# Licensing Challenges for Small Modular Reactor Designs in European Deterministic Regulatory Frameworks

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**Abstract**

Small Modular Reactors (SMRs) represent a promising advancement in nuclear technology, offering enhanced safety features, scalability, and flexibility compared to traditional large-scale reactors. The use of passive safety features combined with the lower source term make an SMR inherently safer than a large Nuclear Power Plant (NPP) and opens the possibility for optimization of the design through a graded approach. Explicit guidance for the grading down of SMR related requirements and recommendations is lacking. Certain SMR-designs have used a risk-informed approach to achieve an overall optimization of safety measures, supporting the effective and balanced implementation of the defence-in-depth concept. However, their deployment faces significant licensing challenges in countries with deterministic regulatory frameworks, which prioritize prescriptive safety standards over risk-informed approaches. The paper explores the complex interplay between risk-informed design methodologies and deterministic regulatory requirements in the licensing process for SMRs. It examines the tension between the desire for innovation and the regulatory imperative for rigorous safety assurance, highlighting a balanced approach that integrates risk assessment principles into existing regulatory frameworks. Through a comparative analysis, the paper identifies key barriers and licensing challenges associated with risk-informed SMR designs within deterministic regulatory environments. Additionally, it underscores the importance of stakeholder engagement, regulatory harmonization, and knowledge sharing to foster a conducive regulatory environment that promotes the safe and efficient deployment of SMRs while ensuring regulatory compliance.

## The future of nuclear technology in Europe

Compared to fossil energy, nuclear technology is and always has been a climate friendly, low emission and clean energy source. Since the beginning of the war in Ukraine in 2022, uncertainty on energy security and dependence on Russian oil and gas have boosted a nuclear revival in Europe. On May 16th 2024, at the Nuclear Alliance meeting in Paris, representatives of 16 participating member states([[1]](#footnote-2)) signed a joint declaration, acknowledging that nuclear power may provide up to 150 GW of electrical capacity by 2050 in the European Union (vs roughly 100 GW today). With several of the current nuclear plants being in decommissioning, only about 35 GW out of this 150 GW capacity is expected to be produced from existing units going to Long Term Operation (LTO). This leaves about 115 GW to be realized from new build projects ([10]). Similar messages resounded at the Nuclear Energy Summit organised by the IAEA in Brussels later that month. And the nuclear landscape may still further evolve. As an example, 3 years ago all Belgian power plants were heading for a complete phase out. Meanwhile, the previous government has granted a 10 year life time extension for 2 of the 7 units, while in the negotiations for a new government, a further extension of the lifetime to 20 years for these 2 units, a life time extension for additional units and a plan to develop for 8 GW of new nuclear capacity are being discussed, according the a leaked negotiation note as released by VRT news on July 19th of this year ([7]).

## How realistic are these numbers and what could be the role of SMR?

These figures raised by the Nuclear Alliance are ambitious, maybe too ambitious? Looking back in history, about 127 GW of nuclear capacity was added in Europe([[2]](#footnote-3)) ([11]) over a period of 20 years (1970-1990), with a development time of 5 to 10 years for the majority of these projects. These numbers may allow to conclude that European ambitions are high, but still manageable.

But times and circumstances have changed and, ever since, lessons learned from accidents like Chernobyl and Fukushima have significantly impacted the licensing framework and process, and complicated public acceptance. This evolution can lead to increased duration and cost of new build projects in Europe. The recent example of the Olkiluoto 3 new build project in Finland showed a project duration of 17 years and a cost that was approximately 3 times higher than initially estimated. Even if a certain degree of overrun in time and budget can be expected for a First-Of-A-Kind project and the changed licensing conditions were just one of the contributors, such uncertainty makes it difficult to find the necessary investments for such large Nuclear Power Plant (NPP) new build programs.

In such context, SMR technology represents a set of assets to reduce cost and construction time, and thus uncertainty on the return of investment. Two basic benefits of an SMR are embedded in the acronym, i.e. the limited footprint (Small), making it possible to deploy them in a larger variety of locations, and its Modularity, which relates the possibility for complete modules to be factory-assembled and transported and installed as such. This modularity lead to reduced construction time and allows to systematically add new SMRs to match the energy demand (Scalability), of course if the site layout and electrical grid allow it. Besides, in an energy landscape where the share of intermittent renewables becomes increasingly important, new large NPP designs still don’t have the desired flexibility, even if improved compared to former designs. With a power output between 50 and 300 MWe per reactor, and each reactor potentially being composed by more than one reactor-module, a nuclear fleet composed of SMR is more flexible in terms of switching off (or on) 1 or more modules/reactors or through a hybrid mode with temporary heat storage, and therefore more compatible in an energy system with a high share of intermittent renewables. European research initiatives, like TANDEM, have been launched to study the development of such hybridization of nuclear and renewable energy sources.

All of the above makes it clear that there is room for SMR technology to claim its place in the nuclear landscape. The market analysis performed by the SMR pre-Partnership initiative ([3]) provides that SMRs could represent about 30% on the installed nuclear fleet in 2050.

## The licensing challenge

Besides the beneficial properties on the size and modularity discussed in the previous paragraph, SMR technologies typically envisage a proper reduction of the radiological risk compared to the traditional large NPP. Indeed, the reduced core inventory and source term combined with the application of passive safety systems or inherent safety characteristics are expected to lead to better safety performances and increased safety margins. In the absence of tailored licensing approach for an SMR, applying the existing regulation on large light water reactors may seems as a logic and obvious choice. However, considering the differences in technology and safety properties of an SMR, imposing these safety requirements may lead to excessive design options that are not commensurate to the radiological risk of an SMR.

While licensing of nuclear facilities remain the sovereign responsibility of each countries, EU member states generally consider the deterministic safety assessment (DSA) as the preferred approach. However, despite several initiatives to harmonize safety requirements (*e.g. by Western European Nuclear Regulators Association (WENRA) for WENRA, or by IAEA NHSI (Nuclear Harmonization and Standardization Initiative) at a more global scale*), there are still some significant differences in the overall safety approach and the interpretation of some basic nuclear safety principles between different European countries.

The benchmark on the application of current regulatory practice in different European countries ([13]) confirmed this complexity when applied to SMR. The benchmark applied to the acceptability by different safety authorities of a set of risk-based design features proposed by SMR designers. Such features may not be fully aligned to the deterministic framework, but would typically still meet the overall quantitative risk objectives. Even if, individual Safety Authorities may still be open for discussions on a case by case basis, the diversity between regulatory positions in different member states makes it difficult for a designer to develop the concept of standardization.

An example of such situation is the application of the Single Failure Criterion (SFC). This criterion is a generally accepted deterministic concept applied to Design Basis Conditions (DBC) in the safety analysis for large NPP. It requires that safety systems preserve their safety functions in the presence of any single and resultant failures. In some European countries, the application of the single failure criterion has been extended to safety features for Design Extension Conditions, even for DEC-B and independent of the size of the reactor. The rigorous application of this criterion to an SMR in the different accident conditions (in DBC, DEC-A and DEC-B) combined with a strict implementation of independency between the safety systems in different DiD levels, as presented by WENRA O3.2 Position 2 ([16]), and the principle that each module of a multi-module unit shall have its own safety systems and features, could, for a two-module SMR and in most conservative interpretation lead to a design with 12 emergency diesel generators per reactor([[3]](#footnote-4)). This number will be reduced but still high in other countries, if one or more of the above requirements are not valid. In the design process, the designer will have to balance between a bounding interpretation covering all member states or limiting the number of target countries based on less restrictive requirements.

Moreover, when assessing the safety features of SMRs that rely on passive safety systems, it is crucial to adapt the applicability of general reliability design requirements. Demonstrating compliance with requirements such as the single failure criterion, redundancy, independence, and diversification is challenging, as passive systems typically rely on well-defined physical phenomena to function, regardless of the number of safety trains used. If the conditions necessary for these physical phenomena are not met or are impaired, all safety trains are simultaneously affected.

The differences with the existing regulatory framework can be even more pronounced for non-Light Water Reactor (LWR) SMR, like the High Temperature Reactor (HTR-SMR). For example, HTR designs (pretend to) represent even significantly lower source terms from the use of Accident Tolerant Fuel (ATF). In such case, risk-based insights may even challenge the existence of Defence-in-Depth (DiD) levels 4 and 5, as no Design Extension Conditions with core melt will occur. In extreme accident conditions, the fuel effects may typically be limited to a degradation of the fuel, potentially leading to some permeation through the coating as the worst case consequences. This represents reduced and delayed releases, allowing to conclude that the HTR technology meets the safety objectives in DiD level 4 by design and avoiding the need for DiD level 5. As a consequence, the severe requirements on the leak tightness of the containment that apply to an LWR can be excluded or at least reduced for HTR as its’ role in the confinement function as the 3rd barrier is limited compared to a LWR NPP. As for LW-SMR, initiatives are ongoing to rethink (and harmonize) the regulatory requirements for such alternative SMR designs. In this context, Tractebel participates in the GEMINI 4.0 project to assess the extent to which the different requirements from IAEA SSR 2/1 apply and propose appropriated, alternative wording.

Overall, Tractebel considers that all stakeholders would benefit from a balanced, common regulatory framework for SMR. Such set of technology-specific requirements for SMR could still embody a deterministic approach, using demonstrable risk-insights to allow grading of certain requirements in the existing framework. Such considerations should include the inherent safety features, like passive system, resulting in lower accident frequencies (DBA/DEC) and the reduced consequences from the smaller source term or the use of ATF. This shall allow to improve standardization of SMR-designs, without concession to nuclear safety.

### Towards a European risk-based approach?

The above examples explain the complex European licensing landscape for generic designs and indicate the interest for a harmonized regulatory approach between European member states with the potential for grading to allow for optimization and standardization of SMRs. Overall safety requirements should be tailored commensurate to the specificities of SMR designs obviously without concessions to the overall nuclear safety objectives and the European sensitivities.

An example of such technology inclusive, risk-informed and performance based approach is already recommended in the American regulation, more specifically through the adding of 10 CFR 53 “Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors”, currently available as proposed rule under SECY-23-0021 ([17]). IAEA TECDOC-1436 ([18]) may be outdated (it dates from 2005), but provides also a generic basis for understanding the philosophy behind the development of integrated decision making process. In such approach, a crucial role is typically reserved for the Probabilistic Risk Assessment (PRA), a well-established practice in the United States, e.g. to justify a relaxation of Operating Licensed Conditions.

It can however be noted that 10 CFR 53 foresees a second possibility, based on a more deterministic, Alternative Evaluation for Risk Insights (AERI)s. The AERI framework offers an alternative to the traditional PRA by allowing applicants to use different methods to evaluate risk insights, based on a demonstrably conservative risk estimate and provided certain conditions are met. Such approach may be of particular interest for design applications in the European context as it seems to meet the different concerns raised earlier. US NRC refers to NEI 18-04 ([19]) as a possible guidance in developing the AERI framework while assessing defence-in-depth adequacy.

Both approaches (PRA or AERI) however still represent a set of licensing challenges. Obviously, the level of maturity of the technology and the design is also important in a traditional regulatory framework, but uncertainties about the SMR technology-dependent transients and accident conditions or the behavior of the passive safety features under such conditions complicate a reliable estimation of the risk. This becomes particularly complex when aiming for a graded approach-based regulatory framework that is expected to be technology-inclusive. As such, further R&D on these phenomena and design features is necessary to develop confidence in the technology as a basis for waiving some requirements. This challenge may be surmounted by capturing this uncertainty by applying conservatisms, but the risk exists that it would lead back to the traditional, fully deterministic approach.

Even if the risk-based approach would not be applied to grade the framework overall but rather be allowed as a basic principle to optimize an individual design, it would require for the designer to start the modelling in parallel with the design. The European Utility Requirements strongly promote the development of PRA as early as possible in the design stage, but it is recognized as a significant cost in the development phase, with relatively limited added value in the current, deterministic European context.

Besides, the benefits of a risk-based approach seem obvious, but may not be straightforward. E.g. if Design Extension Conditions are minor contributor to the Core Damage Frequency (CDF), the benefit of reducing the number of safety features like in the example of the emergency diesel generators mentioned earlier, may not stand out. Also, the passive systems should lead to better CDF values, but it may be complex to demonstrate without a consolidated and exhaustive methodology for the estimation of the reliability of passive systems if the risk profile is dominated by active components. As such, the advantage of SMR designs may be more obvious in level 2 or level 3 PRA, which are less strongly promoted in EUR or in risk-based approach and could be a real challenge for some design with a vague definition of the severe accident (DEC-B). Level 3 PRA are generally not performed by the designer and barely required in European countries.

Finally, there may be discussions on how and compared to which objectives the grading should be aligned. While European Safety Authorities tend to impose more stringent overall safety objectives to SMR ([20]), existing PRA-risk metrics may become obsolete as the definition of core damage becomes vague like in the example of the HTR and even more for advanced technologies using e.g. liquid fuels.

### Specific point of attention - Hazards

The beneficial risk characteristics explained in the previous paragraphs should also allow to locate SMR closer to the end-user and increase the number of potential locations compared to large NPP. However, new locations may represent higher risk profiles in relation to the natural or man-made external hazards. In Europe, the general approach is to define hazard intensities with a return period of at least 10.000 years as Design Basis Events (DBE). Events that are more severe than the design basis events are identified as part of DEC analysis, to demonstrate the robustness of, and the margin in, the protection concept against the hazard. As SMRs have the potential to be sited at locations that are typically not selected for large NPP, like remote locations with limited power demand, adjacent to non-electrical end-users (like a hydrogen production plant) or closer to high populated areas, designers may define a broader standard plant parameter design envelope than for large NPP.

Considering the operating experience from available hazard PRAs and the expected risk metrics for internal events for SMR, hazards may become very dominant in the risk profile of an SMR, if specific safety features like the passive systems show insufficient robustness against the extreme loads induced by hazards. Even for conditions resulting from extreme hazards, the boundary conditions for successful operation of the passive systems should still be met. If the overall safety objectives for SMR would become more stringent, this may lead to the conclusion that more extreme hazards levels must be considered in the safety demonstration for SMR compared to traditional large NPP.

And finally, hazards may lead to multiple failure events, including multi-module events, which limits the benefits of the reduced core inventory. As such, if legislation on single SMR unit/module is adapted commensurate with the radiological risk, the legislation should be extended to deal with multi-module designs or multi-unit site.

As such, grading for hazards may rather be found in the hazard characterization of the site-specific hazard. E.g., as most SMR standard designs use a design basis earthquake representative for a peak ground acceleration of 0.3g (or more), no full Probabilistic Seismic Hazard Analysis should be required to characterize the seismic hazard in low seismic areas like Western or Northern Europe. An example of such approach has been developed in IAEA-TECDOC-2042 ([21]).

## Conclusion

Innovative design features like the use of passive components or accident tolerant fuel are expected to significantly improve the safety performance of an SMR, both light water SMR as more advanced reactor.

The current European regulatory framework is however, still typically inspired by the deterministic application of a set of mandatory requirements and prerequisites developed for large Light Water Reactors (LWR). In addition, significant differences exist in the interpretation and practical implementation of these requirements and prerequisites throughout different European member states. The current paper provides a set of such examples, indicative for the licensing challenge for designers of an SMR standard plant.

To facilitate standardization of the SMR-technology and make it market competitive to enable tackling the European ambitions on the development of nuclear energy by 2050, stakeholders would benefit of an graded and harmonized regulatory framework commensurate with the radiological risk it represents. This should enable designers to optimize their SMR design without confessions to overall nuclear safety objectives.

The paper calls for urgent action from stakeholders to implement the possibility for grading in a global, harmonized and balanced framework at European scale that accounts for the specific context allowing to consider the risk insights for the different SMR technologies. The paper identifies the AERI approach, using demonstrably, but still conservative risk insights, as a promising basis to develop such grading in the European context. To implement such approach, additional R&D of the specific design features is still needed. The potential for grading should also be considered in the process of siting commensurate with the standard design plant parameter envelope.

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1. Belgium, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Hungary, Netherlands, Poland, Romania, Slovenia, Slovakia, Sweden, United Kingdom as invitee and Italy as observer. [↑](#footnote-ref-2)
2. Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain and Sweden [↑](#footnote-ref-3)
3. 3 levels of DiD x 2 EDG for redundancy per level of DiD x 2 modules/unit = 12 EDG/unit [↑](#footnote-ref-4)