

Article

Sustainability Features of Nuclear Fuel Cycle Options

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Abstract: The nuclear fuel cycle is the series of stages that nuclear fuel materials go through in a cradle to grave framework. The Once Through Cycle (OTC) is the current fuel cycle implemented in the United States; in which an appropriate form of the fuel is irradiated through a nuclear reactor only once before it is disposed of as waste. The discharged fuel contains materials that can be suitable for use as fuel. Thus, different types of fuel recycling technologies may be introduced in order to more fully utilize the energy potential of the fuel, or reduce the environmental impacts and proliferation concerns about the discarded fuel materials. Nuclear fuel cycle systems analysis is applied in this paper to attain a better understanding of the strengths and weaknesses of fuel cycle alternatives. Through the use of the nuclear fuel cycle analysis code CAFCA (Code for Advanced Fuel Cycle Analysis), the impact of a number of recycling technologies and the associated fuel cycle options is explored in the context of the U.S. energy scenario over 100 years. Particular focus is given to the quantification of Uranium utilization, the amount of Transuranic Material (TRU) generated and the economics of the different options compared to the base-line case, the OTC option. It is concluded that LWRs and the OTC are likely to dominate the nuclear energy supply system for the period considered due to limitations on availability of TRU to initiate recycling technologies. While the introduction of U-235 initiated fast reactors can accelerate their penetration of the nuclear energy system, their higher capital cost may lead to continued preference for the LWR-OTC cycle.

Keywords: nuclear fuel cycle; analysis; nuclear reactor technologies

Nomenclature

CAFCA: Code for Advanced Fuel Cycle Analysis	MT: Metric Ton
CR: Conversion Ratio	MTHM, tHM: Metric Ton of Heavy Metals
EPRI: Electric Power Research Institute	MWd: Mega Watt Day
FBR: Fast Breeder Reactor	NEI: Nuclear Energy Institute
FP: Fission Products	OTC: Once Through Cycle
FR: Fast Reactor	O&M: Operations and Maintenance
GWe: Electric Giga Watt	PWR: Pressurized Water Reactor
kW: Kilo Watt	Pu: Plutonium
LWR: Light Water Reactor	RBWR: Reduced Moderation Boiling Water Reactor
MA: Minor Actinides	SWU: Separative Work Unit
MIT: Massachusetts Institute of Technology	TRU: Transuranic Material
MOX: Mixed Oxide Fuel	U: Uranium

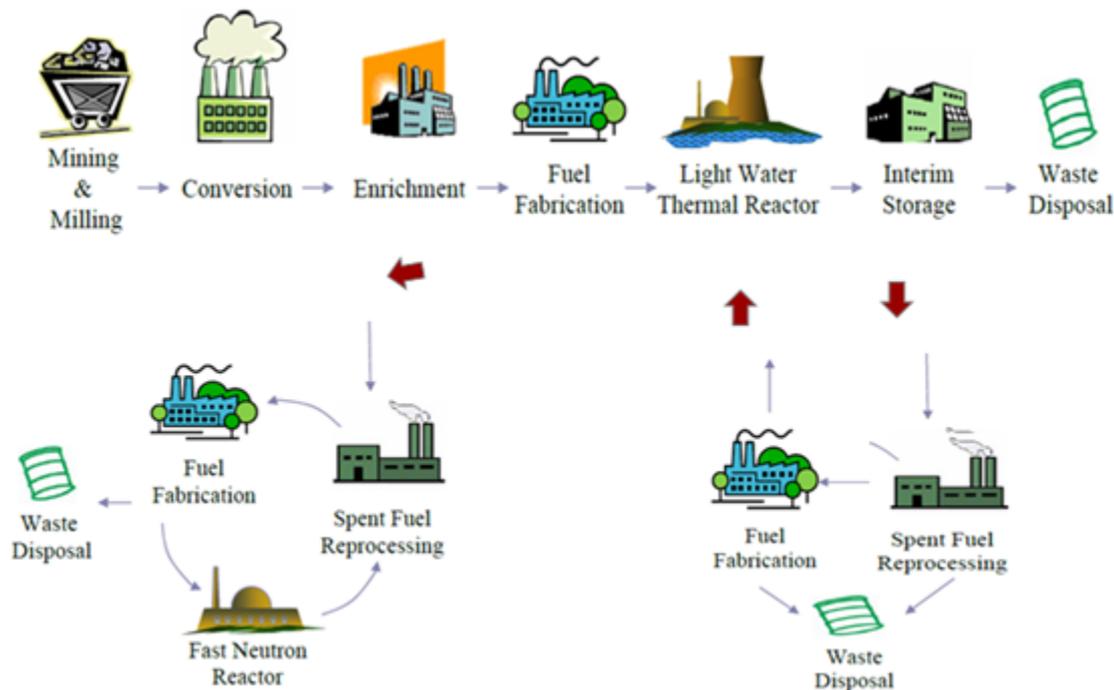
1. Introduction

Since the beginning of application of nuclear energy for civilian electricity supplies, several issues related to its deployment were identified: sustainability (both on the resource supply as well as on the treatment of used fuel to extend the supply of energy), health and environmental impact, proliferation of materials useable as weapons and economic competitiveness became part of an intense and continuous debate around this energy source. Despite more than 50 years of experience and many technological improvements, the same issues are still debated today in comparing nuclear energy to other energy sources and in optimization of the energy portfolio of developed and developing countries [1,2]. To properly address those issues, however, it is necessary to study not only the performance of nuclear reactors per se, but also of the entire system in which they are expected to operate, namely the corresponding nuclear fuel cycle (see Figure 1). Such an analysis should model and represent all the individual stages of the nuclear fuel cycle as well as the interactions between them.

The methodology of nuclear fuel cycle system analysis can therefore help bring a better understanding of the strengths and weaknesses of fuel cycle alternatives [3–5]. The analysis of complex systems like the Nuclear Fuel Cycle can be approached in two ways: static and dynamic analysis. Static analysis implies the use of steady-state models which commonly assume equilibrium states and commercial maturity of the involved technologies. Those models do not take into account the time-dependent nature of a dynamically evolving system like the nuclear fuel cycle. In particular, the nuclear industry is characterized by long time scales, of the order of tens of years, and actions taken today may not have a significant impact until several years later. Indeed in a nuclear fuel cycle, it can require decades/centuries to approach quasi-state equilibrium between the deployed technologies. Therefore, when analyzing the performance of nuclear fuel cycle options, it is important to use a dynamic analysis approach. The time dependent behavior of the system accounts for time delays, dynamic feedbacks and constraints, which, compared to the corresponding steady state analysis,

negatively impact the performance of candidate fuel cycles, and thus should be properly taken into account [6–8].

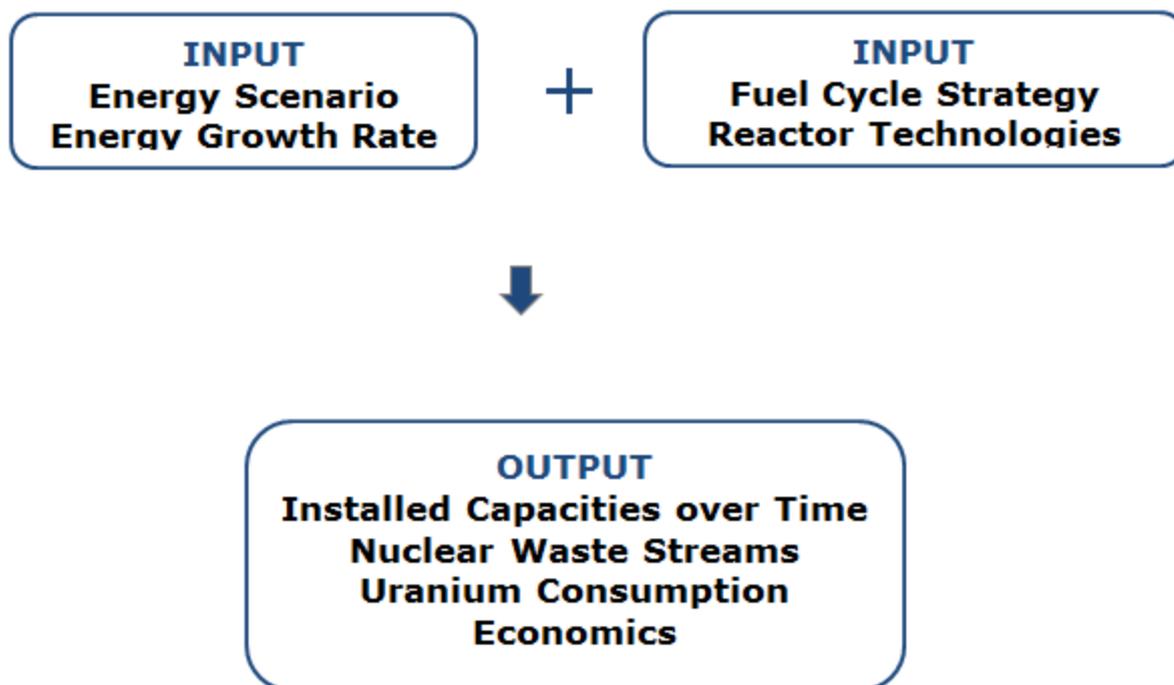
Figure 1. Schematic of the nuclear fuel cycle stages.



1.1. Code for Advanced Fuel Cycle Analysis Developed at MIT

Over the past ten years a tool for nuclear fuel cycle dynamic analysis, named CAFCA (Code for Advanced Fuel Cycle Analysis) has been developed at MIT. The current version is coded in the System Dynamics-VEINSIM platform and is the systems analysis tool used to produce the results reported in the MIT Nuclear Fuel Cycle Study [9,10]. CAFCA has been the object of an extensive benchmarking exercise together with other state of the art nuclear fuel cycle analysis codes [11–13]. The nuclear fuel cycle model built in CAFCA includes non-linear connections, feedback loops and constraints typical of complex systems evolving over time. As inputs, CAFCA accepts assumptions on the energy scenario to be simulated (in particular the nuclear energy demand growth rate) as well as on the fuel cycle strategy and the reactor technologies assumed to be available for the specific scenario. As outputs, CAFCA provides several data and metrics of interest in nuclear fuel cycle analysis, such as: the installed capacities over time of the available reactor technologies, nuclear waste streams, uranium consumption, economics, *etc.* (see Figure 2).

Figure 2. Code for Advanced Fuel Cycle Analysis (CAFCA) input/output logic.



In CAFCA, several fuel cycle schemes (such as Once Through Cycle, Twice Through Cycle, Fast Burner Cycle, Fast Breeder Cycle) are available and can be selectively activated. In addition, several reactor technologies can be coupled with the desired fuel cycle scheme, such as UO₂ Fueled LWRs, mixed UO₂-PuO₂ (MOX) Fueled LWRs, UO₂ Fueled RBWRs, Metal Fueled FRs, Oxide Fueled FRs and Uranium-235 initiated FRs. The FR designs available in CAFCA cover a wide range of conversion ratios, from pure fast burner to fast breeder reactor [11,14–17]. CAFCA is a discrete time code, which adopts a continuous flow approach to mass balances in the system (*i.e.*, no fuel batches) and deals with equilibrium core calculations. The code does not actively perform any reactor physics calculation or isotope tracking and, as such, the spent fuel composition for a given reactor technology is fixed and can be specified by the user. Previous benchmark between CAFCA and other codes that account for isotopic decay [11] showed that the impact of not explicitly tracking isotopes on the results was not large [12]. CAFCA tracks the amount of TRU in the system by performing mass balances on the cumulative amount of TRU as specified in spent fuel composition input tables. Alternatively, it is possible to externally use a neutronic depletion code and use more refined calculations to estimate the isotopic composition of spent fuel.

2. Reference Case Scenario and Fuel Cycle Options

All the cases examined in this paper represent the U.S. energy scenario and in particular start from the existing LWR fleet, considering also the amount of spent fuel currently in dry interim storage or in spent fuel pools at the reactor sites. For all cases, a nuclear energy demand growth rate of 2.5% per year from 2020 on will be assumed (following a slower increase from 100 GWe to 120 GWe in 2020); the spent LWR fuel legacy is assumed to be 56,800 tHM and a minimum cooling time after discharge of 5 years before reprocessing for all the types of fuel. Those represent the same set of assumptions

used to produce the results discussed in the MIT study on the future of nuclear fuel cycle [9,11]. Sensitivity studies to various assumptions have been made in the MIT study, and showed that conclusions derived from the base line case of 2.5% do not change within a growth range between 1% and 4%. In order to allow full comparison with the results discussed in the MIT study, the same base line case of 2.5% growth rate per year is analyzed in this paper, even if we recognize that current projections may see nuclear growing around 2% per year.

The energy growth rate is one of the key assumptions impacting the presented results and therefore the reader should be aware that assuming a significantly different energy growth rate may change the quantitative results and trends discussed in this paper. Similarly, also different assumptions on reprocessing facilities, their deployment schedule and capacity can have significant impact on the results. In this paper, thermal reprocessing facilities are characterized by a unit capacity of 1000 tHM/year, with a deployment rate limited to one plant every four years. Fast reprocessing facilities are, on the other hand, characterized by unit capacity of 500 tHM/year (for FR CR = 1.0 and FR CR = 1.23) and 200 tHM/year (for FR CR = 0.75) and a deployment rate limited to 1 plant every two years. The deployment rates were also assumed to be doubled after 2050 (for thermal reprocessing plants) and 2065 (for fast reprocessing plants).

The base-line scenario as fuel cycle option will be the once-through cycle based on the current LWR design. A number of alternative fuel cycle and recycling technologies (see Section 2.1) will then be explored and compared to the results obtained for the OTC cycle scenario. It is recognized that the analyzed fuel cycle alternatives do not cover the entire range of options and that some of them, such as, for example, “modifies open” cycles with the deployment of traveling wave reactors may have considerable impact on several metrics of interest, such as uranium and SWU utilization as well as required reprocessing capacity.

2.1. Alternative Fuel Cycles and Recycling Technologies

Other than the OTC cycle based on LWR technology, the impact of introducing the following fuel cycle options and recycling technologies will be explored in this paper:

- (1) Twice-Through Cycle, characterized by one time Pu recycling in LWRs as MOX fuel;
- (2) Closed Fuel Cycle characterized by TRU multi recycling in fast burners (FR CR = 0.75);
- (3) Closed Fuel Cycle characterized by TRU multi recycling in self-sustaining fast reactors (FR CR = 1.0);
- (4) Closed Fuel Cycle characterized by TRU multi recycling in self-sustaining epithermal light water reactors (RBWR CR = 1.0);
- (5) Closed Fuel Cycle characterized by TRU multi recycling in fast breeders (FBR CR = 1.23);
- (6) Closed Fuel Cycle characterized by TRU multi recycling in fast burners (FR CR = 0.75) with LWRs being replaced by U-235 initiated FRs;
- (7) Closed Fuel Cycle characterized by TRU multi recycling in self-sustaining fast reactors (FR CR = 1.0) with LWRs being replaced by U-235 initiated FRs;

- (8) Closed Fuel Cycle characterized by TRU multi recycling in fast breeders (FBR CR = 1.23) with LWRs being replaced by U-235 initiated FRs.

Specific assumptions are made regarding the introduction dates of the recycling technologies and of the reprocessing plants needed for fuel cycle closure. Most of the assumptions are taken directly from the MIT fuel cycle study [9,11]; here only the main ones will be listed as well as the ones for cases 4, 6, 7, 8, which are additional scenarios to the one described in the fuel cycle study [9]. For the Twice-Through scenario (recycling case 1), the first thermal reprocessing plant starts operation in 2025 and the separated plutonium is immediately used to make MOX fuel. In the scenarios involving fast reactors (cases 2, 3 and 5), the first thermal reprocessing plant starts in 2035 and conventional fast reactors (oxide fueled designs are considered in this paper, but the fuel cycle evolution would not be significantly altered if a different fuel material was considered) and reprocessing plants are introduced in 2040. Conventional fast reactors considered in this study are sodium-cooled fast reactors and specifically three designs characterized by different conversion ratios: 0.75 (burner fast reactor), 1.0 (self-sustaining fast reactor) and 1.23 (breeder fast reactor). The data for the fast reactor designs considered in this study are taken from [9,11,17,18] and summarized in Table 1.

Table 1. Relevant Data for Conventional FR Designs.

Reactor Type	FR CR = 0.75	FR CR = 1.0	FR CR = 1.23
Capacity Factor	0.85	0.85	0.85
Cycle Length (year)	0.747	1.19	1.92
Specific Power (kW/kgHM)	72.16	59.7	27.09
Discharge Burnup (MWd/kgHM)	99.6	73	103.23
TRU enrichment (%)	21.21	13.86	8.90
Unit power (GWe)	1	1	1
Fuel Annual loading (MTHM)	8.203	11.192	14.84
Fuel Core mass (MTHM)	36.47	45.5	97.13
Residency time (year)	4.44	4	5.75

2.1.1. RBWR Design

The RBWR (Reduced Moderation Boiling Water Reactor) is a Light Water Reactor design derived from the existing Boiling Water Reactor technology [19], which aims at achieving a self-sustaining fissile material conversion ratio (CR = 1.0). To do so, the amount of water inventory in the core region responsible for neutron energy moderation is reduced, and as a consequence the average void fraction and steam quality is higher than a typical BWR design [20]. As a result, the neutron spectrum is also harder, which reduces neutron parasitic captures in the coolant while favoring neutron capture in the fuel (mainly due to the presence of U-238), and relying more on fissions by the epithermal energy neutrons making possible the achievement of a high conversion ratio in a design based on light water cooled reactor technology [19–21]. From a fuel cycle point of view, in which the focus is on the mass balances more than on the reactor technology deployed, such a design should be compared with a more typical self-sustaining metal cooled fast reactor design. Table 2 reports the main data of interest for the two designs (RBWR [21] and FR CR = 1.0 [11]) available for use in CAFCA. The data are normalized for the same electrical output, namely 1000 MWe.

Table 2. Relevant data for the Reduced Moderation Boiling Water Reactor (RBWR) and FR CR = 1.0 Designs.

Reactor Type	RBWR	FR CR = 1
Capacity Factor	0.9	0.85
Cycle Length (year)	1	1.19
Number of batches	4.62	3.42
Specific Power (kW/kgHM)	29.65	59.7
Discharge Burn Up (MWd/kgHM)	45	73
Residency time (year)	4.62	4.06
Fuel Annual loading (MTHM)	21.55	11.192
Fuel Core mass (MTHM)	107	45.5
TRU enrichment	0.1235	0.1386

As can be seen, the specific power (the power per unit fuel mass) for the self-sustaining fast reactor is twice that of the RBWR design, and as a result the fuel core mass and the annual loading are much larger for the RBWR than for the self-sustaining fast reactor. This suggests that the deployment of the RBWR may be slower because of the larger TRU requirement; on the other hand being based on LWR technology, the RBWR could potentially be commercially available earlier than the self-sustaining fast reactor (we made the assumption of introducing the RBWR in 2025, while fast reactors are introduced in 2040). A fuel cycle code like CAFCA can help compare the impact of the two designs from a fuel cycle point of view; these respective results are reported in Section 3.

2.1.2. U-235 Initiated Fast Reactor Design

As discussed in the MIT Fuel Cycle Study, the rate of introduction of traditional fast reactors over time is limited by the availability of separated TRU from LWR spent fuel, which represents the real bottleneck for a fast deployment of a FR fleet. This limitation is associated with the capacity of spent fuel reprocessing facilities making impossible the full use of the spent fuel legacy, which represents the source of fuel for the initial installation of fast reactor in a closed fuel cycle perspective. To overcome this limitation and allow for a quicker introduction of fast reactor technologies, an alternative has been studied at MIT [22,23] for using U-235 initiated fast reactors, which would require U-235 enriched fuel, at higher levels than the light water reactors but within the allowable 20% limit on civilian use of enriched uranium. Therefore, use of the same chain of supply already in place for the existing fleet would continue, without requiring reprocessing facilities and separation of TRU material to start up and feed the fast reactor. Three designs characterized by three different fuel forms have been studied (oxide, metal and carbide); in this paper only the oxide fueled U-235 initiated fast reactor design will be presented and its fuel cycle performance characterized. It is also expected that the other two designs would show similar performance characteristics with respect to the fuel cycle. Table 3 reports the main design data of interest for the U-235 initiated FR and a typical LWR design.

Table 3. Relevant data for the U-235 initiated FR- UO_2 and for the LWR designs.

Reactor Type	U-235 initiated FR	Light Water Reactor
Capacity Factor	0.85	0.90
Cycle Length (year)	1.22	1.5
Specific Power (kW/kgHM)	81.10	38.7
Discharge Burnup (MWd/kgHM)	166.00	50
U235 enrichment	18.45%	4.23%
Unit power (GWe)	1.00	1.00
Fuel Annual loading (MTHM)	4.73	19.5
Fuel Core mass (MTHM)	28.86	87.77
Residency time (year)	6.10	4.5

As can be seen, the two designs are quite different; in particular discharge burnup, specific power and U-235 enrichment. As a result, the fuel mass balances are quite different, but the total U-235 content in the core is similar and that will also bring about similar natural uranium requirement, as shown in Section 3. It is also interesting to observe the significantly different composition of the discharged fuel from the LWR and FR designs considered in this paper (Table 4).

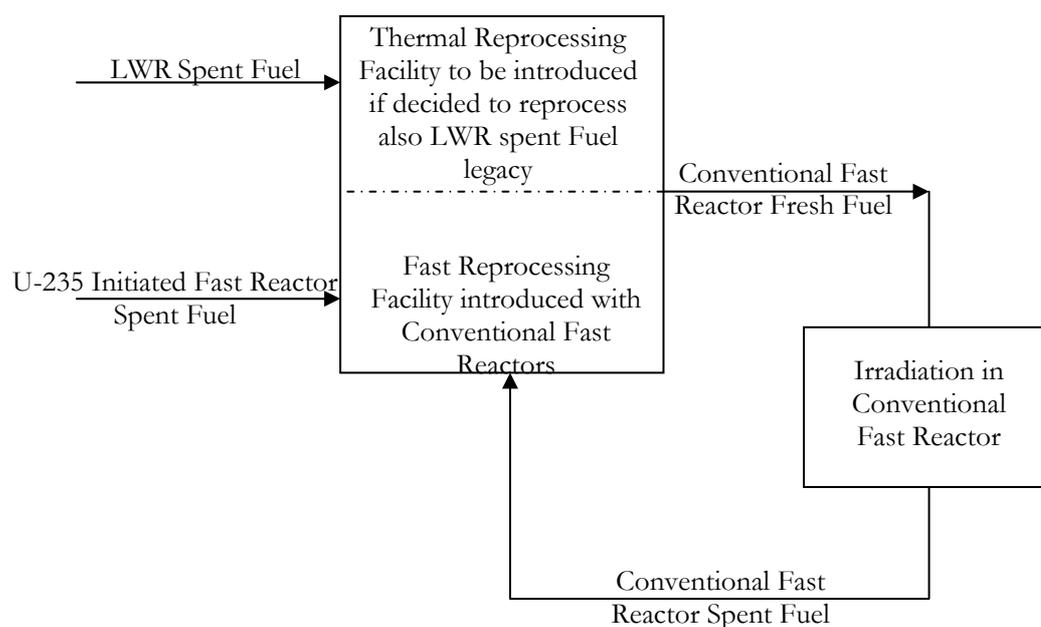
Table 4. Composition of spent fuel for the U-235 initiated FR, LWR and conventional FR designs.

Reactor Type	U-235 initiated FR	LWR	FR CR = 0.75	FR CR = 1.0	FR CR = 1.23
Spent fuel cooling time	5 years	5 years	5 years	5 years	5 years
U fraction	75.91%	93.56%	70.12%	78.30%	84.02%
Pu fraction	7.65%	1.15%	NA	NA	10.15%
MA fraction	0.33%	0.13%	NA	NA	0.23%
TRU fraction	7.98%	1.28%	19.20%	14.04%	10.38%
FP fraction	16.11%	5.16%	10.68%	7.66%	5.60%

The spent fuel composition is different because of the different neutron spectrum and as a result, the relative TRU content in the spent fuel coming from the U-235 initiated fast reactor design is about six times the TRU content in a typical LWR spent fuel per unit mass of spent fuel (while burnup is about three times larger). This suggests that the stream of spent fuel from U-235 initiated fast reactors would be extremely valuable for reprocessing and TRU separation to be then used to build a conventional FR fleet and increase the rate of introduction of conventional FRs compared to what can be achieved with an LWR fleet. In addition, the introduction of U-235 initiated fast reactor (USFRs) could make unnecessary the reprocessing and recycling of the spent LWR fuel as feed fuel to conventional fast reactors. Thermal reprocessing of spent LWR fuel is expensive given the low concentration of the fissile content and the required revision of regulatory frameworks. It is also more challenging than the reprocessing of spent FR fuel also because of the much smaller TRU content. The LWR spent fuel legacy would be, in such a case, simply sent to the geological repository and fast reprocessing deployed with the introduction of USFRs will feed a fleet of conventional FRs and achieve fuel cycle closure. CAFCA gives priority to recycling technologies (in this case conventional FRs) as long as enough separated TRU material is available for fresh FR fuel. USFRs, similarly to how LWRs are

treated in the other closed fuel cycle scenarios, are installed to make up the remaining difference between energy demand and current installed capacity. In all scenarios considered, conventional FRs spent fuel is continuously recycled in fast reprocessing plants to take advantage of its high TRU content, as shown in Table 4. Figure 3 shows schematically how fuel cycle closure would be realized in the two cases (with and without thermal reprocessing). In both cases, there will be two streams of spent fast reactor fuel to be reprocessed. Furthermore, in both cases, U-235 Initiated fast reactors are introduced to replace entirely the LWR fleet following its decommissioning schedule.

Figure 3. Fuel cycle closure through U-235 initiated and conventional fast reactors.



In this paper we investigate the deployment of U-235 fast reactor followed by fuel cycle closure through the deployment of three different conventional fast reactor designs characterized by three different conversion ratio values ($CR = 0.75$, $CR = 1.0$, $CR = 1.23$ corresponding to scenarios 6, 7 and 8 respectively as listed in Section 2). In all cases the initiated U-235 fast reactor fleet will be introduced first in 2040 and will gradually replace the LWR fleet following its decommissioning schedule. The USFRs base case scenarios presented and discussed in the next section include also thermal reprocessing of spent LWR fuel.

3. Results and Discussion

The impact of various fuel cycle options in the context of the U.S. energy scenario is presented in this section. In particular, over the span of 100 years, four metrics will be shown: the number of reactors installed, the uranium utilization, the total amount of TRU in the system and the economics of the nine fuel cycle options listed and discussed in Section 2.

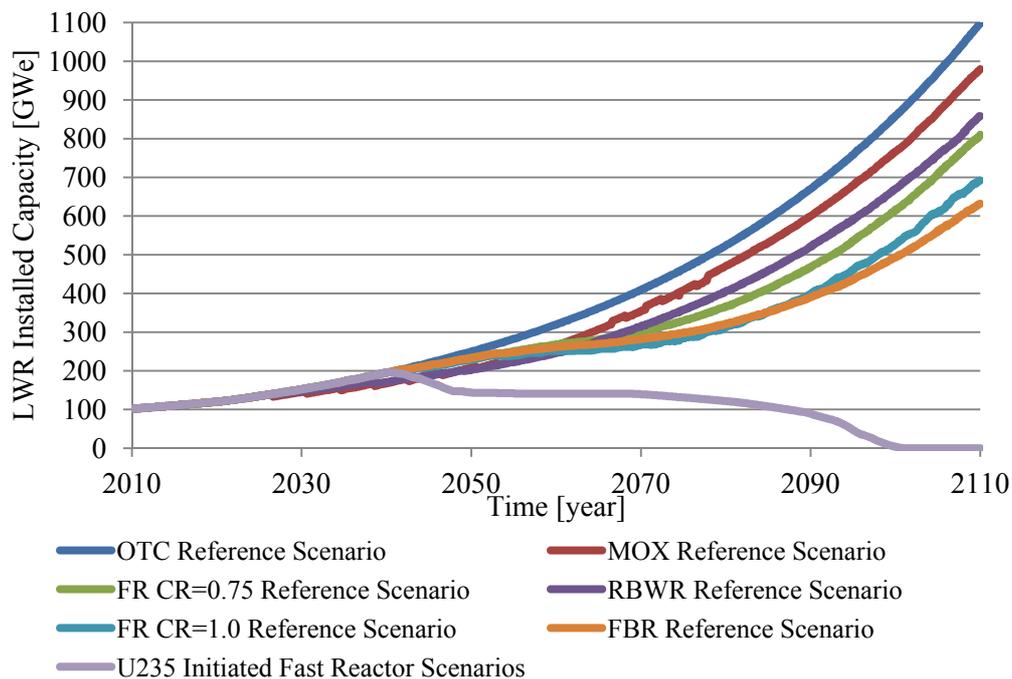
Figure 4. LWR Installed capacities over time.

Figure 4 shows the installed capacities of LWRs for all scenarios. The installed capacity of LWR is maximum for the OTC case, for which it is the only reactor technology available. The OTC line represents also indirectly the total electricity generation capacity required to satisfy the energy demand growth rate described in Section 2. Therefore, for the closed fuel cycle scenarios deploying recycling technologies, the lower the LWR installed capacity line, the higher the penetration of recycling technologies over time. The fast breeder reactor scenario shows the lowest need for LWR installed capacity, followed closely by the self-sustaining fast reactor scenario [9,11]. In the LWR installed capacity plot, all the U-235 initiated fast reactor scenarios collapse into a single line, corresponding to the retirement of the existing LWR fleet over time and assuming life extension to 60 years for all the existing plants. This is because, as already mentioned in Section 2, the LWR fleet is assumed to be replaced by the U-235 initiated fast reactors starting in 2040, a fuel cycle closure is achieved in 2040 with the introduction of conventional fast reactor designs. Figure 5 shows the installed capacity of U-235 initiated fast reactors over time for the three different fast reactor technologies to be coupled for fuel cycle closure. Initially (2040–2050) U-235 initiated FRs are needed to replace the LWR fleet being decommissioned. Between 2060 and 2080, following the introduction of conventional FRs which have priority in CAFCA, fewer U-235 initiated FRs are needed to satisfy the energy demand growth. Finally, after 2090 consistently with the slowing down in the conventional FRs installed capacity (which follows the availability of separated TRU), additional U-235 initiated FRs are needed. The installed capacity of U-235 initiated fast reactors was found to be highest for the CR = 0.75 and conventional FR cases, while lowest for the CR = 1.23 conventional FR case, depending on the conventional FR installed capacity in the three cases, shown in Figures 6–8.

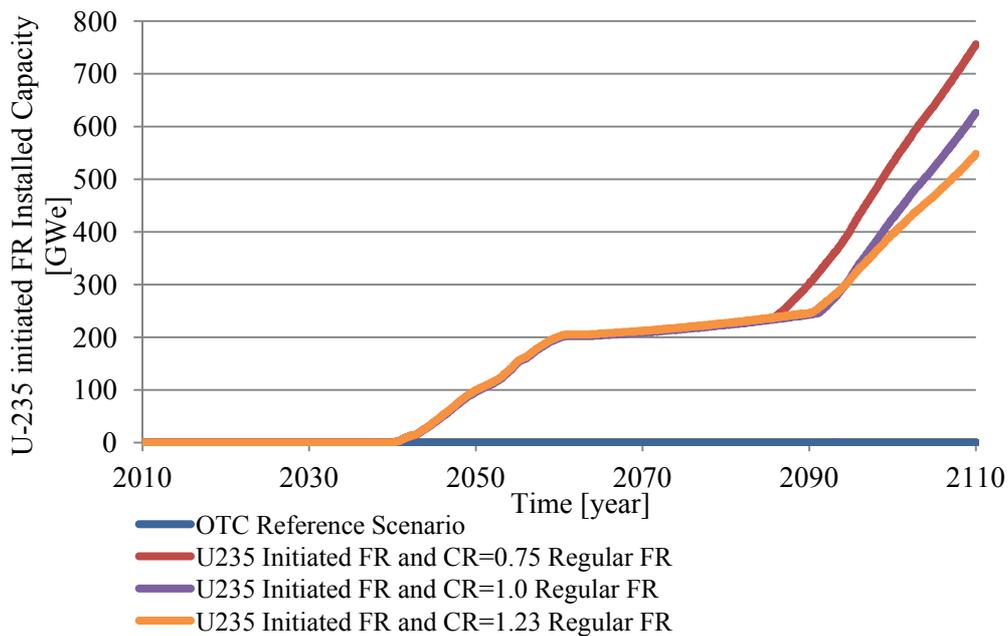
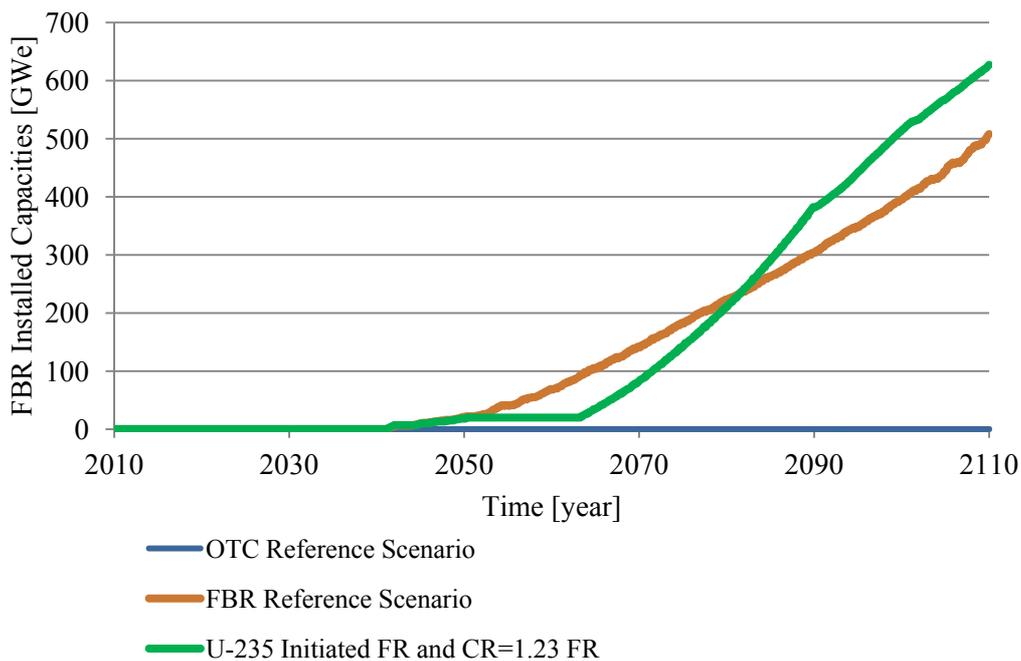
Figure 5. U-235 Initiated FR installed capacities over time.**Figure 6.** Fast breeder reactor installed capacities over time.

Figure 6 shows the fast breeder reactors capacity installed over time for the reference scenario and for the scenario with U-235 initiated fast reactors. As can be seen, thanks to the high TRU stream out of U-235 initiated fast reactors, the number of conventional fast breeder reactors that can be installed is larger than in the reference scenario in 2110. This supports the deployment of U-235 initiated fast reactors as a booster technology for fuel cycle closure through conventional fast reactor technology. Similar results can be observed also in Figures 7 and 8 for CR = 0.75 and CR = 1.0 recycling technologies.

Figure 7. Self-sustaining reactor (CR = 1.0) installed capacities over time.

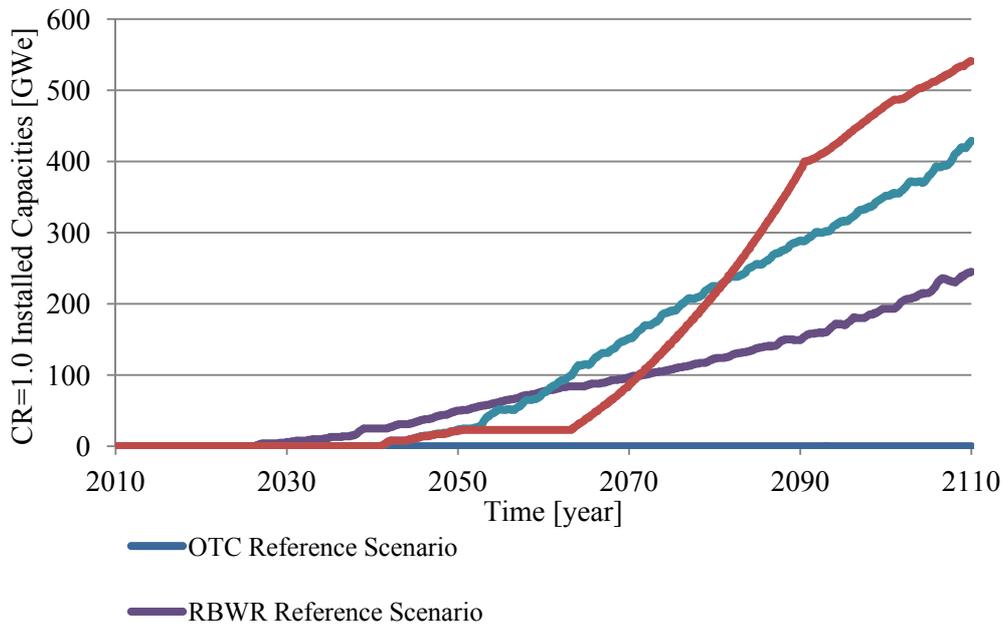
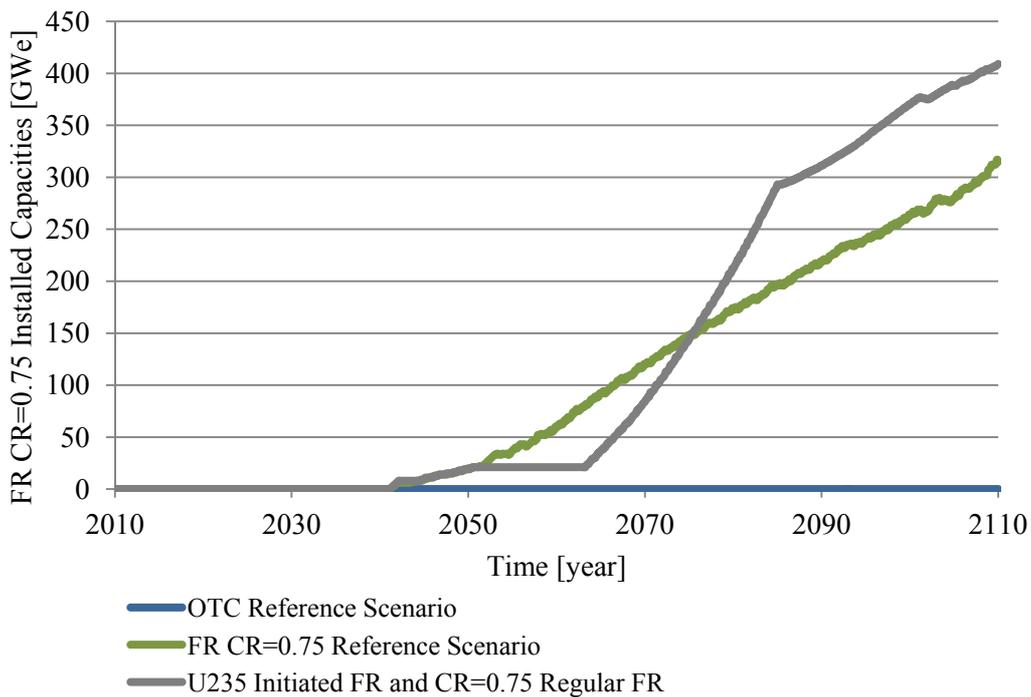


Figure 8. Fast reactor (CR = 0.75) installed capacities over time.



The plateau in the installed capacity of conventional FRs that can be observed in Figures 6–8 reflects the temporary limited amount of separated TRU following the LWR decommissioning schedule and the initially limited number of fast reprocessing plants. After 2065, however, enough fast reprocessing plants are available to sustain a steeper growth of conventional FRs.

It is possible to summarize the findings from Figures 4 through 8 reporting the installed capacities for all reactor technologies as follows:

- LWR's are the dominant technology for each energy scenario, excluding the ones characterized by the introduction of U-235 initiated Fast Reactors. This is reinforced in Tables 5 and 6;
- U-235 initiated Fast Reactors help increase the penetration of fast reactors in the energy supply over time. By 2100, the increase is almost a factor of 30% compared to the reference scenarios;
- RBWR technology can be installed in larger numbers than conventional CR = 1.0 fast reactors until 2060, when the trend inverts itself because of the much lower TRU requirement for the conventional FR design compared to the RBWR design;

Table 5. Summary of the installed capacity in 2050 and 2100 for reference case scenarios.

	LWR-UO2 installed		MOX installed		FR CR = 0.75 installed		RBWR installed		FR CR = 1.0 installed		FR CR = 1.23 installed	
	Capacity (GWe)		Capacity (GWe)		Capacity (GWe)		Capacity (GWe)		Capacity (GWe)		Capacity (GWe)	
Date	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
LWR	250	859	0	0	0	0	0	0	0	0	0	0
MOX	209	767	41	92	0	0	0	0	0	0	0	0
FR CR = 0.75	233	617	0	0	20	263	0	0	0	0	0	0
RBWR	203	670	0	0	0	0	50	193	0	0	0	0
FR CR = 1.0	228	527	0	0	0	0	0	0	23	351	0	0
FR CR = 1.23	233	494	0	0	0	0	0	0	0	0	21	395

Table 6. Summary of installed capacity in 2050 and 2100 for U235 initiated FR scenarios.

	LWR-UO2 installed		FR CR = 0.75 installed		FR CR = 1.0 installed		FR CR = 1.23 installed		U-235 FR Installed	
	Capacity (GWe)		Capacity (GWe)		Capacity (GWe)		Capacity (GWe)		Capacity (GWe)	
Date	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
U-235in FR FR CR = 0.75	144	4	19	370	0	0	0	0	99	531
U-235in FR FR CR = 1.0	144	4	0	0	22	479	0	0	96	426
U-235in FR FR CR = 1.23	144	4	0	0	0	0	18	514	100	397

Two other metrics of interest are the natural uranium requirement and the total amount of transuranic (TRU) material in the system, shown in Figure 9 and 10 for all the scenarios analyzed.

Figure 9. Cumulative natural uranium requirement over the simulation period.

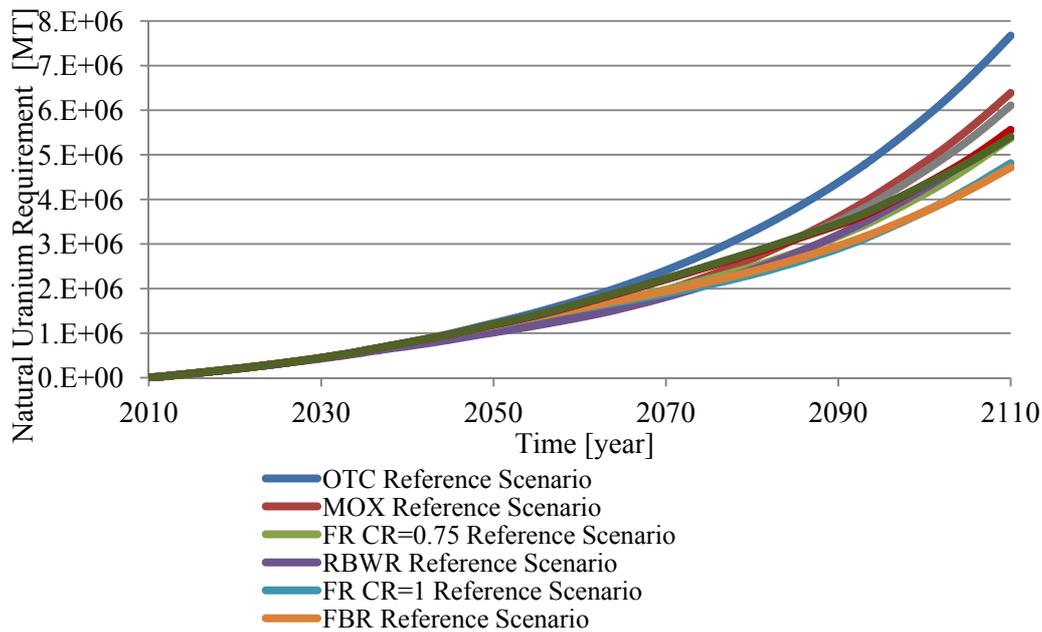
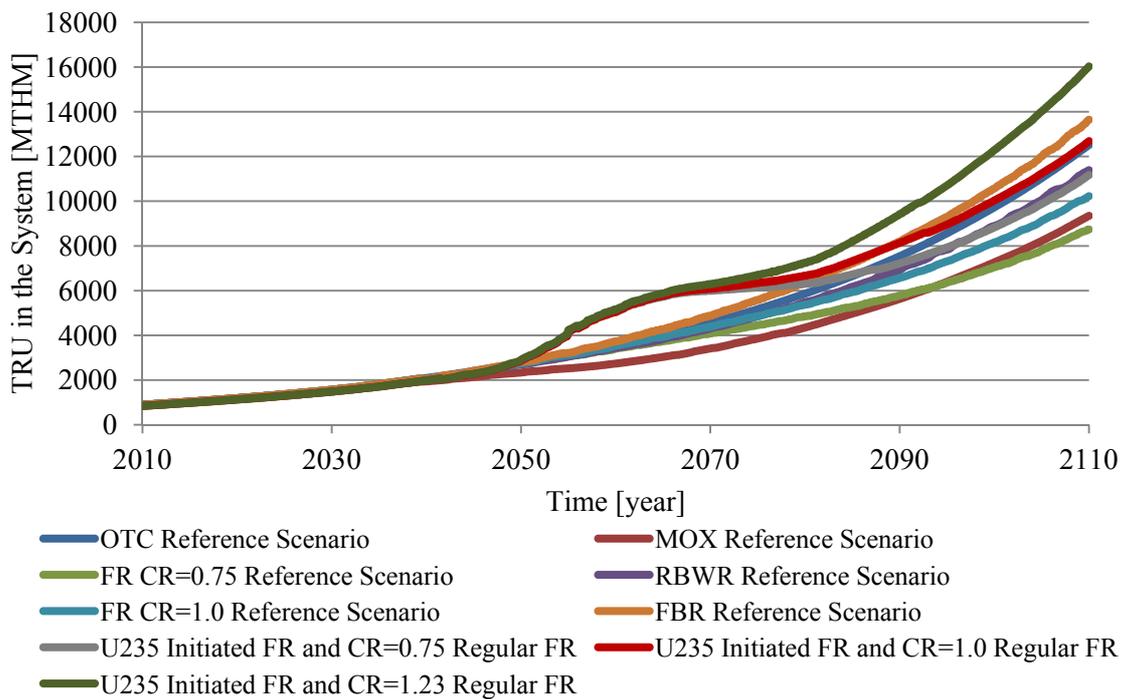


Figure 10. Total amount of TRU in the system.



As can be seen, the introduction of recycling technologies reduces the natural uranium requirement compared to the OTC reference scenario. The introduction of U-235 initiated fast reactors reduces the natural uranium requirement compared to the OTC case, but requires more uranium than the conventionally started fast reactors which do not rely on any mined uranium.

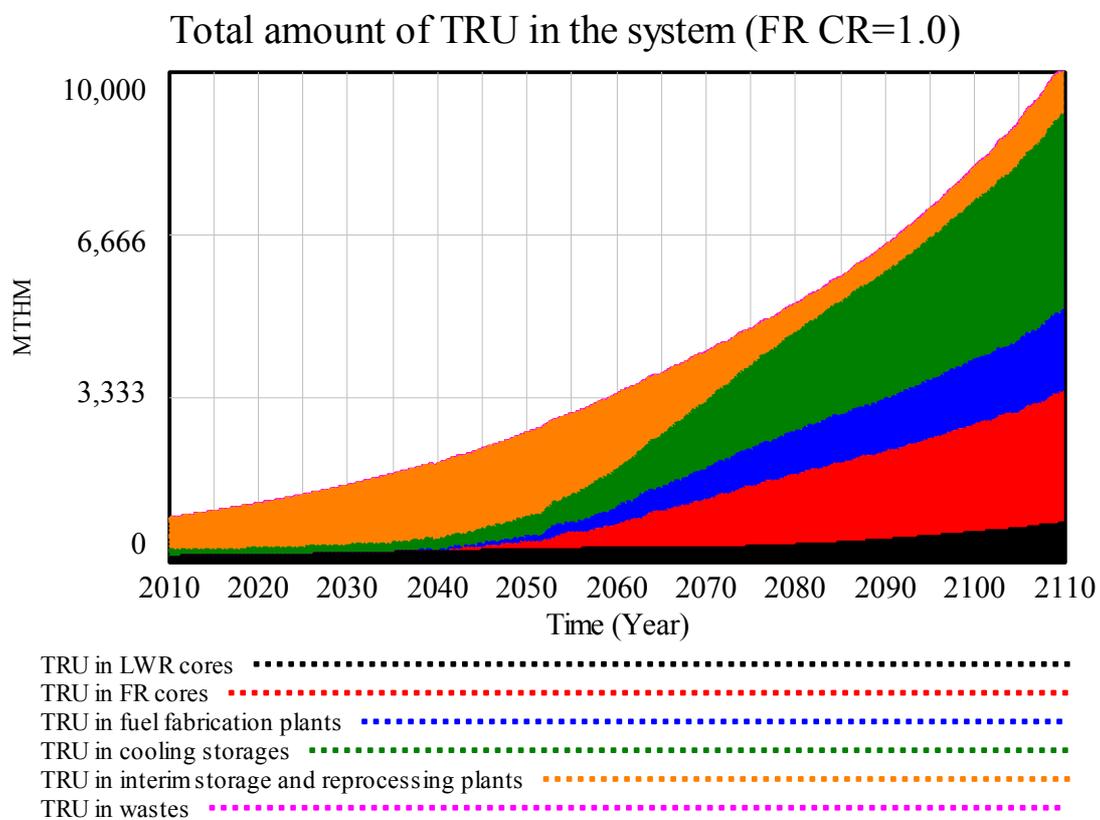
The total amount of transuranic material in the system exhibits different trends compared to what is seen for natural uranium requirement. Recycling technologies, while not requiring mined uranium, may have in fact a positive, neutral or negative transuranic impact according to their conversion ratio.

Examining the reference cases first, Figure 10 shows that, except for the Fast Breeder Reactor scenario, the deployment of recycling technologies reduces the amount of TRU in the system compared to the OTC scenario. In particular, the fast burner scenario ($CR = 0.75$) is characterized by the minimum amount of TRU in the system. The fast breeder ($CR = 1.23$) reactor scenario, due to the conversion ratio of the recycling technology being greater than one, is characterized by a larger amount of TRU in the system compared to the OTC scenario.

The introduction of U-235 initiated fast reactor causes the amount of TRU in the system to be larger than any of the other reference cases especially between 2040 and 2060 when U-235 initiated fast reactors are installed at a high rate. This is because of the high TRU content in the U-235 initiated fast reactor spent fuel compared to the amount of TRU in light water reactors spent fuel (see Table 4). The combination of U-235 initiated fast reactors and fast breeder reactors increases the amount of TRU by about 50% compared to the OTC cycle.

Of course the amount of TRU in the system does not tell the form or the location of TRU. Figure 11 shows the distribution of TRU for the $CR = 1.0$ reference scenario among reactor cores, cooling storage, interim storage, reprocessing and fuel fabrication plants and waste. As can be seen, the amount of TRU under waste form in a closed fuel cycle is extremely small, and most TRU actively stays in the fuel cycle and keeps being recycled.

Figure 11. Distribution of TRU in the system for the FR $CR = 1.0$ scenario.



Another metric of interest is the required industrial capacity for enrichment technologies, which is also relevant to the proliferation resistance of a given nuclear fuel cycle option. Figure 12 shows the total SWU consumption per year for all the fuel cycle scenarios analyzed. The introduction of

recycling technologies reduces the SWU requirement, in particular for the U-235 initiated fast reactor scenarios. However, the demand for enrichment is increasing over time in all the scenarios analyzed. In addition, the difference in the U-235 enrichment value between LWR and U-235 initiated FRs should also be separately taken into consideration, recognizing that higher U-235 enrichment also reduces the additional SWU needed to produce a significant quantity of highly enriched uranium from civilian feed stock.

Figure 12. Total SWU consumption per year.

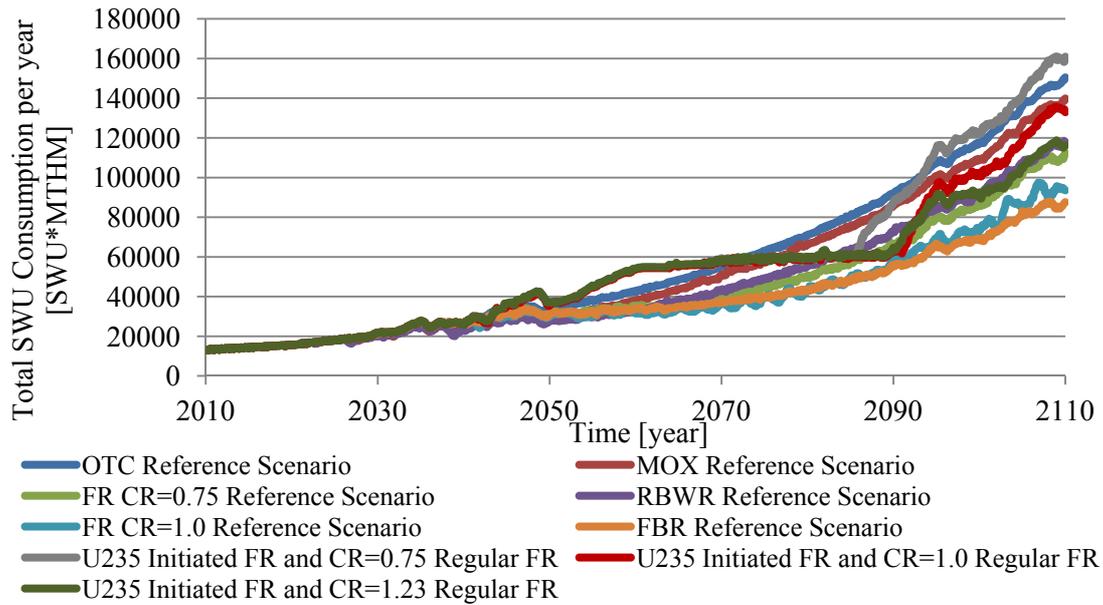


Figure 13. Thermal reprocessing installed capacity.

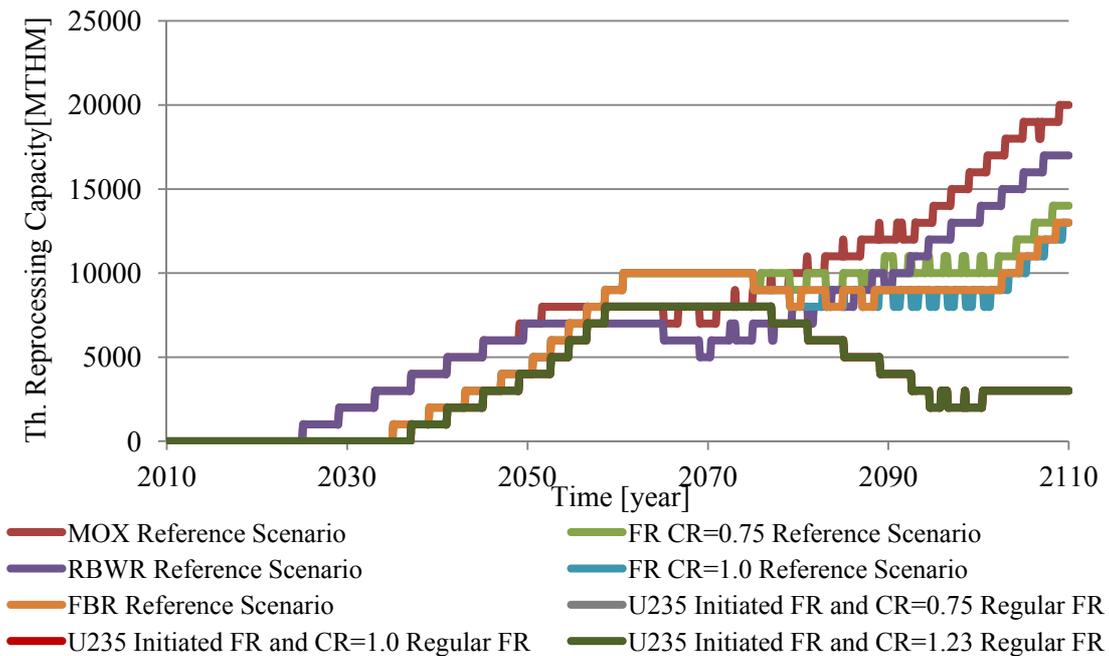


Figure 13 shows the development of thermal reprocessing capacities in the analyzed scenarios. Recall that the unit capacity is 1000 tHM/year and that can be added at a limited rate of one plant each

four years until 2050, after which the rate doubles, and that thermal reprocessing is introduced in 2025 for the MOX and RBWR scenario vs. 2035 in U-235 initiated and conventional FR scenarios. Figures 14–16 show the development of the fast reprocessing capacity for different conversion ratios of recycling technologies. Recall that the unit capacity is 200 tHM/year in the burner case, and 500 tHM/year in the self-sustaining and breeder scenarios, and both units can be added each two years, until 2065, before doubling that rate is allowed.

Figure 14. Fast reprocessing installed capacity for FR CR = 0.75 scenarios.

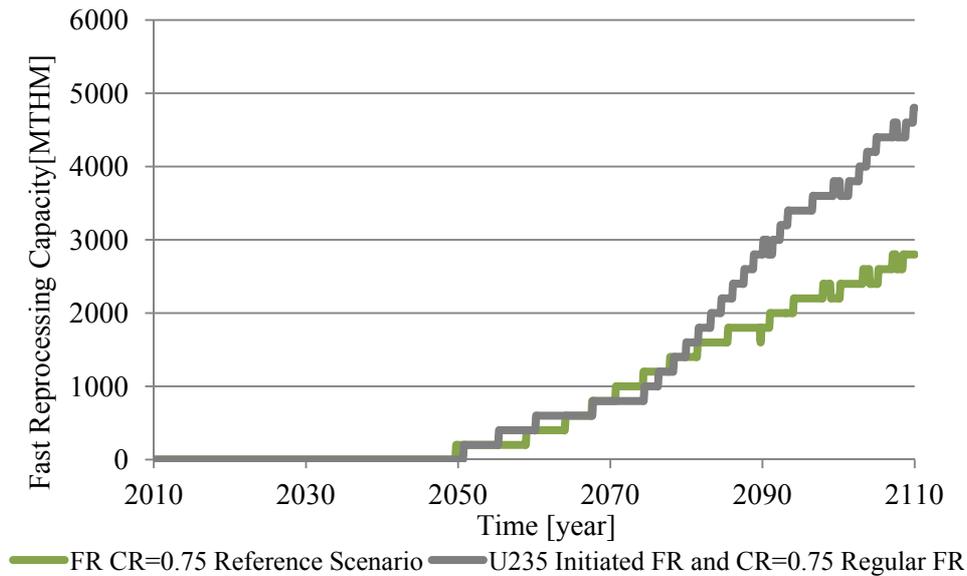


Figure 15. Fast reprocessing installed capacity for CR = 1.0 scenarios.

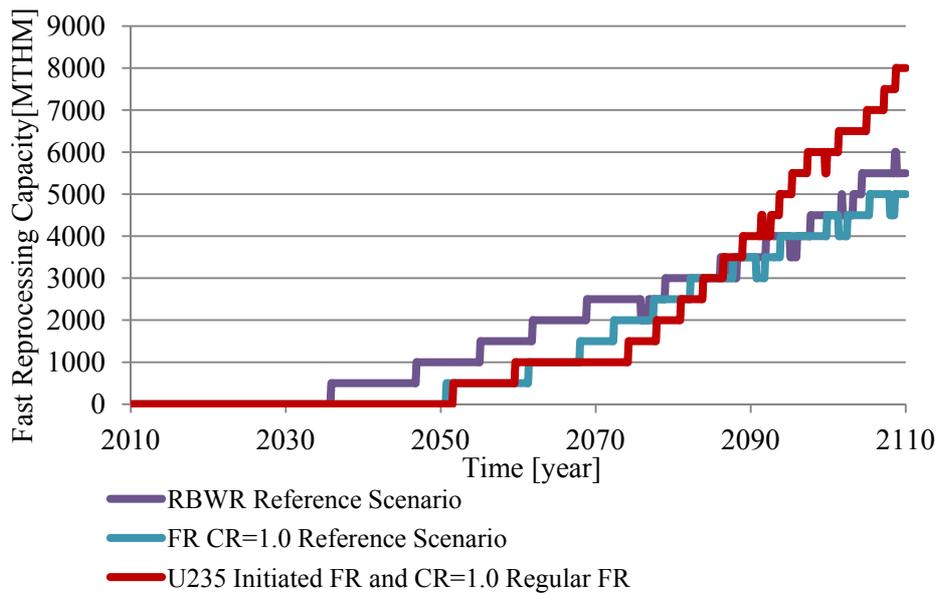
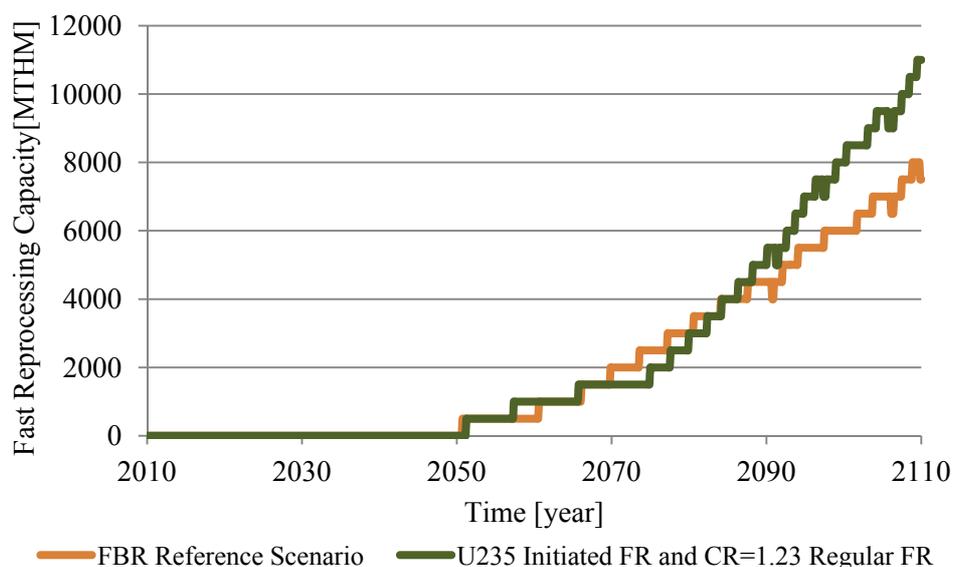


Figure 16. Fast reprocessing installed capacity for FBR scenarios.

As expected, by switching to U-235 initiated FRs, the need for thermal reprocessing is reduced, while more fast reprocessing facilities are needed to reprocess a much larger amount of spent fast reactor fuel compared to the conventional fast reactor scenarios.

Figures 17 and 18 show the dynamic levelized cost of electricity and the fuel cycle cost component of levelized cost of electricity, calculated according to the waste-base accounting scheme [11], as a function of time for all the scenarios analyzed. The main assumptions underlying this economic analysis are fully described in [9,11]. Table 7 summarizes the most relevant ones (with recycling costs included in fuel fabrication costs):

Table 7. Summary of main assumptions for economic analysis.

Economic Assumptions-Overnight Costs	
Uranium Ore Purchase (\$/kgHM)	100
Depleted Uranium Purchase (\$/kgHM)	10
Yellow Cake Conversion (\$/kgHM)	10
Enrichment (\$/SWU)	160
LWR Fuel Fabrication (\$/kgHM)	250
MOX Fuel Fabrication (\$/kgHM)	2000
FR Fuel Fabrication (\$/kgHM)	2000
LWR Construction Cost (M\$/GWe)	4000
FR Construction Cost (M\$/GWe)	4800
O&M Cost [M\$/(GWe*year)]	70
Disposal of Spent UO ₂ Fuel (\$/kgIHM)	687
Disposal of Spent MOX Fuel (\$/kgIHM)	4550
Disposal of MA, FP, TRU (\$/kg)	3250

Figure 17. Levelized cost of electricity.

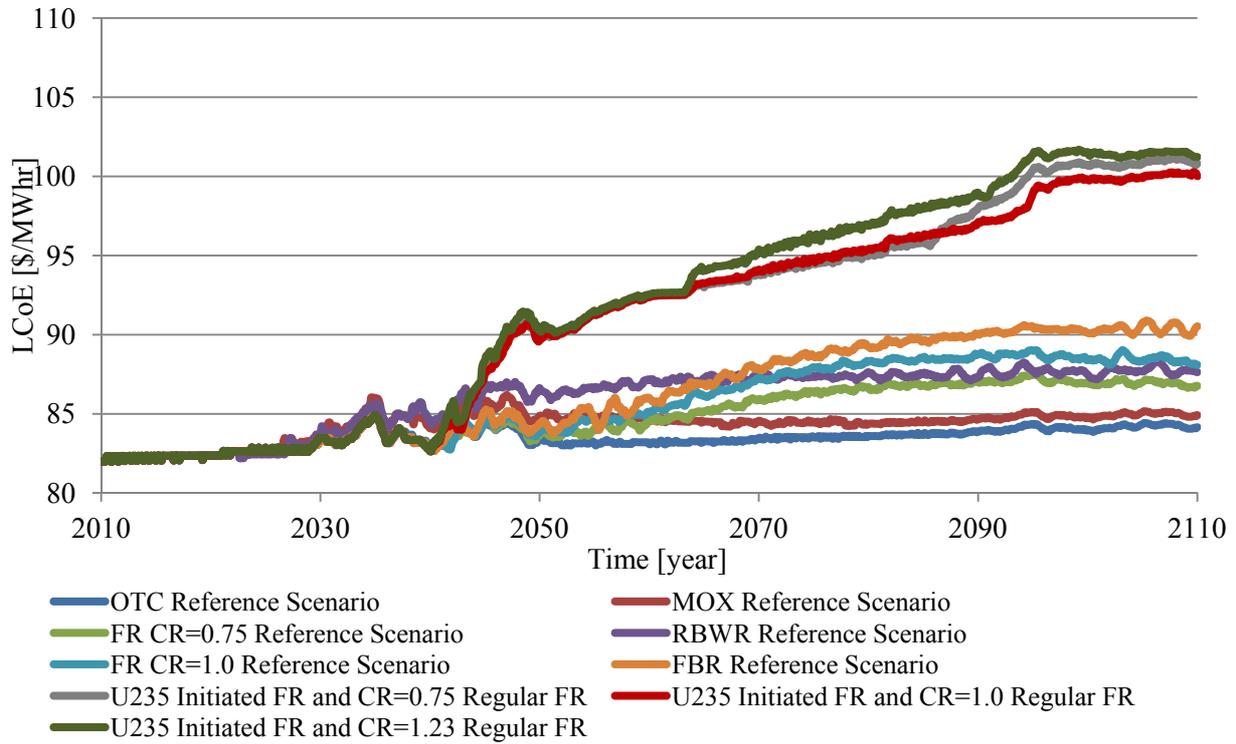
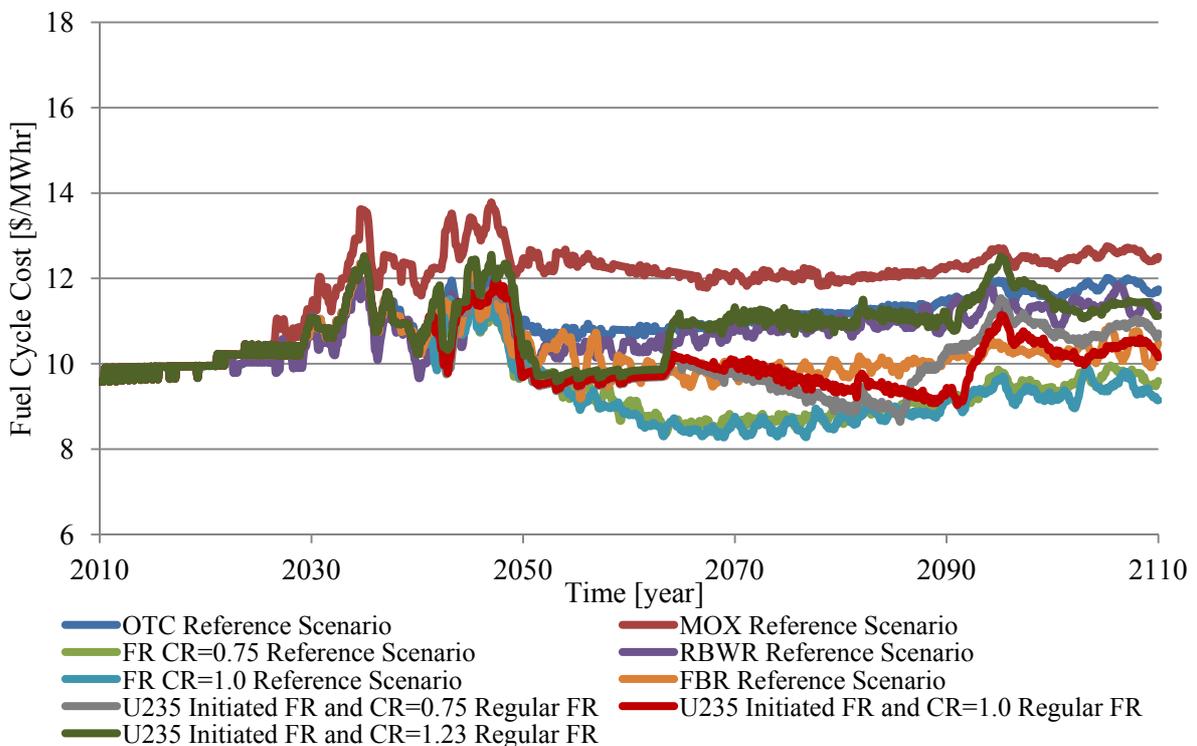


Figure 18. The fuel cycle cost component of levelized cost of electricity.



As seen in Figure 17, OTC is the least expensive fuel cycle option, while the introduction of recycling technologies translates into higher levelized cost of electricity (due to the assumed higher overnight cost of fast reactors compared to the cost of light water reactors). The scenarios

characterized by the introduction of U-235 initiated fast reactors show a considerably higher levelized cost of electricity due to the larger deployment of fast reactors to replace the existing LWR fleet.

Figure 18 shows a component of the levelized cost of electricity, namely the fuel cycle cost. In this case trends are different and favor the use of recycling technologies which are characterized by a lower fuel cycle cost compared to the OTC fuel cycle. However, the order of magnitude of this part of cost is about 12% of the total cost of electricity and the difference in capital costs has a higher influence on the total cost.

The observed oscillations are due to the implemented methodology of dynamic levelized cost of electricity that takes into consideration the specific composition of the reactor fleet at each point in time and over the lifetime of the installed reactors [11].

4. Conclusions

This paper analyzed different fuel cycle options for the U.S. nuclear energy. Besides the existing once through cycle, a number of recycling technologies that more fully utilize the energy potential of uranium and lead to reduced content of actinides in the wastes of the fuel cycle are analyzed. In all cases considered, the LWR was found to be the dominant technology over the century because of the limited availability of TRU material for the installation of recycling technologies over time. This trend could be changed by deploying a higher fissile conversion ratio reactor to replace the existing LWR fleet, in particular the U-235 initiated Fast Reactors, whose spent fuel has a much higher TRU enrichment and is therefore more valuable in a closed fuel cycle perspective. It was shown that the replacement of the LWR fleet with the U-235 initiated fast reactor design allows for a much higher penetration (up to a factor of 2) of recycling technologies, namely conventional fast reactors. The closure of nuclear fuel cycle through the deployment of recycling technologies was also shown to reduce the natural uranium requirement over time, while the amount of transuranics into the system may also increase, depending on the characteristics and the fissile material conversion ratio of the reactor design installed. Even in the cases of recycling technologies in which the absolute amount of TRU increases compared to the OTC cycle, only a very small fraction of the total TRU ends up in the waste (namely, losses from the reprocessing plants and reprocessing facilities). The accumulation over several recycling cycles of isotopes making the handling of spent fuel more difficult over time was not explicitly taken into consideration, and may impact the results especially beyond the time range analyzed.

When examining the economics, the OTC based on LWR technology shows the least levelized cost of electricity, since the recycling technologies, in particular fast reactors, are assumed to have 20% higher capital costs. The fuel cycle component of the levelized cost of electricity, on the other hand, is lower for most recycling technologies, also because of the corresponding lower natural uranium requirement. However, the fuel cycle cost is a relatively small fraction of the total (about 1/8); the difference in the capital cost is ultimately what causes the levelized cost of electricity to favor the LWR once through cycle as long as the supplies of uranium remain available at moderate costs.

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Conflict of Interest

The authors declare no conflict of interest.

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