NUCLEAR SCALING INITIATIVE

# Fuel Cycle Strategy for a Secure and Scalable Nuclear Energy Future

By Scott Roecker and Ross Matzkin-Bridger

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### About the Authors

**Scott Roecker** is a lead advisor at NSI. In this role, he shapes NSI's efforts to enable the responsible expansion of nuclear energy. He also serves as vice president of the Nuclear Threat Initiative's Nuclear Materials Security Program. With prior leadership roles at the National Nuclear Security Administration and the National Security Council, he brings deep expertise in managing weapons-usable materials, minimizing proliferation risks, and shaping international policy frameworks critical to securely scaling nuclear energy.

**Ross Matzkin-Bridger** is a senior advisor at NSI, where he leads work exploring fuel cycle choices that will enable rapid, economical, and secure nuclear energy scaling. He is also senior director of the Nuclear Threat Initiative's Nuclear Materials Security Program, where he focuses on the intersection of clean energy and security — advancing nonproliferation norms, reducing weapons-usable nuclear materials, and promoting solutions for nuclear waste. He brings extensive international experience from prior roles at the U.S. Department of Energy and the U.S. Embassy in Tokyo, where he shaped energy and security policy.

# Introduction

As energy demand increases across much of the world — driven in part by growth in artificial intelligence, next-generation manufacturing, and transportation electrification — nuclear energy can play a key role in propelling an advanced global economy.

How governments and industry handle the nuclear fuel cycle and manage spent nuclear fuel will play a large role in determining whether efforts to scale nuclear energy succeed or stall. Policies that promote the fastest, most cost effective, and most secure path to scaling nuclear energy can unleash an affordable new wave of reliable heat and electricity. Missteps could saddle nuclear energy with an overwhelming set of unnecessary costs that prevent rapid progress.

# The Two Options

There are two possible options for managing spent fuel and the back end of the fuel cycle.

The first is **direct disposal,** a proven process that permanently dispositions spent fuel. By focusing financial resources on proven technologies and using infrastructure and expertise already in place, direct disposal minimizes the need for expensive, complex facilities and enables nuclear energy to rapidly and safely scale to meet skyrocketing energy demand. Most countries with nuclear energy around the world elect to pursue direct disposal for its simplicity, cost savings, and strong safety and security basis.

The second is **reprocessing,** a process with a troubled track record that will require additional time and investment. Reprocessing refers to a technology that attempts to recover plutonium, uranium, and sometimes other elements from spent fuel for reuse. Reprocessing is often called "recycling," which is a misnomer. Recycling is the separate practice of taking those reprocessed elements and using them as fuel for a reactor. Several countries have elected to pursue reprocessing, however their efforts to recycle have largely failed, with the vast majority of reprocessed material left sitting in storage or awaiting disposition as waste. Reprocessing adds significant costs to the nuclear fuel cycle and has never proven to be commercially viable without costly state subsidies, adding more risk with little return for industry or consumers. It also poses serious security risks, as it yields plutonium that can be used to make a nuclear weapon.

Both reprocessing and direct disposal require a permanent repository for nuclear waste, the siting of which has proven a challenge for some countries. Countries with clear, straightforward direct disposal policies have made the most progress locating and constructing permanent repositories. Finland is in the final stage of opening the world's first permanent repository for spent power reactor fuel, and Sweden and Canada are not far behind.

**Table 1:** Comparing approaches

| | DIRECT DISPOSAL | REPROCESSING |
|---|---|---|
| Waste and Environmental Management | ➲ Requires geologic repository<br>➲ Single waste stream for spent nuclear fuel | ➲ Requires geologic repository<br>➲ Multiple solid, liquid, and gaseous waste streams<br>➲ Increased waste volume |
| Cost | ➲ Costs of storage and repository<br>➲ Simplified uranium fuel fabrication using existing facilities and expertise<br>➲ No need for expensive new fuel cycle facilities | ➲ Costs of storage and repository<br>➲ Requires complex reprocessing and plutonium fuel fabrication facilities that cost tens of billions of dollars |
| Nuclear Energy Scaling | ➲ Leverages existing supply chains to enable a faster nuclear energy expansion | ➲ Long-lead infrastructure build-out<br>➲ Competes for limited resources that could be spent on accelerating technologies that can be deployed immediately |
| Safety & Security | ➲ Does not produce weapons-usable materials<br>➲ Waste stays in a stable, solid form | ➲ Creates new weapons-usable plutonium stockpiles<br>➲ Yields new streams of liquid and gaseous radiological waste |

# A Closer Look

## DIRECT DISPOSAL

### Direct disposal enables rapid nuclear energy scaling and innovation.

Most current and next-generation advanced reactors are already optimized for direct disposal of spent fuel, which means they can be built faster. The most cutting-edge reactor designs, including the most rapidly scalable small modular reactors (SMRs), are all optimized for direct disposal.

### Direct disposal is the most cost-effective.

It consolidates spent fuel into a stable waste form for permanent storage without requiring new, capital-intensive, risky facilities. Instead of pouring resources into building new infrastructure for a process that has not proven to be commercially viable, countries that pursue direct disposal can invest in proven storage and repository solutions, saving billions of dollars that can be directed towards scaling nuclear energy faster and more economically.

### Direct disposal creates more jobs than reprocessing with less capital need.

The best way to create new jobs is to speed the deployment of new nuclear reactors. Instead of tying up funds in costly and unproven technologies, direct disposal frees investment to support far more jobs across the nuclear energy ecosystem: in reactor construction and operation, fuel production, and the many other industries that will benefit and grow from new, reliable electricity supply.

### Direct disposal is the most safe, secure, and environmentally friendly way to manage spent fuel.

Direct disposal keeps spent fuel intact and never introduces weapons-usable material into the fuel cycle, unlike reprocessing which chops up spent fuel, produces radioactive waste in liquid and gas forms, and separates weapons-usable plutonium. By keeping waste in one solid form, direct disposal avoids releasing radioactive elements into the environment. This makes direct disposal the safest, most secure, and most environmentally friendly option for waste management.

# REPROCESSING

## Reprocessing is not recycling.

Spent fuel is largely not recyclable with any of the technologies available or proposed today. Despite claims that 90 percent or more of spent fuel — primarily its plutonium and uranium contents — is recyclable, the reality is starkly different. The few countries that have deployed large-scale reprocessing are only able to recycle 0-2 percent of the recovered material. This means that even after reprocessing, the vast majority of spent fuel goes to long-term storage and disposal.

The gap between reprocessing's promise and practice is fueled by economic problems with reusing both plutonium and uranium:

- **Reprocessed plutonium is prohibitively expensive** because it requires specialized fuel fabrication facilities and procedures given its heightened radiological hazards. These facilities must provide added shielding, strict throughput limits, and enhanced safety protocols. Additionally, because plutonium is weapons-usable, it demands a much more stringent security posture. Together, these expensive infrastructure requirements drive up costs and prevent reprocessed plutonium from being an economical fuel choice. As a result, utilities around the world overwhelmingly favor fresh uranium fuels. Even in countries that mandate reprocessing, utilities often minimize plutonium use, leading to large stockpiles of unused reprocessed plutonium.
- **Reprocessed uranium has stubborn impurities** that make it inefficient and uneconomical to use. Before it is reusable, uranium from spent fuel requires significant additional processing and enrichment in expensive, dedicated facilities. Consequently, almost no reprocessed uranium is recycled today because it cannot compete with the ease and lower price of fresh uranium.

Some companies are proposing to revive pyroprocessing, a decades-old reprocessing technology, claiming it will lead to more efficient recycling than aqueous reprocessing, which is used today. However, no country has ever commercialized pyroprocessing. It does not solve the problems of today's technology and, in some cases, exacerbates them. Notably, it is even less efficient than current reprocessing techniques at filtering out the impurities that hinder recycling. While pivoting away from failed reprocessing technologies makes sense, reviving technologies like pyroprocessing that the market has already rejected for good reason is not the answer.

## Reprocessing slows reactor deployment.

Funding for nuclear energy expansion will come from both government and private sector sources, and it will be limited. To produce results quickly, money will need to be spent in a targeted, disciplined way towards technologies that are ready to move out. Reprocessing ties nuclear expansion to decades-long, unproven infrastructure projects with records of massive overruns. Every dollar spent taking the reprocessing detour adds years of delay.

## Reprocessing derails nuclear infrastructure scaling.

It diverts tens of billions into unproven technology, rather than reactors and grids that deliver power and jobs. Pursuing direct disposal will open the door to the construction of scores of new reactors. A diversion towards reprocessing would take resources away from efficient scaling, inhibiting nuclear energy's job-creating potential.

## Reprocessing has proven to be a financial drain.

Reprocessing and plutonium fuel fabrication facilities must meet far more stringent safety and security standards than those for uranium. This is because plutonium is a much greater radiological hazard and can be used as-is in a nuclear weapon. As a result, plutonium facilities must operate with complex, remotely controlled equipment that requires specialized maintenance, a fleet of highly trained security personnel, and lower throughput.

The combination of these high-stakes operational demands and sizable capital costs makes plutonium fuel significantly more expensive than abundant uranium fuel, which can get the job done more cheaply, cleanly, and safely. Every country that has attempted reprocessing has had to rely on massive state subsidies to make it economically feasible. Either taxpayers pay for these subsidies or utilities are forced to pass the high costs of reprocessing onto ratepayers.

## Reprocessing passes costs to consumers.

Every kilogram of spent fuel costs many times more to reprocess than store directly. Utilities recover these costs by raising electricity rates, which means households and businesses pay higher bills.

## Reprocessing threatens security.

All reprocessing technologies on the market today produce purified plutonium, which can be used to make nuclear weapons. Increasing the prevalence of these materials increases the risk for diversion or theft. Spreading reprocessing technologies contradicts decades of commitment by the United States and the majority of the international community to preventing the proliferation of nuclear weapons-usable materials.

# Global Lessons

Today, many countries are actively expanding their nuclear energy programs or embarking on new programs; they all can learn important lessons from reprocessing's failures and direct disposal's successes.

France is often heralded as a gold standard for reprocessing but has suffered from high costs and limited success with recycling — reusing only about 1 percent of spent fuel, far less than its goal of 90-96 percent. Meanwhile, as its stockpile of nuclear material grows, France is also working to establish a geologic repository for its waste. The country is grappling with the reality that reprocessing does not eliminate nuclear waste or reduce it in any meaningful way; it actually increases waste volume by converting spent fuel into different forms — solids, liquids, and gases — that are more complex to manage.

Japan commenced construction of its Rokkasho Reprocessing Plant in 1993 with a scheduled completion date of 1997. Thirty-two years later, the facility has yet to start up, with Japanese taxpayers left to cover the billions of dollars in costs — underlining that reprocessing is incredibly expensive and the technology is difficult to scale, even for the most advanced economies.

The United Kingdom operated a reprocessing facility for decades, but was never able to get to the stage of recycling. Significant technical and cost challenges made it impractical to use the recovered nuclear material, so it accumulated in storage for decades. The government abandoned reprocessing in 2022 — citing mounting challenges with cost, waste management, and security — and concluded that the most prudent and least burdensome path forward was to dispose of the material, reinforcing reprocessed material as a liability, not an asset.

On the other hand, direct disposal's successes are plain to see. Countries with clear, straightforward direct disposal policies have made the most progress siting and constructing permanent repositories. Finland is in the final stage of opening the world's first permanent repository for spent power reactor fuel, Onkalo, which is expected to be operational this decade. Sweden and Canada are not far behind.

# Conclusion

As countries seek to scale nuclear energy at a critical moment of rising global demand, the choice between direct disposal and reprocessing is a key determinant of their success. The evidence is clear: direct disposal offers a faster, safer, and more cost-effective path forward. It enables rapid reactor deployment, minimizes environmental and security risks, and avoids the financial pitfalls of reprocessing. By prioritizing proven solutions over risky detours, governments and industry can unlock the full potential of nuclear energy and build a secure and scalable nuclear energy future.

The Nuclear Scaling Initiative is a collaborative effort of Clean Air Task Force, the EFI Foundation, and the Nuclear Threat Initiative to build a new nuclear energy ecosystem that can quickly and economically scale to 50+ gigawatts of safe and secure nuclear energy globally per year by the 2030s. NSI's plan for revolutionizing how nuclear energy is constructed, financed, and regulated will advance climate goals, spark economic development, expand energy access, and ensure that nuclear technology is used for only peaceful purposes.

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