREX reprocessing or USD 110/kgU if the cost of the metal fuel fabrication is reduced by 50%. The authors conclude pyro-SFR may have economic advantages but it is not clear if this is due to the multi-recycling approach rather than an intrinsic advantage of the pyro-chemical processing option.

Rodríguez et al. [38] report results from a fuel cycle study comparing the OTC, FR cycles with U, Pu MOX fuel only or also with MA transmutation and MA transmutation in ADS. The results are from European PATEROS and CP-ESFR projects and use the LCOE approach to make relative comparisons between options (using the code TR_EVOL developed by CIEMAT, Spain). Calculations are made on a European basis where it is assumed that 386.6 t Pu were available in 2010 and a further 126.7 t made available in 2022. Separate reprocessing plants are assumed for LWR fuel, SFR fuel and ADS fuel with cooling times of five years and a recovery of 99.9% for actinides in reprocessing. No capital costs for LWR, UOX and MOX fuel fabrication plants were included as there were operating plants in Europe in 2010. Probabilistic calculations on unit costs were used to estimate uncertainties in LCOE, and component costs were correlated if there was a strong interdependence.

It was calculated that the reference OTC scenario would require 3.3 Mt U by 2210, whereas closed cycles would require ca. 1 Mt U; however, uranium availability was not considered a constraint given global reserves. There are also depleted uranium stocks for around a thousand years of closed fuel cycle operations (no recycle of reprocessed uranium was assumed). To maintain plutonium supply, without building up stocks in storage, breeding ratios of ca. 1.08 were used up to 2110 and between 1.01 and 1.03 thereafter. By 2210, reductions in plutonium inventories of factors between 93 and 225 were calculated for closed cycles and in the P&T scenarios MA inventories were reduced by factors of over 500. With respect to HLW for disposal, >400,000 t of SNF in the open cycle is reduced to 6000–7000 t from thermal reactors reprocessing plus around 9000 t from SFR reprocessing for the closed cycles analysed. Rodríguez et al. [38] reported that 60–69% of the base energy cost is due to investment; of this, ~21% is interest during construction. A summary of their cost analysis is given in Table 8, where it can be seen that the LCOE increases by 20–33% for the closed cycles. The decreases in DDD (decommissioning, dismantling and waste disposal) costs are due to the reductions in HLW/SNF for disposal; they conclude that the cost of HLW disposal can be reduced by a factor of 4–5 for the closed cycles (Figure 10) but that equates to a reduction of only 3.7 to <1% in the LCOE. A Monte Carlo probabilistic analysis showed that there was significant overlap between the open and closed cycles' costs and the contributions to the uncertainties in each scenario are dominated by the investment costs (>80%) and so conclude that R&D should be focused on reduction in capital costs of future technologies.

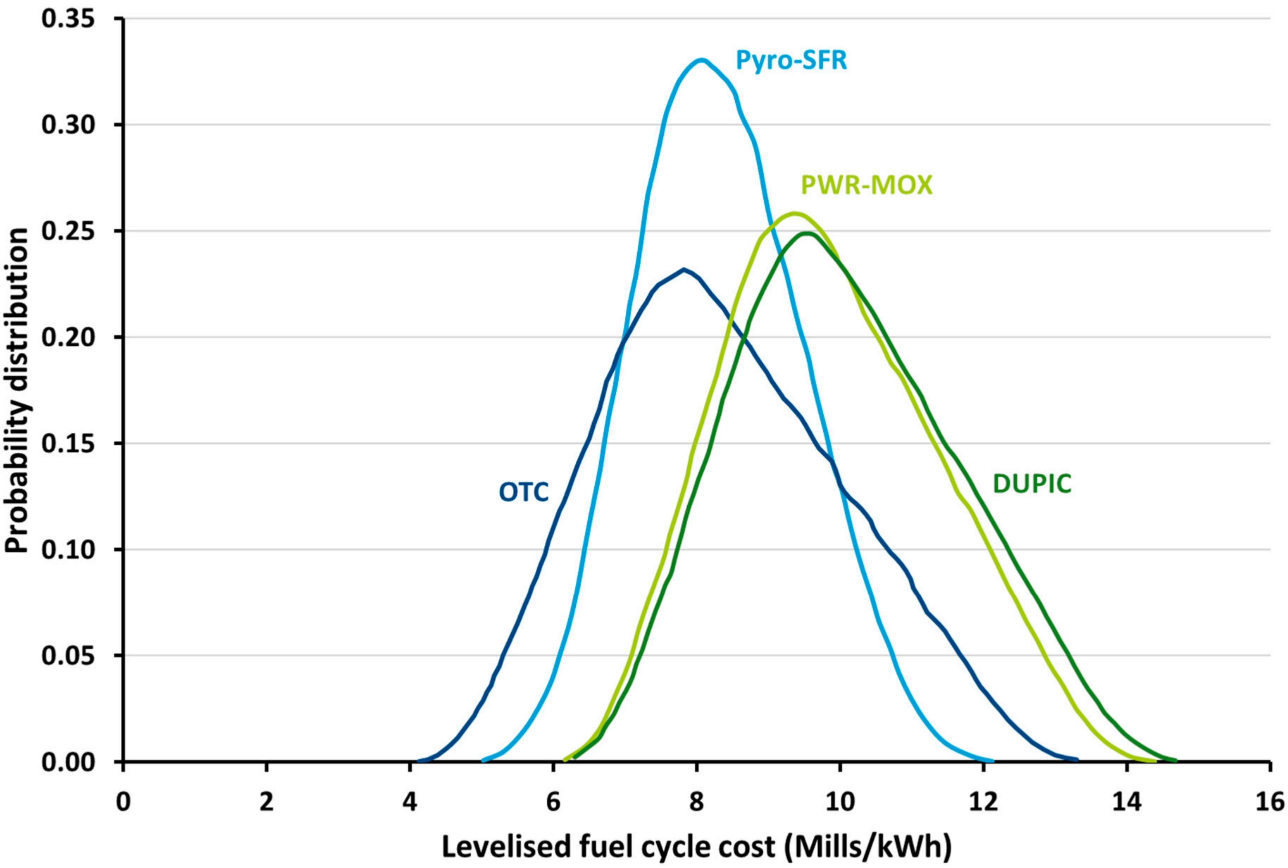

Figure 9. Probabilistic density functions for LFCC, calculated for fuel cycle scenarios by Ko and Gao [40].

Table 8. Summary of costs calculated by Rodríguez et al. [38] for their four scenarios.

	SCN-1	SCN-2	SCN-3	SCN-4
LCOE (centEuro/kWhe)	4.65	5.58	6.20	6.09
Investment (%)	61.3	68.8	60.4	68.1
Fuel (%)	10.9	6.4	18.0	8.8
O&M (%)	22.2	21.6	19.0	20.3
DDD (%)	5.6	3.2	2.6	2.8

Note: SCN-1 is the OTC; SCN-2 is the transition to SFR with Pu fuels by 2100; SCN-3 is SFR-2 but includes MA transmutation in SFR and SCN-4 includes SFR for Pu and ADS for MA transmutation.

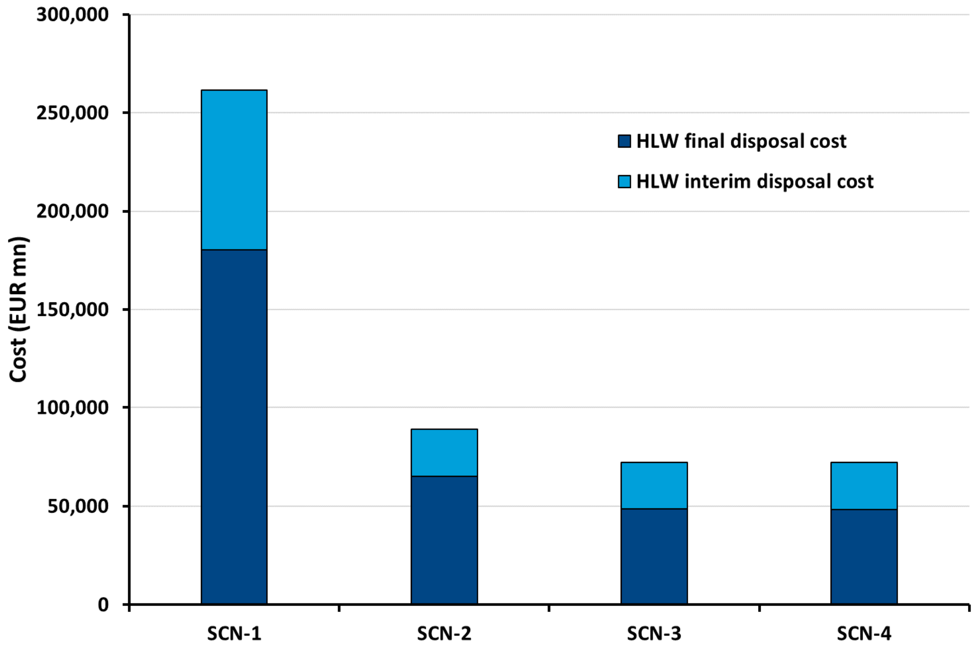

Figure 10. HLW interim (ID) and final disposal (FD) costs for various scenarios. SCN-1 is the OTC; SCN-2 is the transition to SFR with Pu fuels by 2100; SCN-3 is the same as SCN-2 but includes MA transmutation in SFR and SCN-4 includes SFR for Pu and ADS for MA [38].

Table 9. LFCC calculations for fuel cycle scenarios analysed by Ko and Gao [40].

	OTC	DUPIC	TTC	Pyro-SFR
Minimum	3.99	5.68	5.74	4.51
Maximum	13.79	15.30	14.77	12.64
Mean	8.35	10.06	9.83	8.31
SD	1.69	1.57	1.55	1.16

Choi et al. [39] assessed fuel cycle economics for the Korean situation comparing the OTC (PHWR and PWR fuels for disposal) and a closed cycle based on burner-type SFRs with pyroprocessing of both PWR oxide and SFR metal fuels (PHWR SNFs are still directly disposed). They assumed four phases of growth in nuclear power reaching 70 GWe by 2100 (59% share of electricity). Although nuclear energy policy has since changed in Korea, the general findings of the study remain relevant to this paper. This again was a probabilistic Monte Carlo simulation based on analysis of the LCOE with 0% (undiscounted) and 3% discount rates applied. The fuel cycle objective was to keep the amount of PWR SNF in storage to ~5000 t, equivalent to assuming 10 years storage before reprocessing. In line with elsewhere, Choi et al. calculate ~75–80% of the total LCOE is due to reactor costs and the mean costs for the closed cycle are ~3.8% higher than the open cycle. The sensitivity analysis generated broad distributions in both cases and there is ~90% overlap in the ranges although the probability that the closed cycle is more expensive is calculated to be 85%

(Figure 11). The primary contributor to the higher cost for the closed cycle is the SFR capital cost and both cases are most sensitive to the reactor capital costs. Ignoring reactor costs, the fuel cycle costs were actually slightly less in the closed system than the open system mainly due to the costs assumed for interim storage. The cost of pyroprocessing contributes most to the uncertainty in the fuel cycle costs; therefore, this can influence the competitiveness of the closed fuel cycle versus the open fuel cycle (when considered apart from the reactor costs).

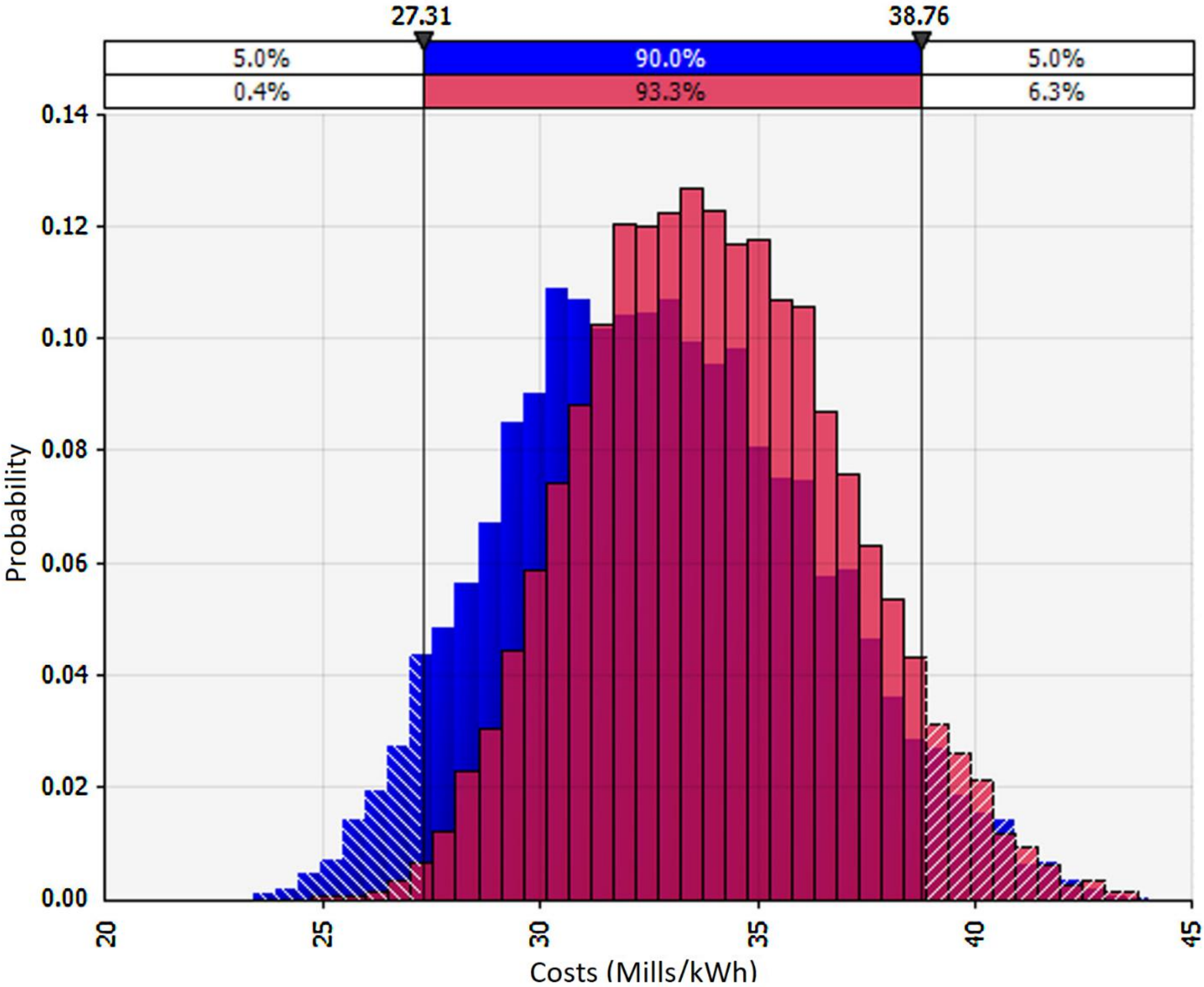

Figure 11. Probability functions for LCOE estimates for OTC and closed fuel cycle (PWR and SFR fuels with pyroprocessing) compared [39].

Rodríguez-Penalonga et al. [66] used data from the OECD-NEA [60] to analyse LCOE for the OTC, TTC and AFC (multi-recycling in fast reactors) for varying lifetimes of the plant (40–80 years), varying capacities (25–800 TWh/a) and discount rates (0 and 3%), primarily aimed at the SNF management options for Spain. Table 10 summarises the results. Their results showed:

- Between 25 and 75 TWh there is a sharp decrease in LCOE for 0% discount.
- The LCOE for the AFC is lowest which disagrees with other studies and is due to calculated savings in the front end of the fuel cycle.
- The TTC is generally lower than the OTC for the 0% rate but higher when the 3% rate is applied.
- The difference between the OTC and closed cycle are <8% which is not discriminating as back-end costs are only about 5% of the overall LCOE.

Table 10. LCOE values for the SNF management options analysed by Rodríguez-Penalonga et al. [66], calculated as a percentage relative to the costs of the OTC for 25 TWh/a generation at a 0% discount rate (reported as USD 10.65 (2010)/MWh.

Electricity Production	0% Discount Rate			3% Discount Rate		
TWh/a	OTC	TTC	Multi-Recycling	OTC	TTC	Multi-Recycling
25	100%	96%	71%	63%	63%	54%
75	64%	58%	46%	49%	51%	47%
400	50%	52%	46%	44%	48%	47%
800	48%	45%	40%	43%	42%	42%

Using the Mariño model, Rodríguez-Penalonga and Moratilla-Soria [67] analysed SNF management options for Spain based on the OTC with or without centralised interim storage and reprocessing abroad with return of vitrified HLW but without MOX fuel recycling (i.e., U and Pu products were stored pending disposal). The DGR was available in 2070 and costs of HLW disposal were set at 40% of SNF. Nominal storage costs were zero for uranium and 50% of the reprocessing cost for plutonium. Unsurprisingly the lowest cost option was the scenario with no new centralised storage and the most expensive option was the reprocessing option (nearly 200%). More interesting were the sensitivity analyses in which impacts of reducing the reprocessing cost and plutonium storage cost could narrow the gap to within about 32%. Furthermore, extending the lifetime of the reactors benefited all options (more electricity generation) but the benefit was highest for the reprocessing option and delaying reprocessing by 35 years could almost halve the total cost of the reprocessing option. The study unsurprisingly confirms that reprocessing without recycling of plutonium in MOX fuel is a poor choice economically (as well as for safety and security reasons) but it is interesting that even in this non-optimum scenario the costs can converge if factors such as storage and reprocessing costs or other assumptions are varied.

Elsewhere, according to González-Romero [32], fully closed fuel cycles would realise a 10–20% increase in electricity cost compared to the LWR OTC. Poinssot and co-workers [13] calculated that the cost of recycling is only 2.9% of the overall cost of electricity in the French TTC (see Figure 12, although no details are given on how these data are calculated). Whilst the exact figures may only apply to the French situation and vary from those in Figure 1, they also point to the relatively small impact of the back end of the fuel cycle on the LCOE.

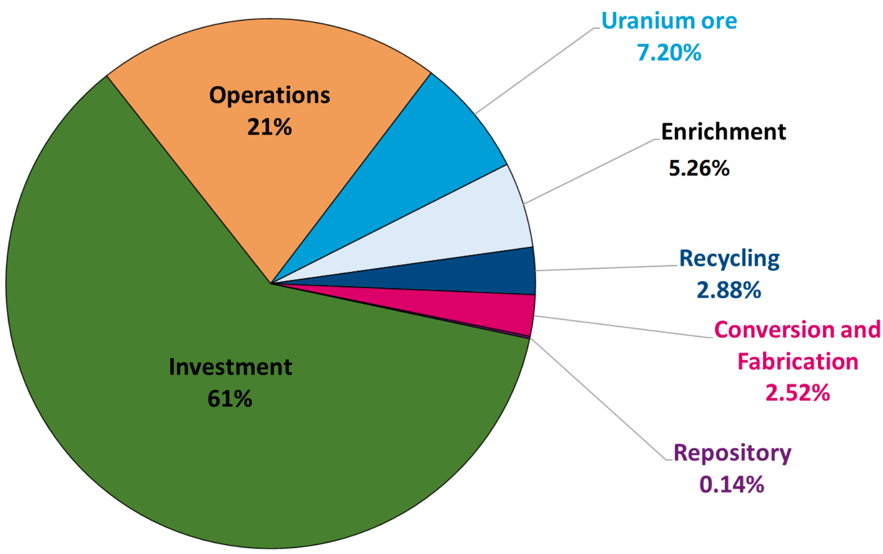

Figure 12. Relative contributions of nuclear fuel cycle stages to the total cost of nuclear electricity in France (TTC) [13].

Lastly, whilst the focus of the discussion here, and in the available literature, is on LCOE calculations, the UNECE has recently suggested that there is a need to consider VALCOE—the value adjusted levelised cost of energy—that accounts for the benefits ascribed to broader societal benefits, namely, meeting decarbonisation and United Nations' sustainable development goals [68]. Clearly, this may be particularly relevant when considering different nuclear fuel cycle options.

4. Discussion

4.1. Economics

There is general agreement that the reactor accounts for around 80% of the LCOE and the costs of the back end of the fuel cycle are a small component of the overall LCOE from nuclear energy, and probably smaller than the uncertainties in capital build costs of the reactor. Furthermore, whilst the (average) costs of the OTC are lower than closed cycles in almost all analyses, the uncertainties in cost estimates can exceed the calculated differences between open and closed cycles [4]. Uncertainties relate to the assumptions used in the models, obviously including the values attributed to the costs of different stages of the fuel cycle, as described above, which is where the approach taken by various groups to assess uncertainties via Monte Carlo methods provides valuable insight. However, as Bunn [42] points out, the "difference between producing electricity at slightly higher or lower cost than competitors is the difference between bankruptcy and profit . . . where fuel cycle costs are among the few costs reactor operators can readily control". Based on their reference values, Bunn estimates that (in 2003) the cost of reprocessing and recycling SNF compared to direct disposal would be an additional expense of around USD 1 M p.a. for a typical LWR. Peters [43] notes that back-end costs account for 20–30% of power generation costs for operators, and others have made similar remarks [46]. Moreover, the economic studies almost universally focus on the costs of the closed and open fuel cycle options, while job creation, exports and wider socio-economic benefits are rarely considered [43] (and have not been considered in this review). Amongst others, Bunn also considers the effects of ownership on costs. This is an issue that should be considered in broader terms; whether "national" or "commercial" ownership models are followed is related to operating individual reactors (or fuel cycle plant) versus fleet or whole programme operations. This in turn can affect the financing costs that have a substantial impact on LCOE and system economics. Furthermore, whether a strategic approach to the integrated development of the fuel cycle, that minimises environmental impacts and maximises societal benefits, can be most effectively adopted.

Similarly, there is broad agreement that even though closed cycles will massively extend uranium resources the availability of uranium is probably not a major problem at least for most of this century [6]. Therefore, nearly all studies to date conclude the price of uranium will remain too low to be a driver for SNF recycling. However, these models are based on past assumptions about the growth of nuclear energy. Whether these calculations on how quickly the uranium price may change over this century will be affected by the new commitments many countries are now making to decarbonisation (and if this leads to a greater uptake of nuclear energy worldwide) should now be assessed.

Nevertheless, as of today the OTC is the SNF management strategy of many countries with civil nuclear programmes. However, few countries are actually constructing a DGR to implement SNF disposal, which means that most of the global SNF inventory is in interim dry or wet storage and the global accumulation of SNF in storage is likely to persist. It is recognised that, without strong societal drivers to deal with SNF, safe and secure interim storage for several decades saves utilities large sums of money by enabling set-aside funds to accrue interest. Whilst this does not really meet the aims of sustainable development, there is a less recognised advantage that this period can be used to allow technology to develop alternative solutions that may be preferred by societies in the later 21st century, as long as R&D programmes are progressed in the interim period. Radiation and heat generation also reduce through radioactive decay thus reducing the challenge in SNF management, to some degree at least. Preserving options during this period of interim storage thus opens up the potential for more optimised solutions for SNF management to be deployed in the longer term [4,34,42].

All the scenario models reviewed take existing fuel cycle data (material flows, costs, historic industrial experience and processes) and analyse the outputs to compare predefined fuel cycle variants. Very few studies use new data from R&D programmes or use the results obtained to suggest performance targets for advanced fuel cycles. There is a clear gap to use these models to set goals for research and technology development programmes; for example, what reductions in capital costs of an advanced reprocessing plant should be targeted to make closed cycles more economically competitive under different scenarios? It may be, of course, that either the inherent uncertainties, large range of differing scenarios or together, would make such an analysis challenging.

4.2. Integration of Economic and Environmental Impacts: Issues of Sustainability

Our previous paper reviewed the environmental impacts of open versus closed fuel cycles and some key conclusions were summarised in Section 2.4. The environmental benefits of recycling were clearly delineated through:

- Greenhouse gas emissions;
- The overall environmental footprint (range of environmental indicators assessed by LCA);
- Reductions in HLW volumes, heat generation and radiotoxicity;
- Consequent reductions in DGR size (area, volume) and "lifetime" (longevity of waste); and
- Extension of natural uranium resources (reduced needs for uranium mining).

The relative magnitudes of the improvements depended on the degree of recycling and also assumptions made by individual studies. Therefore, it is reasonable to state that closed fuel cycles generate environmental benefits but with a probability of marginally higher costs that are needed to enable materials recycling, particularly if fast reactors are part of the closed cycle. Some secondary impacts are that closed cycles lead to nearer term operating costs for reactor operators, the fact that benefits from closed cycles are accrued over rather a long timeframe and that fully closed cycles and ANT require significant R&D to raise technological maturity (the OTC is the technically simplest option). The question is then what value is to be placed on these environmental benefits?

A number of authors comment that environmental impacts and economics are only two aspects of any sustainability assessments of future nuclear systems and fuel cycles; other factors to be addressed include societal and security impacts (including public acceptance and proliferation risk). Technology readiness is also a major factor in deployment of some advanced systems that needs analysing in its own right [69]. Park et al. [70] quite usefully summarized the key questions for nuclear power as:

1. "How can we use uranium resources efficiently?
2. How can we environmentally-safely manage the generated waste?
3. How can we prevent proliferation of nuclear materials and technologies?
4. How can we maximise the economic benefits of nuclear energy?"

All of these questions relate to fuel cycle issues and Park also stated: "there is no particular nuclear fuel cycle option that satisfies all these issues perfectly". Given the complexity of trying to integrate the different factors, multi-criteria decision-making tools are often applied. For example, Gao and Ko [71] developed a novel method in the form of the random multi-attribute utility function (RMAUF) that analysed five factors, shown in Table 11.

Table 11. Evaluation criteria from Gao and Ko [72].

Evaluation Criteria	Indicator	Unit of Measure
Resource security	Natural U consumption	tU/TWh
Environmental effects	SF or HLW for disposal	m^3/TWh
Economics	LCOE	Mills/kWh
Proliferation resistance	Long-term proliferation resistance (Pu inventory)	kgHM/TWh
Technological readiness	Technological availability	0–1

Regarding the development of future nuclear fuel cycles, the OECD-IEA (International Energy Agency of the OECD) and OECD-NEA in their technology roadmap [73] recommended that governments should:

- " ... recognize the long term benefits of developing generation IV (Gen IV) systems in terms of resource utilization and waste management ... "
- " ... support R&D in advanced recycling technologies to reduce volume and toxicity of high-level waste".

They also recommend that " ... environmentally sustainable uranium mining should be developed ... ". As has been reported in this paper, recycling potentially offers a better alternative means of achieving the goal of improved environmental sustainability by reducing the amount of mining required.

Similar assessment criteria are outlined by MIT: economics; safety; waste management; environment; resource utilization and non-proliferation [28]. The authors also warn against developing policies based on equilibrium, rather than dynamic, states, since "policy and technology changes occur on a time scale shorter than the fuel-cycle transition times" thus that such endpoints "may never be reached". There is a trade-off with storage time too, since as SNF ages the activity and heat decrease reducing reprocessing costs. The R&D needs MIT specified as being necessary to meet the objectives of advanced fuel cycles are shown in Table 12.

Table 12. Fuel cycle R&D needs synthesised by MIT to meet the objectives of AFCs [28].

Objective	R&D Need
Safety and security	Coupled reprocessing-repository facilities to reduce process risks
Waste management	Tailored waste forms/advanced fuel designs for disposal Special management of actinides or long-lived fission products Novel separations with waste stream minimization Transmutation—waste destruction Repository with multi-century retrievability Co-located fuel cycle facilities to maximize local benefits
Resource availability and utilization	Fast spectrum reactors with open, modified or closed fuel cycle
Non-proliferation and safeguards	Advanced safeguards

In 2021, the OECD-NEA published a guide for policy makers on back-end fuel cycle strategies that summarized many of the different aspects related to decision making [15]. It simplified the options to the OTC, TTC and multi-recycling in the fully closed fuel cycle whilst identifying 14 characteristics that can be used to compare the fuel cycle options. Only a few of these options were considered to be in some way discriminating. Their conclusions are summarised in Table 13. Other factors impacting decisions were considered including the size of a country's nuclear programme and whether it was expanding or contracting.

In summary, the recent (2021) UNECE report [68] has summarised that recycling "arguably increases the long-term sustainability of nuclear energy" in the following ways:

- "Enhancing the security of energy supply.
- Reducing the volumes of radioactive waste for disposal (to the DGR).
- Reducing the duration that waste stays radioactive and needs to be isolated for from millions year timeframe to thousands of year time frame.

- Simplifying the safety and security and safeguards assessment of the geological disposal facility because of the minimization of the amount of fissile content and thermal load
- Reducing the consumption of mined uranium while preventing the disposal of valuable material such as plutonium and uranium.
- Supporting ongoing scientific progress due to the continuous development of the recycling technologies.
- Providing rare and unique radio-isotopes recovered from reprocessing used nuclear fuel for further application in medicine, space industry, metallurgy etc".

Table 13. Summary of factors affecting decisions on fuel cycle options defined by the OECD-NEA [15].

Characteristic	Related to:	Discriminating?	Conclusion
Technical		Y	Greatest challenge for multi-recycle option
Financial		N	Small differences but recycle incurs nearer term costs and there are economies of scale for larger nuclear programmes
Geology		N	All options require deep geological disposal but recycle reduces challenge (based on improved waste characteristics)
Social acceptance		N	All options have similar issues
Economic development	Opportunities when implemented	Y	Recycle has opportunities for greater economic benefits
Natural resources		Y	Recycle improves resource preservation
Waste characteristics		Y	Recycle reduces problems with wastes
Energy independence		?	Recycle increases energy independence
Future generations		?	Interests of future generations are inherent in decisions related to all options although multi-recycling can bring highest benefits
Proliferation		N	Must be controlled (safeguards) whatever option
Security		N	Location is bigger factor than fuel cycle option
Worker safety		N	Must be managed whatever option
Public safety		N	Main issues are mining and transport
Sustainability		?	All options are consistent with principle but recycle options relatively more sustainable than OTC

Note: "?" indicates no definitive conclusion was made on whether the factor was discriminating or not.

Thus, it is apparent that there are various factors that affect the choices of spent fuel management and associated fuel cycles, most of which can be considered under the overall "sustainability" model, balancing the needs of the environment, society and economics. Technological maturity is of course another factor to consider. The use of multi-attribute decision analysis (MADA) is frequently recommended by researchers to quantify the widely different benefits and disbenefits of particular reactor systems, fuel cycles or in combination, but even this has its own problems. In particular, it is potentially difficult for decision makers to understand the outcomes of such analyses and it is still subject to the values placed on different attributes that can cause an inherent variability in the outcomes of MADA. As an alternative approach, Butler et al. [36] developed a generic feasibility assessment (GFA) that allows a wide range of factors to be qualitatively and easily compared against a well-known reference system (usually the OTC with gigawatt LWRs). This may avoid some of the pitfalls of other evaluation methods.

Lastly, perhaps the most under-rated factor is the inherently long timescales (decades to centuries) needed to deal effectively with SNF either by open or closed cycles. This is a cause of the overall level of uncertainty in determining optimum solutions and whilst this cries out for work on critical paths the lack of hard deadlines for implementation makes it difficult to argue for decision makers to commit to developing the range of solutions that may be needed in the longer term (e.g., progress on DGRs and advanced fuel cycle technologies). In this regard, perhaps the defining argument is that it would be very unfortunate if the management of SNF, either as a waste or as a resource, and disposal of the consequent radioactive waste in the DGR, was found to be the key obstacle to the large-scale deployment of low carbon nuclear energy needed to decarbonise our economies in the very near future, particularly when there is plenty of time to address the necessary technology development needs for both open and advanced closed cycles.

5. Conclusions

A critical survey of the literature regarding the economics of open versus closed nuclear fuel cycle options has been made to search for generalised conclusions that can be derived from the broad base of international studies and publications. This supplements the previous review of environmental impacts [6] and together these papers support an understanding of how the choices of fuel cycle can enhance the overall sustainability of nuclear power generation.

Firstly, it is found that the capital costs of reactors dominate LCOE for nuclear power and it has been pointed out simply that the uncertainty in reactor costs is greater than the entire anticipated back-end fuel cycle costs; back-end fuel cycle costs typically being estimated as less than 5 and up to 20% by various studies. The consequence of this is that the choice of open or closed fuel cycle does not significantly affect the economics, as determined by LCOE.

However, studies indicate that closed cycles are, on average, higher cost than the OTC (usually again in the range of <5–20%), although, where they have been made, sensitivity studies show a large overlap in uncertainty ranges. This supports the suggestion that it is difficult to discriminate between the choice of back-end fuel cycle based on economics alone. Although closed cycles are usually assumed to be implemented alongside power generation, requiring substantial near term capital investment in recycling plants, whereas the OTC offers a long period of relatively cheap interim storage before the costs of geological disposal are incurred. Of course, this does need to be the case. However, whilst operational timescales to deploy nuclear energy, operate reactors and dispose of wastes are long (greater than a century) for both open and closed cycles, models show that closed cycles require significantly longer timescales to deliver optimum benefits, requiring a capability to plan far into the future. This may, in fact, be the most fundamental challenge with implementing advanced closed cycles based on multiple recycling of uranium, plutonium and minor actinides (the P&T scenario).

Furthermore, whilst the impact of the back-end choices on the LCOE are not significant, there is a general consensus that near-term reprocessing and fuel recycling lead to higher running costs for reactor operators. This can affect the profitability of nuclear power stations. On the other hand, there are socio-economic benefits that accrue related to creation of skilled jobs and revenue generation. How new concepts for small modular reactors and other innovative systems, which are expected to be more economic than large scale nuclear power reactors, affect these calculations, is a question that also needs further analysis.

Many commentators (advocates of both open and closed cycles) thus have presented the view that the choice of back-end strategy should depend on other factors, such as technology readiness, proliferation risk or sustainability, rather than economics. Hence, even if national policies are to follow the OTC there is, therefore, real value in keeping options open during the period of decades-long interim storage before disposal is implemented because during this time both technology and society can change substantially. Of course, this requires investment in R&D during that period of storage to develop viable alternative approaches, otherwise this is simply deferring a legacy to future generations. In this respect it should be considered critical to maintain a broad base of capabilities in the fuel cycle and spent fuel management, particularly in countries with substantial nuclear programmes. The cost to insulate such a skill base is relatively small but enables alternative options to be activated in case of future changes in direction from the expected pathway. A focus only on high TRL or single solutions for the nuclear fuel cycle can mean a loss of flexibility to respond to changes or failures of the selected sole solution.

From the two reviews, it is clear that further work to analyse fuel cycle options in the overarching framework of sustainability is most definitely needed. Such studies should be based on the use of a diverse range of tools (such as: fuel cycle models, LCA, GFA, engineering-scale models, techno-economic assessments, waste and environmental type assessments such as BAT (best available technology), proliferation risk models, etc.). Integrated assessments will be of huge value in understanding optimised pathways for generating low carbon energy that include nuclear power. Reliance on single tools, however valuable they are perceived to be, should be avoided if a rigorous understanding of sustainability is desired.

Given that for many countries, including the UK, there will be long periods of interim storage before SNF or HLW can be disposed of in a DGR, R&D programmes should be maintained that develop alternative solutions for SNF management that could be deployed in the longer term by future generations. Keeping options open for SNF recycling as well as direct disposal in a DGR is thus recommended. This is particularly relevant for countries that may develop large nuclear programmes to meet the challenge of net zero carbon emissions by 2050 and beyond, where capacity at the DGR could be constrained or together.

In summary, to underpin policy objectives that support the growth of low carbon nuclear energy as part of the global efforts to reduce the impacts of anthropogenic climate change, R&D programmes are needed to underpin the scientific basis of decision making. These should address the development of advanced fuel cycle options (with reduced environmental impacts, waste generation and costs as well as enhanced flexibility, proliferation barriers and public acceptability) and in parallel assess the sustainability of those options, considering all relevant economic, environmental and social impacts.

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