Future Nuclear Inventory Analysis of the European Union with CYCLUS, an Agent-Based Fuel Cycle Simulator.

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1 Introduction

This paper uses CYCLUS, the agent-based simulator [**?**] to analyze the future nuclear inventory in the European Union. This paper focuses on different scenarios of France, and how potential French legislation and policy can change the nuclear landscape of the European Union. This paper begins with analysis of a once through fuel cycle, where all the spent nuclear fuel, goes to a central repository after discharge from reactors. Next, a reprocessing fuel cycle is evaluated. In this fuel cycle only French Pressurized Water Reactor (PWR)s accept mixed oxide (MOX) fuel, where the spent uranium oxide (UOX) from all the member states is recycled in France. Finally, a Light Water Reactor (LWR) to Sodium-Cooled Fast Reactor (SFR) transition scenario [**?**] is modeled, where a once-through-cycle transitions to a closed cycle with continuous reprocessing of Plutonium and minor actinides.

2 Methodology

This mainly utilizes CYCLUS, an agent-based simulator, to simulate the nuclear fuel cycle and track material flows in EU nations. An open-source database from International Atomic Energy Agency (IAEA) called Power Reactor Information System (PRIS) 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. Various plots are generated with matplotlib to describe the output data which includes mass of fuel used, final used nuclear fuel inventory, and major isotope mass inventory over time.

3 Time Scope and Future Projections

Because of the fast reactor transition scenario, the simulation should run to a distant future to demonstrate substantial change. In this case, the year is set from 1970 to 2160. From 1970 to 2017, the existing data is used for the simulation. For the near future (~2035), different projections and plans made by each governments are taken into account to estimate the direction of nuclear fleets in the EU (explained further in later sections). For the far future (2035 2100), an equilibrium capacity is set and decommissioned reactors are replaced by European Pressurized Reactors (EPR)s or SFRs.

3.1 Depletion Calculations

Depletion calculations of the nuclear fuel are done naively, with a model burnup depletion recipe (mass fraction) used for each reactor type, and the mass of the fuel adjusted linearly with capacity. For example, a PWR of 1,000 MWe capacity has 193 assemblies of 3.2% enriched uranium fuel, with each assembly with a mass of 523.4 kg. The core has a 18 month cycle, where one-third of the core (64 assemblies) are discharged per refueling. The refueling is assumed to take 2 months to complete, during which the reactor is shut down. For the fast reactor, a 14-month cycle is used, with a one month refueling outage. The reactor specification including the fissile and fertile fuel mass is specified by Martin et al [**?**].

For the compositions of the fuel, a reference depletion calculation from ORIGEN is used (see appendix). The recipe has also been used for [[[[[[PA-PER?????]]]]]]

3.2 Scenario Descriptions

The simulation follows the model fuel cycle, where a 'source' provides natural uranium, which is enriched by an 'enrichment' facility to UOX, while disposing enrichment waste (tailings) to the 'sink' facility. The enriched UOX is used in the LWRs and UOX waste is produced. Then the waste would either go directly to the sink (scenario 1), or is reprocessed for further use (scenario 2 and 3). In scenario 2, the waste is separated in the separations facility (reprocessing plant), into two streams, Plutonium and Uranium. The plutonium is mixed with depleted uranium from enrichment to create MOX, and the reprocessed uranium is stockpiled in the fabrication facility. The produced MOX is then used in French PWRs. In scenario 3, the waste goes through the same process but is mixed to create SFR fuel.

3.3 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 [**?**]. The presence of neutron-absorbing isotopes ^{234}U and ^{236}U requires reprocessed uranium to require a higher enrichment of ^{235}U. There is trace amounts (2 ppb) of fissile istope ^{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 [?]. However for this simulation the reprocessed uranium is simply stockpiled.

4 Scenario Definition

The following scenarios are considered:

- Halt reprocessing at 2020.
- MOX reprocessing for French PWRs.
- Continuous recycle with SFRs.

5 Scenario Specifications

The simulation is run from year 1970 to 2160. Year 2030 is chosen for the SFR development consideration.

- **Simulation Time:** 1970-2160
- **SFR Available Year:** 2030
- **Reprocessing Capacity:** 91.6 MTHM per month [?]
- **Reprocessing Efficiency:** 99.8%
- **Reprocessing Streams:** Plutonium and Uranium
- **MOX Fabrication:** 10% Reprocessed Pu and 90% Depleted Uranium
- **MOX Fabrication Throughput**: 30 MTHM per month per facility [?]
- **Reprocessing and Fabrication Facility Addition:** one more each in 2020 for continued reprocessing and fast reactor transition scenario.
- **Future Predictions:** New deployment so that installed capacity remains constant, either with EPR or SFR.
- **MOX and SFR Fuel Reprocessing Stage:** Infinite - used MOX and fuel gets reprocessed again.
- **Reprocessed Uranium Usage?:** None. Stockpile reprocessed Uranium.

6 Reactor Specifications

There are three main types of reactors in this scenario: current PWRs [?], EPRs, and SFRs [?].

6.0.1 PWRs

- **PWR Cycle Time:** 18 months
- **PWR Refueling Outage:** 2 months
- **Fuel Mass per Assembly:** 523.4 kg
- **Number of Assemblies per Core:** 257 for 1,330 MWe, linearly adjusted
- **Number of Assemblies per Batch:** 1/3 of the core
- **Fuel:** Prefers MOX but also accepts UOX

6.0.2 EPRs

- **EPR Cycle Time:** 18 months
- **EPR Refueling Outage:** 2 months
- **Fuel Mass per Assembly:** 523.4 kg
- **Number of Assemblies per Core:** 216
- **Number of Assemblies per Batch:** 72
- **Net Capacity (MWe):** 1600
- **Fuel:** Prefers MOX but also accepts UOX when MOX is unavailable.

6.0.3 SFRs

- **SFR Cycle Time:** 12 months
- **SFR Refueling Outage:** 2 months
- **SFR Core Mass (tHM):** 51
- **Fuel Need (tHM/yr):** 8.1 Fissile, 8.7 Fertile (16.8 of averaged recipe)
- **Net Capacity (MWe):** 1510

7 Current Status

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

8 Future Nuclear Projections

This section lists the future projections and plans of different EU countries. Only the major contributors have been listed.

8.1 France

The Energy Transition for Green Growth Bill passed by the National Assembly for 50% of nuclear contribution for electricity by 2025, from 63.2GWe. The 2015 amendment tried to remove the cap, but this was not accepted by the lower house. Currently there is a 1600MWe reactor unit under construction at Flamanville, for operation from 2018. However, the general atmosphere is to close nuclear power plants when they reach the end of their lifetime, while not building new ones. This is due to the decreasing public support for nuclear, along with the lectricit de France (EDF)'s troubling financial situation [**?**].

8.2 Germany

Germany, despite its past success with nuclear energy back in the 1970s, has a dwindling nuclear program. The two incidents, Chernobyl and Fukushima, caused the public and the government to stall and reduce its nuclear fleet. In March 2011, the government declared a moratorium,which planned to immediately shut down nuclear power plants that began prior to 1980. Furthermore, the government passed a phase-out plan to close all reactors by 2022 [**?**].

8.3 Czech Republic

The Czech Republic has six nuclear reactors ($3,904$ MWe), and the government is committed to the future of nuclear energy, which is reflected in its 2015 energy policy to build more nuclear power plants. The country plans to build two more AP1000s ($2,400$ MWe) by 2035. The public support of nuclear energy is also very strong [**?**].

8.4 United Kingdom

United Kingdom not only has a substantial amount of nuclear power (total of 15 units and $8,883$MWe), but also has fuel cycle facilities like a reprocessing plant. The government claimed that nearly 25GWe of nuclear should be generated by 2025, but there hasn't been a fixed amount. After the government became more favorable towards nuclear in 2006, utilities began planning for new plants. Also, many different foreign utilities, from France (EDF), Russia (Rosatom), and China (China General Nuclear Group). This led up to a total proposed number of 13 units ($17,900$ MWe) by 2030, with a mixture of EPR, ABWR, and AP1000s [**?**].

8.5 Belgium

Belgium currently has seven nuclear reactors ($5,943$ MWe), but with little government support for nuclear energy, all of them are expected to shutdown in 2025. The government said that its stance on nuclear phase-out "is now final". There are no known plans to build new reactors [?].

8.6 Sweden

Sweden has nine reactors that generate 40% of the country's electricity. Sweden had four reactors that would close by 2020 due to decreasing profits, with the nuclear tax of .75 Euro cents/kWh, which is one-third of the operating cost. The country plans to shut down all reactors by 2050 [?]

8.7 Finland

Finland currently has four reactors (2700 MWe), two BWR and two VVER, with a fifth and sixth one (EPR of 1600 MWe, VVER of 1200 MWe, respectively) planned. The EPR is to start operation in 2018 and the VVER in 2024. Finland, the country closest to an operating permanent geological repository, has a very optimistic view of nuclear energy [?].

8.8 Bulgaria

Bulgaria currently has two nuclear reactors that provide 1926 MWe capacity. The government has been historically in favor of nuclear power, and uses Russian technology for its reactors, namely the VVER. The government attempted to build new plants in 1980, but it was aborted in 1991 due to lack of funds. Yet, the government planned to add another unit to the currently existing site. There are bids in progress, and the most probable type and vendor seems to be Westinghouse's AP1000 with a capacity of 950 MWe [?].

8.9 Poland

Poland has traditionally been using coal for most of its electricity generation, but due to recent concerns of CO2 emissions and air quality, its government decided to invest on nuclear, and plans to construct 6,000 MWe capacity up till 2035. The government is yet to decide on which type from which vendor, but estimates the operation date to be 2029 for the first 3,000 MWe, and 2035 for the other 3,000 MWe. [?]

8.10 Summary

With all the other countries only taking up a minute portion of the entire EU nuclear fleet, it is assumed that they will not have additional constructions, but will cease nuclear generation when their current operating reactors shut down.

In summary, the current, and the future of nuclear energy in Europe is organized in the table by the World Nuclear Association [**?**]:

Table 1: Power Reactors under construction and planned [**?**]

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

Though nuclear reactors are notorious for not being built on time, for this paper it is assumed that all the reactors listed above are built on time, and operating on the January of their years. Also,all the newly built reactors are assumed to have a lifetime of 60 years.

9 Appendix

9.1 Fresh and Used Fuel Composition

Table 2: Fresh Fuel and Used Fuel Composition for LWR.

isotopes	UOX 33 Bu fresh	UOX 33 Bu SF	MOX-PN fresh	MOX-PN SF
He4	0	2.09687731425456E-07	0	2.51087058608741E-05
Ra226	0	1.18893043712383E-14	0	6.85864649540962E-14
Ra228	0	6.05164592554536E-21	0	1.0769444927185E-19
Pb206	0	7.66855132237399E-20	0	3.63781250186619E-18
Pb207	0	6.51861860354101E-17	0	1.05894542041679E-15
Pb208	0	1.2309279798986E-13	0	2.00189681933373E-12
Pb210	0	2.49685391210951E-20	0	1.1829390296063E-19
Th228	0	6.56361597079969E-13	0	4.90174735683015E-12
Th229	0	1.70690013134599E-13	0	1.43792588721374E-12
Th230	0	0.000000001	0	2.39987630689358E-09
Th232	0	1.56490843910748E-10	0	8.76554821092882E-10
Bi209	0	2.5848487636376E-17	0	2.68786146372081E-16
Ac227	0	3.45679774696139E-15	0	2.46087316302713E-14
Pa231	0	2.25186824592336E-10	0	7.06963562072402E-10
U232	0	1.39991809249232E-10	0	5.93369416879439E-10
U233	0	1.31692294843742E-09	0	1.03594660580906E-08
U234	0.0002558883	0.0001558909	0.0001737978	0.0002656863
U235	0.0319885317	0.0080635282	0.0071419086	0.0043397763
U236	0	0.0038647739	0.005308932	0.0051097366
U238	0.96775558	0.9441447592	0.8562890395	0.8283573053
Np237	0	0.0003316806	0.0065989155	0.0043297768
Pu238	0	0.0001076937	0.0032759581	0.0060396887
Pu239	0	0.0050287058	0.0660791542	0.0410078864
Pu240	0	0.0022528682	0.0312595999	0.0283985363
Pu241	0	0.0012229284	0.0147098117	0.0146892429
Pu242	0	0.0004725724	0.0091628827	0.0098784908
Pu244	0	1.24592710231816E-08	0	2.18888718157919E-07
Am241	0	2.97982565401936E-05	0	0.0021278903
Am242m	0	3.55779183791976E-07	0	5.0357404506317E-05
Am243	0	7.89053833418348E-05	0	0.0020828926
Cm242	0	1.15793225079007E-05	0	0.0002752858
Cm243	0	0.00000024	0	1.26393485496395E-05
Cm244	0	2.20987070314859E-05	0	0.0010179475
Cm245	0	1.02693991499258E-06	0	0.0001275934
Cm246	0	9.56844016218499E-08	0	6.14068350026396E-06
Cm247	0	8.39550878897535E-10	0	1.20593784421403E-07
Cm248	0	4.3267468472959E-11	0	9.15852795618264E-09
Cm250	0	1.99688316479083E-19	0	3.73380755414193E-17
Cf249	0	4.3937429274366E-14	0	4.05679090711136E-11
Cf250	0	8.11752505346616E-14	0	2.9328488367162E-11
Cf251	0	3.16081506454872E-14	0	1.4479253718258E-11
Cf 252	0	1.66790241305513E-14	0	7.53461165518465E-12
H3	0	5.74866365267024E-08	0	1.02694706965821E-07
C14	0	2.63084607239092E-11	0	3.95879595791321E-11
Kr81	0	2.16087356991135E-11	0	7.34462144755557E-11
Kr85	0	2.41685859253852E-05	0	2.05489408777763E-05
Sr90	0	0.0005372686	0	0.000408279
Tc99	0	0.0007822542	0	0.0011189423
I129	0	0.0001810894	0	0.0003505819
Cs134	0	0.0001230928	0	0.0002101892
Cs135	0	0.0003052821	0	0.0009355518
Cs137	0	0.0012009297	0	0.0018309056