Synergistic Spent Nuclear Fuel Dynamics Within the European Union

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1 Abstract

The French strategy recommended by 2012-2015 Commission Nationale d'Evaluation reports [?] emphasizes preparation for a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs). This paper uses Cyclus to explore the feasibility of using Used Nuclear Fuel (UNF) from other EU nations for French transition into a SFR fleet without additional construction of LWRs. A Cyclus simulation is run from 1950 to 2160 for EU to track the UNF mass and to determine the necessary reprocessing and mixed oxide (MOX) fabrication capacity to support the transition into SFRs. The study concludes that France can avoid deployment of additional LWRs by accepting UNF from other EU nations.

2 Introduction

This paper uses Cyclus, the agent-based simulator [3] to analyze the future nuclear inventory in the European Union. This paper focuses on the used fuel inventory in European Union (EU) member states in 2050, and analyzes a potential strategy of used fuel management. A major focus of this paper is to determine the extent to which France has an incentive to receive all the UNF from EU nations to create MOX. The MOX created will fuel French transition to a SFR fleet and may allow France to avoid building additional LWRs.

Past research, which focuses solely on France, has made the assumptions that additional LWRs, namely European Pressurized Reactorss (EPRs) are constructed in order to supply UNF required for MOX production [?], 9, [?]. There has been studies on implementation of partitioning and transmutation in a regional (European) context, with Accelerator-Driven Systemss (ADSs) and Gen-IV reactors [?]. There has been little attention in reprocessing legacy UNF from other EU nations to produce MOX for the newly deployed SFRs.

The present work finds that this collaborative strategy can reduce the need to construct additional LWRs in France.

3 Methodology

The work relies on CYCLUS, an agent-based simulator, to simulate the nuclear fuel cycle and track material flows in EU nations. The Power Reactor Information System (PRIS) open-source database from International Atomic Energy Agency (IAEA) was used to populate the simulation with deployment information. That database is imported as a csv file, listing the country, reactor unit, type, net capacity (MWe), status, operator, construction date, first criticality 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. A python script is written up to generate a CYCLUS input file from the csv file, which lists the individual reactor units as agents. After running the CYCLUS input file, the output file is analyzed by another python script. All the scrips and data used in this paper are available in `https://github.com/jbae11/transition-scenarios`.

Two CYCLUS simulations are run for this paper. The first simulation calculates how much used fuel and tailings EU nations accumulate from 1970 to 2050, as well as the amount of MOX that can be created with the UNF inventory. The paper models a once-through cycle for all EU nations with the exception of France. France can reprocess used uranium oxide (UOX) and MOX to produce MOX from reprocessed plutonium and depleted uranium (tailings). The simulation assumes MOX is reprocessed infinitely.

After obtaining the UNF inventory of all EU in 2050, the second simulation is run, where the UNF inventory is reprocessed and used as fuel for the newly deployed SFR reactors. The SFRs are deployed to make up for the decommissioned capacity of LWRs in France, to remain a constant installed capacity of 60,000 MWe up to 2160. SFR reactors in this paper models after the ASTRID reactor, and use MOX fuel created from 11% reprocessed plutonium and 89% tailings to a burnup of approximately 100 GWdth/t. The high burnup allows breeding of plutonium. Eventually, the entire fleet of SFRs are fueled by MOX created from recycled MOX.

3.1 Assumptions

This paper makes the following assumptions:

- SFR technology available for deployment in 2040
- Decay has no effect on reprocessing viability
- Reactor construction is always completed on time
- Separated uranium is stockpiled

- LWRs have a lifetime of 60 years, unless stated otherwise (early shutdown)
- Newly deployed SFRs have a lifetime of 80 years.
- (Only for SFR Case) Reprocessing and MOX fabrication begins in 2020.
- (Only for SFR Case) French nuclear capacity remains constant at 60,000 MWe
- (Only for SFR Case) Infinite reprocessing and fabrication capacity

3.2 Deployment Timeline

Projections of future reactor deployment in this simulation were assessed based on analysis from references such as PRIS for reactors planned for construction [5], the World Nuclear Association and two other papers for future plans in EU nations [1, 7, 2]. The projections extend to 2050 at the latest. This allows the simulation to take place from 1970 to 2050, the latest foreseeable future. The specific plans for each EU nation are explained in detail in later sections.

It is also assumed that all reactors that are currently operating have a lifetime of 60 years, unless their government plans early shutdown. This will approximate when and how many SFRs need to be built to make up for the shutdown of LWRs.

3.3 French SFR Deployment Schedule

From 2040, when SFRs become available, 600-MWe SFRs are deployed to make up for the decommissioned LWR capacities. Note that a second separate simulation is run to emphasize France apart from all other EU nations.

Initially in 2040, 22 SFRs are deployed for the previously decommissioned LWRs. From then, SFRs are deployed to make up for the decommissioned LWR capacity. This results in an installed capacity of 60,000 MWe of SFR by 2076.

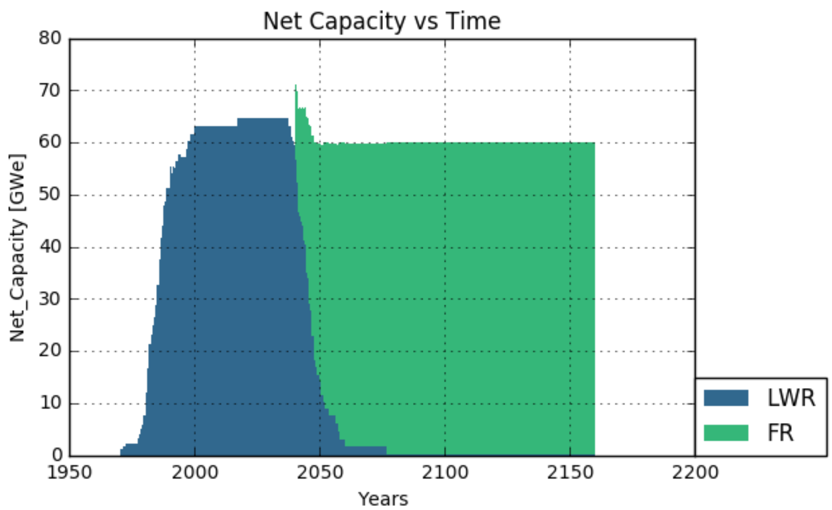

Figure 1: French Transition into an SFR Fleet

Figure 1 displays the French transition into SFRs over time. The steep transition from 2035 to 2060 is due mainly to French aggressive growth from 1975 to 2000. Note the jump in 2040 is due to an attempt to make up for the gap between the mass decommission of old LWRs and the availability of SFRs.

3.4 Depletion Calculations

Depletion calculations of the nuclear fuel are recipe-based, such that a fresh and used fuel recipe is used for each reactor type. For the compositions of the fuel, a reference depletion calculation from ORIGEN is used (see table 10). The recipe has also been used for [11].

3.5 Scenario Descriptions

The simulation follows the model fuel cycle, where a 'source' provides natural uranium, which is enriched by an 'enrichment' facility to produce UOX, while disposing enrichment waste (tailings) to the 'sink' facility. The enriched UOX is used in the LWRs and UOX waste is produced. The used fuel is then reprocessed to separate plutonium and uranium. The plutonium is mixed with depleted uranium (tailings) to MOX. The reprocessed uranium is stockpiled. The cycle is illustrated in fig. 2.

The second scenario separates plutonium from the UNF inventory from the previous simulation. The separated plutonium is mixed with the depleted uranium inventory from the previous simulation to create MOX, which is used

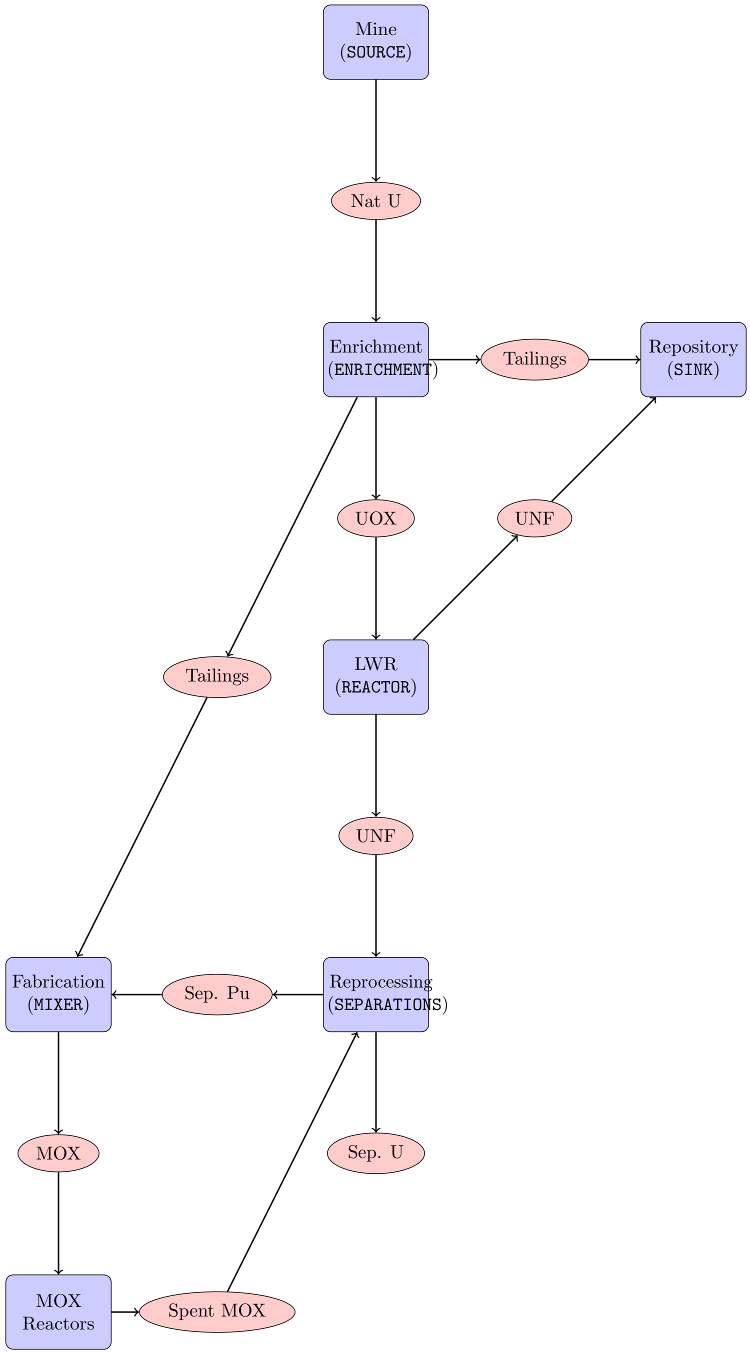

Figure 2: Model Fuel Cycle with MOX Reprocessing

in the SFRs. The used MOX is also reprocessed to extract plutonium, which is also mixed with depleted uranium to produce MOX.

3.6 Reprocessed Uranium

Reprocessed uranium contains a range of uranium isotopes, from ^{232}U to ^{238}U. This brings complications in reusing reprocessed uranium as a fuel source [6]. The presence of neutron-absorbing isotopes, ^{234}U and ^{236}U, requires reprocessed uranium to be enriched to have a higher concentration of ^{235}U. There are trace amounts (2 ppb) of fissile isotope ^{233}U, which provides little benefit. Also, ^{232}U has a decay chain of short-lived daughter products that undergo intense beta and gamma radiation. The French nuclear program utilizes a fraction (1/3) of reprocessed uranium as fuel [6]. However for this simulation the reprocessed uranium is simply stockpiled.

4 Scenario Specifications

Two simulations are run for this paper. The first simulation is a historical operation of EU reactors, with a realistic reprocessing and MOX fabrication capacity, modeled after the French La Hague and MELOX site [10, 4]. The second simulation is an ideal French Transition scenario to SFR, where an ASTRID-type SFR is deployed to make up for the decommissioned capacity of LWRs in France. The specifications of the simulations are listed in tables 1 and 2.

Specification	Value
Simulation Time	1970-2050
Reprocessing Capacity	91.6 MTHM of UNF per month [10]
Reprocessing Efficiency	99.8%
Reprocessing Streams	Plutonium and Uranium
MOX Fabrication	9% Reprocessed Pu + 91% Depleted U
MOX Fabrication Throughput	16.25 MTHM of MOX per month [4]
MOX Fuel Reprocessing Stage	Used MOX gets reprocessed infinitely.
Reprocessed Uranium Usage	None. Stockpile reprocessed U

Table 1: Specification for Historical Operation of EU Case

5 Reactor Specifications

Two major reactors are used in the simulation, Pressurized Water Reactor (PWR) and ASTRID - type reactors. For simplicity, the few Boiling Water Reactorss (BWRs) in the EU fleet are assumed to be PWRs.

For PWRs, a linear core size model was assumed to capture varying reactor capacity. For example, a PWR of 1,330 MWe capacity has 257 assemblies UOX.

Specification	Value
Simulation Time	1970-2160
SFR Available Year	2040
Reprocessing Capacity	infinite
Reprocessing and Fabrication Begins	2020
Reprocessing Efficiency	99.8 %
Reprocessing Streams	Plutonium and Uranium
Used UOX and Depleted U Inventory	Mass from first simulation
Additional Used UOX or Depleted U	None
MOX Fabrication	11% Reprocessed Pu + 89% Depleted U
MOX Fabrication Throughput	infinite
MOX Fuel Reprocessing Stage	Used MOX gets reprocessed infinitely.
Reprocessed Uranium Usage	None. Stockpile reprocessed U.

Table 2: Specification for French Transition to SFR case

with each assembly a mass of 523.4 kg. The core has a 18 month cycle, where one-third of the core (85 assemblies) are discharged per refueling. The refueling is assumed to take 2 months to complete, during which the reactor is shut down. The specifications are defined in table 3.

For the SFR, a model design is adopted from Marsault-Marie-Sophie et al. [8]. The specifications are defined in table 4.

Specification	Value
PWR Cycle Time	18 months
PWR Refueling Outage	2 months
Fuel Mass per Assembly	523.4 kg
Burnup	51 GWd/tons
Num. of Aseem. per Core	257 for 1,330 MWe, linearly adjusted
Num. of Assem. per Batch	1/3 of the core
Fuel	French PWRs prefer MOX but also accept UOX

Table 3: PWR Specifications

6 Current Status

The current status of the EU reactors can be identified easily in an IAEA PRIS database [5]. The acquired csv file from PRIS is then used to create a Cyclus input file.

Specification	Value
SFR Cycle Time	12 months
SFR Refueling Outage	2 months
Fuel Mass per Batch	11,136 kg
Batch per Core	4
Power Output	600 MWe
lifetime	80 years
Fuel	MOX (89% Tailings, 11% Separated Pu)

Table 4: SFR ASTRID Specifications
[8]

7 Future Nuclear Projections

The future of nuclear energy in EU nations is organized in the table by the World Nuclear Association [1]. It is assumed in the simulations that all the planned constructions are completed in their expected date without delay or failure. Also, the newly constructed nuclear power plants are assumed to have a lifetime of 60 years.

Table 5 lists the reactors that are currently planned or under construction.

Table 5: Power Reactors under construction and planned [1]

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	AP1000?	950
2026	UK	Hinkley Point C1	EPR	1670
2027	UK	Hinkley Point C2	EPR	1670
2029	Poland	Choczewo?	N/A	3000
2035	Poland	East?	N/A	3000
2035	Czech Rep	Dukovany 5	?	1200
2035	Czech Rep	Temelin 3	AP1000?	1200
2040	Czech Rep	Temelin 4	AP1000?	1200

For each EU nation, 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 spectra:

- Aggressive Growth
- Modest Growth

- Maintenance
- Modest Reduction
- Aggressive Reduction

The growth trajectory and specific plan of each nation in the EU is listed in Table 6.

Nation	Growth Trajectory	Specific Plan
UK	Aggressive Growth	13 units (17,900 MWe) by 2030.
Poland	Aggressive Growth	Additional 6,000 MWe by 2035.
Finland	Modest Growth	Additional EPR in 2018, VVER in 2024.
Bulgaria	Modest Growth	Additional AP1000 (1,000 MWe) construction in 2035.
Romania	Modest Growth	Additional 1,440 MWe by 2020.
Hungary	Modest Growth	Additional 2,400 MWe (VVER-1200) by 2025.
Czech Rep.	Modest Growth	Additional 2,400 MWe (AP1000s) by 2035.
Spain	Maintenance	No plans to expand or early shutdown.
Italy	Maintenance	No plans to expand or early shutdown.
France	Maintenance	Shutdown nuclear plants if they reach end of lifetime. No new construction.
Belgium	Aggressive Reduction	All shut down 2025.
Sweden	Aggressive Reduction	All shut down 2050.
Germany	Aggressive Reduction	All shut down by 2022.

Table 6: Future Nuclear Programs of EU Nations [1]

let's discuss how to discuss results.

8 Results

8.1 Historical Operation of EU Reactors

Table 7 lists the important metrics obtained from the first simulation. The following values are the EU inventory and history at year 2050.

not a result, more like an input definition

Figures 3 and 4 display the timeseries of number of reactors and installed capacity in EU nations.

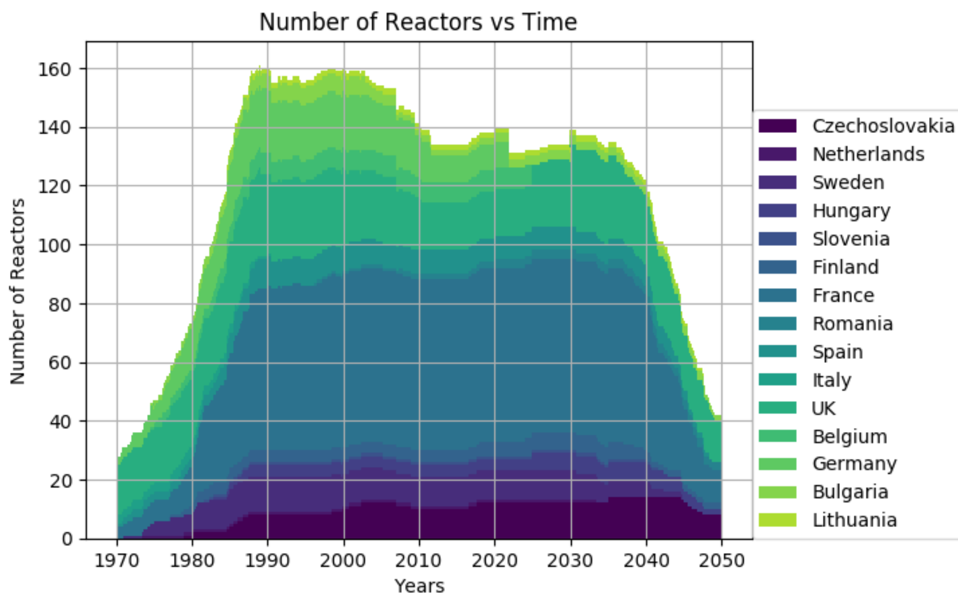

Figure 3: Timeseries of number of reactors in EU.

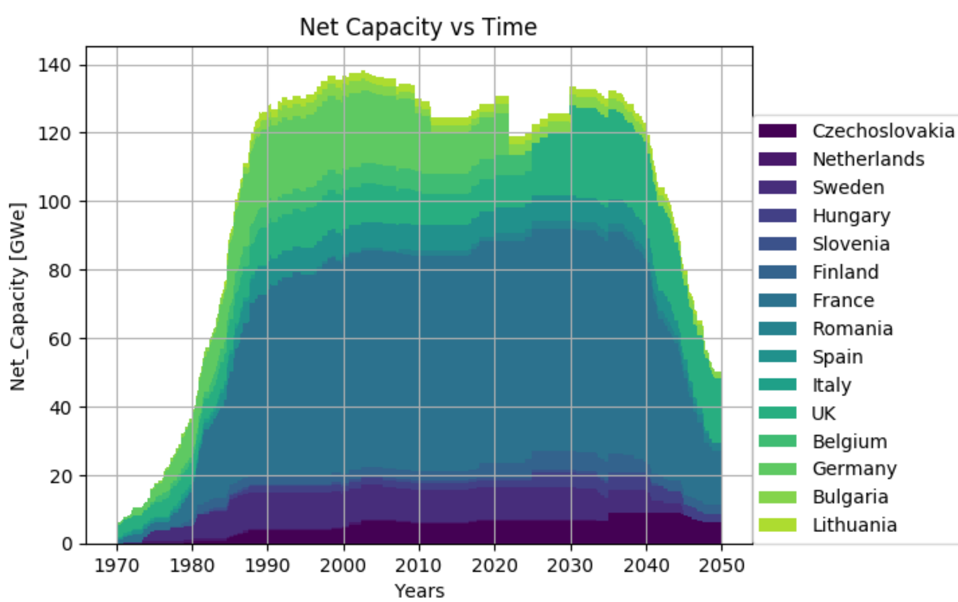

Figure 4: Timeseries of installed nuclear capacity in EU.

Category	Unit	Value	Specifics
Total UOX Usage	MTHM	178,865	
Total MOX Usage	MTHM	8,909	
Total Used UOX Stored	MTHM	157,472	UNF that are not reprocessed
Total Used MOX Stored	MTHM	679	UNF that are not reprocessed
Total Tailings	MTHM	1,063,909	
Total Natural U Used	MTHM	1,251,658	

Table 7: Simulation Results for Historical Nuclear Operation of EU Nations

Figures 5 and 7 show the timeseries of mass of tailings and used fuel accumulation in EU.

Figure 6 shows the amount of fuel used in EU.

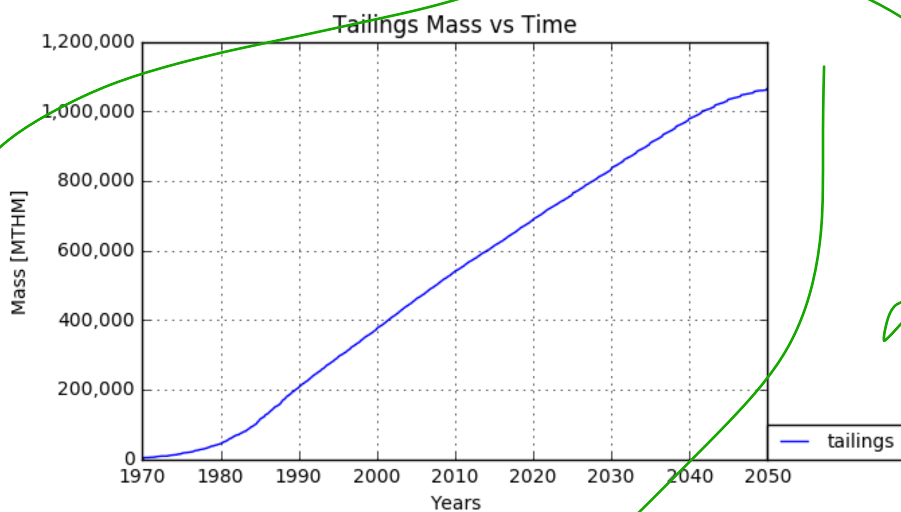

Figure 5: Timeseries of Tailings Mass in the EU.

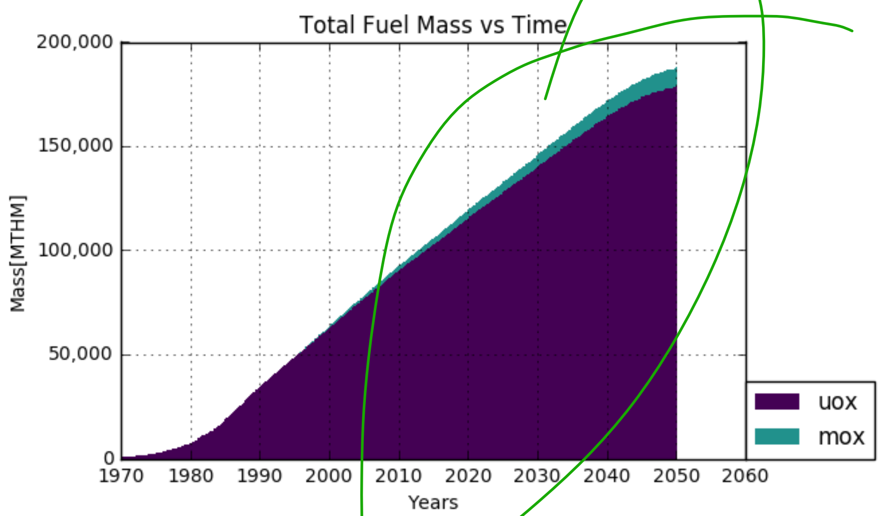

Figure 6: Timeseries of Total Fuel Usage in EU.

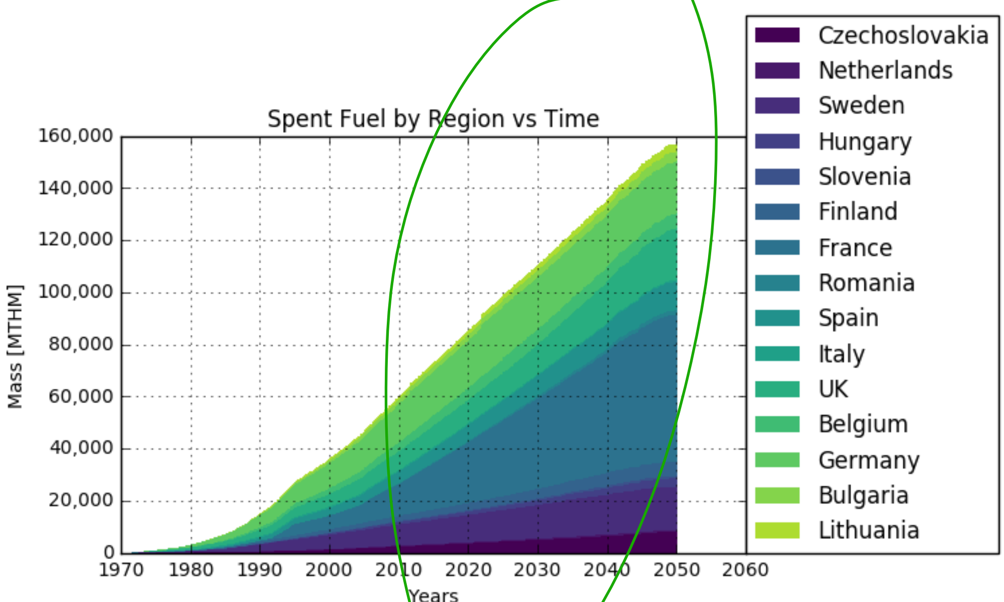

Figure 7: Timeseries of Used Nuclear Fuel in EU.

Isotope	Mass Fraction in Used Fuel [%]	Quantity [t]
Total	.9358	1,473
Pu238	.0111	17.47
Pu239	.518	815.7
Pu240	.232	365.33
Pu241	.126	198.41
Pu242	.0487	76.68

Table 8: Plutonium From Used Fuel

To create MOX for an ASTRID, 11% Pu and 89% depleted uranium is used. Thus $1,473$ tons of plutonium yields $13,390$ tons of MOX. Table 8 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory.

8.2 French SFR Transition Scenario

From Varaine et al. [8], a French ASTRID-type SFR of capacity 600 MWe needs 1.225 tons of plutonium a year, with an initial plutonium loading of 4.9 tons. Thus, the number of SFRs that can be loaded with the reprocessed plutonium from UNF can be estimated to $\frac{1,473}{4.9} \approx 300$ SFRs, assuming infinite reprocessing and fabrication capacity as well as abundant depleted uranium supply.

Also, assuming that MOX can be recycled indefinitely, used MOX from an ASTRID reactor contains enough plutonium to produce a MOX fuel with the same mass, if mixed with depleted uranium. For example, used MOX from an ASTRID reactor is assumed to be 12.6% plutonium in this simulation (see table 10), whereas a fresh MOX is 11% plutonium. Separating plutonium from used MOX from an ASTRID reactor can create MOX of the mass of used MOX. The plutonium breeding ratio in this simulation is thus assumed to be ≈ 1.145.

The second scenario, with the tailings and used UOX inventory, evaluates if the French can transition into SFR without constructing additional LWRs. This simulation assumed infinite reprocessing and fabrication capacity.

Figure 8 shows the timeseries mass of MOX used in the SFRs separated by their origin. Note that the plot shows MOX accumulation prior to SFR deployment from 2020.

Figure 10 shows the amount of reprocessing waste (minor actinides, fission products) over time. Note that reprocessing waste from UOX reprocessing is substantially greater than waste from MOX reprocessing due to its lower plutonium and uranium content.

Figure 9 shows the isotopics of the plutonium that are reprocessed from the used fuel inventory.

9 Discussion

This work demonstrated that, given infinite reprocessing and MOX fabrication capacities, France, by receiving UNF from other EU nations, can transition into

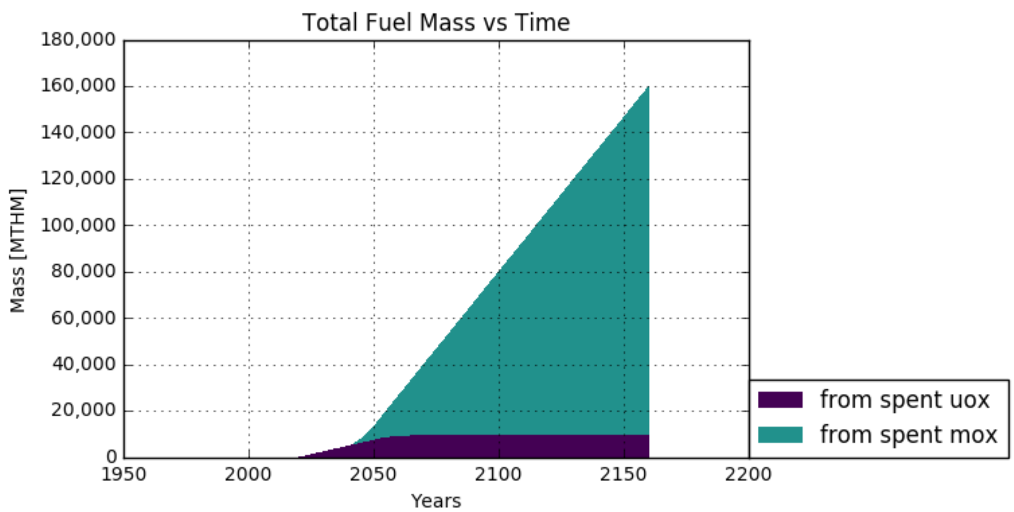

Figure 8: Timeseries of fuel used in the SFRs [tons]

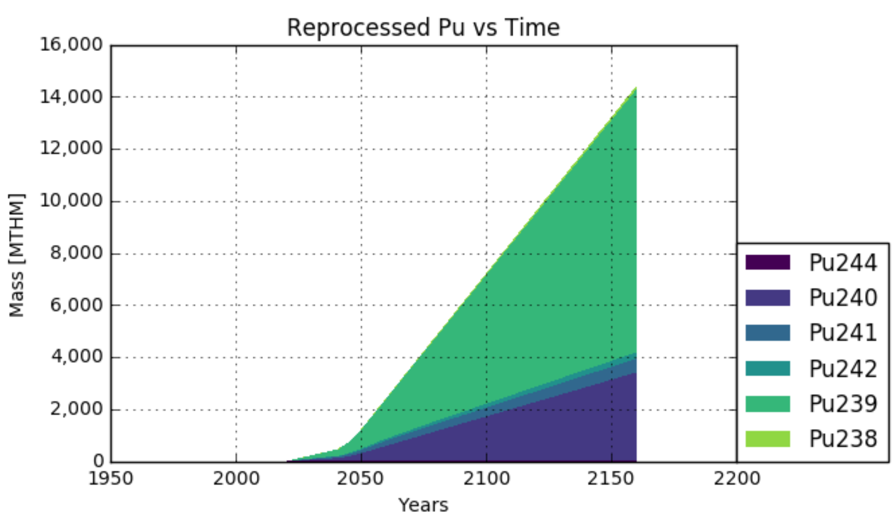

Figure 9: Plutonium timeseries separated by isotope

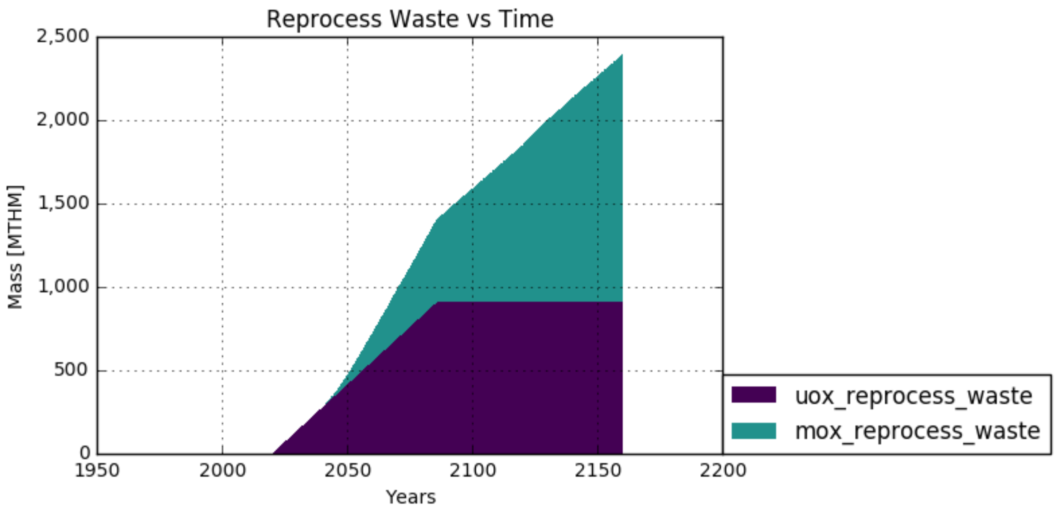

Figure 10: Reprocessing Waste for French Transition Scenario.

Category	Unit	Value
Total MOX used	MTHM	116,115
Total SFRs Deployed		200
Total Plutonium Reprocessed	MTHM	14,414
Total MOX from UOX Waste	MTHM	9,729
Total MOX from MOX Waste	MTHM	150,426
Total Tailings used	MTHM	105,664
Total legacy UNF reprocessed	MTHM	97,298
Total Reprocessed Uranium Stockpile	MTHM	251,100
Total Reprocess Waste	MTHM	14,414

Table 9: SFR Simulation Results

a full SFR fleet with installed capacity of 60,000 MWe by 2076. The initial fuel demand is filled by MOX from reprocessed UNF, which later on will be met by MOX created from recycled MOX.

Since most EU nations do not have an operating UNF repository or a management plan, they have a strong incentive to send all their UNF to France. Especially, the nations with aggressive nuclear reduction can phase out nuclear without constructing a High Level Waste repository. France has a financial incentive to take this fuel, since reuse of used fuel from other nations will allow France to meet their MOX demand without new construction of LWRs.

Though complex political and economic factors have not been addressed, and various assumptions were made for this scenario, this option may hold value for the EU as a nuclear community, and for France to advance into a closed fuel cycle.

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10 Fresh and Used Fuel Composition

Isotope	Fresh UOX Fuel	Spent UOX Fuel (BU: 51 $\frac{GWdth}{MTHM}$)	Fresh SFR Fuel	Spent SFR Fuel
He4		9.474E-07		7.827E-06
Ra226		9.788E-14		5.151E-14
Ra228		2.750E-20		4.904E-21
Pb206		5.574E-18		1.210E-18
Pb207		1.685E-15		1.892E-16
Pb208		3.688E-12		5.875E-11
Pb210		3.023E-19		8.143E-18
Th228		8.475E-12		1.004E-10
Th229		2.727E-12		4.065E-12
Th230		2.625E-09		2.139E-09
Th232		4.174E-10		4.425E-11
Bi209		6.607E-16		2.600E-14
Ac227		3.096E-14		4.840E-15
Pa231		9.246E-10		1.300E-10
U232		0.000		0.000
U233		2.213E-09		5.528E-09
U234	0.000	0.000		0.000
U235	0.032	0.007	0.002	0.000
U236		0.005		0.000
U238	0.968	0.920	0.887	0.808
Np237		0.000		0.000
Pu238		0.000	0.001	0.001
Pu239		0.006	0.060	0.085
Pu240		0.002	0.027	0.027
Pu241		0.001	0.014	0.003
Pu242		0.000	0.005	0.001
Pu244		2.864E-08	1.508E-07	5.461E-09
Am241		6.442E-05		0.001
Am242m		8.533E-07		7.961E-05
Am243		0.000		0.000
Cm242		2.589E-05		5.331E-05
Cm243		0.000		3.242E-06
Cm244		8.561E-05		0.000
Cm245		5.721E-06		3.936E-05
Cm246		7.295E-07		1.434E-05
Cm247		0.000		5.317E-07
Cm248		7.691E-10		0.000
Cm250		4.280E-18		6.407E-15
Cf249		1.649E-12		6.446E-10
Cf250		2.041E-12		6.703E-11
Cf251		9.865E-13		1.903E-12
Cf 252		6.579E-13		4.014E-14
H3		8.584E-08		1.747E-07
C14		4.057E-11		
C Other				
Kr81		4.216E-11		8.038E-12
Kr85		3.444E-05		2.950E-05
Kr Other		0.000		0.000
Sr90		0.001		0.001
Sr Other		0.000		0.000
Tc99		0.000		5.391E-05
Tc Other		0.000		0.002

Table 10: Fresh and Spent Fuel Compositions