# Controlling Investment Risks by Integrating Decommissioning by Design in SMR Development

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**Abstract**

The development of Small Modular Reactors (SMRs) offers promising advancements in nuclear technology, emphasizing safety, flexibility, and cost-effectiveness. However, the slow pace of SMR deployment highlights significant investor concerns and reluctance to invest the large sums needed for actual realization of plants. Investors' hesitation stems from uncertainties in financial returns and liabilities, including those associated with decommissioning, with many SMR designs lacking comprehensive decommissioning plans. Unlike large-scale reactors, SMRs often face higher per-unit decommissioning costs due to their smaller size. This paper explores the concept of "Decommissioning by Design," advocating for integrating decommissioning considerations into the initial design phase to mitigate these challenges. By incorporating strategies such as modular construction, advanced digital technologies like Building Information Modeling (BIM), and Design for Disassembly (DfD), the decommissioning process can be optimized for efficiency and cost reduction. Centralizing dismantling activities and leveraging digital tools can streamline decommissioning, reduce radiation exposure, and minimize waste. These proactive measures not only lower investment risks but also enhance the sustainability and public acceptance of SMRs, ensuring a more viable future for nuclear energy.

## INTRODUCTION

The development of Small Modular Reactors (SMRs) represents a significant innovation in nuclear technology, offering the potential for safer, more flexible, and cost-effective energy solutions. However, the realization of these facilities has been slow, with only four of the 84 designs detailed in the IAEA SMR Booklet of 2022 [1] having been constructed to date, and only a few others showing promise in securing funding for construction projects. This disparity between design and deployment underscores a critical barrier to SMR adoption: the perceived investment risk associated with these reactors. Investors, both private and governmental, are wary of the uncertainties surrounding the financial return on investment and the liabilities. One such liability is the shutdown plant at the end of its operational life.

The reasons for the reluctance to invest in actual SMR construction are not genuinely expressed, but concerns over decommissioning costs and liabilities are a likely driver. Of the 84 SMR designs in the IAEA SMR Booklet, only eight mention any form of decommissioning plan, and these plans are often limited to spent fuel management, ignoring other significant waste disposal issues. The decommissioning of nuclear plants involves not just the management of spent fuel but also the dismantling and disposal of the entire facility, which can be complex and costly. In addition, even when decommissioning the facility is discussed, it sometimes still contains traditional methods like entombment of the below ground facilities at the plant site by backfilling them with concrete, a practice not compatible with the multiple character of SMRs and sustainable development. However, for another design also the transporting of the reactor module after its service life to “globally accepted recycling centers” is mentioned. In general, this lack of comprehensive decommissioning planning contributes to investor hesitation.

The challenge is further compounded by the unique position of SMRs in industrial cogeneration. Unlike traditional large-scale nuclear plants, which are often closely tied to government utilities, SMRs are frequently developed for private industrial energy consumers. These consumers do not have the same governmental backing and thus will exert greater scrutiny when it comes to decommissioning liabilities.

A significant issue with current SMR designs is the tendency to mimic the decommissioning practices of traditional large-scale nuclear plants. This approach is unsustainable for several reasons. Only for larger plants (>400MWe) decommissioning costs scale more or less linearly with the size of the plant, but smaller plants like SMRs often incur relatively higher decommissioning costs per unit of energy produced. A study comparing one 1340 MWe large LWR with four 335 MWe LWR-type SMRs showed that the expected SMR decommissioning cost would be slightly more than a factor of three higher, based on economy of scale only [2].

Already one concept to address these challenges has been identified: Decommissioning by Design [3]. This is a proactive approach where nuclear facilities are designed with their eventual decommissioning in mind. This strategy involves considering the end-of-life phase from the outset, allowing designers to make choices that facilitate safer, more efficient, and cost-effective decommissioning. It draws on best practices and lessons learned from past experiences to optimize the final phase of a reactor’s lifecycle, aiming to reduce radiation exposure, minimize radioactive waste, and ease the burden on waste facilities and future generations. It does not only involve physical design features, it also includes how businesses are structured to plan and conduct the decommissioning activities. Thinking upfront which components could be decontaminated, free-released and recycled, will significantly reduce the waste volume. This approach has been championed by various industry experts and is being gradually adopted in new reactor designs.

In this paper, the current practice of decommissioning cost evolution will be discussed, followed by some suggestions for a future practice of SMR decommissioning.

## current decommissioning and dismantling practice and costs

The decommissioning and dismantling of nuclear reactors is an intricate and costly process, reflecting the complexity and scale of nuclear technology. The costs and methodologies associated with decommissioning have evolved based on experiences with large-scale reactors, but as SMRs gain traction, it is imperative to adapt these practices to align with the unique characteristics and advantages of SMRs. This chapter explores the current practices and costs of decommissioning, drawing from international experiences and specific case studies.

Decommissioning nuclear reactors, in the past typically taking 15 to 20 years, involves several critical phases, each with unique activities and costs. The pre-decommissioning phase focuses on planning and securing regulatory approvals, which include developing detailed decommissioning plans and safety protocols. The shutdown phase involves halting reactor operations and starting decontamination to reduce radiation levels. Dismantling, the most labour-intensive and expensive phase, includes disassembling the reactor and managing the resulting radioactive waste using advanced technologies for safety and efficiency. Waste processing, storage, and disposal are essential to minimize environmental impact and comply with regulations, involving waste treatment and long-term storage. The final site cleanup phase includes removing remaining radioactive materials, demolishing structures, and restoring the site for future use.

The IAEA indicates the cost of decommissioning a nuclear power reactor typically ranging from $500 million to $2 billion [3]. These figures encompass the associated waste management costs, which are a significant component of the overall expenditure. Cost figures show a large variation with regard to the reactor type, for instance, gas-cooled graphite moderated reactors are considerably more expensive to decommission compared to pressurized or boiling water reactors, primarily due to their larger size and greater complexity, mainly caused by their voluminous pre-stressed concrete reactor vessel. Here comes also a caveat when transposing decommissioning cost figures from the past on SMR: gas-cooled graphite moderated SMR, also designated as High-Temperature Gas-cooled Reactors (HTGR), are designed with steel vessels like LWR, contributing to a much simpler overall design.

A report by the European Commission on the market for decommissioning in the European Union [4] identifies two primary factors influencing decommissioning costs: the availability of waste management routes and the duration of the decommissioning project. The first factor comprises:

* the availability of interim storage capacity, pending the availability of a geological disposal site,
* established procedures and processes for decontamination of waste of the lower level categories.

The duration of the decommissioning project is mainly determined by:

* regulatory regimes: country-specific requirements and authorization processes,
* human resource management: the combination of the push to use available utility personnel which then need to be trained on decommissioning & dismantling (D&D) tasks, and the acquisition of specific D&D competences on the market.

Prolonged projects can escalate costs due to extended operational, security, and maintenance needs.

Swissnuclear, the association of the Swiss nuclear power plant operators, provided in their latest decommissioning cost study (2021, [5]) specific insights into the decommissioning costs of currently operating Swiss nuclear power plants, with cost estimates ranging from 564 to 926 million CHF per plant for the first phase, the release from nuclear energy legislation. A notable aspect of these costs is the inclusion of a surcharge accounting for uncertainties, which ranges from 19% to 28% of the total cost estimate. These uncertainties encompass forecast inaccuracies, potential hazards, and a general safety surcharge. Also, a cost deduction is included for opportunities, reflecting the potential for cost savings through innovative approaches and efficiencies, but this turns out to be very small. The unique nature of each decommissioning project introduces a degree of variability and unpredictability, resulting in such a large uncertainty share.

The concept of Building Information Modelling (BIM) already entered the decommissioning scene: a digital representation of the physical and functional characteristics of a facility, providing a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception to demolition. In nuclear decommissioning, BIM is utilized to enhance project efficiency, safety, and cost management. By creating detailed 3D models of nuclear facilities, BIM allows for precise planning and visualization of decommissioning activities. Additionally, BIM facilitates the management of radioactive waste by accurately tracking the location, condition and radiological data of materials, ensuring compliance with regulatory requirements. Different scenarios can be simulated, workflows can be optimized, and potential issues can be identified before they arise. However, as every nuclear power plant decommissioning project is unique by character, not all utilities are convinced of the value of the upfront investment in software acquisition and staff training. For instance, when investigating the markets for BIM in decommissioning in selected European countries, it could be observed that in the United Kingdom, where a centralised strategy regarding nuclear decommissioning is being pursued, the use of BIM is more advanced than in Germany, where every utility develops its own strategy and practice.

## De-risking smr decommissioning

Decommissioning Small Modular Reactors (SMRs) presents unique challenges and opportunities for cost reduction and efficiency improvements. Effective decommissioning strategies can significantly reduce investment risks associated with SMR projects. By integrating advanced planning, innovative technologies, and optimized processes, the nuclear industry can mitigate the complexities and costs of decommissioning SMRs. This chapter explores these strategies in detail, drawing on relevant literature and industry practices.

### Recognized Cost Reduction Strategies

The study [2] mentioned above has shown the possibility of cost reduction by an example of four 335 MWe SMR, resulting in a cost reduction factor of 0.78 compared to a single plant. Additionally, design features that minimize radiation levels or contamination can facilitate decommissioning by reducing the effort and cost required to remediate components and structural surfaces. For the 335 MWe SMR of the example, this resulted in a cost reduction factor of 0.81. However, in this case study both multiple units and the saving by design will not be making up for the economy of scale, the cost of decommissioning the four SMR would still be twice as high as the cost of decommissioning one large reactor. If significantly larger series of the same SMR design could be realized, the benefit of series dismantling will be reflected in a more pronounced cost reduction.

The European Commission report [4] underscores that the most cost-efficient way to conduct decommissioning and dismantling (D&D) projects is to send spent fuel and radioactive waste away from the site for disposal as soon as it is generated. This approach helps avoid supplementary onsite logistics and storage costs and is particularly relevant for SMRs, where the smaller size and modular design facilitate more manageable waste disposal processes.

### Optimizing SMR Decommissioning Practices

To further optimize decommissioning of future SMR, the following strategies should be implemented:

* 1. Minimize On-site Work: Just as the front-end assembly can be centralized in factory halls, the decommissioning process should also be centralized. Conducting as much of the dismantling work as possible off-site in controlled factory environments can reduce on-site activities, lower radiation exposure risks, and minimize logistical challenges. This approach leverages the modular nature of SMRs, allowing components to be transported to specialized facilities for disassembly and processing.
	2. Leverage Digital Technologies: BIM has already become a mandatory practice in the construction industry and will therefore also be used in the SMR construction process. By creating detailed 3D models of the facilities to be constructed, BIM also allows for precise planning and visualization of decommissioning activities. When expanding design and construction models throughout the operational period to include detailed material and radiological data (activation and contamination levels), the decommissioning process can be streamlined upfront and risks will be much reduced. Already for construction it is estimated that using BIM can save around 20% in capital costs due to better project scope understanding and reduced contingencies [6]. Expanding to the decommissioning phase, the inclusion of a share accounting for uncertainties in the cost estimate, in the Swiss case ranging from 19% to 28%, can be greatly reduced if not almost eliminated. This approach also facilitates compliance with regulatory requirements and enhances overall project transparency.
	3. Design for Disassembly: Already an existing concept in the construction world is Design for Disassembly (DfD): an architectural and engineering approach aimed at facilitating the deconstruction of buildings and other structures to maximize the reuse and recycling of materials [7]. The core principle is to design with the end of life in mind, ensuring that materials and components can be easily dismantled, removed and repurposed. SMRs benefit from DfD through their modular design, where reactor modules can be transported back to the factory for decommissioning, thus reducing the onsite workload and enhancing safety. The application of DfD to SMRs involves integrating design elements that allow for straightforward disassembly and safe removal of components. This includes using standardized, easily separable materials and implementing construction techniques that facilitate dismantling, not only metals and plastics but also concrete [8]. By planning decommissioning from the outset, developers can significantly reduce radiation exposure risks, minimize waste, and therefore lower overall decommissioning costs. This holistic approach not only supports sustainability by promoting material reuse but also provides economic advantages by mitigating long-term investment risks and ensuring compliance with regulatory frameworks from the start.

## conclusion

Incorporating decommissioning considerations into the design phase is critical for SMRs. This involves planning for the end of the reactor's life cycle from the outset, ensuring that the decommissioning process is efficient and cost-effective. By adopting a Design for Disassembly approach, SMRs can be constructed with their eventual decommissioning in mind, similar to practices in other industries.

Designing SMRs with decommissioning in mind involves several key elements:

* Modular Construction: Modular construction allows for easier disassembly and transport of components. This reduces on-site work and minimizes radiation exposure risks;
* Material Selection: Choosing materials that are less prone to contamination and easier to clean simplifies the decommissioning process and reduces waste management costs;
* Documentation and Data Management: Maintaining detailed records of components materials used with their locations and radiological data within the facility ensures efficient and safe dismantling procedures.

In conclusion, de-risking SMR decommissioning requires a multi-faceted approach that combines cost-effective waste management, centralized dismantling, advanced digital tools, and thoughtful design strategies. By integrating these practices, the nuclear industry can achieve safer, more efficient, and less costly decommissioning processes for SMRs. The adoption of these strategies not only reduces investment risks but also contributes to the long-term sustainability and public acceptance of SMR technologies.

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