Review of current and future nuclear technologies

Stefan Hirschberg[1], Petrissa Eckle[1], Christian Bauer[1], Warren Schenler[1], Andrew Simons[1]
Oliver Köberl[2], Horst-Michael Prasser[3], Martin Zimmermann[2] and Jörg Dreier[4]
[1] *Laboratory for Energy Systems Analysis, PSI;* [2] *Laboratory for Reactor Physics and Systems Behaviour, PSI;*
[3] *Laboratory for Thermal Hydraulics, PSI, and Laboratory of Nuclear Energy Systems, ETH Zurich;*
[4] *Nuclear Energy and Safety Research Department, PSI*

This work reviews current and future nuclear reactor technologies, with an emphasis on their risk, cost and environmental features. The results are based on the literature and on our own extensive assessments. The evolution of selected, technology-specific indicators is highlighted, showing reduced risks and environmental impacts. Based on the implementations of our interdisciplinary assessment framework within numerous national and international projects, the performance of current and future nuclear technologies in the context of sustainability is briefly addressed.

Worldwide, 433 nuclear power plants, with a total generation capacity of 367 GW, are currently operating in 31 countries. Nuclear energy produces 13.0% of the world's electricity supply. The share in OECD countries is substantially higher, at 21.1%. There are 65 reactors, with a combined generation capacity of 63 GW, currently under construction in 15 countries, and 151 additional reactors are planned in 22 countries.

Following the Fukushima accident, Germany decided to prematurely phase out its nuclear programme by 2022. The continued operation of nuclear power plants in 30 other countries is uncontested. However, political decisions were made in Germany, Switzerland, Italy and Venezuela prohibiting construction of new nuclear power plants, and Japan has scaled back its plans to increase nuclear generation of electricity.

Examples of findings

Our review [1] has addressed specific features of the various generations of nuclear power plants, i.e. GEN II, GEN III/III+ and GEN IV.

Safety and risk aspects – The safety level of GEN II plants around the world is subject to extensive variation and changes over time. The older Swiss plants at Beznau (KKB) and Mühleberg (KKM) have been extensively back-fitted, leading to radical safety improvements. The later plants at Gösgen (KKG) and Leibstadt (KKL) were designed from the beginning to meet increased safety requirements, using higher levels of redundancy and separation. The Core Damage Frequencies (CDFs) and Large Early Release Frequencies (LERFs) for the Swiss plants are shown in Figure 1, along with our estimates for the European Pressurized Reactor (EPR), here representing GEN III/III+ plants. The results are compared with the target values for existing and new plants, established by the IAEA in 1999.

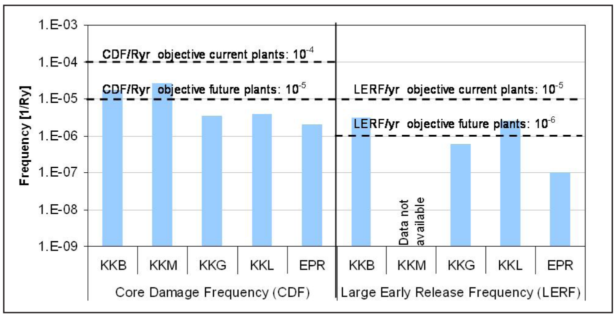

Figure 1: **Risk indicators. For EPR, ranges are provided which primarily depend on the built-in level of protection against seismic hazards.**

The CDFs and LERFs for all operating Swiss plants are clearly below the targets for current plants and below, or slightly to moderately above, the targets for future plants. The expected frequency of accident scenarios with public consequences is typically a factor of 10–100 lower for GEN III plants than for the currently operating top GEN II plants. For some candidate GEN IV designs, there are indications that the maximum credible consequences of hypothetical accidents could be strongly reduced compared with GEN II and GEN III.

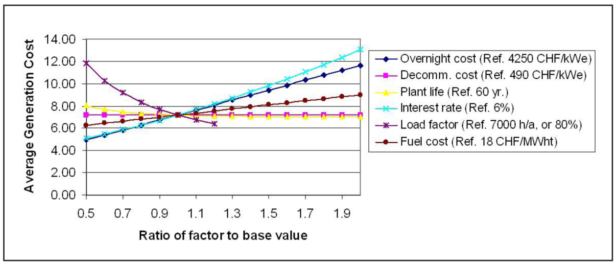

Figure 2: **Cost sensitivity for EPR.**

Costs – Current generation costs of the Swiss nuclear power plants are in the range of 4–6 Swiss cent/kWh (3.3–5.0 euro cent/kWh), with capital costs partially amortized. Based on a review of costs and driving factors, it is PSI's judgment that the cost of a series EPR built between 2020 and 2030 could be between 3500 to 5000 CHF/kWe, with a mid-range value of 4250 CHF/kWe. The estimated production costs are in the range of 6.4–8.0 Swiss cent/kWh (5.3–6.7 euro cent/kWh). Figure 2 shows sensitivity curves for an EPR, varying each parameter from 50% to 200% of the base value shown in the legend.

Environmental impacts – There is a substantially decreasing trend for environmental indicators from Gen II to Gen IV, as shown in Figure 3, with the most pronounced reductions for uranium demand and Greenhouse Gas (GHG) emissions. This improving environmental performance, along with progress in technology development, mainly reflects increased efficiency and reduced demand for fresh uranium.

Innovative designs and fuels – Small Modular Reactors (SMR) and thorium as an alternative fuel have also been considered. There are several dozen SMR designs based on the principle Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) lines and other, non-conventional technologies. The implementation of inherent and passive safety design features can improve defence-in-depth as well as the plant economy, e.g. through reduced design complexity, investment requirements and/or off-site emergency planning. The core damage frequency of SMRs is judged to be comparable to, or lower than, those for state-of-the-art Light Water Reactors (LWRs). The capital investment for a single SMR is much smaller than for a large reactor.

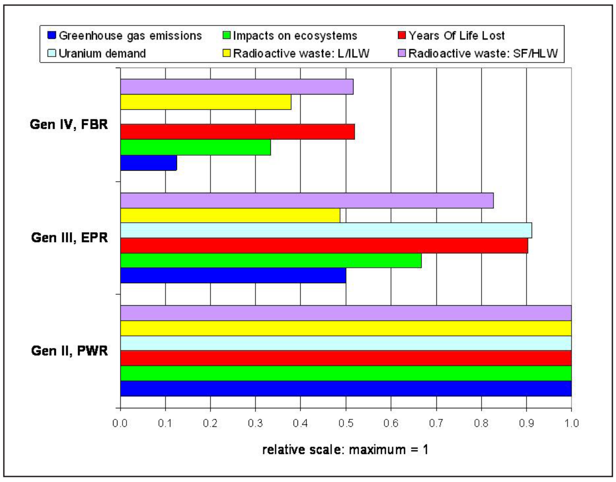

Figure 3: **Relative environmental indicators per kWh generated at Gen II, III, and IV reactors.**

Since the turn of the millennium, there has been a growing interest in the thorium fuel cycle. The use of thorium has several advantages over the established use of uranium, including the avoidance of very long-lived highly radioactive wastes. A final repository is still required, but the necessary confinement time can be significantly reduced. The probability of accidents is mainly influenced by the reactor design and less by the fuel type. Radioactive inventories are significantly smaller in a molten salt reactor and the operating pressure is also lower, leading to a lower expected risk of a major release. This applies both for the use of uranium and thorium. Reliable quantitative estimates of risks and costs are not yet available. Given the need for extensive R&D and stringent regulatory requirements, the commercialisation of the thorium cycle is expected to be highly demanding.

Nuclear energy and sustainability

As with other electricity generation options, nuclear energy exhibits specific strengths and weaknesses. Under Swiss conditions, the positive features include competitive costs, safe and reliable operation, and favourable performance with regard to impacts on climate, ecosystems and human health. The risks associated with current plants are clearly below the internationally established targets, but the public risk perception (which concerns both hypothetical accidents and nuclear wastes) has been strongly affected by the recent Fukushima accident. GEN III/III+ plants offer decisive safety gains with regard to accident prevention and mitigation, as well as minimisation of the residual risk. Nuclear electricity generated by new plants is expected to be economically attractive, in spite of high capital costs, but only under the condition that nuclear projects are implemented as planned and that boundary conditions for operation remain stable for a long time. While fossil and renewable energies struggle with environmental and economic challenges, respectively, nuclear energy must strive to improve its performance with regard to the social dimension of sustainability. This is being further pursued in the context of GEN IV developments.

References

[1] S. Hirschberg et al., *Review of current and future nuclear technologies,* PSI Report prepared for the Swiss Federal Office of Energy, (to be published 2012).