ANCRE

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LIGHT WATER REACTOR TECHNOLOGIES (LWRs) OPERATING (GEN-2) AND ADVANCED (GEN-3/3+)

1. State of the art and current development in different world regions

Nuclear power generation by 2050 will be assured by the continuing operation of Gen-2 Light Water Reactors (LWRs) that are targeted for life extension in most nuclear countries, as well as by new builds of Gen-3 LWRs that globally use the same technologies but are engineered to enhance safety and economic competitiveness. Projects of Gen-3 LWRs include ABWR, ESBWR, AP1000, EPR, AES2006, VVER1200, APR1400, APWR, ATMEA1, ACR1000, CANDU6, CAP1000, Hualong-1, as well as Upgraded-AP1000, Optimized-EPR, Modern-VVER, APR+, CAP1400, CAP1700, etc. Both generations of LWRs will afford sizeable and comparable savings of CO_2 emissions by 2050. Extending the lifetime up to 60 years and beyond for operating Gen-2 LWRs whose construction debt is already paid-off is an attractive option for government energy policy for two reasons: first, it buys extra time for investment in low-carbon technologies; secondly, it maximizes the carbon emission savings from nuclear electricity generation. Furthermore continuous improvements are underway for extending the lifetime of nuclear power plants to 80 years. However extending the lifetime of Gen-2 nuclear power plants postpones the deployment of new Gen-3 plants that have drastically improved safety features and that are likely to ultimately renew the existing aging nuclear fleet completely.

Important notice: For the nuclear family panorama and the comparison with other low-carbon technologies, this template will focus on Gen-3/3+ reactor types that will dominate in 2050.

2. Maturity level and technological perspectives: costs, performances, markets

Maturity of elementary technologies associated with Gen2&Gen3/3+

Methodological information:-2

The maturity level is the TRL, reduced to 5 levels with market deployment enclosed in the higher TRL classes; maturity level scaling: 0 = none; 1 = fundamental research; 2 = R&D; 3 = demonstrator; 4 = low deployment; 5 = large deployment.

	2015	2020	2030	2040	2050
Gen-2	5	5	5	5	5
Gen 3/3+	4	4	5	5	5

As of January 1st, 2014, 70 nuclear units are under construction, and 183 are planned. In 2015, there are 5 Gen-3/3+ units in operation and 33 under construction. This new generation of nuclear power plants is likely to become the majority as soon as 2030.

Potential development of technologies associated with Gen2&Gen3/3+ nuclear power plants

Methodological information:

Potential development is measured as the percentage of the technology's contribution to environmental protection. This means evaluating, in terms of carbon emissions and of carbon emissions reduction, to what extent this new technology can contribute to limiting temperature increase to 2°C above pre-industrial level according to the time horizon considered in this study. Potential development scaling: 0 = not significant; 1 = significant (i.e. more than 1% of global emissions reduction) in some countries; 2 = significant on the global scale; 3 = very significant on the global scale (i.e. up to 3% of global emissions reduction); 4 = major technology vs. climate change (i.e. more than 3% of global emissions reduction).

	2020	2030	2040	2050
Gen-2 & Gen-3/3+	4	4	4	4

Gen-2 nuclear power plants will play an important role in avoiding CO_2 emissions if their life is extended from 40 to 60 years or even to 80 years. This saving amounts to 2 to 4% of total CO_2 emissions currently according to whether coal- or gas-fired plants are considered substitutes.

Gen-3 nuclear power plants will progressively renew the operating nuclear fleet, thus leading to an installed nuclear capacity ranging from 70 to 200 GWe in 2030, which reflects a quite dynamic deployment of this new generation of reactors. If we consider the lower bounds, i.e. a less favorable context, CO_2 emissions avoided by Gen-3/3+ technology would still range from 2 to 4% of the current global emissions in 2040 and 4 to 9% in 2050 (depending on the alternative technology considered —gas or coal without carbon capture).

Those pathways are summarised in the above table with the classification of nuclear as a "major technology vs. the climate change" (higher than 3%).

3. Technological, economic and social bottlenecks

Methodological information:

The following table ranks the bottlenecks according to their impact on the development of the technology. A bottleneck ranking at 6 on the scale will hinder or stall the deployment of the technology compared with bottlenecks ranking at 1; conversely, a bottleneck ranking at 1 will hinder the deployment of the technology much less than bottlenecks ranking at 6. Note that the ranking is relative, meaning that a bottleneck ranking at 6 is not necessarily hard to remove; conversely, a bottleneck ranking at 1 is not necessarily easy to remove. Technologies rank according to: research, finance, regulations, resources & environment, security and acceptability. The table also contains keywords associated with each bottleneck.

It must be stressed that the ranking of such different factors must be considered with caution; as an expert's judgement, not a quantitative assessment.

Technology		**Research & technological bottlenecks**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & Institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
Gen-2	Rank	1	4	5	3	2	6
	Key-words	Research on aging mechanisms, aging monitoring and lifetime prediction	Investment costs amortized but operating costs enhanced by aging	Changing government policies and regulations	Poor use of natural Uranium resource (mainly ^{235}U that is 0.7% only of U_{nat})	Mastery of safety and proliferation risks	Risk perception associated with aging plants compared to climate change
Gen-3	Rank	1	5	4	3	2	6
	Key-words	Research for enhanced safety (including serious accidents) and economic competitiveness Research on fuel cycle back-end options	High investment costs: an issue in free-market countries	Changing government policies and regulations Too country-specific safety goals, codes and standards	Available and suitable sites for new plants Poor use of natural Uranium resource (mainly ^{235}U that is 0.7% only of U_{nat})	Mastery of safety and proliferation risks	Perception of nuclear risk Need for skilled workforce Need for high-level radwaste disposal in deep geological repositories

Ranking in the table above is highly country-dependent. To consider just one example, the capital-intensive nature of nuclear technology is an issue for the deployment of nuclear power in free-market countries: however this will only moderately impact the increase of installed nuclear power worldwide and its impact on CO_2 emissions as most of the nuclear growth is expected to arise in centrally planned economy countries —China, India, Russia, etc.

Liberalized electricity markets are ill-adapted to investments in capital-intensive low-carbon generation: because of the extensive liberalization of electricity markets in some countries to make the private sector bear all investment risks, investment in capital-intensive, new low-carbon generation has been hindered, notably in nuclear power. Indeed such investments being exposed to the uncertainties of long term electricity prices, financers require higher risks premiums, which significantly increase the cost of capital and can make nuclear power projects non profitable.

Government policies and regulations should guarantee long-term stability of nuclear energy: new plants require extensive planning and construction time, and once built, they may operate for 60 years or more; radioactive waste needs to be safely isolated for thousands of years. By increasing financial costs through higher risk premiums, lack of stability in the policy, in the regulatory framework and in the investment framework are therefore a deterrent to investors.

Safety regulations, codes and standards are currently largely country-dependent, which required repeating the licensing process for any target country of export to make it comply with the specific requirements of the country. Initiatives such as MDEP[1], supported by the Nuclear Energy Agency, are underway to progress towards internationally harmonized safety codes and standards.

Reasonably assured Uranium resources at a cost below $130/kg set a ceiling at the Gen-3 nuclear capacity that can be deployed worldwide: ~2000 GWe, thus not a bottleneck.

A need of skilled workforce: achieving the quite rapid rate of deployment envisioned in a “favorable context” scenario will require a major effort to attract and to train skilled workers and regulators.

Nuclear safety and proliferation risks are controlled: efficient tools are in place in the current context to satisfactorily master both nuclear safety and proliferation risks. However continuing a safe deployment of nuclear power worldwide requires to not export sensitive technologies to economically and politically unstable countries, as well as to countries with poor technical and technological capability.

Nuclear risks are perceived as being higher than climate change risks: nuclear risk perception has been exacerbated by the Fukushima accident. Nuclear risk perception does not yet integrate the fact that Gen-3 plants are designed to achieve radical advances in reducing both the frequency and the consequences of serious accidents involving core damages.

High-level, long-lived radioactive waste can be stored or disposed of in deep geological repositories. Proving that radioactive waste management solutions are publicly acceptable, safe and environmentally sound is essential to the further deployment of nuclear power in most countries.

[1] MDEP: Multinational Design Evaluation Programme (www.oecd-nea.org/mdep)

4. Potential radical and incremental innovations

Methodological information:

The following table lists the nature of innovations needed to overcome the bottlenecks mentioned earlier. There are two types of innovations: I stands for 'incremental innovation' (i.e. improving existing products and processes) and R stands for 'radical innovation' (i.e. developing new products and processes).

Technology		**Research & Technological innovations**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & Institutional environment**	**Resources & Environmental impacts** *(including scarcity of raw materials, water, land, climate)*	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
Gen-2	I or R	I					
	Key-words	Accident-tolerant fuel					
Gen-3/3+	I or R	I-R	I-R	I			
	Key-words	High conversion ratio LWRs Small modular reactors Accident-tolerant fuel	Reforms of electricity markets	International convergence of safety regulations, codes and standards National/regional repositories for high-level radwaste			

Major innovations are still expected on **Gen-2&3 Light Water Reactors** to further improve their safety, their economic competitiveness and to minimize the amount of radioactive waste. However they should be considered more as possible improvements to be progressively implemented in LWR generating fleets than as bottlenecks to be removed for the deployment of these reactors to successfully continue worldwide.

Enhanced safety through accident-tolerant fuels: thanks to innovative fuel forms that would be readily usable in operating nuclear plants (i.e. Gen-2) the response time to accidents could be significantly longer. This may give more time to decide on well-informed safety actions and would then contribute to mitigate the potential consequences of accidents. Accident-tolerant fuels include fuels with suppressed oxidation (compared to zirconium alloy cladding), fuels featuring good dimensional stability and fission product retention, and fuels with increased resistance to cladding rupture.

Enhanced use of natural Uranium through higher conversion ratio LWRs: innovative fuels designed to increase the conversion of uranium into plutonium and to enable several recyclings of the plutonium would reduce the uranium consumption of Gen-3 reactors that is typically ~200 tons/GWe.year to about 120/150 tons per /GWe.year by the time a marketable version of Gen-4 fast neutron reactors can be deployed.

Extending the portfolio of marketable LWRs to Small or Medium-size Reactors (SMRs): the scaling effect led so far to progressively build larger nuclear power plants (up to 1.7 GWe) that leave many countries and operators out of the nuclear landscape because their finance is not robust enough or because their grid is too small. Small or medium reactors with unit power ranging from 50 to 300 MWe could adequately supplement the current offering of large size reactors. Provided they can shorten the on-site construction time and can be made economically competitive through simplifications to offset the reverse scaling effect, some nuclear vendors estimate that the market of SMRs could represent an additional installed power of ~200 GWe within the next 20 years.

Reforming the electricity markets to facilitate capital-intensive, low-carbon investments in countries with a free market economy: in order to deliver the low-carbon energy and reliable supplies while minimizing costs to consumers, the electricity market needs reforms like those undertaken in the U.K., such as the "contracts for difference" designed to provide efficient and cost-effective price stabilization for reducing investor exposure to the volatile wholesale price of electricity.

Progressing towards better internationally harmonized safety regulations, codes and standards: if the respective national safety standards are harmonized, the licensing process can be launched without major adaptations. Harmonizing nuclear safety standards could thus facilitate the emergence of a more global market which offers a choice of a few reactor types that are recognized by regulators worldwide as safe and technologically mature[2].

Implementing national/regional interim storages and geological repositories for managing high level radioactive waste and eventually disposing of it.

Radical innovations in nuclear power generation will come through **Gen-4 technologies** that will extend capabilities of nuclear power beyond those of LWRs: fast neutron reactors with a full recycling of spent fuel that will enable using more than 80% of natural Uranium energy value, high temperature reactors that may cogenerate heat for industrial processes… Owing to the lead time necessary to bring next generation reactors to the market, these advanced nuclear systems are not anticipated to contribute much to saving CO_2 emissions by 2050. However, research today on such advanced nuclear technologies is essential for enabling nuclear power to further save CO_2 emissions beyond 2050, or to even increase the capability to do so. In this respect, switching to fast neutron reactors with a closed nuclear fuel cycle when a marketable reactor technology is ready will enable to exceed the ceiling of ~2000 GWe installed nuclear power that applies to LWRs.

[2] Source: WNA's discussion *Benefits Gained through International Harmonization of Nuclear Safety Standards for Reactor Designs* (2008).