Synergistic Spent Nuclear Fuel Dynamics Within the European Union

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1 Abstract

The French 2012-2015 Commission Nationale d'Evaluation reports [1] emphasize 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 ran from 1950 to 2160 for EU to track the UNF mass and tails inventory to support the transition into SFRs (66GWe - 110 SFRs). The study concludes that France can avoid deployment of additional LWRs by accepting UNF from other EU nations.

These simulations demonstrate

2 Introduction

We used Cyclus to analyze the future nuclear inventory in the European Union. Cyclus is an agent-based extensible framework for modeling the flow of material through future nuclear cycles [7]. This paper focuses on the used fuel inventory in European Union (EU) member states in 2050, and focuses on 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 mixed oxide (MOX). The MOX created will fuel French transition to a SFR fleet and allows France to avoid building additional LWRs.

Rewrite

Past research focused solely on France typically assumes that ~~additional~~ LWRs, namely European Pressurized Reactors (EPRs) supply UNF to produce MOX [3, 12, 5]. Studies exist on implementation of partitioning and transmutation in a regional (European) context, with Accelerator-Driven Systemss (ADSs) and Gen-IV reactors [4]. There is little attention paid to 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

The nuclear history of EU nations are modeled~~,~~ using the Power Reactor Information System (PRIS) open-source database from International Atomic Energy Agency (IAEA). That database is imported as a csv file~~,~~ to populate the simulation with deployment information. It lists ~~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, another python script analyzes the output file. All the scripts and data used in this paper are available in https://github.com/jbae11/transition-scenarios.

diagram

No

Two CYCLUS simulations are run for this paper. The first simulation calculates the mass and composition of used fuel and tails EU nations accumulate from 1970 to 2050, as well as the amount of MOX that the UNF inventory creates. All EU nations with the exception of France adopt~~s~~ a once-through fuel cycle. France can reprocess used uranium oxide (UOX) and MOX to produce ~~MOX from~~ reprocessed plutonium and depleted uranium (tails). The simulation assumes infinite MOX reprocessing.

This is ambiguous with capacity

After obtaining the UNF inventory of ~~all EU~~ in 2050, the second simulation runs where the UNF inventory is reprocessed and used as fuel for the newly deployed SFR reactors. SFR reactors in this paper model after the ASTRID reactor. ASTRID-type SFRs make up for the decommissioned capacity of LWRs in France, to remain a constant installed capacity of 66,000 MWe up to 2160. ~~It is assumed that~~ ASTRID-type reactors use MOX fuel created from 11% reprocessed plutonium and 89% tails and burns the MOX fuel to approximately 100 GWdth/t. The high burnup allows breeding of plutonium. Eventually, the MOX created from recycled MOX fuels the entire fleet of 110 SFRs.

These

3.1 Assumptions

bullets table ✓ paragraph ✓

The simulation ran for this paper had the following assumptions:

- SFR technology is available for deployment in 2040.
- Decay is not taken into account.
- Reactor construction is always completed on time.
- Separated uranium is unused and stockpiled.
- LWRs have an assumed lifetime of 60 years, unless shut down prematurely.
- Newly deployed SFRs have a lifetime of 80 years.
- Additional assumptions in the SFR case include:
  - Reprocessing and MOX fabrication begins in 2020.

– French nuclear capacity remains constant at 66,000 MWe.
– Reprocessing and fabrication capacity is unlimited.

3.2 Deployment Timeline

Projections of future reactor deployment in this simulation is based on assessment of analyses from references such as PRIS for reactors planned ~~for construction~~ [9], the World Nuclear Association and two other papers for future plans in EU nations [2, 10, 6]. The projections extend to 2050 at the latest. This allows the simulation to take place from 1970 to 2050, the latest foreseeable future. Later sections explain, in detail, the specific plans for each EU nation. ? NO

Figure 1 displays the timeseries of installed capacity in EU nations.

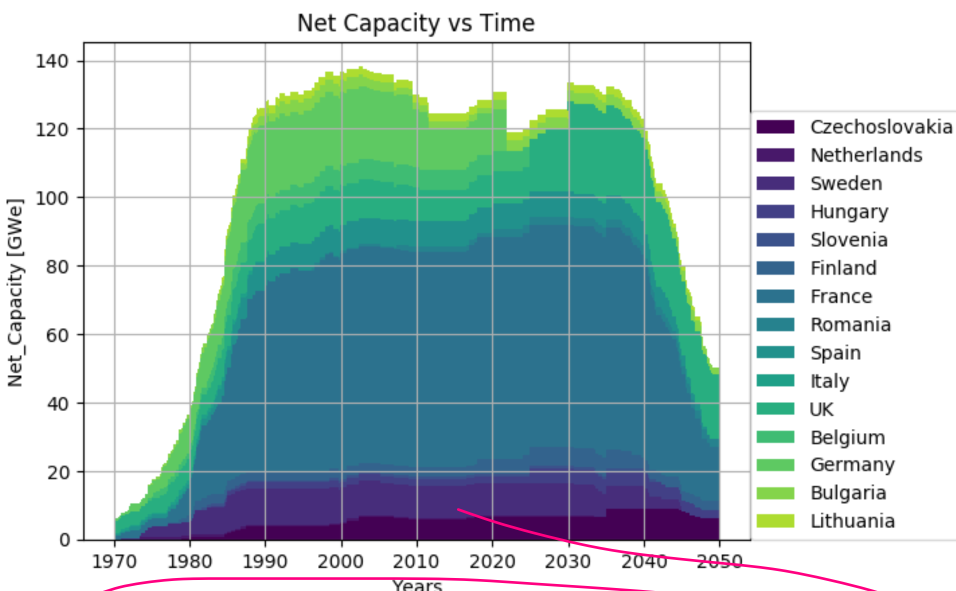

Figure 1: Timeseries of installed nuclear capacity in EU.

3.3 French SFR Deployment Schedule

Once SFRs become available, in 2040, 600-MWe SFRs are deployed to make up for the decommissioned LWR capacities. This results in an installed capacity of 66,000 MWe of SFR by 2076, when the last LWR decommissions.

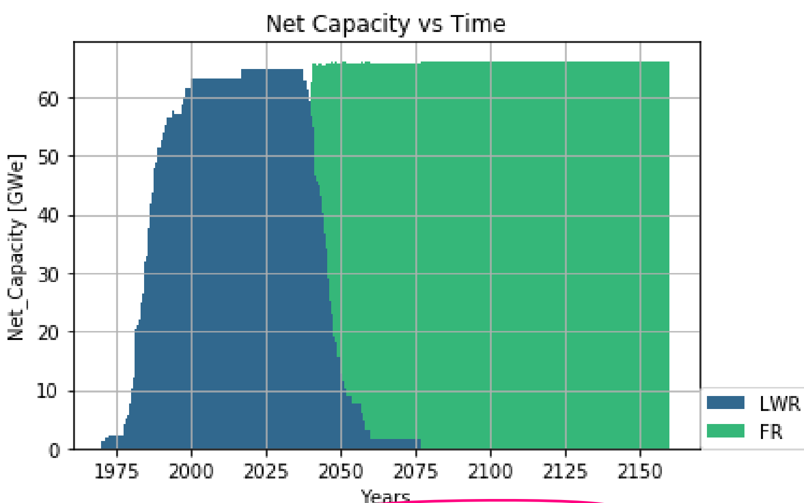

Figure 2: French Transition into an SFR Fleet

more descriptive

interesting!!

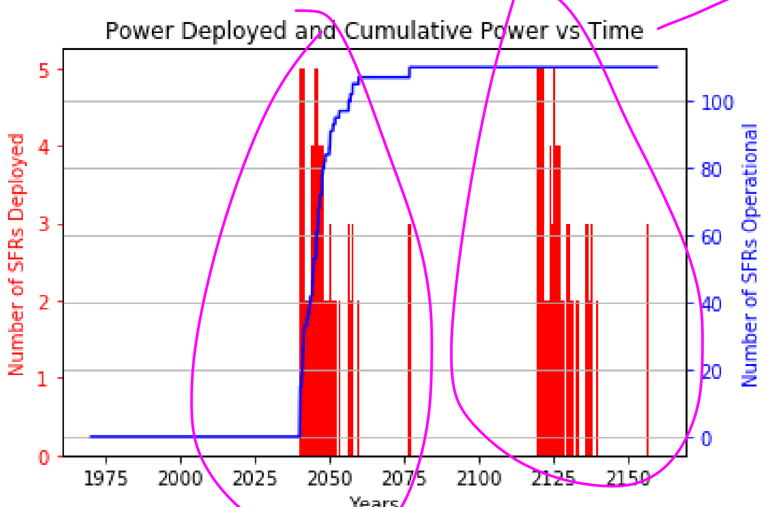

Figure 3: Deployment of French SFRs and total installed capacity

Figure 2 and fig. 3 display the French transition to SFRs over time. 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.

3.4 Material Definitions

what is the deal with this ordering?

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 11). The recipe has also been used for [14].

3.5 Scenario Descriptions

The Simulated ~~simulation follows the model~~ fuel cycle is ~~illustrated~~ in fig. 4. In it, ~~where~~ a 'source' provides natural uranium. That uranium ~~which~~ is enriched by an 'enrichment' facility to produce UOX, while disposing enrichment waste (tails) to the 'sink' facility. The enriched UOX fuels the LWRs and UOX waste is produced. The used fuel is sent to a pool to cool for 3 years [3]. The cooled fuel is then ~~reprocessed to separate~~ plutonium and uranium, ~~or~~ sent to a repository. The plutonium mixed with depleted uranium (tails) makes MOX. ~~The~~ reprocessed uranium ~~is unused~~ and stockpiled. Uranium is reprocessed in order to separate the raffinate (Minor actinides and fission products) from 'usable' material. Though not utilized in this paper, reprocessed uranium may substitute depleted uranium for MOX production. In this paper, there was sufficient depleted uranium inventory that using reprocessed uranium was not considered. However, further in the future where the depleted uranium inventory drains, reprocessed uranium (or, natural uranium) will need to be utilized.

also fuel fab?

Fuel fab MOX...

The second scenario separates plutonium from the UNF inventory from the previous simulation. The separated plutonium mixed with the depleted uranium inventory from the previous simulation creates MOX, which fuels the SFRs.

4 Scenario Specifications

This paper shows results from two separate simulations. 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 [13, 8]. The second simulation is an ideal French Transition scenario to SFR, where an ASTRID-type SFR replaces the decommissioned capacity of LWRs in France. The specifications of the simulations are listed in tables 1 and 2.

this has been said many times

5 Reactor Specifications

Three major reactors are used in the simulation, Pressurized Water Reactor (PWR), glsBWR, and ASTRID - type reactors.

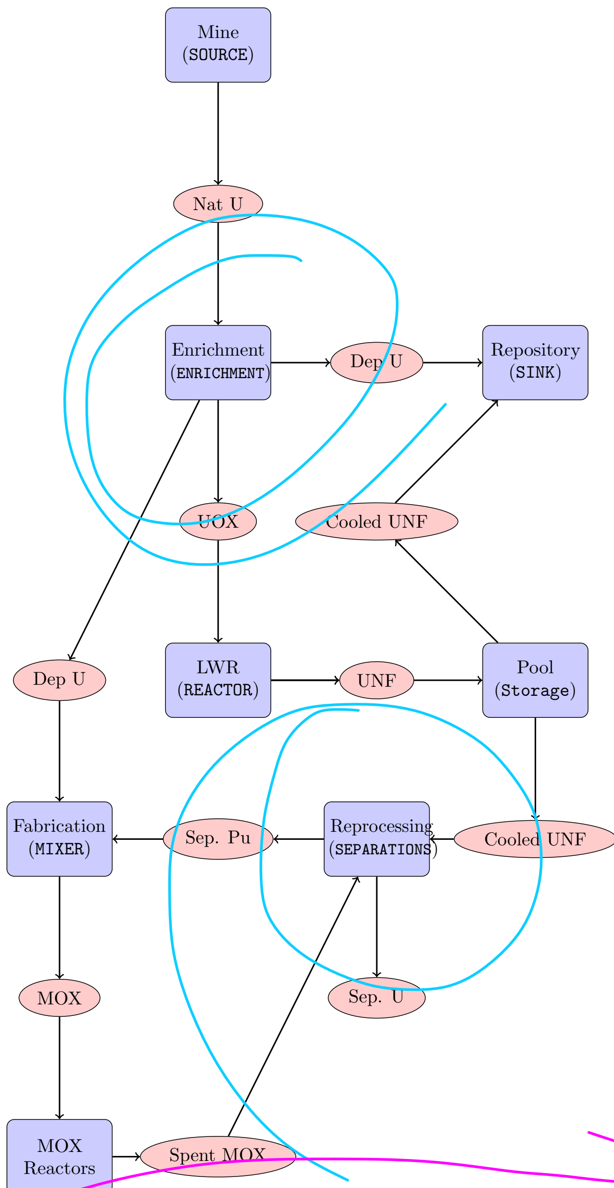

Figure 4: Model Fuel Cycle with MOX Reprocessing

more descriptive

Specification	Value
Simulation Time	1970-2050
Reprocessing Capacity	91.6 MTHM of UNF per month [13]
Reprocessing Efficiency	99.8%
Reprocessing Streams	p~~P~~lutonium and u~~U~~ranium
MOX Fabrication	9% Reprocessed Pu + 91% Depleted U
MOX Fabrication Throughput	16.25 MTHM of MOX per month [8]
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

Specification	Value
Simulation Time	1970-2160
SFR Available Year	2040
Reprocessing Capacity	∞
Reprocessing and Fabrication Begins	2020
Separation Efficiency	99.8 %
Reprocessing Streams	plutonium and uranium
Used UOX and Depleted U Inventory	141,659 MTHM (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

For PWRs, a linear core size model was assumed to capture varying reactor capacity. For example, a 1,000 MWe PWR has 193 UOX assemblies, each weighing 523.4 kg. After each 18 month cycle, one-third of the core (64 assemblies) discharge. Refueling is assumed to take 2 months to complete, during which the reactor is shut down. This value is acquired by averaging the historical refueling outage. The specifications are defined in table 3.

redundant

For Boiling Water Reactors (BWRs), a linear core size model was assumed to capture varying reactor capacity as well. It assumed a assembly size of 180 kg, with 1000 MWe BWR plant having 764 assemblies, adjusted linearly by capacity. The refueling cycle is identical to that of a PWR. The specifications are defined in table 4.

For the SFR, a model design is adopted from Marsault-Marie-Sophie et al. [11]. The specifications are defined in table 5.

redundant with previous section

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	193 for 1,000 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

Specification	Value
BWR Cycle Time	18 months
PWR Refueling Outage	2 months
Fuel Mass per Assembly	180 kg
Burnup	51 GWd/tons
Num. of Aseem. per Core	764 for 1,000 MWe, linearly adjusted
Num. of Assem. per Batch	1/3 of the core

Table 4: BWR Specifications

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 5: SFR ASTRID Specifications [11]

6 Future Nuclear Projections

The future of nuclear energy in the EU ~~nations~~ is organized in the table by the World Nuclear Association [2]. It is assumed in the simulations that all the planned constructions are completed on their expected date without delay or failure. Also, the newly constructed nuclear power plants are assumed to have a lifetime of 60 years.

Table 6 lists the reactors that are currently planned or under construction.

Table 6: Power Reactors under construction and planned [2]

replicated from [2]

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	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, 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 x, given by $\frac{Nuclear\ capacity\ in\ 2040}{Nuclear\ capacity\ in\ 2017}$.

LaTeX cases

- Aggressive Growth ($x \geq 2$)
- Modest Growth ($1.2 \leq x < 2$)
- Maintenance ($0.8 \leq x < 1.2$)
- Modest Reduction ($0.5 \leq x < 0.8$)
- Aggressive Reduction ($x \leq 0.5$)

The growth trajectory and specific plan of each nation in the EU is listed in Table 7.

how was this used in the model?

fewer lines

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 (VVER-1200) by 2025.
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.
Czech Rep.	Modest Growth	Additional 2,400 MWe (AP1000s) by 2035.
France	Maintenance	Shutdown nuclear plants if they reach end of lifetime. No new construction.
Spain	Modest Reduction	No plans to expand or early shutdown.
Italy	Modest Reduction	No plans to expand 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.

Table 7: Future Nuclear Programs of EU Nations [2]

which? name them. Discuss

7 Results

7.1 Historical Operation of EU Reactors

???

Table 8 lists the important metrics obtained from the first simulation. The following values are the EU inventory and history at year 2050, and will be reprocessed in the second simulation.

Category	Unit	Value	Specifics
Total UOX Usage	MTHM	181,471	
Total MOX Usage	MTHM	6,302	
Total Used UOX Stored	MTHM	141,659	UNF that is not reprocessed
Total Used MOX Stored	MTHM	3,611	UNF that is not reprocessed
Total Tailings	MTHM	1,081,826	
Total Natural U Used	MTHM	1,269,897	

Table 8: 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.

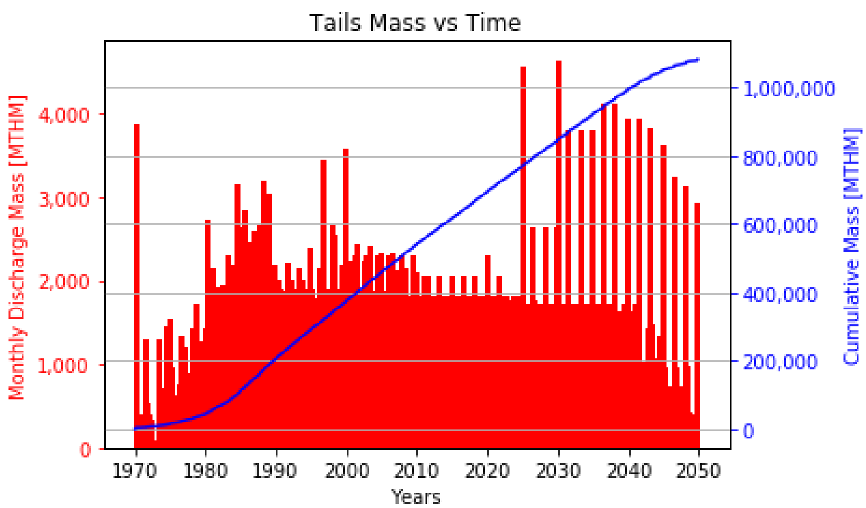

Figure 5: Timeseries of Tails Mass in the EU.

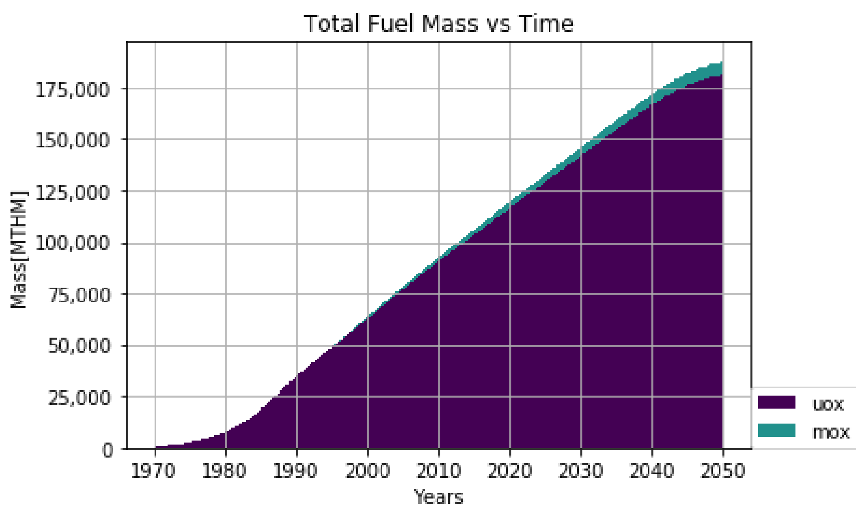

Figure 6: Timeseries of Total Fuel Usage in EU.

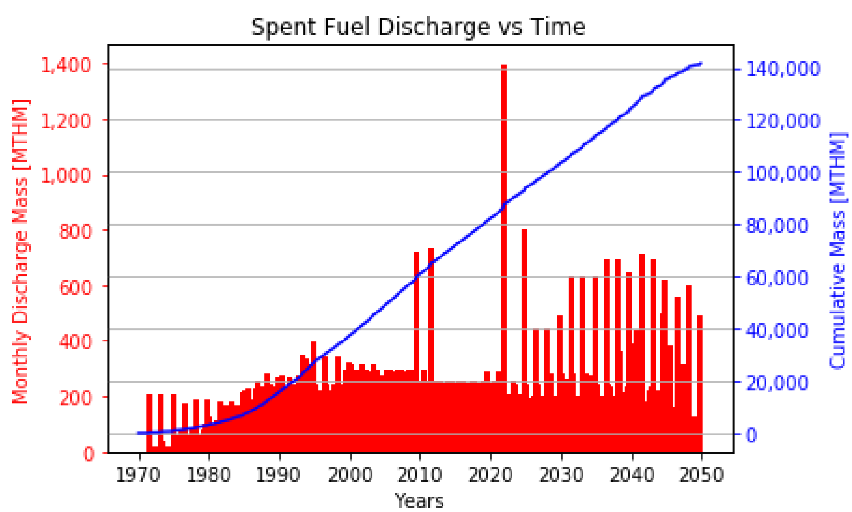

Figure 7: Timeseries of Used Nuclear Fuel in EU.

Isotope	Mass Fraction in Used Fuel [%]	Quantity [t]
Total	0.9358	1,325
Pu238	0.0111	15.72
Pu239	0.518	733.79
Pu240	0.232	328.64
Pu241	0.126	178.49
Pu242	0.0487	68.98

Table 9: Plutonium From Used Fuel

Table 9 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory.

7.2 French SFR Transition Scenario

Reprocessing UNF collected from all EU nations can start approximately 270 SFRs, which is more than enough for two generations of 66GWe SFR fleet. With the SFR breeding ratio of over one, France can transition into a fully SFR fleet without extra construction of LWRs.

From Varaine et al. [11], 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 $\frac{Pu\ from\ legacy\ UNF}{4.9} \approx 270$ 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 11), 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.

Figure 8 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 there are enough amounts of extra plutonium creation by deployed SFRs, the legacy UNF is no longer used.

Figure 10 shows the amount of reprocessing waste (minor actinides, fission products) over time. The spikes in the waste discharge is due to large influx of spent fuel from decommissioned SFRs.Figure 9 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. Table 10 lists metrics obtained from the second simulation.

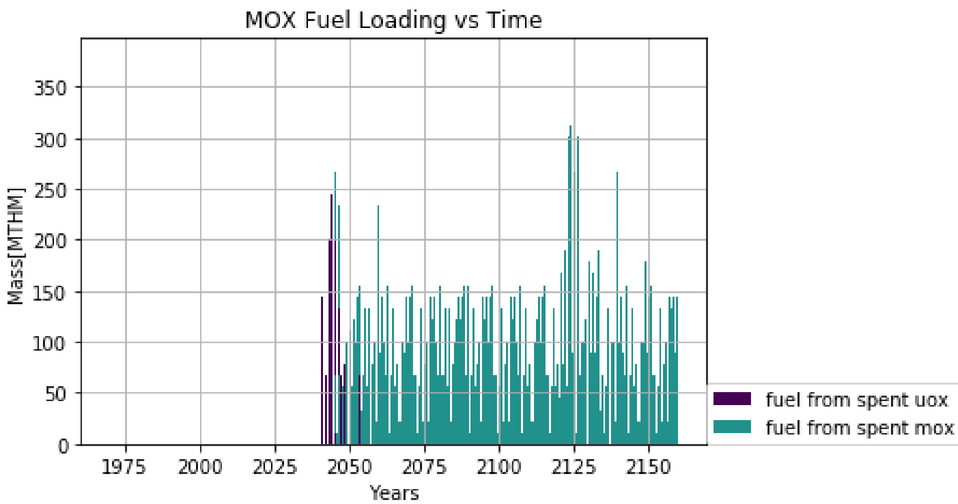

Figure 8: Timeseries of fuel loaded into SFRs

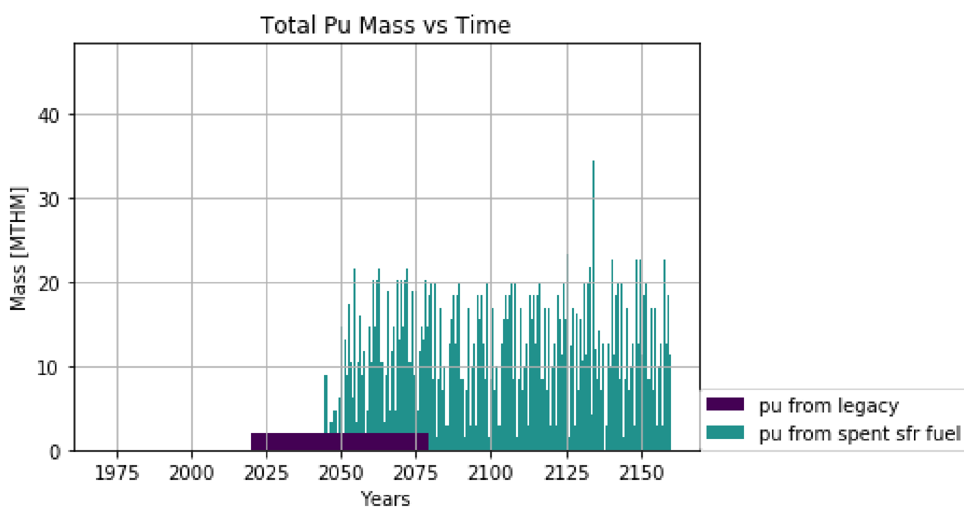

Figure 9: Separated plutonium discharge from Reprocessing Plant

"Reprocess waste" is not a thing. "waste from reprocessing" is ok or possibly "raffinate"

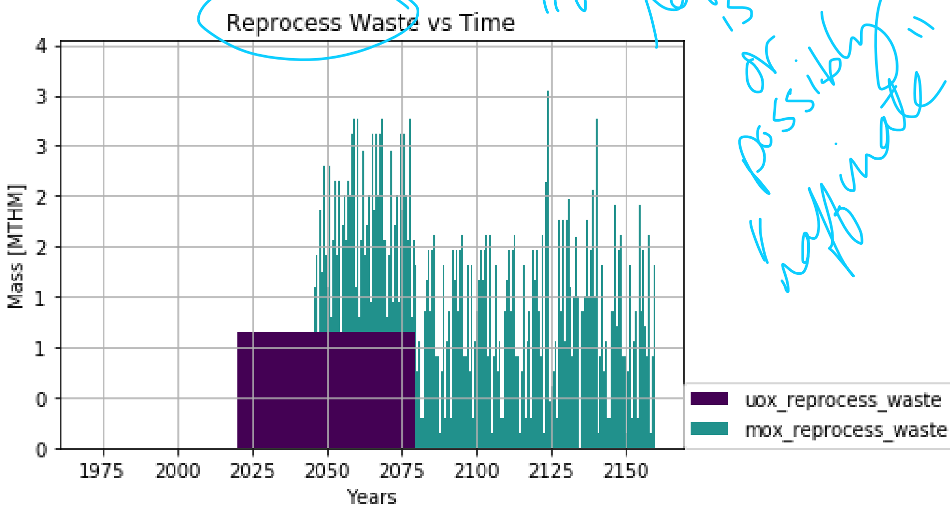

Figure 10: Reprocessing waste discharge from Reprocessing Plant

Category	Unit	Value
Total MOX used	MTHM	127,640
Total SFRs Deployed		220
Total Plutonium Reprocessed	MTHM	16,352
Total MOX from UOX Waste	MTHM	6,570
Total MOX from MOX Waste	MTHM	121,070
Total Tails used	MTHM	116,153
Total legacy UNF reprocessed	MTHM	77,082
Total Reprocessed Uranium Stockpile	MTHM	184,172
Total Reprocess Waste	MTHM	16,352

Table 10: SFR Simulation Results

8 Discussion

This work demonstrated that, with reprocessing capacity of 250 MTHM per month, and a fabrication capacity of 300 MTHM per month, France, by receiving UNF from other EU nations, can transition into, for unchanging nuclear electricity demand, a fully SFR fleet with installed capacity of 66,000 MWe by 2076. MOX from reprocessed UNF meets the initial fuel demand, which later on is supplied by MOX created from recycled MOX.

Major run-on sentence. Break apart!

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. The nations with aggressive nuclear reduction will be able phase out nuclear without constructing a High Level Waste repository. France has an 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 are not addressed, and various assumptions present 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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9 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 11: Fresh and Spent Fuel Compositions