Closing The Loop: Why The Nuclear Fuel Cycle Matters For A Sustainable European Energy System

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ABSTRACT

Europe is entering a period of rapidly rising electricity demand, driven by electrification, digitalization, synthetic fuels, and industrial reshoring. At the same time, energy policy is increasingly constrained by land use, material intensity, cost volatility, and long-term environmental impact. In this context, nuclear energy is regaining strategic relevance — not as an ideological choice, but as a response to physical, material, and systemic constraints.

This paper examines the Closed Nuclear Fuel Cycle (CFC) as a system-level solution rather than a collection of individual technologies. Drawing on historical experience with fast reactors and fuel recycling in Europe and internationally, this contribution argues that the long-term sustainability of nuclear energy may be a function of scaling the CFC. The scalability of the CFC depends on deliberate development of recycling capacity and fuel-cycle infrastructure. Deployment rate of reactors in a CFC is directly limited by the amount of recycled materials being made available, and once the reactors are operating the scalability is a function of "compounding interest". Every reactor can produce a certain amount of fissile material per year, and new reactors can be started only as more fissile material becomes available. The earlier the recycling is started and the higher capacity of recycling, the greater the scalability for reactor capacity would be.

Using Europe as a worked example, the presentation explores the scale, sequencing, and governance implications of transitioning from a once-through fuel cycle to a mature CFC based on fast-spectrum reactors. The analysis highlights that the most significant rate-limiting factor in such a transition may initially be the pace at which fuel recycling can be industrially scaled under robust safeguards and regulatory oversight. Expansion rate of an FBR fleet is a function of available plutonium.

Non-proliferation, cross-border material governance, and institutional continuity are treated as foundational design constraints, not secondary considerations.

Rather than proposing a specific technology roadmap or political programme, the paper frames the closed fuel cycle as a boundary condition imposed by physics, resource efficiency, and land-use constraints, if deep decarbonization is to be achieved without large-scale industrialization of natural landscapes. The CFC is presented not as a radical departure from existing nuclear practice, but as the completion of an energy system with the potential to operate in a fully cyclic manner with minimal overall footprint.

Keywords: *Closed Fuel Cycle, Recycling nuclear fuel, Reprocessing, Safeguards, Multi-national, Europe*

1 INTRODUCTION

Today we are facing several challenges with regards to energy.

There is a mutual acknowledgement that we must seek to abandon the use of fossil fuels in order to reduce global warming. Higher use of energy and ongoing efforts to electrify transport, industries and homes, all increase the total demand for electric energy.

ETIP Wind has made forecasts for the energy demand in Europe. The electricity grids in Europe deliver roughly 3000 TWh per year today. ETIP Wind predicts that this may more than double within 2050. [1]

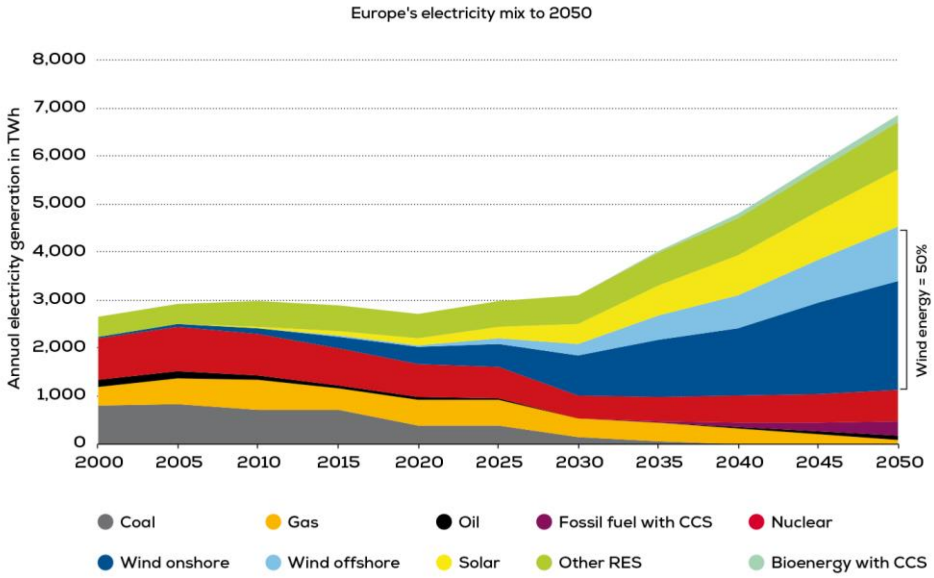

Figure 1: ETIP-Wind Forecast

It is likely that parts of commercial shipping convert to the use of synthetic fuels like ammonia, e-methanol or hydrogen. This would further increase the demand for electric energy.

Support for nuclear is growing due to several real constraints, and some important constraints also affect the nuclear industry. [2]

However, current nuclear deployment models remain largely based on a once-through fuel cycle, which raises questions regarding long-term resource efficiency, waste management, and scalability.

The CFC is re-emerging as a plausible and potentially important solution.

This paper examines the role of a multinational closed fuel cycle in Europe, focusing on scaling dynamics, infrastructure requirements, and safeguards constraints at system level.

The analysis builds on established reactor physics, fuel-cycle concepts and existing industrial experience.

Unlike many earlier studies focusing primarily on reactor technologies, waste reduction, or non-proliferation aspects in isolation, this paper examines the closed fuel cycle as an integrated long-term energy system constrained simultaneously by breeding dynamics, recycling throughput, safeguards scalability, industrial implementation and multinational governance. The analysis illustrates how deliberate long-term coordination in Europe could allow the CFC to become a major contributor to the future energy system, while potentially addressing several long-term challenges associated with energy security, resource efficiency, waste accumulation and land-use intensity.

2 BACKGROUND

The concept of the closed fuel cycle is rooted in early nuclear development.

Nuclear scientists early discovered the transmutation of U238 to the fissile Pu239. Obviously, this was interesting due to its military use, but scientists also saw the potential of designing reactors that were both delivering power to the grid while breeding more fuel from the abundant and otherwise less useful U238. By reprocessing the used fuel, the plutonium could be reintroduced into new fuel, hence the name Closed Fuel Cycle.

The CFC has been discussed as an option on several occasions through the last 50 years, with varying focus on what would be the key motivation. (AFCI & GNEP programs in the USA [3]) Today, renewed interest in the CFC is increasingly linked to broader concerns including energy security, decarbonization, resource efficiency and long-term system resilience.

This broader systems-oriented framing, combining energy security, industrial scaling, safeguards scalability and multinational governance, is one of the aspects that differentiates this paper from many earlier studies focused primarily on reactor technology, waste reduction or non-proliferation in isolation.

Reprocessing technology was being developed mainly in two directions.

Fuel from the Experimental Breeder Reactor (EBR-II) was intended to be recycled through pyro-processing [4] as part of the Integral Fast Reactor (IFR) concept. The process was extensively studied and demonstrated at laboratory and engineering scale, but has not been deployed as a commercial industrial recycling process. Today, ongoing initiatives in the USA aim to complete designs for process-lines based on the Pyro-process.

In Europe and Japan the chosen process was the PUREX process, which was industrialized and is today the major existing process. Also in Europe politicians cancelled the promising development of Fast Breeder Reactors (FBRs) just as industrialization of such was about to emerge on the horizon. [5]

Notably, while the main industrialized process in Russia is the PUREX process, several processes have been studied in parallel. This work include pyroprocess and adapted processes for nitride fuels. A comprehensive assessment of Russian fuel-cycle developments is beyond the scope of this paper. However, the continued Russian development of fast reactors and associated recycling technologies indicates that significant technical experience remains available internationally. [6]

The reasons for the cancellations were a mix of political pressure due to costs, perhaps misunderstood anti-nuclear movement and sufficient amounts of available fossil fuels and uranium at reasonable cost. The politicians did not share the vision of the scientists.

Following the political resignation of the CFC the Light Water Reactors (LWRs) became the norm, and were optimized into a very efficient and cost-effective open fuel cycle.

However, mounting stockpiles of used fuel are causing concern, and final deposition of it in Deep Geological Repositories (DGR) will be an expensive ordeal.

The Closed Fuel Cycle is re-entering the discourse.

Not as an ideal, but in a growing realization that we may have to do this in order to continue to have a high-energy society while also decarbonizing and avoiding the shortcomings of existing energy systems.

While the technological foundations of the closed fuel cycle are well established, its large-scale implementation has not been realized. The following sections therefore examine how such a system could be developed and scaled in a European context.

3. THE CLOSED FUEL CYCLE AS A SYSTEM

3.1 Fundamental Principles

Plutonium availability becomes a central enabling factor for scaling, in contrast to uranium availability in a once-through fuel cycle.

In simplified terms, the following transmutation chain is the key behind it all:

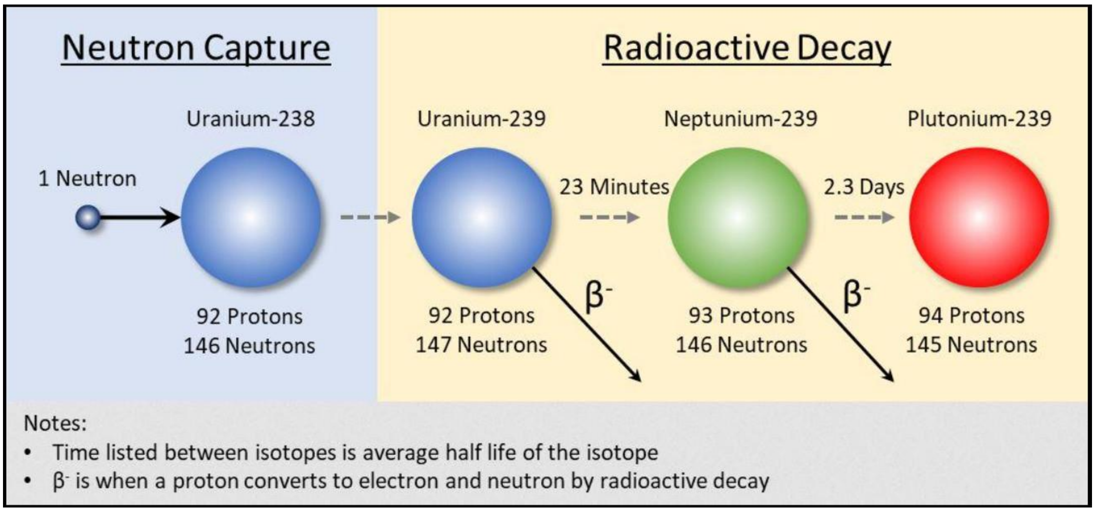

Figure 2: Simplified U238→Pu239 transmutation pathway - Civilsdaily.com

In a closed fuel cycle, energy production and fuel generation are intrinsically linked through neutron economy. This distinguishes the system fundamentally from a once-through fuel cycle.

Pu-239 has a relatively long half-life and is manageable within established nuclear handling frameworks.

3.2 Fuel Cycle Process

Reprocessing is the key mechanism enabling access to fissile material within a closed fuel cycle.

Plutonium for new fuel is extracted from irradiated uranium in the form of used fuel or blankets in FBRs.

Reprocessing plants separate useful materials from waste.

In the USA efforts have been made towards the Pyro-process, which was under development under the EBR projects and the following Integral Fast Reactor project (IFR). [4]

In the Pyro process the used materials are dissolved in a high temperature molten chloride solution, and undergo electrolysis. In the Pyro process clean uranium is extracted on one electrode, whereas a mix of plutonium and Minor Actinides are extracted on the second electrode. The process was not industrialized due to political decisions.

It has been argued that pyroprocessing may present certain proliferation-resistance advantages due to contamination and remote handling requirements compared to PUREX, as plutonium remains mixed with minor actinides rather than being separated in pure form. However, all recycling technologies involving separation and handling of fissile material inherently require robust safeguards and material accountancy. A report from 1992 outlined such concerns related whether the pyro-process is actually as proliferation-resistant as claimed. [7] Repeated processing could in principle also increase plutonium purity over time. Consequently, the overall suitability of a future industrial recycling process may depend not only on proliferation considerations, but also on factors such as industrial maturity, scalability, operational complexity and economic viability.

The major industrialized process today, the PUREX process is in use in France, where roughly 1000 tonnes of used Low Enriched Uranium (LEU) fuel is reprocessed every year at La Hague. [8]

In the PUREX process the used fuel is dissolved in an aqueous solution with nitric acid, and pure Plutonium and uranium is extracted into an organic fluid, leaving Minor Actinides (MAs) and fission products behind in the aqueous solution.

When use of MAs in reactors become industrially viable, MAs can be extracted from the remains after the PUREX process. [9]

The GANEX-process [10] has also been studied in Europe in an effort to develop an efficient industrial process with potentially less proliferation concerns than the PUREX process. By using a different set of extraction chemicals plutonium would not be extracted separately, but rather together with MAs. The intention is to create a more proliferation-resistant alternative to the PUREX process. The process has been demonstrated in laboratories, but is not yet proven in a pilot program. If this process becomes ready at industrial scale in time for a large scale expansion of reprocessing it could potentially be an alternative to the PUREX process.

In a CFC system, used fuel would cease to be considered waste. It becomes a resource waiting to be recycled. Used fuel is cooled down in wet storage while the most intense decay is unfolding. When the thermal and radiotoxic load is sufficiently reduced, the used fuel is entering recycling, where it is dissolved and separated. [11] Plutonium and uranium are separated for reuse, and MAs are increasingly separated as ability to effectively utilize them in reactors is maturing. Fission products are left for vitrification and final safe disposal.

3.3 Reactor Roles in a CFC

Fast Breeder reactors enable the transmutation and fissioning of isotopes that would progressively degrade neutron economy and reactor reactivity in a thermal spectrum reactor. Plutonium is bred through transmutation from U238 in both thermal and fast spectrum reactors. The process is sustained efficiently in an FBR, where also plutonium further transmuted to heavier and challenging isotopes are fissioned and/or further transmuted before fissioning. Effectively, due to the high neutron energy in an FBR, it is not significantly challenged by a mix of isotopes that would quickly slow down the reactivity of a thermal reactor. An FBR can potentially manage also most of the Minor Actinides.
This makes the FBRs superior for handling fuel after multiple rounds of recycling. [12]

Reactors for a Closed Fuel Cycle

There are several types of FBRs which each can play an important role in a fleet of FBRs.

The **Sodium Cooled Fast Reactor (**SFR) [13] is the most mature, after several prototypes have been operated, and notably the BN-600 in Russia has been in operation for ~40 years. The chemical reactivity of Sodium is one of the major operational challenges. Several amending techniques are available and recent operation show that that the challenges are manageable.
One of the major benefits of an SFR in a CFC perspective is the superior potential for achieving high Breeding Ratios (BR). The low density of sodium and near pressure-less container provides for a light-weight reactor. This implies that an SFR can be built very large before high weight becomes a challenge. This makes for a potentially superb neutron economy and thus also superior BR. High breeding ratios may be achievable in optimized breeder configurations with extensive blanket regions and large core geometries. Indications from industry mention a potential BR beyond 1.4.

The **Lead Cooled Fast Reactor** (LFR) [14] is under development, seeking the same benefits as the SFR, while eliminating the challenges of reactive sodium. The added challenge is that molten lead acts corrosive on containment vessels, pipes and pumps. Lead also makes it challenging to monitor the condition of internals of the reactor. The high density of the coolant is limiting the potential size of reactor cores. This is subsequently limiting the BR. Indications from industry mention a potential BR of up to 1.15.

A **Fast Molten Salt Reactor** (Fast MSR) [15] has some unique characteristics derived from the use of dissolved fuel. This makes it highly tolerant to use of fuel with high content of Minor Actinides.

These mentioned reactors could complement each other in a large CFC system. SFRs build inventory faster, LFRs could potentially become a preferred type where size is restricted due to lower energy demand. Fast MSRs could potentially serve as dedicated MA transmutation systems while maintaining approximately neutral fissile inventory, perhaps as a special purpose plant where several Fast spectrum MSRs are grouped together with a local fuel recycling plant. [16]

3.4 System Implications

Consequentially, this implies that the need for large DGRs could be significantly reduced, potentially by 95%, [17] and subsequently the projected cost of final disposal of nuclear waste could be similarily reduced, (potentially by an order of magnitude). It could make sense for many nations to consider establishing mutual DGRs where cost is shared.

In a CFC system, when most of the materials are reused, and U238 is added as needed from Depleted Uranium (DU) stockpiles, the need for fresh uranium could be substantially reduced over time.

Reducing reliance on fresh uranium is indeed an expressed goal of the fifth council on nuclear energy in France. [18]

Europe already possesses significant quantities of fissile material in existing spent fuel inventories, which could, in principle, form the basis for a multi-century closed fuel cycle.

This suggests that a closed fuel cycle may provide a structurally more robust and resource-efficient foundation for long-term and resilient energy supply in Europe

4. ESTABLISHING A MULTINATIONAL CFC – SCALING AND SAFEGUARDS

One of the important concerns regarding the CFC is the inherent potential for using the facilities to produce weapons material. [19]

This is a real and legitimate concern. Breeder reactors and reprocessing plants are the tools one would need to achieve such goals.

A Closed Fuel Cycle must address this in a convincing and robust way. Safeguards by Design is encouraged by the IAEA. This should be considered to form a central foundation of a CFC system. [20]

Transparency is essential. A high degree of transparency would be required to ensure confidence that the system is used exclusively for civilian purposes. All nations joining the CFC must agree to binding, mutual restricting rules.

The first part of the rationale for why a Multinational CFC could be more feasible and acceptable than national programs is the transparency and shared responsibility that would come with a multinational operation. The facility and operator would answer to all the partner nations including Euratom and IAEA, being much less in position to be used for proliferation purposes. By primarily locating the fuel cycle facilities in a nation that already operate such and is already a Nuclear Weapons State (NWS) such as France, proliferation concerns would be more manageable.

The second part of the rationale would be that the economy of scale could make the program more feasible financially. Fuel cycle facilities require substantial financial lifting, even on national scale. By scaling existing designs to suffice for the need of several nations, the cost for each nation could be less than if one nation was to establish this for its own use. By potentially also sharing joint DGRs there could be significant savings also to the final disposal, compared to national programs.

A multinational framework may also improve long-term continuity by distributing financial, political and industrial ownership across several participating nations.

4.1 Scaling Dynamics

A CFC is inherently slow to initiate:

While the technologies involved are largely known, a revived effort would aim to utilize optimized processes and designs. Fuel will also have to be tested and qualified for the new reactors. Copying earlier reactors would not be an option.

This paper projects a 20 year timeline to the actual industrial start of the CFC.

Based on publicly available data from European inventories of spent fuel, this paper estimates that Europe in 2025 held approximately 56500 tonnes of used LEU, 6500 tonnes of used Mixed Oxide fuel (MOX) and 160 tonnes of used FBR-MOX (MOX for FBRs). These contain roughly 1%, 6.5% and >20% plutonium.

In total we have in the order of 1000 tonnes of plutonium sitting in used fuel. Hypothetically but not realistically we could assume that we can reprocess it all, and use all for making fuel for FBRs. To establish how much can actually be recycled would require a very expansive investigation.

Each GWe equivalent of FBR reactor cores require roughly 15 tonnes of Plutonium (pending type and design). The nature of the FBR makes the isotopic composition less critical than in a MOX fueled LWR. [21]

In this case we could load 60 GWe of FBRs. Which is far from sufficient for transforming Europe into a future fueled by the CFC as the dominant energy source. If the UK would make their 140 tonnes of separated plutonium available to use in FBRs, we could load 9 GWe equivalent FBRs more. [22]

Expansion of the CFC beyond these ~60 GWe would require active and deliberate production of additional plutonium.

This paper presents a modified variant of energy predictions based on the ETIP Wind forecast shown above. The paper does not challenge the predicted total energy demand, but rather focuses on the energy sources and scaling of the CFC. In the following illustration the numbers of the ETIP wind forecast are kept up till 2050, the energy mix is kept up to 2025, and the timeline is extended to 2075. It illustrates how Nuclear Power and the CFC can transform our energy system if sufficient political and industrial commitment is established.

A brief explanation of the illustration:

The scenario presented is illustrative and depends on several assumptions, including breeding ratios, reprocessing efficiencies, and deployment rates. Variations in these parameters may significantly affect the timeline and achievable capacity. The analysis is therefore intended to demonstrate system dynamics rather than provide a precise forecast.

Hydro is kept at the same level throughout the timeline (blue).

LWR nuclear power is being expanded from 2030 to 2040, assuming several new reactors and life extensions of existing (red).

The CFC is initiated in 2045, as sufficient amounts of separated plutonium become available. New FBRs running on recycled material go critical as more material become available (green).

Before sufficient recycled material is available, it could be possible to load early FBR cores with an enriched uranium core. This approach is introduced as a means of enabling earlier expansion of the FBR fleet, while the recycling infrastructure is catching up. Once this is initiated, further adding of LWRs is ceased. As the breeding of plutonium from the growing CFC becomes increasingly available, these early FBRs would be refueled with recycled materials and effectively become part of the CFC. (Yellow / dashed transition line)

Land-intensive energy sources such as wind and solar is grouped together with fossil fuel. Given the predicted growth of demand for electricity, a mix of these will have to deliver the energy gap until nuclear is scaled sufficiently. This paper does not consider the internal mix of these (gray)

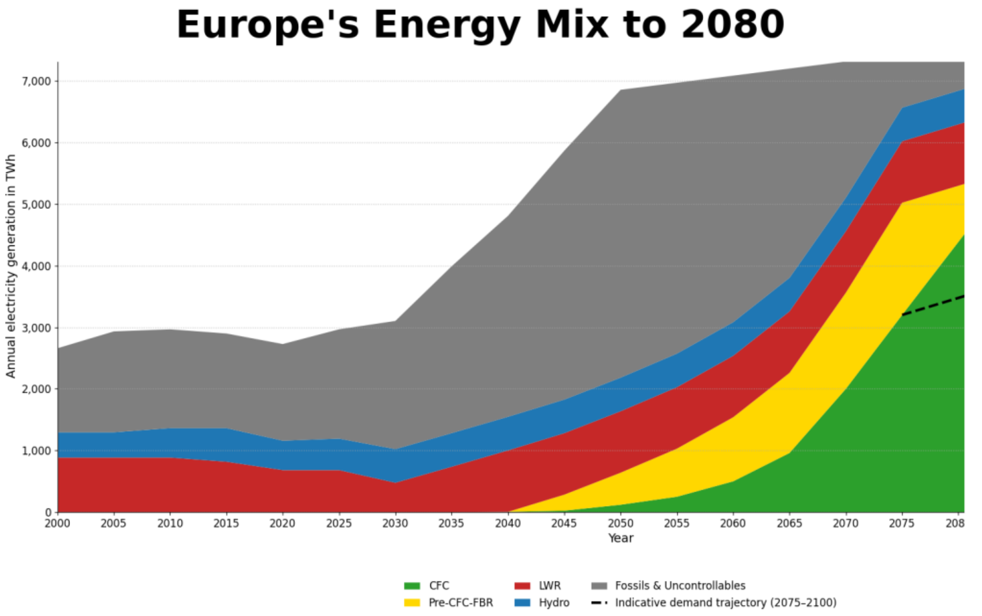

Figure 3: Illustrative projection of scaling of European CFC

Under illustrative assumptions, including an average breeding ratio of 1.15 across the FBR fleet and progressive establishment of recycling capacities of 7200 t/y LEU and 1200 t/y MOX and scale recycling capacity for used FBR fuel as the reactor fleet expands, the CFC could reach 300 GWe as we approach the end of the century.

These values are indicative and intended to illustrate system dynamics. Meanwhile, the stockpiles of used fuel could largely be gone. With a CFC capacity beyond 300GWe the potential for further expansion through breeding becomes potentially higher than we could build new FBRs. At such stage further building of FBRs could be adjusted to existing demand, and they could be loaded for reduced BR or even iso-breeding as needed.

The expansion of recycling plants is perhaps the most critical part of the establishing of a CFC, as this is defining for the rate at which new FBRs can be started.

4.2 Industrial Implementation

Orano is currently making plans for an upgrade of its facilities in La Hague, nicknamed “Aval du futur”, or “Backend of the future” in english. [23]

The new process lines will be designed based on decades of experience, and can be expected to be very efficient and operationally safe. With a goal of the CFC to consume existing stockpiles of used fuel it would make economic and technical sense to build additional copies of the same, identical process lines as those being planned today. This could be a cost-efficient and comparatively lower industrial and operational risk strategy. Used LEU could be the first major source of plutonium for future FBRs.

Recycling of used MOX will take a different process, or at least a modified one. With the commencing of recycling of used LEU for FBR fuel there would be time to develop an optimal process line for used MOX.

The PUREX process in use in France, which is also planned for the coming upgrade of La Hague is a process that comes with concerns of proliferation. By separating plutonium in a pure form it raises proliferation concerns. However, it is the process that represents the most mature industrial-scale recycling process currently in operation after being used in France for decades on industrial scale, and there is long experience in maintaining acceptable Safeguards. Scaling a process that is already optimized on an industrial scale will benefit the scalability of the CFC. This paper considers that increasing expansion of existing French recycling infrastructure may be considered a plausible approach, provided that Safeguards are maintained in coordination with Euratom and IAEA. Should the GANEX process become industrially available within timelines compatible with plans for establishing the CFC, it would be reasonable to assess and compare these two processes as a part of the preparatory work.

For the recycling of used fuel from FBRs, the PUREX/GANEX processes may not be ideal, much due to criticality concerns of high concentrations of plutonium in an aqueous solution.

As many FBRs are refueled, the amount of used FBR fuel will start to grow. Until then, existing used FBR MOX from Superphenix can be used for research and development, and there will be ample time to design recycling process lines for used FBR fuel. The paper considers that there is currently limited industrial experience with large-scale recycling of used FBR fuel.

Indeed, establishing a multinational European CFC will be a costly investment. We could however significantly reduce the cost of DGR, and we could have a robust, reliable, resilient and decarbonized energy system.

Considering that the capacity of the CFC could be in the hundreds of GWe beyond 2060-2070, it could be considered to abandon the use of MOX in LWR reactors. Using recycled LEU in FBRs might create better value.

Given such expansion of the CFC, we could see the end of the stockpiles of used fuel as we approach the end of the century. This is including a higher rate of added used LEU fuel due to expanded LWR fleets from today. All materials would be either loaded in reactor cores, cooling down in wet storage, or being recycled or refabricated into new fuel.

Europe could see the CFC delivering more than 50 % of the energy in the grid as we move beyond ~2075.

One potential approach with significant long term impact could be to require that fuel used in Europe is compatible with recycling. This would set a stop for the adding of stockpiles that cannot be recycled.

4.3 Safeguards and Non-Proliferation

Such a growing CFC does not come without challenges.

Modernizing reporting systems into a common, digital system could reduce reporting burdens, especially with much larger numbers of reactors. Current safeguards implementation remains fundamentally based on nuclear material accountancy principles established under Euratom and the INFCIRC/153 safeguards system in the early 1970s. Increasingly complex fuel cycles and larger material flows may require modernization, digitalization and adaptation of safeguards approaches. [24] [25]

Large numbers of FBRs in NNWS nations (Non-Nuclear Weapons State) is not to be taken lightly. Maintaining sufficient and robust Safeguards reporting and verification would require strict and efficient systems and effort. Fuel forms involving dissolved fissile material may require adapted approaches to material accountancy and verification. There is currently not much experience with this in a Safeguards setting.

Growing number of, and throughput capacity of recycling plants will be a demanding task for Euratom and IAEA. Plentiful loops and flows in large plants will take a significant effort for Safeguards to both map, understand and inspect. Today the IAEA treats 8 kg of Plutonium as the limit between insignificant and significant. In a recycling plant, the verifiable material accounting must be accurate enough that the margin of error is less than 8 kg plutonium. [26]

Today La Hague processes roughly 1000 tonnes of used LEU with 1% Pu.

Yearly processing 10 tonnes of Plutonium means a required accuracy of accounting within 8kg/10000kg. That is not a light task. In a larger plant with higher flow, or a plant that processes used MOX, the task becomes more challenging. A plant that processes 1000 tonnes of used MOX at 6,5% Pu has a yearly flow of 65 tonnes Pu. And still the margin of error must be less than 8 kg. This illustrates that safeguards requirements may scale non-linearly with throughput in large recycling systems. The facilities own material accounting may be significantly more precise, but

Safeguards must be able to assess independently, and this may be challenging to achieve at the same level of precision.

As the numbers above imply, we will see a need for improving measuring accuracy, potentially by one order of magnitude (paper observation).

If such expanded reprocessing is done in France, where it is already being done, and as France is already a NWS (Nuclear Weapons State), the expansion might raise fewer additional safeguards concerns.

If we at some point see the need to establish recycling plants in other countries, and even in NNWS, simply due to lack of space in France, this could be a more serious concern to the IAEA.

The transfer and establishment of sensitive fuel cycle technologies, including reprocessing, are subject to international export control regimes such as the Nuclear Suppliers Group guidelines (INFCIRC/254), in addition to IAEA safeguards requirements. [27]

All in all, Euratom and IAEA will require significantly increased funding in order to manage a large multinational CFC.

In a multinational system such concerns could be mitigated by strict transparency and shared responsibility, in close dialogue with Euratom and IAEA. This paper assumes that with experience and development of tools, methods and systems, robust Safeguards will be possible to maintain.

4.4 Transport and Logistics

Increasing amount of nuclear materials being transported cross borders in Europe will create logistical challenges. Today most national states have their own regulations for transport containers, and transportation rules. According to Euratom regulations all nations must authorize a transport from, through and to that nation prior to it taking place. All affected nations also have a veto to stop such a transport. [28]

In a large, multinational CFC such transports would become everyday business. With the regime of today this could become an administrative and operational burden.

One potential approach to improving the system efficiency of the multinational CFC could be for all nations in the CFC, (and potentially all nations in Europe) to come together with Euratom to harmonize, or perhaps, -to unify all transportation rules. This would not mean reduced safety. It could even be stricter than today, as long as it is only one mutual transportation regime. And it could be considered to introduce a more centralized authorization framework, potentially including a single point of authorization. Rules could be sufficiently unified that there is no longer a reason to have more than one point of Authorization.

Perhaps an international coordinating body could manage all such transports and the reporting of such? This could be considered as a potential approach.

5. DISCUSSION

5.1 Energy Systems Implications

Growing demand for low-emission energy, combined with increasing requirements for stability and resilience in energy systems is contributing to renewed interest in nuclear power. [29] Electrification of transport, industry and heating, as well as potential production of synthetic fuels, are expected to significantly increase electricity demand in Europe over the coming decades.

At the same time, variability and land-use requirements associated with certain renewable energy sources introduce system-level challenges. This has contributed to a broader reassessment of the role of firm, dispatchable energy sources.

Within this context, the analysis presented in this paper suggests that a closed fuel cycle may represent a structurally different approach to nuclear energy deployment. Rather than relying on a continuous inflow of fresh fuel and accumulation of spent fuel, the system introduces a feedback loop where fuel is recycled and reused. This implies that the long-term scalability of nuclear power becomes linked not only to reactor deployment, but to the capacity of the fuel cycle infrastructure.

5.2 Resource and Economic Implications

The findings of this paper indicate that fuel availability in a closed fuel cycle is governed by plutonium inventory and breeding dynamics, rather than by access to natural uranium. While uranium resources are generally considered sufficient, expansion of mining and conversion capacity may face economic, environmental and geopolitical constraints.

At the same time, current once-through fuel cycle strategies result in increasing stockpiles of spent fuel and corresponding investments in DGRs. Existing national programmes already involve substantial financial commitments. This suggests that current allocations to long-term disposal represent a significant opportunity cost if large-scale recycling were to be pursued.

A closed fuel cycle could reduce both the volume and long-term radiotoxicity of final waste, potentially decreasing the required scale and cost of geological disposal. This implies that part of the capital currently allocated to final repositories could, in principle, be redirected towards establishing recycling infrastructure.

However, such a transition would require substantial upfront investment and long development timelines. The analysis therefore indicates that the economic case for a CFC is closely linked to long-term system planning rather than short-term cost optimization.

5.3 Institutional and Safeguards Implications

The expansion of a multinational closed fuel cycle introduces significant institutional and safeguards challenges. The analysis in this paper highlights that safeguards requirements scale with both the number of facilities and the throughput of fissile material, -measured in both material flow and fissile content.

In particular, the requirement to maintain material accountancy within strict limits (e.g. the IAEA significant quantity threshold of 8 kg of plutonium) becomes increasingly demanding as processing volumes increase. This suggests that safeguards systems may need to improve in both accuracy and efficiency.

In addition, the potential deployment of fast reactors and recycling facilities in NNWS introduces further complexity. This implies that transparency, standardization of reporting, and possibly new institutional arrangements will be required to maintain confidence in the system.

The findings also suggest that digitalization and harmonization of safeguards reporting could play an important role in managing increased system complexity.

5.4 Why could implementation become possible this time? What could stop the CFC again?

Implementation of a CFC has been discussed several times in the past. What is different that could make it possible this time?

Historical motivations

Past efforts and discussions have been based on several of the same motivations as today. The focus have often been on one or two of the following concerns:

-Available space for final disposal of waste

-Available uranium for future needs

-Reducing proliferation risk by providing all fuel cycle services from one NWS at a price that discourage nations from choosing to develop their own fuel cycle programs.

Noteably, the AFCI and the GNEP programs focused on avoiding proliferation by providing fuel services from the USA at an attractive cost, and they focused on the growing challenge of space for final disposal of waste.

Historically, these motivations have not been sufficient to proceed with the plans to establish a CFC, usually due to expected financial cost. Technical challenges with associated costs have made politicians abort FBR programs.

Present day drivers

Today we are facing a range of challenges that together present a broader motivation with a greater feeling of urgency. Several additional drivers are contributing to renewed interest in closed fuel cycle concepts, including concerns related to climate policy, energy security, resilience, long-term resource utilization and fuel supply chains:

- Concern over climate change
- Energy independence and national resilience
- A push to abandon fossil fuels
- Growing stockpiles of used fuel
- Concerns regarding land-use intensity of energy systems
- Increasing concerns regarding grid stability and system balancing and concerns over whether energy will be available when needed
- Volatile and often expensive cost of energy

Expansion of nuclear power alone could address several of these concerns. However, a mature CFC may additionally contribute to long-term fuel sustainability, reduced dependency on fresh uranium supply, and reduced accumulation of used fuel inventories.

It is however not clear how the CFC would affect the cost of energy. Indeed it could be expected to reduce volatility of cost of energy, but overall cost may in a short term perspective be higher than we would wish.

This paper considers that a multinational large scale program where nations share facilities for both fuel recycling and DGRs to some extent may counter such added cost. Further reduction of added cost may be achieved by directing existing funds from final disposal to recycling facilities and from funds for green energy in general to recycling facilities. In a longer perspective, as financial discounting has largely proceeded, we may see significant drop in cost of electric energy. The infrastructure will be in place, and the resources (used fuel) will be readily available.

Potential failure modes

This paper foresees that the greatest concerns for why an effort to close the fuel could fail also this time could be:

- Cost of establishing the CFC is (again) considered to be too expensive,
- Unwillingness of national states to align parts of their regulatory frameworks in such perceived sensitive matters.
- Exceedingly affordable methods for extracting fresh uranium all over the world are developed (i.e. extraction of uranium from sea water becomes efficient and affordable on industrial scale.)
- General fracture of cooperation between the European nations. Disbanding of the European Union could make it more difficult to align on large scale multinational programs.

5.5 Implementation and Open Questions

The analysis presented in this paper identifies several key uncertainties and open questions that will influence the feasibility and timing of a CFC in Europe.

These include:

- To what extent existing spent fuel inventories can be efficiently and economically recycled at scale
- The achievable breeding ratios and their impact on system growth
- The rate at which recycling capacity can be deployed and industrialized

- The ability of safeguards systems to scale with increased material flows
- The institutional framework required to govern a multinational system
- Potential to share facilities for final storage
- Potential alignment of regulations for transportation of nuclear materials

These questions indicate that the development of a closed fuel cycle is not solely a technical challenge, but a combined industrial, regulatory and institutional undertaking.

Significant room for optimization may be found, pending the will of national states to resign sovereign regulations to a unified set of regulations shared by all member states.

This suggests that early coordination between industry, regulators and international organizations may be necessary to define realistic pathways for implementation.

6 CONCLUSION

This analysis identifies that early investment in recycling capacity and regulatory alignment may be a prerequisite for large-scale nuclear expansion in Europe.

A multinational CFC in Europe may be achievable, as we largely have the knowledge and technology we need, and we have significant experience with inter-European collaboration.

Serious implications for Safeguards must be addressed. Due to the multi-generational nature of a CFC, it is crucial that European nations ensure that the public is given fundamental nuclear technology literacy. This does not imply that all citizens must be engineers, but rather that the public debate could be more grounded in factual understanding and scientific literacy. Such literacy could contribute to multi-generational operation of the CFC in an orderly, responsible and predictable manner.

The analysis indicates that the closed fuel cycle may represent a necessary structural evolution of nuclear energy systems if long-term scalability, resource efficiency and waste management are to be addressed in parallel.

Europe may ultimately find that the key constraint to nuclear expansion is not reactor technology, but whether it chooses in time to close the fuel cycle

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