Synergistic Spent Nuclear Fuel Dynamics Within the European Union

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Abstract

The French 2012-2015 Commission Nationale d'Evaluation Reports emphasize preparation for a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs). We used the Cyclus nuclear fuel cycle simulator to explore the feasibility of enabling a French transition to an SFR fleet by using Used Nuclear Fuel (UNF) from other European Union (EU) nations. A Cyclus simulation captured nuclear power deployment in the EU from 1970 to 2160. In this simulation, France begins its planned transition to SFRs as existing LWRs are decommissioned. These SFRs are fuelled with UNF accumulated by other EU nations and reprocessed in France. The impact of reactor lifetime extensions and SFR breeding ratios on time-to-transition were investigated with additional simulations. These simulations demonstrate that France can avoid deployment of additional LWRs by accepting UNF from other EU nations, that lifetime extensions delay time-to-transition, and improved breeding ratios are not particularly impactful.

Keywords: nuclear fuel cycle, simulation, transition, nuclear engineering, europe, systems analysis

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1. Introduction

The stated long term plan for nuclear deployment in France targets a technology transition to Sodium-Cooled Fast Reactors (SFRs)[1]. However, the current inventory of French Used Nuclear Fuel (UNF) is insufficient to fuel that transition without building new Light Water Reactors (LWRs).

If instead, France accepted UNF from other European Union (EU) nations and used it to produce Mixed Oxide Fuel (MOX) for new SFRs, the MOX created will fuel a French transition to an SFR fleet and allow France to avoid building additional LWRs.

We used the Cyclus nuclear fuel cycle simulator [2] to simulate EU spent nuclear material inventory accumulation and to model the proposed French technology transition from LWRs to SFRs. Cyclus is an agent-based extensible framework for modeling the flow of material through future nuclear fuel cycles. We calculated the used fuel inventory in EU member states and propose a potential collaborative strategy of used fuel management.

Past research focuses solely on France and typically assumes that additional LWRs, namely European Pressurized Reactors (EPRs), supply the UNF required to produce MOX [3, 4, 5]. The strategies in these works claim full SFR transition in 2100. However, little recent work considers synergistic international spent fuel arrangements. This work finds that a collaborative strategy can reduce the need to construct additional LWRs in France, if it turns out that a commercially competitive SFR design can actually be deployed, as has been proposed [6]

2. Methodology

We simulated the nuclear reactor operating history in the EU beginning in 1970 including MOX production and use in France. The simulation captured all discrete regions, reactor facilities, and materials involved in EU historical reactor operation using Cyclus fuel cycle simulation framework and Cycamore agents. In this simulation, the UNF from EU nations is stored for later use in French SFRs and France begins production of fuel for SFRs in 2020 by recycling the stored UNF. The SFRs are modeled after the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) breeder reactor [7].All scripts and data used for the simulations in this article are available in [8].

2.1. Cyclus

Cyclus is an agent-based fuel cycle simulation framework [2], which means that each reactor, reprocessing plant, and fuel fabrication plant is modeled as an agent.

A Cyclus simulation contains prototypes, which are fuel cycle facilities with pre-defined parameters, that are deployed in the simulation as `facility` agents. Encapsulating the `facility` agents are the `Institution` and `Region`. A `Region` agent holds a set of `Institutions`. An `Institution` agent can deploy or decommission `facility` agents. The `Institution` agent is part of a `Region` agent, which can contain multiple `Institution` agents. Several versions of `Institution` and `Region` exist, varying in complexity and functions [9]. `DeployInst` is used as the institution archetype for this work, where the institution deploys agents at user-defined timesteps.

At each timestep (one month), agents make requests for materials or bid to supply them and exchange with one another. A market-like mechanism called the dynamic resource exchange [10] governs the exchanges. Each material resource has a quantity, composition, name, and a unique identifier for output analysis.

In this work, each nation is represented as a distinct `Region` agent, that contains `Institution` agents, each deploying `Facility` agents. The `Institution` agents then deploy agents according to a user-defined deployment scheme.

2.2. Nuclear Deployment in the EU

The International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [11] contains worldwide reactor operation history. We import this database directly as a csv file, to populate the simulation with deployment information, listing the country, reactor unit, type, net capacity (Mega Watt electric (MWe)), status, operator, construction date, first criticality

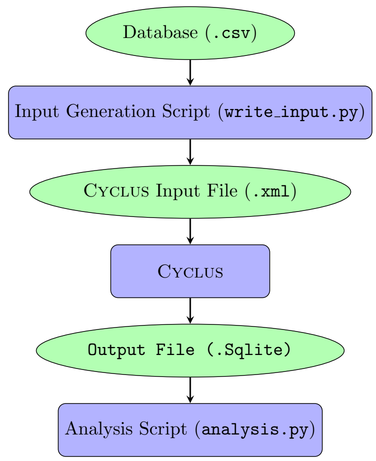

Figure 1: Computational workflow in this work. The green circles represent files, and the blue boxes represent codes that process the files.

date, first grid date, commercial date, shutdown date (if applicable), and unit capacity factor for 2013. Then only the EU countries are extracted from the csv file. We developed a python script to generate a Cyclus input file from the csv file, which lists the individual reactor units as agents.

Projections of future reactor deployment in this simulation are based on assessment of analyses from references such as PRIS for reactors planned for construction [11], the World Nuclear Association [12], and literature concerning the future of nuclear power in a global [13] and European context [14]. Existing projections extend to 2050.

Table 1 lists the reactors that are currently planned or under construction. In the simulation, all planned constructions are completed without delay or failure and are assumed to reach a lifetime of 60 years.

Table 1: Power Reactors under construction and planned. Replicated from [12].

Exp. Operational	**Country**	**Reactor**	**Type**	**Gross MWe**
2018	Slovakia	Mochovce 3	PWR	440
2018	Slovakia	Mochovce 4	PWR	440
2018	France	Flamanville 3	PWR	1600
2018	Finland	Olkilouto 3	PWR	1720
2019	Romania	Cernavoda 3	PHWR	720
2020	Romania	Cernavoda 4	PHWR	720
2024	Finland	Hanhikivi	VVER1200	1200
2024	Hungary	Paks 5	VVER1200	1200
2025	Hungary	Paks 6	VVER1200	1200
2025	Bulgaria	Kozloduy 7	[1]AP1000	950
2026	UK	Hinkley Point C1	EPR	1670
2027	UK	Hinkley Point C2	EPR	1670
2029	Poland	Choczewo	N/A	3000
2035	Poland	N/A	N/A	3000
2035	Czech Rep	Dukovany 5	N/A	1200
2035	Czech Rep	Temelin 3	AP1000	1200
2040	Czech Rep	Temelin 4	AP1000	1200

For each EU nation, we categorize the growth trajectory is categorized from "Aggressive Growth" to "Aggressive Shutdown". Aggressive growth is characterized by a rigorous expansion of nuclear power while Aggressive Shutdown is characterized as a transition to rapidly de-nuclearize the nation's electric grid. A nation's growth trajectory is categorized into five degrees depending on G, the growth trajectory metric.

[1]The fate of many planned reactors are uncertain. The proposed reactor types are also unclear. The ones marked 'N/A' for type are assumed to the Pressurized Water Reactors (PWRs) in the simulation.

$$G = \left\{ \begin{array}{ll} \text{Aggressive Growth,} & \text{for } G \geq 2 \\ \text{Modest Growth,} & \text{for } 1.2 \leq G < 2 \\ \text{Maintanence,} & \text{for } 0.8 \leq G < 1.2 \\ \text{Modest Reduction,} & \text{for } 0.5 \leq G < 0.8 \\ \text{Aggressive Reduction,} & \text{for } G \leq 0.5 \end{array} \right\} = \frac{C_{2040}}{C_{2017}}$$

$$G = \text{Growth Trajectory } [-]$$

$$C_i = \text{Nuclear Capacity in Year i } [MWe]$$

The growth trajectory and specific plan of each nation in the EU is listed in Table 2. Meanwhile, fig. 2 displays the timeseries of installed capacity in EU nations.

Table 2: Future Nuclear Programs of EU Nations [12]

Nation	**Growth Trajectory**	**Specific Plan**
UK	Aggressive Growth	13 units (17,900 MWe) by 2030.
Poland	Aggressive Growth	Additional 6,000 MWe by 2035.
Hungary	Aggressive Growth	Additional 2,400 MWe by 2025.
Finland	Modest Growth	Additional 2,920 MWe by 2024.
Slovakia	Modest Growth	Additional 942 MWe by 2025.
Bulgaria	Modest Growth	Additional 1,000 MWe by 2035.
Romania	Modest Growth	Additional 1,440 MWe by 2020.
Czech Rep.	Modest Growth	Additional 2,400 MWe by 2035.
France	Modest Reduction	No expansion or early shutdown.
Slovenia	Modest Reduction	No expansion or early shutdown.
Netherlands	Modest Reduction	No expansion or early shutdown.
Lithuania	Modest Reduction	No expansion or early shutdown.
Spain	Modest Reduction	No expansion or early shutdown.
Italy	Modest Reduction	No expansion or early shutdown.
Belgium	Aggressive Reduction	All shut down 2025.
Sweden	Aggressive Reduction	All shut down 2050.
Germany	Aggressive Reduction	All shut down by 2022.

2.3. French SFR Deployment Schedule

Figure 3 and 4 display the French transition to SFRs modeled in this simulation. Starting in 2040, France deploys 600-MWe SFRs to make up for decommissioned French LWR capacity. This results in an installed SFR capacity of 66,000 MWe by 2078 when the final LWR is decommissioned.

Figure 5 displays the total deployment scheme of the simulation. The steep transition from 2040 to 2060 reflects the scheduled decommissioning of reactors built in the 1975-2000 era of aggressive nuclear growth in France.

These figures reflect that, for the given assumptions, bursts of construction are necessary to maintain capacity. In reality, a construction rate of five reactors

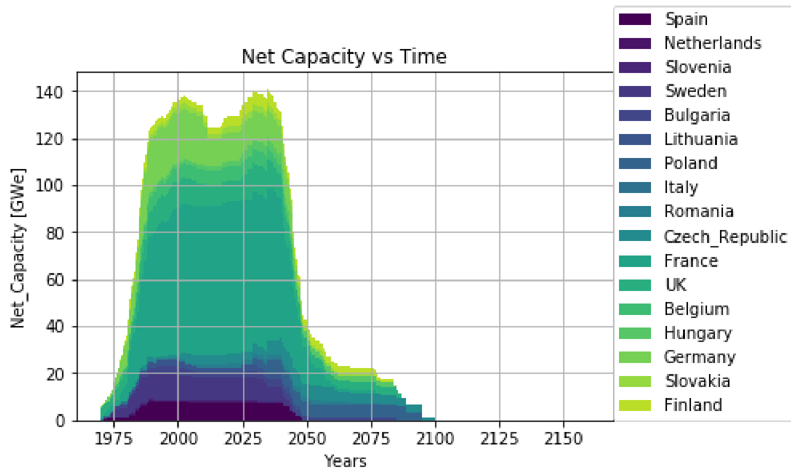

Figure 2: The timeseries of installed nuclear capacity in the EU is separated by `Regions` in CYCLUS. The sudden drops in capacity are caused by nuclear phaseout plans by nations such as Germany and Belgium.

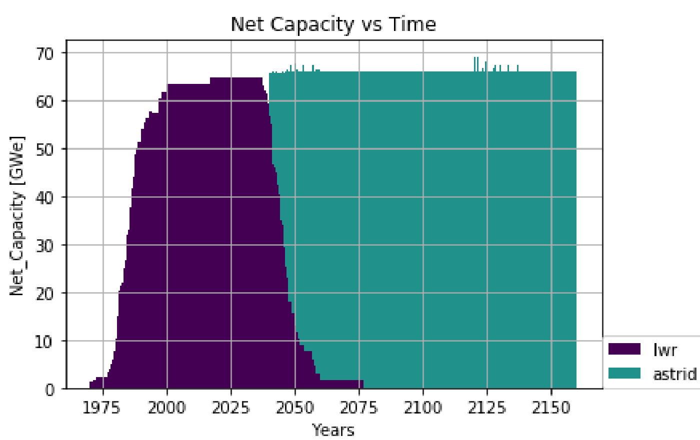

Figure 3: This plot shows the potential French transition from LWRs to SFRs. The aggressive growth of nuclear in the 1980s leads to a substantial shutdown of nuclear in the 2040s, which, in the simulation, are replaced by new SFRs. The net capacity is kept at a constant of 66 GWe.

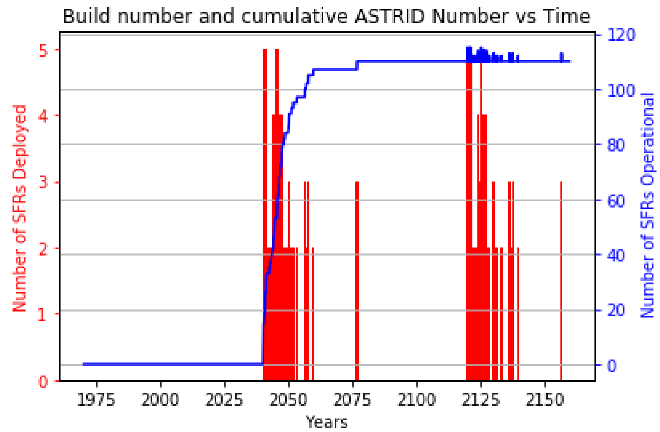

Figure 4: The deployment of SFRs in France is characterized by a period of aggressive building. Four reactors on average are built per year to make up for the decommissioned power plants built in the 1980s and 1990s. The second period of aggressive building occurs when the first generation of SFRs decommission after 80 years.

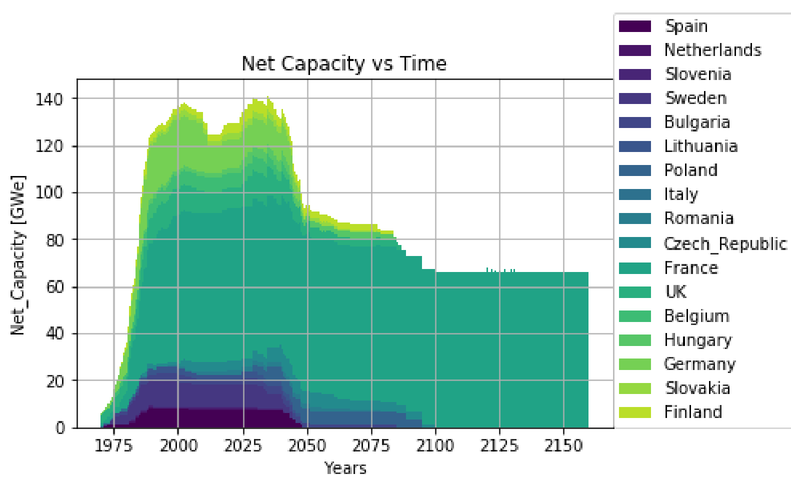

Figure 5: The total deployment scheme of the simulation. The historical operation EU reactors is followed by the French transition to SFRs.

every year is highly unrealistic. However, this analysis is to analyze material flow, and demonstrates that, if such an aggressive deployment scheme took place, the SFRs would have enough fuel. More realistically, the deployment of new SFRs can be spread out by staggering scheduled decommissioning of LWRs through lifetime extensions. For example, we increased the original lifetime of French LWRs (60 years) randomly by sampling from a uniform distribution from zero to 25 years. This results in a more moderate transition and ASTRID construction burden, as shown in figure **??** and **??**.

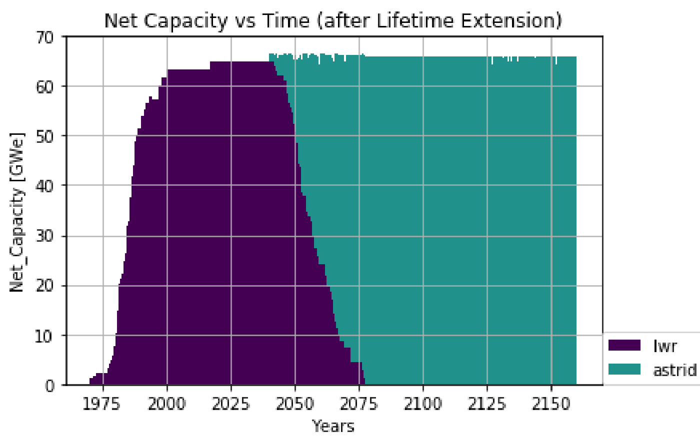

Figure 6: Transition to ASTRIDs becomes less gradual if the French LWRs are given lifetime extensions from a uniform distribution from zero to 25 years.

effect of LWR lifetime extension is discussed in Section 6.2.

2.4. Material Flow

The fuel cycle is represented by a series of facility agents whose material flow is illustrated in figure 8, along with the Cyclus archetypes that were used to model each facility.

A mine facility provides natural uranium, which is enriched by an enrichment facility to produce Uranium Oxide Fuel (UOX). Enrichment waste (tails) is disposed of to a sink facility representing ultimate disposal. The enriched UOX

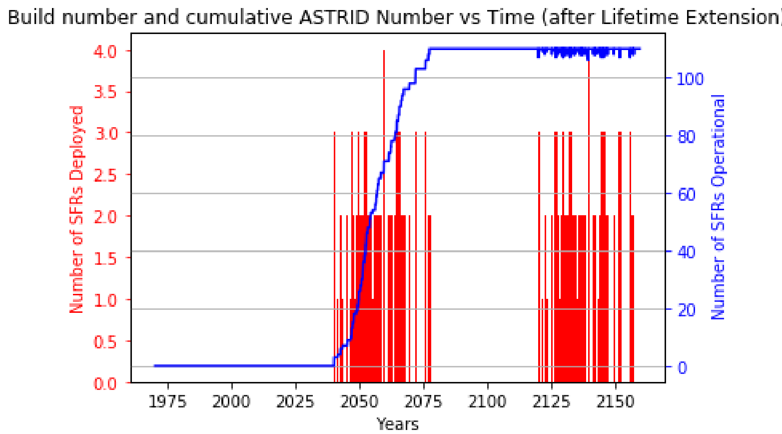

Figure 7: The construction burden of ASTRIDs lessen if the lifetime of French LWRs are extended by a uniform distribution from zero to 25 years.

fuels the LWRs which in turn produce spent UOX. The used fuel is sent to a wet storage facility to cool for at least 3 years [3].

The cooled fuel is then reprocessed to separate plutonium and uranium, or sent to the repository. The plutonium mixed with depleted uranium (tails) makes MOX. Reprocessed uranium is unused and stockpiled. Uranium is reprocessed in order to separate the raffinate (minor actinides and fission products) from usable material. Though neglected in this work, reprocessed uranium may substitute depleted uranium for MOX production. In the simulations, sufficient depleted uranium existed that using reprocessed uranium was overlooked. However, further in the future where the depleted uranium inventory drains, reprocessed uranium (or, natural uranium) will need to be utilized.

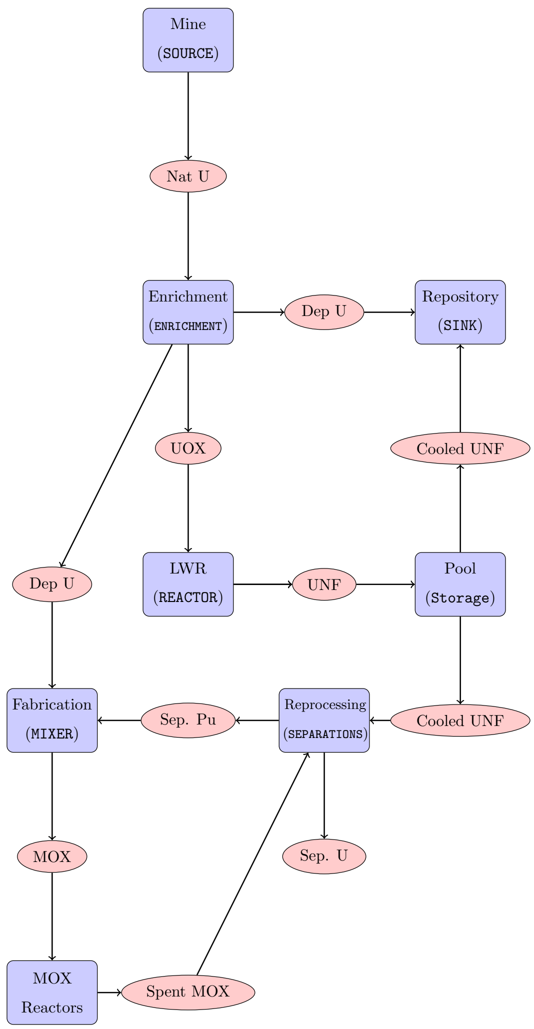

Figure 8: The blue boxes represent fuel cycle facilities, and the red ovals represent materials. The facility names in parenthesis are archetype names used in Cyclus. MOX Reactors include both French PWRs and SFRs.

3. Scenario Specifications

The scenario specifications are listed in table 3. The reprocessing and MOX fabrication capacity in France prior to 2020 is modeled after the French La Hague and MELOX sites [15, 16].

Table 3: Simulation Specifications

Specification	**Value**
Simulation Starts	1970
Simulation Ends	2160
Production of ASTRID fuel begins	2020
Year SFRs become available	2040
Reprocessed uranium usage	None. Stockpile reprocessed U
Used fuel cool time prior usage	36 months
Separation efficiency	99.8%
Reprocessing streams	plutonium and uranium
Reprocessing capacity before 2020	91.6 tonnes of UNF per month [15]
Reprocessing capacity after 2020	∞
LWR MOX fab. throughput	16.25 tonnes of MOX per month [16]
ASTRID MOX fab. throughput	∞
LWR MOX fuel rep. stage	Used MOX is not reprocessed.
ASTRID MOX fuel rep. stage	Used MOX is reprocessed infinitely.

4. Reactor Specifications

Three major reactors are used in the simulation, PWR, Boiling Water Reactor (BWR), and ASTRID-type SFR reactors.

For LWRs, we used a linear core size model to capture varying reactor capacity. For example, a 1,200 MWe PWR has $193 * \frac{1{,}200}{1{,}000} = 232$ UOX assemblies, each weighing 523.4 kg. After each 18 month cycle, one-third of the core (77 assemblies) discharges. Refueling is assumed to take two months to complete, during which the reactor is shut down. The specifications are defined in table 4 which details the reactor specifications in this simulation.

Table 4: Model LWR and ASTRID specifications used for the simulations are listed, and LWRs are modified linearly for varying power capacity.

Specification	**PWR [17]**	**BWR [18]**	**SFR [7]**
Lifetime [y] [2]	60	60	80
Cycle Time [mos.]	18	18	12
Refueling Outage [mos.]	2	2	2
Rated Power [MWe]	1000	1000	600
Assembly mass [kg]	523.4	180	–
Batch mass [kg]	–	–	5,568
Discharge Burnup [GWd/tHM]	51	51	105
Assemblies per core [3]	193	764	–
Batches per core	3	3	4
Initial Fissile Loading [t]	3.1 ^{235}U	4.2 ^{235}U	4.9 Pu
Fuel	UOX or MOX	UOX	MOX

[2] The simulated reactor lifetime reaches the licensed lifetime unless the reactor is shut down prematurely.

[3] Number of assemblies and corresponding LWR core masses are reported for a 1000-MWe core. Reactors with different core powers are modeled with a linear mass assumption.

4.1. Material Definitions

Depletion calculations of the nuclear fuel are recipe-based, such that a fresh and used fuel recipe is defined for each reactor type. For the compositions of the used fuel, a reference depletion calculation from ORIGEN is used (see table A.11). ORIGEN is a computer code system for calculating buildup, decay, and processing of radioactive materials [19] The recipe has also been used for repository performance modeling [20].

Table 5: Fresh fuel compositions used for the simulation [20, 7].

	Composition [%]		
Recipe	U-235	U-238	Pu
Fresh UOX Fuel	3.1	96.9	-
Fresh LWR MOX Fuel	0.2	90.7	9.1
Fresh ASTRID Fuel	0.2	77.7	22

5. Results

5.1. Nuclear Material Inventory

Table 6 lists EU material inventory in 2050. The materials continue to accumulate after 2050, but the UNF France receives before 2050 is most impactful for the feasibility of the transition.

Table 6: Nuclear material inventory in the EU in 2050 is summarized. The UOX in the simulation is either stored or reprocessed to create MOX

Category	**Value** [MTHM]	Specifics
UOX Loaded	158,794	UOX that is loade
MOX Loaded	6,671	MOX that is load
Used UOX Available for Reprocessing (EU except France)	**95,161**	Used UOX from a
Used UOX Available for Reprocessing(France)	**9,979**	Used UOX from a
Reprocessed French UOX	53654	French used UOX
Tails	979,463	(Tails generated a
Natural U Used	1,141,916	

Figures 9 and 11 show the accumulation of tails and used fuel over time in the EU. Tails accumulate as a by-product of uranium enrichment. For every ton of UOX fuel, about nine times of tails is produced. Spent fuel is discharged from reactors every refueling period. The entire core is discharged when the reactor decommissions. A total of about $1,000,000$MTHM of tails and $100,000$MTHM of UNF accumulate in 2050. Figure 10 shows the amount of fuel used in the EU.

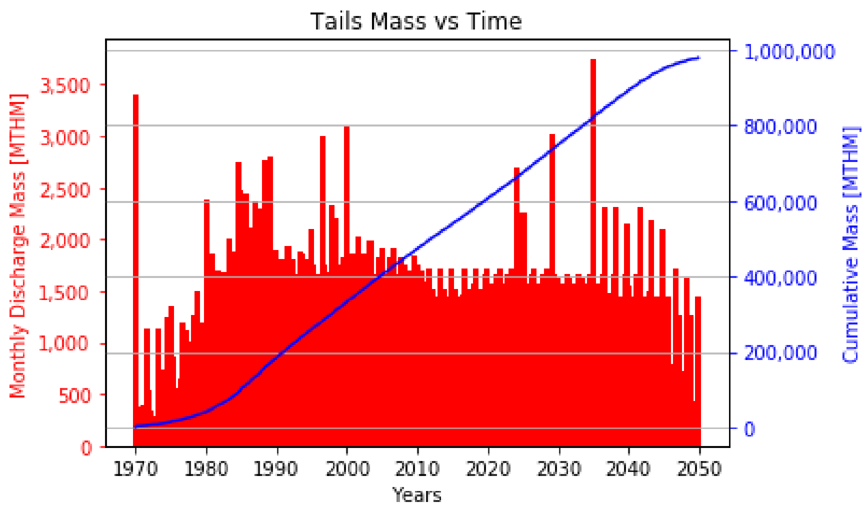

Figure 9: This plot shows the timeseries of tails mass accumulation and discharge in the EU nations. Tails mass accumulation is fairly steady, with peaks occurring when new reactors are deployed.

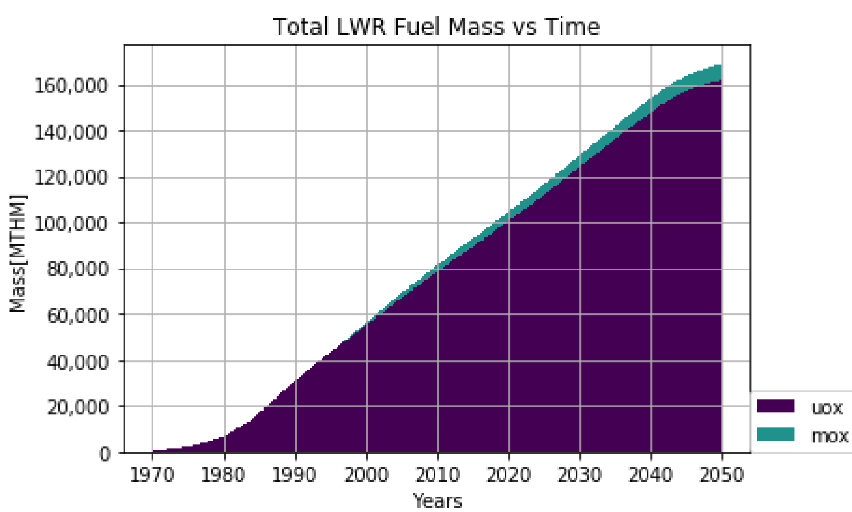

Figure 10: This plot shows the timeseries of total fuel usage in the EU nations.

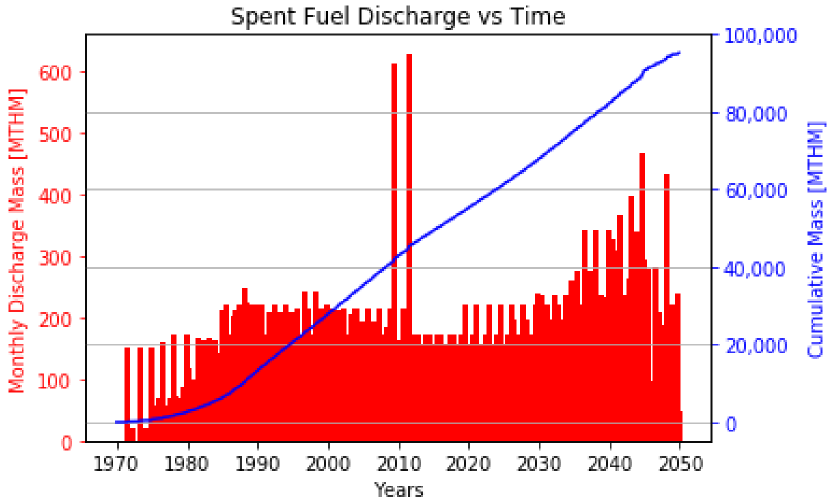

Figure 11: This plot displays the timeseries of UNF accumulation and discharge in the EU nations. The peaks are caused by decommissioning of reactors, where all the core is sent to the repository.

Table 7: Plutonium from UNF inventory.

Isotope	Mass Fraction in Used Fuel [%]	Quantity [t]
Pu238	0.0111	10.5628
Pu239	0.518	492.93
Pu240	0.232	220.7
Pu241	0.126	119.9
Pu242	0.0487	46.3
Total	**0.9358**	**890.5**

5.2. French SFR Deployment

Reprocessing UNF collected from all EU nations can start approximately 180 SFRs. Table 7 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory. With the SFR breeding ratio above one, France can transition into a fully SFR fleet without extra construction of LWRs.

From Varaine et al. [7], a French ASTRID-type 600MWe SFR consumes 1.225 tonnes of plutonium a year, with an initial plutonium loading of 4.9 tonnes. Thus, the number of SFRs that can be loaded with the reprocessed plutonium from UNF can be estimated to be 249, assuming infinite reprocessing and fabrication capacity as well as abundant depleted uranium supply.

Used MOX from an ASTRID reactor is 23.95% plutonium in this simulation (see table A.11), whereas a fresh MOX is 22% plutonium. The plutonium breeding ratio in this simulation is thus assumed to be ≈ 1.08.

Figure 12 shows MOX loaded in the SFRs per month. The spikes are due to initial fuel demand for new deployment of SFRs. The initial loading of new SFRs are done with the MOX created from legacy UNF. Once the deployed SFRs create enough amounts of extra plutonium, the legacy UNF is no longer used.

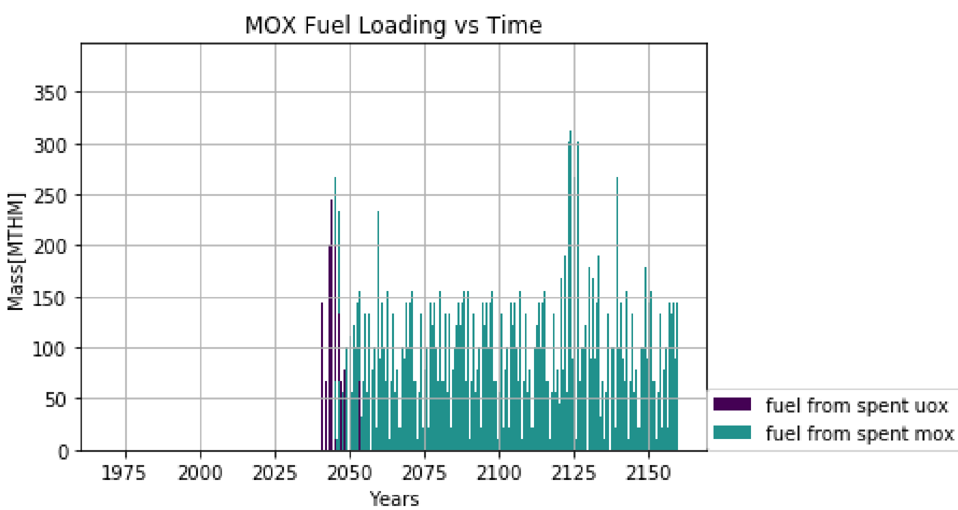

Figure 12: This plot shows the timeseries of fuel loaded into SFRs. The plot has peaks during a period of aggressive deployment of SFRs followed by an equilibrium at 150 MTHM. The peaks reoccur with the deployment of the second generation of SFRs.

Figure 13 shows the separated plutonium discharge per month from the reprocessing plant. The plutonium outflux does not precisely follow the fuel demand because Cyclus agents have material buffers that store commodity fuel for later usage. The reprocessed plutonium from legacy UNF is stored for the initial loading of SFRs. Table 8 lists metrics obtained from the second simulation.

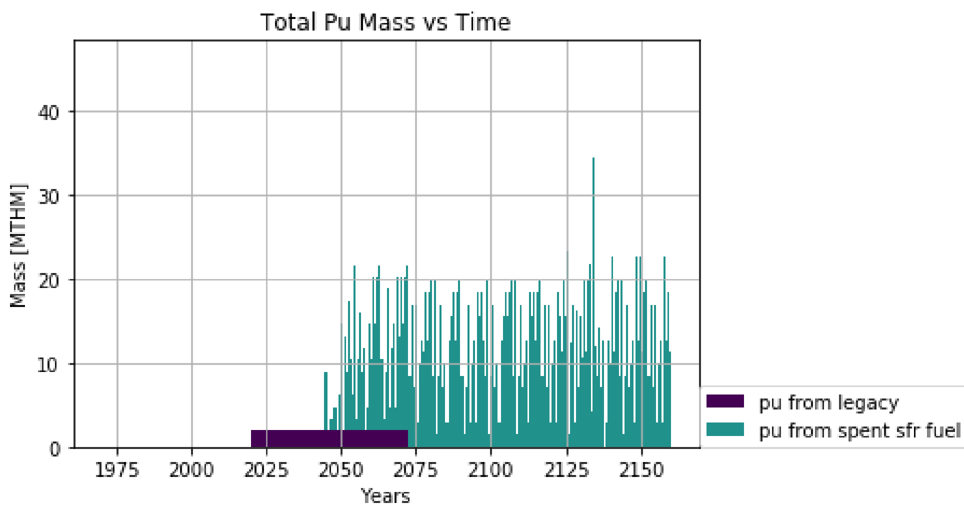

Figure 13: This plot shows the separated plutonium discharge from the reprocessing plant. The reprocessing demand for the first aggressive deployment of SFRs are lessened because the plutonium demand is met with plutonium separated from legacy UNF. The plutonium from reprocessing legacy fuel is a flat rectangle because the reprocessing throughput was set to 20 $\frac{tonnes}{month}$ to avoid reprocessing all the legacy in one timestep.

Despite the large amount of initial plutonium that has to be reprocessed prior to ASTRID deployment, the 20 years of preparation of ASTRID fuel (2020-2040) allows a reasonable level of average UOX reprocessing capacity demand. UOX reprocessing continues until 2057, when the ASTRID spent fuel can supply the plutonium for its own fuel.

Table 8: In the French transition to SFRs, the total legacy UNF reprocessed is the amount of UNF France needs for a transition into a fully SFR fleet.

Category	**Unit**	**Value**
Total MOX used	MTHM	63,820
Average UOX Reprocessing	MTHM/month	**118.92**
Average Total Reprocessing	MTHM/month	**73.27**
Average Fuel Fabrication	MTHM/month	**45.2**
Total SFRs Deployed		220
Total Plutonium Reprocessed	MTHM	15,099
Total ASTRID fuel from UOX Waste	MTHM	2,923
Total ASTRID fuel from MOX Waste	MTHM	60,535
Total Tails used	MTHM	49,779
Total legacy UNF reprocessed	MTHM	**54,111**
Total Reprocessed Uranium Stockpile	MTHM	183,740
Total Raffinate	MTHM	33,806

6. Sensitivity Analysis

An important aspect of any fuel cycle transition scenario is the accrual of fissile materials for new reactor deployment. The collaborative strategy makes a transition possible from the perspective of material availability, but the aggressive transition demands a significant increase in reprocessing capacity.

We explored the impact of two key variables, the lifetime of French LWRs and the breeding ratio of ASTRID reactors. The range over which we varied these parameters (table 9) sought to capture the full span of their uncertainty.

Table 9: Two parameters were varied for the sensitivity analysis - the lifetime of French LWRs and the breeding ratio of ASTRIDs. The parameters are increased to analyze their impact on the reprocessing demand for the transition.

Parameter	**Default**	**Values**
Breeding Ratio of ASTRIDs	1.08	1.11, 1.15, 1.18
Lifetime of French LWRs [years]	60	65, 70, 80

6.1. Breeding Ratio

Increase in the breeding ratio of ASTRID reactors decreases the monthly reprocessing demand, as shown in figure 14. Increase in breeding ratio also reduces the number of total UOX UNF required for the transition, because the ASTRID creates more plutonium.

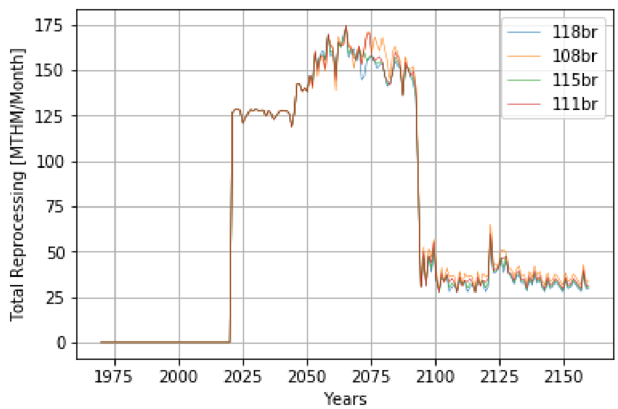

Figure 14: Increasing the breeding ratio decreases the monthly reprocessing demand. The demand up to 2050 is unaffected by breeding ratio because only UOX UNF is reprocessed.

6.2. Lifetime Extension of French LWRs

Extending the lifetime of French LWRs dramatically lowers the average monthly UOX reprocessing demand, since the ASTRID deployment becomes delayed (shown in figure 18). The plutonium demand is delayed, allowing the reprocessing plant more time to prepare plutonium for ASTRID reactors.

Figure 16 shows the decrease in the average monthly UOX reprocessing burden with increased LWR lifetimes, which reduces to the current capacity of the La Hague site if all the French LWRs extended their operation for 20 years. Figure 17 shows that lifetime extension has little effect on the average total monthly reprocessing demand, because the amount of plutonium in the ASTRID used fuel remains the same. The initial increase is caused by the delay of ASTRID deployment delaying the first ASTRID UNF reprocessing. The

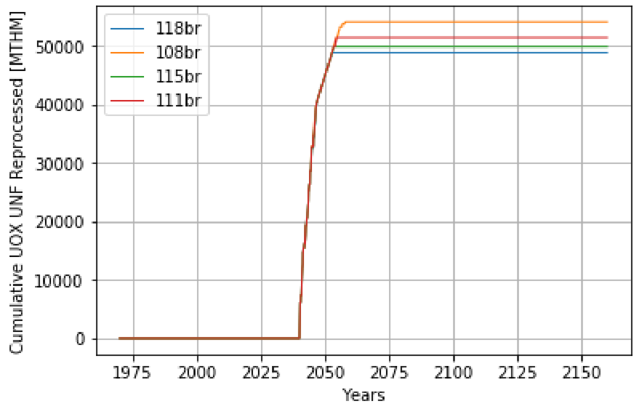

Figure 15: Increasing the breeding ratio decreases the number of total UOX UNF required. The ASTRIDs produce more plutonium, reducing the plutonium demand from reprocessed UOX.

period of which ASTRID UNF is reprocessed decreases, which increases the average.

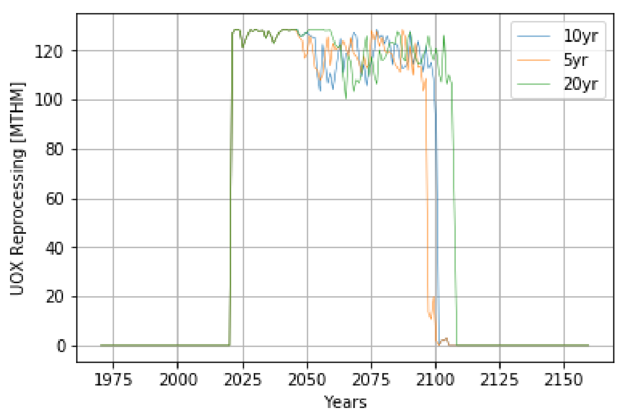

Figure 16: Increasing the lifetime of French LWRs decreases the monthly UOX reprocessing demand, by allowing a less aggressive transition to ASTRIDs.

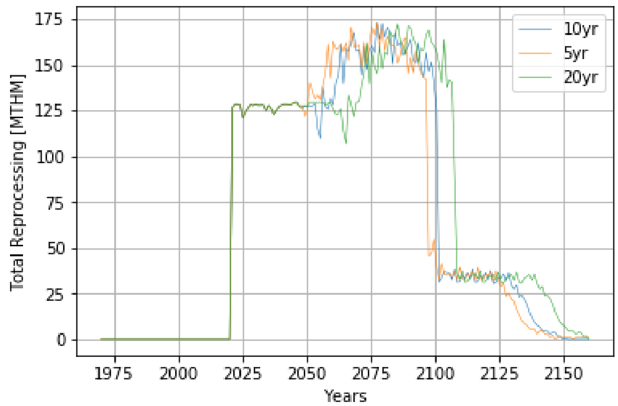

Figure 17: Increasing the lifetime of French LWRs simply delays the reprocessing demand, and has little impact on the amount of reprocessing required.

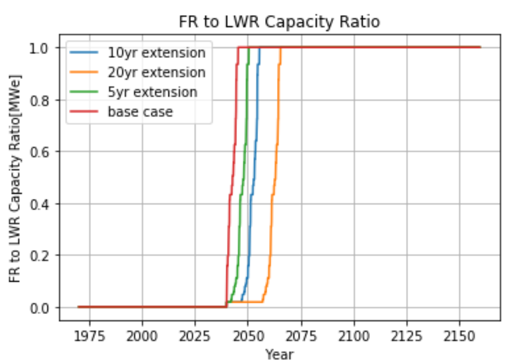

Figure 18: This plot shows the ratio of ASTRIDs to LWRs in France. The delay in ASTRID deployment allows more time for the reprocessing plant to prepare the plutonium for ASTRID fuel production.

7. Conclusion

This work demonstrates that France can transition into a fully SFR fleet with installed capacity of 66,000 MWe without building additional LWRs if France receives UNF from other EU nations. Supporting the SFR fleet requires an average reprocessing capacity of 73.27 MTHM per month, and an average fabrication capacity of 45.29 MTHM per month.

Since most EU nations do not have an operating UNF repository or a management plan, they have a strong incentive to send their UNF to France. In particular, the nations planning aggressive nuclear reduction will be able phase out nuclear without constructing a permanent repository. France has an incentive to take this fuel, since recycling used fuel from other nations will allow France to meet their MOX demand without new construction of LWRs.

Table 10 lists EU nations and their UNF inventory in 2050. We propose a strategy in which the nations reducing their nuclear fleet send their UNF to France. The sum of UNF from Italy, Slovenia, Belgium, Spain and Germany provides enough UNF for the simulated transition ($\approx 54,000$ MTHM). Sweden is not considered because of its concrete waste management plan.

In these simulations, some complex political and economic factors were not incorporated and various assumptions were present in this scenario (For example, Germany's current policy is to not reprocess its LWR fuel [21], which creates a shortage in the supply of LWR UNF for ASTRID MOX production). However, the collaborative option explored here may hold value for the EU nuclear community, and may enable France to advance more rapidly into a closed fuel cycle.

Table 10: EU nations and their respective UNF inventory. The bolded countries' UNF inventory adds up to the required UNF amount for French SFR transition.

Nation	**Growth Trajectory**	**UNF in 2050** [MTHM]
Poland	Aggressive Growth	1,807
Hungary	Aggressive Growth	3,119
UK	Aggressive Growth	13,268
Slovakia	Modest Growth	2,746
Bulgaria	Modest Growth	3,237
Czech Rep.	Modest Growth	4,413
Finland	Modest Growth	5,713
Netherlands	Modest Reduction	539
Italy	**Modest Reduction**	**583**
Slovenia	**Modest Reduction**	**765**
Lithuania	**Modest Reduction**	**2,644**
Belgium	**Aggressive Reduction**	**6,644**
Spain	**Modest Reduction**	**9,771**
France	**Modest Reduction**	**9,979**
Sweden	Aggressive Reduction	16,035
Germany	**Aggressive Reduction**	**23,868**

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Appendix A. Fresh and Used Fuel Composition

Isotope	Used ASTRID Fuel	Used UOX Fuel	Used MOX Fuel
He4	8.2631E-05	9.4745E-07	2.5108E-05
Ra226	2.306EE-13	9.7885E-14	6.8586E-14
Ra228	6.029EE-21	2.7508E-20	1.0769E-19
Pb206	5.2269E-18	5.5747E-18	3.6378E-18
Pb207	1.0722E-15	1.6859E-15	1.0589E-15
Pb208	4.4347E-10	3.6888E-12	2.0018E-12
Pb210	1.3841E-16	3.0238E-19	1.1829E-19
Th228	7.7910E-10	8.4756E-12	4.9017E-12
Th229	3.5259E-11	2.7278E-12	1.4379E-12
Th230	1.1419E-08	2.6258E-09	2.3998E-09
Th232	6.3415E-11	4.1748E-10	8.7655E-10
Bi209	2.5042E-13	6.6077E-16	2.6878E-16
Ac227	2.8317E-14	3.0968E-14	2.4608E-14
Pa231	8.8076E-10	9.2465E-10	7.0696E-10
U232	1.4693E-07	0.0000	5.9336E-10
U233	4.0461E-08	2.2139E-09	1.0359E-08
U234	0.0010	0.0001	0.0002
U235	0.0003	0.0076	0.0043
U236	0.0005	0.0057	0.0051
U238	0.5864	0.9208	0.8283
Np237	0.0038	0.0006	0.0043
Pu238	0.0096	0.0002	0.0060
Pu239	0.0981	0.0060	0.0410
Pu240	0.0890	0.0029	0.0283
Pu241	0.0155	0.0017	0.0146
Pu242	0.0273	0.0008	0.0098
Pu244	1.779EE-07	2.8648E-08	2.1888E-07
Am241	0.0077	6.4427E-05	0.0021
Am242m	0.0005	8.5336E-07	5.0357E-05
Am243	0.0091	0.0001	0.0020
Cm242	0.0004	2.5898E-05	0.0002
Cm243	0.0000	0.0000	1.2639E-05
Cm244	0.0067	8.5616E-05	0.0010
Cm245	0.0017	5.7217E-06	0.0001
Cm246	0.0009	7.2956E-07	6.1406E-06
Cm247	0.0000	0.0000	1.2059E-07
Cm248	4.0265E-06	7.6916E-10	9.1585E-09
Cm250	1.076EE-12	4.2808E-18	3.7338E-17
Cf249	1.6590E-07	1.6499E-12	4.0567E-11
Cf250	9.5219E-09	2.0419E-12	2.9328E-11
Cf251	3.2032E-10	9.8655E-13	1.4479E-11
Cf 252	8.3754E-12	6.5797E-13	7.5346E-12
H3	3.1829E-07	8.5846E-08	1.0269E-07
Kr81	1.5156E-11	4.2168E-11	7.3446E-11
Kr85	0.0000	3.4448E-05	2.0548E-05
Sr90	0.0009	0.0007	0.0004
Tc99	0.0029	0.0011	0.0011
I129	0.0009	0.0002	0.0003
Cs134	0.0001	0.0002	0.0002
Cs135	0.0051	0.0006	0.0009

Table A.11: Spent Fuel Compositions