Nuclear Development
2012

The Economics of Long-term Operation of Nuclear Power Plants

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NEA
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Nuclear Development ISBN 978-92-64-99205-4

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NEA No. 7054

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Foreword

In 2011, 289 reactors in the world were older than 25 years, and only 45 new units were connected to the grid in 2000-2011. Without life extensions, nuclear capacity will thus fall dramatically in the next decade, especially if the construction of new nuclear power plants also slows as a result of the Fukushima Daiichi accident. Refurbishments and long-term operation (LTO) of existing nuclear power plants (NPPs) are therefore important to the competitiveness of the nuclear industry in OECD countries as these existing NPPs are able to produce baseload power at low and stable costs.

Licence renewal and periodic safety reviews (PSRs) are the two basic regulatory approaches that have been adopted for authorisation of LTO of nuclear power reactors. Some countries use aspects from one or both approaches in determining whether, and under what conditions, to allow continued operation.

The aim of this study was to collect and analyse technical and economic data on the upgrade and lifetime extension experience in OECD countries. An OECD/NEA Ad Hoc Expert Group on the Economics of Long-term Operation of Nuclear Power Plants was established for this purpose with representatives from eight countries (list of members can be found in Appendix 2).

This study applies a multi-criteria approach for assessing the range of issues important in any decisions related to LTO, based on the current and future financial conditions of operation, political and regulatory risks, the state of the plants' equipment and the general role of nuclear power in the country's energy policy. One should note that a favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original lifetime or term authorised by the regulator (or expected by the operator). Other factors will have a role and an approval is required from the nuclear safety authority to confirm that the refurbished plant complies with their requirements for safe and secure operation.

The study found that in nearly all cases, the continued operation of NPPs for at least ten more years is profitable even taking into account the additional costs of post-Fukushima modifications. These modifications reflect changes in regulatory requirements after the Fukushima Daiichi accident that primarily concern reinforcement of protection against extreme events, dealing with accident management in potentially harsh environments, long-duration loss of power or cooling functions and accidents affecting multiple units at the same time. The preliminary estimates of the economic impact of post-Fukushima modifications are about 10-17% of the initially projected LTO investment.

Despite the economic attractiveness of LTO, there are several risks and uncertainties that can influence the utilities' decision to extend the operational lifetime of NPPs, such as public acceptance, changes in national policies or security concerns.

The members of the OECD/NEA expert group representing national nuclear regulatory bodies are not responsible for the opinions or judgments contained in the chapters on the economic aspects of long-term operation of nuclear power plants.

Acknowledgements

The principal author of this report is Dr Alexey Lokhov, OECD/NEA Nuclear Development Division, and was written based on input from the members of the Ad Hoc Expert Group on the Economics of the Long-term Operation of Nuclear Power Plants, co-chaired by Mr Luc Dufresne (Belgium) and Mrs Anne Giraud (France). Chapter 2 on the Regulatory and legal requirements for long-term operation in different countries was written by Mr Nicolas Osouf (France), based on the work of the NEA Committee on Nuclear Regulatory Activities. Chapter 3 on Safety initiatives following the Fukushima Daiichi accident was written by Mr Alejandro Huerta of the OECD/NEA Nuclear Safety Division.

Dr Ron Cameron, Head of the OECD/NEA Nuclear Development Division, provided managerial oversight as well as substantial comments throughout the process. The work was overseen by the Working Party on Nuclear Energy Economics. The report was endorsed for publication by the OECD/NEA Nuclear Development Committee.

The authors would like to thank Mr David Bradish, Nuclear Energy Institute (United States) and Dr Andy Hall, Office for Nuclear Regulation (United Kingdom), for their valuable inputs and comments.

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Executive summary

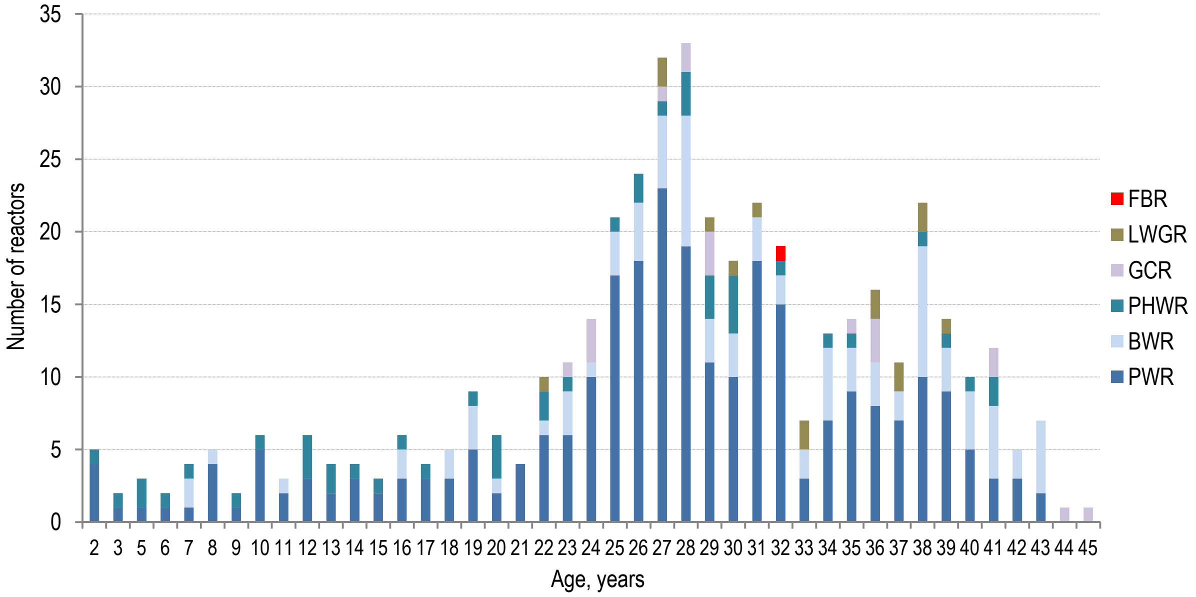
Long-term operation of nuclear power plants in the world

In 2011, 289 reactors in the world were older than 25 years (see Figure E1), and only 45 new units were connected to the grid in 2000-2011. Projections of nuclear generating capacity to 2030 show that some 160 reactors globally could be retired in the next 10 years on the basis of their original design lifetimes. Without life extensions, nuclear capacity would thus fall dramatically in the next decade, especially if the construction of new nuclear power plants (NPPs) also slows as a result of the Fukushima Daiichi accident. Refurbishments and long-term operation (LTO) of existing NPPs are therefore important to the competitiveness of the nuclear industry in OECD countries as these existing NPPs are able to produce baseload power at low and stable costs.

A number of NPPs, most notably 73 units in the United States (US) (as of June 2012), have been granted lifetime extensions of up to 60 years, a development that is being keenly watched in other OECD countries. In many countries (e.g. France, Switzerland), there is no legal end to the operating licence, but continued operation is based on positive outcomes from periodic safety reviews (PSRs). The overview of LTO programmes in selected countries is given in Table E1.

Depending on the design, lifetime extension can imply replacement of some large components of the nuclear island (e.g. steam generators, head of the reactor pressure vessel [RPV], etc.) as well as major refurbishments or replacements on the conventional islands (turbogenerator, condenser, transformers).

Figure E1. Distribution of reactors operating in 2011 by age and type



Note: Based on data from the Power Reactor Information System (PRIS), International Atomic Energy Agency (IAEA).

The primary aim of the OECD Nuclear Energy Agency (NEA) project "Economics of Long-term Operation of Nuclear Power Plants" was to collect and analyse technical and economic data on the upgrade and lifetime extension experience in OECD countries.

Table E1. Current status of LTO programmes in the world (July 2012)

Country	Status
Belgium	Ten-year licence extension for one unit.
Canada	Ongoing refurbishments and lifetime extension process.
Finland	Twenty-year licence extension of four units.
France	No legal end to the licence. Periodic safety review (PSR) every ten years.
Germany	Phase-out planned.
Hungary	Twenty-year extension of four units.
Japan	Used to have no legal end to the licence term. Currently envisages limiting the lifetime to 40 years.
Korea (Republic of)	No legal end to the licence.
Russia (Federation of)	Licence extension of different reactors by 15-25 years.
Sweden	No legal end to the licence. Replacement of NPPs allowed, but no additions.
Switzerland	No legal end to the licence.
Ukraine	Twenty-year extension of two units and ongoing LTO programmes for several others.
United Kingdom	Licence extensions for several years.
United States	Twenty-year licence extension of 73 units approved and 13 in review.

One should note that a favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original lifetime or term authorised by the regulator (or expected by the operator). Other national or organisational factors will also need to be taken into consideration. In addition an approval is required from the nuclear safety authority to confirm that the refurbished plant complies with their requirements for safe and secure operation.

Regulatory and legal requirements for long-term operation in different countries

Acceptance of an NPP for LTO must be based on evidence that the plant will comply with the "licensing basis" over the extended period of service. How this is achieved will depend on regulatory strategies in individual countries. In general, this requires an assessment of the current and projected condition of the plant and, in particular, of the systems that perform fundamental safety functions, to ensure that these systems will continue to perform their safety functions during the extended operating period. The strategy used could range from an approach that mainly addresses the impact of ageing to one that seeks changes in safety level based on the expectations for newer plants.

Licence renewal and PSRs are the two basic regulatory approaches that have been adopted for authorisation of LTO of nuclear power reactors. Some countries use aspects from one or both approaches in determining whether, and under what conditions, to allow LTO (see Table E2).

Table E2. Regulatory approaches to LTO in different countries

	Licence renewal	Periodic safety review (PSR)	Comment
Belgium		Yes	In Belgium, service life (operating licence) for NPPs is set by law at 40 years. Utilities have to conduct a PSR for their operating NPPs every ten years and have to submit the PSR report to the federal regulator for nuclear control for review and approval. In the case of Tihange 1, there will be the possibility of a one-off extension of ten years of the operating licence, under the condition that the results of the next PSR for this reactor are approved by the federal regulator.
Finland		Yes	According to the Nuclear Energy Act, the operating licences are granted for a fixed term. The licence conditions may by changed during its period of validity by the government. The licence can also be revoked if the licensee is failing to comply with the licence conditions and the nuclear regulator (STUK) is given power to monitor the operation of the plants and take any measures required to ensure public safety.
France		Yes	In France, the operating licence for a nuclear reactor does not set a limit for service life. However, article 29 of the Transparency and Nuclear Safety Act (13 June 2006) requires that the operator of a nuclear reactor performs a safety review of the facility every ten years.
Hungary		Yes	According to current Hungarian regulations the operating licence is subject to a PSR, which is performed (every 10 years) as a self-assessment by the licensee under the control and approval of the regulatory body during the original design lifetime (30 years for the currently operating NPPs). The licensee has to prepare and submit to the regulatory body a licence renewal request for permitting LTO, justifying a design lifetime, up to 20 years beyond the original design lifetime.
Korea, Republic of		Yes	A PSR has to be conducted every ten years and submitted for regulatory review and approval to justify the next ten years of continued operation. The "final ten-year PSR" may also be used to request extension of the original service life by another ten years. The service life of existing designs is between 30-40 years.
Russian Federation	Yes		The operating licence is limited to the original design lifetime of the plant (30 years for the currently operating NPPs). Relicensing by the regulator (Rostekhnadzor) is a prerequisite for the extension of the operational lifetime. The duration of the licence extension is determined individually for each unit based on residual life. The licensee has to prepare and submit to the regulatory body a proposal for permitting an LTO period of which depends on revised, justified and approved longer than the original design lifetime. The Russian plants undergo constant reviews and inspections, and Rostekhnadzor can order the shutdown of the unit or take any other actions to ensure public safety.
Switzerland		Yes	In Switzerland, the service life for NPPs is not limited. Article 10 of the Nuclear Energy Ordinance (NEO) defines the principles for the design of the safety functions of NPPs. These include, in particular, single failure criterion, principles of redundancy and diversity, functional and physical separation, automation principle and conservativism in design. In the NEO and the Nuclear Energy Act it is stipulated that the licence holder shall upgrade the NPP to the extent that it is necessary in keeping with operational experience and the current state of back fitting technology, and beyond insofar as further upgrading is appropriate and results in a further reduction of the risk to human beings and the environment.
United Kingdom		Yes	In the United Kingdom, a single non-transferable licence is granted to cover the life of the nuclear site from start of construction to final decommissioning. There is no pre-determined end date for operation. Nuclear facilities are permitted to continue to operate for as long a period as the licensee can demonstrate that it is safe do so. The PSRs (conducted with a periodicity of around ten years maximum since the early 1990s) should confirm that original safety standards will be maintained, identify any life-limiting features on the plant, and demonstrate that all reasonably practicable measures to improve the plant to modern standards are being implemented. The regulator may require the licensee to carry out plant modifications that have been identified during the PSR as reasonably practicable or undertake other activities, e.g. perform additional analyses. If the plant cannot be brought sufficiently close to modern standards, the licensee may be required to cease operation. The end points of past PSRs of UK's facilities have included all of these potential outcomes.
United States	Yes		The US Atomic Energy Act of 1954 allows the Nuclear Regulatory Commission (NRC) to issue licences for commercial power reactors to operate for up to 40 years. The NRC regulations allow the renewal of these licences for an additional period of 20 years if the reactor satisfies safety and environmental criteria. Although the licensing process does not require PSRs, the US nuclear plants undergo constant reviews and inspections and the NRC can revoke the licence or take any other actions to ensure public safety.

Immediately after the Fukushima Daiichi accident, the regulators and international organisations have initiated activities aimed at analysing the lessons learnt from this accident.

The changes in regulatory requirements after the Fukushima Daiichi accident primarily concern reinforcing protection against external events, dealing with accident management in potentially harsh environments or long duration accidents affecting multiple units at the same time. These changes concern all operating units independently of their age. However, these additional requirements might have costs that should be included when considering an LTO programme.

Lifetime-limiting factors

Considerable research and development (R&D) efforts have already been conducted on material degradation of RPVs, primary piping, core internals, secondary systems, welds, concrete structures, cable insulation, buried piping and other components.

During the operational lifetime of a nuclear reactor many of its components (heavy equipment, pipes, valves, cables, electronics, etc.) are replaced. However, there are some irreplaceable parts that constitute the critical life-limiting components, namely the RPV and the containment building.

It appears that the impact of irradiation on the RPV is strongly dependent on the chemical composition of the vessel material. The RPVs and welding material of older reactors (typically fabricated before 1972) sometimes had relatively high quantities of copper and phosphor that strongly affect the fracture toughness of the vessels. However, newer RPVs are made from steel that is much more resistant to irradiation damage than vessels of the first generations. According to the R&D results, most of the vessels have sufficient safety margin below the pressurised thermal shock (PTS) screening criterion. However, even if the material properties are favourable to LTO, complete inspections of the RPV are needed to ensure the global structural integrity of the vessel.

The primary containment is the key safety-related concrete structure in NPPs. It is the third (and final) barrier to radioactive release in case of a severe accident (the first is the fuel cladding; the second is the RPV and the primary circuit).

With respect to LTO, the containment structure and containment liner are subject to ageing management review to identify age-related degradations. In many countries the leak tightness of containments is experimentally verified (by pressurising) during PSRs (every ten years at minimum).

Economics of long-term operation of nuclear power plants

Assessment criteria

The economic assessment of LTO of NPPs should take into account various factors and parameters reflecting current and future financial conditions of operation, political and regulatory uncertainties, the state of the plant's equipment and the general role of nuclear in the country's energy policy. The OECD/NEA Ad Hoc Expert Group on Economics of Long-Term Operation of Nuclear Power Plants has selected the following criteria as appropriate for the assessment of LTO programmes:

- production and asset portfolio;
- predictability of future electricity prices;
- need for NPP equipment upgrade and replacement;
- impact of refurbishment activities on the decennial average of the energy availability factor (EAF);

- risk and uncertainty (site-dependence, political, financial, and regulatory);
- overnight cost of refurbishment;
- LCOE$_{EO}$ – levelised cost of electricity generation after LTO activities;
- country's carbon policy and security of energy supply.

Factors that affect the economics of LTO include replacement of obsolete equipment, safety upgrades to current standards and the ageing of irreplaceable components such as the RPV or containment building. The general characteristics listed above are considered valuable in assessing the different options that the utility or government might consider. This is done using a three-point grading system, see Table E3.

Table E3. Summary of assessment methodology

Criteria	★★★ Most positive outcome for LTO	★★ Neutral outcome for LTO	★ Least positive outcome for LTO
Production and asset portfolio	If the share of nuclear generation in the electricity mix is large (more than 30%), NPPs have a potential for load-following, or the cross-border electricity capacity is limited, the score for LTO of NPPs is three stars.	If the share of nuclear generation is important (10-30%) but the remaining electricity mix is well diversified, and there is a potential for cross-border electricity trading, then the score for LTO of NPPs is two stars.	If the share of nuclear generation is small (less than 10%) and the remaining part of the electricity mix is well diversified, NPPs have low potential for load-following and the cross-border electricity capacity is significant, the score for LTO of NPPs is one star.
Predictability of future electricity prices	If the prices are predictable, and there are no plans for specific limitations/regulations restricting the operation of NPPs, the score for LTO of NPPs is three stars.	If utilities operate in a liberalised market with volatile electricity prices or in case of specific regulation/taxation in place marginally affecting the operation of NPPs, the score is two stars.	If the prices are strongly volatile, or in case of special regulations or taxes that potentially will make operation of NPPs significantly less favourable in the future, the score is one star.
Need for NPP equipment upgrade and replacement	If most equipment or systems of the plant are up to date the score is three stars.	If a significant part of the equipment or systems of the plant is up to date, the score is two stars.	If a large part of equipment or systems of the plant are out of date, the score is one star.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	If the EAF is marginally affected (less than -3%) over a ten-year period by lifetime management activities, the score is three stars.	If the EAF is slightly affected (3-6% decrease) over a ten-year period by lifetime management activities, the score is two stars.	If the EAF is strongly affected (more than -6%) over a ten-year period by lifetime management activities, the score is one star.
Risk and uncertainty (site-dependence, political, financial, regulatory)	If risks are low compared to building replacement capacity the score is three stars.	If risks are moderate compared to building replacement capacity the score is two stars.	If risks are significant compared to building replacement capacity the score is one star.
Overnight cost of refurbishment	If the overnight cost of refurbishment is smaller than the investment needed to build a replacement capacity, and the utility is not limited by financing, the score is three stars.	If the overnight cost of refurbishment is comparable with the costs of building a replacement capacity, and some external funding is needed, the score is two stars.	If the overnight cost of refurbishment is significantly higher than the costs of building an alternative (non-nuclear) generating capacity, and it can only be covered by external funds, the score is one star.
LCOE$_{EO}$ – levelised cost of electricity generation after LTO activities	If the LCOE$_{EO}$ is lower than projected costs of electricity (replacement plant, imports, etc.) the score is three stars.	If the LCOE$_{EO}$ is comparable to projected costs of electricity the score is two stars.	If the LCOE$_{EO}$ is higher than projected costs of electricity the score is one star.
Country's carbon policy and security of energy supply	If there is a strong national policy on reducing CO_2 emissions or if there is a carbon pricing mechanism in place, and the contribution of nuclear power to security of energy supply is considered important, the score is three stars.	If there is a national policy on reducing CO_2 emissions but nuclear electricity is not counted as a carbon-free source of electricity, or if there are no immediate intention to introduce carbon taxes, the score is two stars.	If there are no binding policies on reducing CO_2 emissions, and nuclear energy is not seen as an important factor of security of energy supply, the score is one star.

Economic assessment

The LTO programmes vary from country to country, for instance:

- In the **United States**, 73 reactors (of 104 units) have obtained an extension of their licence for 20 years, as of June 2012. Many nuclear plants in the US are planning to apply for a second extension (from 60 to 80 years) in order to operate beyond 60 years (the first nuclear plant to reach 60 years of age will be in 2029). Research is currently underway to determine the effects of ageing on important systems, structures and components.
- The initial design lifetime of **French** reactors was 40 years. However, according to the French regulatory framework, there is theoretically no time limit for NPP operation. Every ten years, the French Nuclear Safety Authority (ASN) performs a PSR consisting of conformity checks and safety reassessments. In France, 34 reactors of the PWR-900 series obtained a licence extension of 10 years in 2002, and 20 units of the PWR-1300 series were granted a 10-year licence extension in 2006. The total investment in all the fleet of 58 reactors until 2025 is about USD$_{2010}$ 70 billion.
- In the **Russian Federation**, the original lifetime (licence) of Russian nuclear reactors was 30 years. Several reactors of different technology and designs (VVER-440, VVER-1000, RBMK and sodium-cooled BN-600) have obtained a 15- to 25-year extension of their original design lifetime. For example, the older PWR/VVER-440 reactors have obtained a 15-year extension, and larger VVER-1000 have obtained a 25-year lifetime extension.

In the countries that have participated in this study[1], LTO programmes currently cost in the range of USD$_{2010}$ 500-1 100/kWe (kilowatt electric) (see Table E4), as reported by the licensees, depending on the extent of prior refurbishments and additional regulatory requirements or other plant performance improvement (like power uprates).

The preliminary estimates of the economic impact of post-Fukushima modifications are about 10-17% of the initially projected LTO investment.

Table E4. Cost summary of LTO and refurbishment programmes in selected countries

Country	Specific investment in LTO	Comment
Belgium	USD$_{2010}$ 650/kWe	Including ~11% increase due to post-Fukushima measures.
France	USD$_{2010}$ 1 090/kWe	Including all investments from 2011 to 2025: maintenance, refurbishment, safety upgrades, performance improvement; and ~10% increase due to post-Fukushima measures.
Hungary	USD$_{2010}$ 740-792/kWe	Including 10-17% increase due to post-Fukushima measures.
Korea, Republic of	USD 500/kWe	Including ~10% increase due to post-Fukushima measures.
Switzerland	USD$_{2010}$ 490-650/kWe	Specific future investment in NPP refurbishment and maintenance (approximately the double of the specific LTO investment) is USD$_{2010}$ 980-1 300/kWe.
United States	About USD$_{2010}$ 750/kWe	Electric Power Research Institute (EPRI) survey data and current spending on capital improvement.
Russian Federation*	About USD$_{2010}$ 485/kWe	Data for Novovoronezh 5 unit (first series of VVER-1000: V-187).
Ukraine*	About USD 300-500/kWe	Public statements by Energoatom and Ukrainian prime minister.

* These countries did not participate in the study.

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[1] Belgium, Finland, France, Hungary, Republic of Korea, Switzerland, the United Kingdom and the United States.

The results of the assessment of LTO programmes in selected OECD/NEA member countries, performed by the NEA expert group using the methodology summarised in Table E3, are provided in Table E5. In most of the cases, the continued operation of NPPs for at least ten more years is profitable even taking into account the additional costs of post-Fukushima modifications. The levelised costs of electricity generation after refurbishment (LCOE_{EO}) are expected to be significantly smaller than the projected electricity generation costs with alternative sources.

Table E5. Summary of the economic assessment of LTO programmes in selected OECD countries

	Belgium	Finland	France	Hungary	Korea, Republic of	Switzerland	United States
Production and asset portfolio	★★	★★★	★★★	★★★	★★★	★★★	★★★
Predictability of future electricity prices	★	★★★	★★★	★★★	★★/★★★	★★	★★
Need for NPP equipment upgrade and replacement	★★	★★★	★★/★★★	★★	★★★	★★★	★★★
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★/★★★	★★★	★★★	★★	Wolsong 1 (CANDU): ★ Kori 1 (PWR): ★★★	★★★	★★/★★★
Risk and uncertainty (site-dependence, political, financial, regulatory)	★	★★/★★★	★★	★★★	★★	★/★★	★★★
Overnight cost of refurbishment	★★★	N/A	★★/★★★	★★★	★★★	★★	★★★
LCOE_{EO} – levelised cost of electricity generation after LTO activities	★★★	N/A	★★★	★★★	★★★	★★★	★★/★★★
Country's carbon policy and security of energy supply	★★	★★★	★★★	★★/★★★	★★	★★★	★★

Note: Score "★" is the least positive outcome of that criterion for NPP LTO and score "★★★" is the most positive outcome for NPP LTO.

N/A = Not available.

Currently, the LCOE_{EO} for the countries considered in this study[2] is in the range of USD_{2010} 30-58/MWh (megawatt-hour) in the case of continued operation for 20 additional years and in the range of USD_{2010} 30-71/MWh in the case of continued operation for 10 additional years.

The LTO programmes also remain cost effective compared to alternative replacement sources (see examples for Belgium and the US in Figure E2 and Figure E3).

Despite the economic attractiveness of LTO, there are several risks and uncertainties that can influence the utilities' decision to extend the operational lifetime of NPPs such as public acceptance, changes in national policies or security concerns. Also, in the US, the LTO decision could be economically challenged if the price of natural gas remains extremely low for a long period of time.

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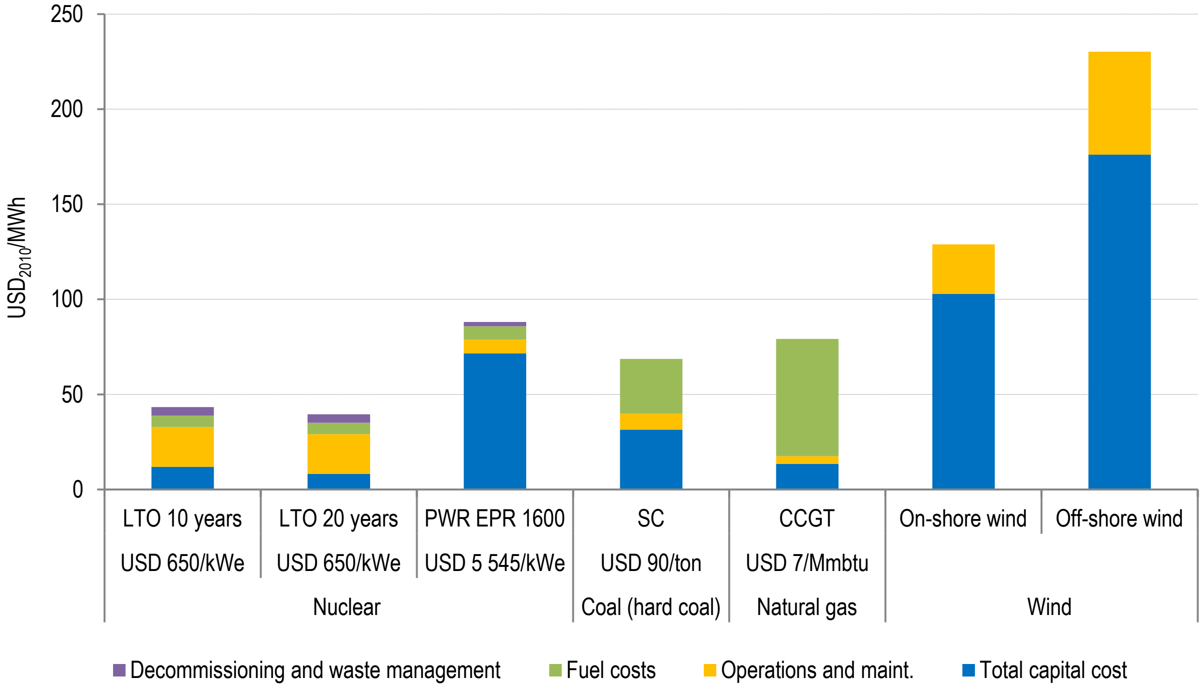
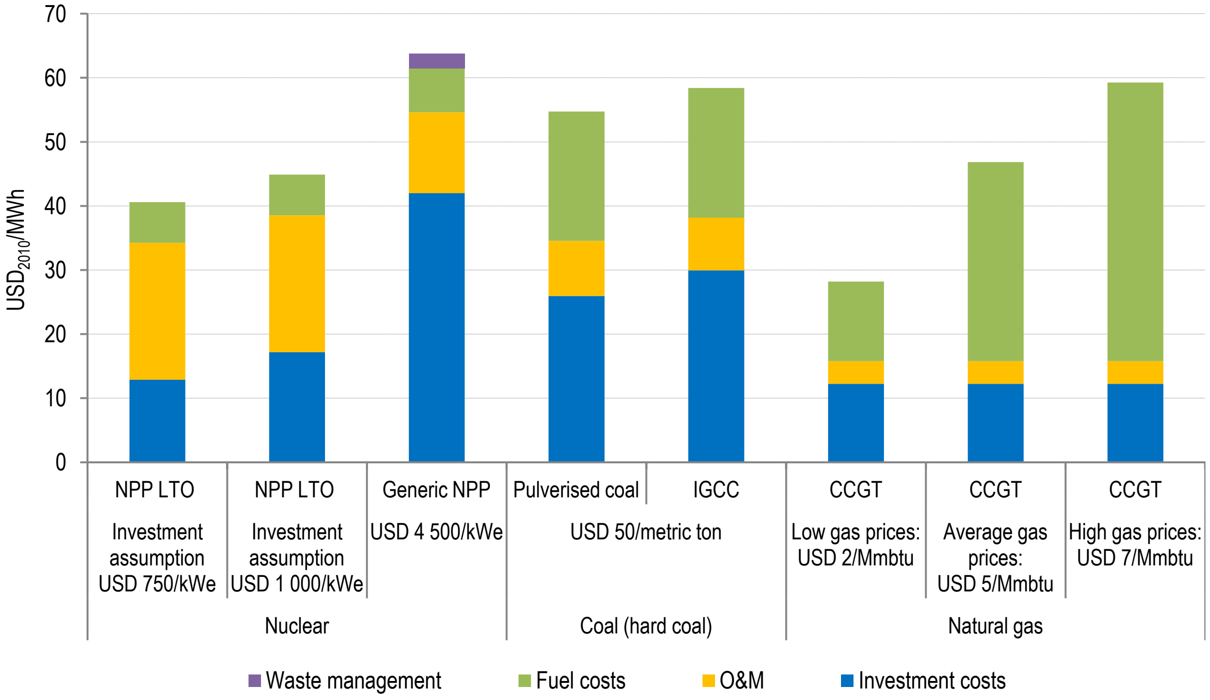
[2] Estimates for Belgium, France, Hungary, Republic of Korea, Switzerland and the United States.

Figure E2. Projected costs of electricity generation in Belgium, at 8% real discount rate



Note: CCGT = Combined-cycle gas turbine. PWR = Pressurised water reactor; EPR = European pressurised reactor; SC = Supercritical.

Figure E3. Projected costs of electricity generation with alternative sources in the United States, at 8% real discount rate



Note: CCGT = Combined-cycle gas turbine; IGCC = Integrated gasification combined cycle.

Conclusions and recommendations

The analysis presented in this study shows that LTO of NPPs has significant economic advantages for most utilities envisaging LTO programmes.

The multi-criteria approach provides a valuable method for assessing the range of issues important in any decisions related to LTO, since the criteria identified allow consideration of national issues and priorities, which should be included in the decision-making process.

In addition, a favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original term authorised by the regulator (or expected by the operator). An authorisation from the nuclear safety authority is required, confirming that the reactors continue to meet the licensing basis.

In most cases, the continued operation of NPPs for at least ten more years is profitable[3] even taking into account the additional costs of post-Fukushima modifications, and remain cost effective compared to alternative replacement sources.

The OECD/NEA Ad Hoc Expert Group on the Economics of Long-term Operation of Nuclear Power Plants recommends that:

- A multi-criteria approach should be used for assessment of the LTO of NPPs, since they allow the various factors, both quantitative and qualitative, to be included.
- Stakeholders should learn from the experiences and assessments of other countries.
- Given that there is a lack of public knowledge on the extent of the refurbishment and upgrading that accompanies a decision to extend the operational lifetime of a reactor, it would be valuable for industry to provide more detailed information to the public and other stakeholder groups on the extensive and demanding nature of an LTO programme.
- It is good practice to anticipate the safety requirements regarding ageing management and safety margin improvements throughout the plant lifetime. In this regard, ongoing monitoring programmes are important and continuous replacement programmes should be carried out.
- An effective ageing management programme is a key element of safe and reliable operation of NPPs during the originally planned operation time frames, as well as for periods of LTO. LTO of NPPs could be a key element in the decarbonising of electricity generation since they maintain low carbon sources of baseload electricity which cannot easily be replaced by other low-carbon technologies.
- Further work should be undertaken to establish a more complete technical basis for decisions on LTO beyond the currently demonstrated periods.

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[3] In some countries there are additional taxes or special situations that affect the overall profitability of nuclear.

Chapter 1. Overview of long-term operation programmes in the world

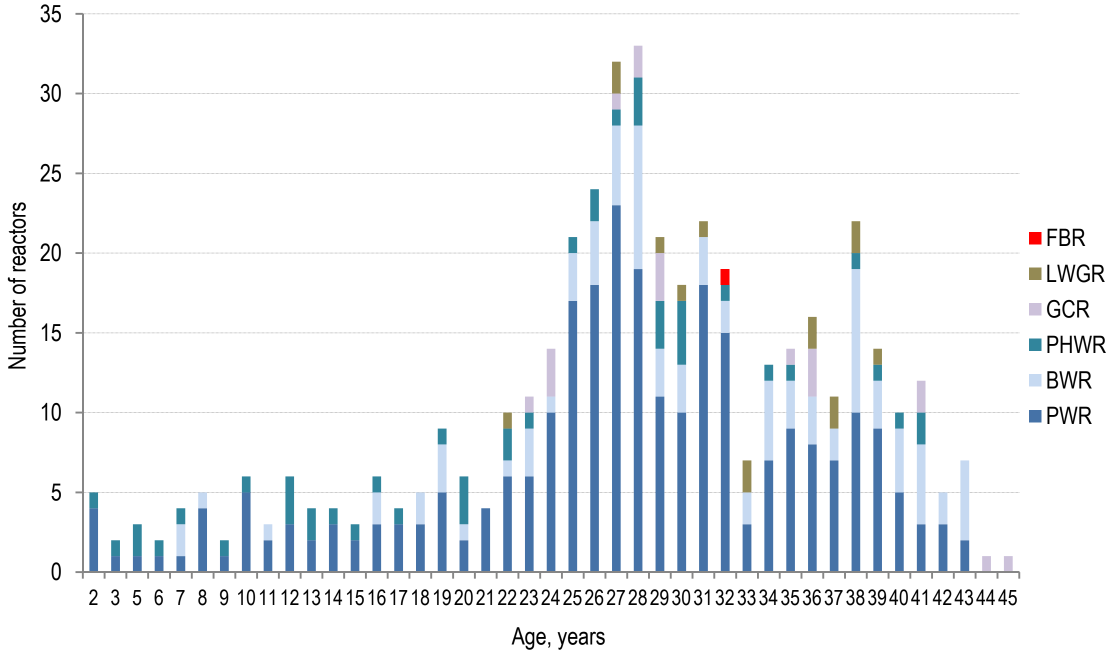
Introduction

In 2011, 289 reactors in the world were older than 25 years (see Figure 1.1 and Table 1.1), and only 45 new units were connected to the grid in 2000-2011. Projections of nuclear generating capacity to 2030 show that some 160 reactors globally could be retired in the next 10 years on the basis of their original design lifetimes. Without life extensions, nuclear capacity would thus fall dramatically in the next decade, especially if the construction of new nuclear power plants (NPPs) is also slowed down as a result of the Fukushima Daiichi accident. Refurbishments and long-term operation (LTO) of existing NPPs today are therefore important to the competitiveness of the nuclear industry in OECD countries as existing NPPs are able to produce baseload power at low and stable cost.

A number of NPPs, most notably 73 units in the United States (US), have been granted lifetime extensions of up to 60 years (see Table 1.2), a development that is being keenly watched in other OECD countries (see Leon et al, 2010). In many countries (e.g. France, Switzerland), there is no legal end to the operating licence, but continued operation is based on the outcomes of periodic safety reviews (PSRs).

Depending on the design, lifetime extension can imply replacement of some large components of the nuclear island (e.g. steam generators, head of the reactor pressure vessel [RPV], etc.) as well as major refurbishments or replacements on the conventional islands (turbogenerator, condenser, transformers).

Figure 1.1. Distribution of reactors operating in 2011 by age and type



Note: Based on data from IAEA PRIS.

Table 1.1. Number of reactors older than 25 years in 2010, in selected countries

Country	Number of reactors >25 years old
Belgium	7
Canada	11
Czech Republic	1
Finland	4
France	37
Germany	13
India	6
Japan	29
Korea (Republic of)	5
Russia (Federation of)	24
Slovak Republic	2
Slovenia	1
South Africa	2
Spain	6
Sweden	10
Switzerland	5
United Kingdom	14
United States	81

Note: Based on data from the Power Reactor Information System (PRIS) International Atomic Energy Agency (IAEA).

Table 1.2. Current status of lifetime extension programmes in the world (July 2012)

Country	Status
Belgium	Ten-year licence extension for one unit.
Canada	Ongoing refurbishments and lifetime extension process.
Finland	Twenty-year licence extension of four units.
France	No legal end to the licence. Periodic safety review (PSR) every ten years.
Germany	Phase-out planned.
Hungary	Twenty-year extension of four units.
Japan	Used to have no legal end to the licence term. Currently envisages limiting the lifetime to 40 years.
Korea (Republic of)	No legal end to the licence.
Russia (Federation of)	Licence extension of different reactors by 15-25 years.
Sweden	No legal end to the licence. Replacement of NPPs allowed, but no additions.
Switzerland	No legal end to the licence.
Ukraine	Twenty-year extension of two units and ongoing LTO programmes for several others.
United Kingdom	Licence extensions for several years.
United States	Twenty-year licence extension of 73 units approved and 13 in review.

In some cases the investment in maintenance and refurbishment needed to reach 40 years is adequate to operate for 60 years. The IAEA study (IAEA, 2002) estimated in 2002 that 60% of the lifetime extension programmes in the world would require less than about USD 500/kWe (kilowatt electric) of investment. Probably this figure now somewhat underestimates the costs of investment in lifetime extensions. For instance, the IHS CERA Power Capital Cost Index[1] indicates that the construction costs of new NPPs have grown by more than 100% between 2000 and 2009. Hence some inflator to the IAEA figure should be applied to make the estimate more current. In particular, the cost of large equipment and components has grown significantly between 2000 and 2010. However, the cost of some equipment might decrease in the future since reactor builders have significantly developed their equipment manufacturing capacities during recent years, and they may have overcapacity because of the possible slowdown in nuclear plants building rates following the Fukushima Daiichi accident. Thus, it is unclear what the costs of refurbishment of NPPs will be today.

First estimates indicate that lifetime extension is a profitable option from an economic point of view in the great majority of cases even when assuming significant investment costs of refurbishment. It is of course the principal purpose of this project to verify these estimates on the basis of detailed plant-level data and in different regulatory frameworks.

Independently of LTO, equipment in NPPs is regularly upgraded following technology progress and to fulfil new requirements. These requirements are subject to change due to external or internal events and, generally speaking, it is a reflection of learning from the whole experience of the nuclear industry. For example, the design of NPPs changed after the Three Mile Island accident (instrumentation and control [I&C], human-system interface, etc.).

Further changes and safety upgrades are currently being implemented following the accident at Fukushima Daiichi NPP. Requirements for external event resistance of plants and spent fuel storage facilities (e.g. against seismic and tsunami as well as the capabilities to survive losses of offsite power) need to be enhanced in some plants. The economic impact of refurbishments associated might influence the decision about life extension or not.

The economics of upgrade and lifetime extension programmes is thus a key issue for further development of nuclear development programmes in OECD member countries.

The primary aim of the OECD Nuclear Energy Agency (NEA) project “Economics of Long-term Operation of Nuclear Power Plants” was to collect and analyse technical and economic data on the upgrade and lifetime extension experience in OECD countries.

This report is organised in the following way: In Chapter 2, regulatory and legal requirements for LTO in different countries are analysed. Chapter 3 summarises the safety initiatives following the Fukushima Daiichi accident and some preliminary implications for the nuclear regulation.

The methodology of multi-criteria analysis of the economics of LTO is presented in Chapter 4. Some crucial elements are required for a successful justification of lifetime extension programmes in a given country (e.g. high level of safety, high level of performance of nuclear reactors and economic competitiveness, and favourable public opinion).

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1. IHS CERA Power Capital Cost Index (PCCI): www.ihsindexes.com.

The economic assessment of LTO of NPPs should thus take into account various factors and parameters reflecting current and future financial conditions of operation, political and regulatory uncertainties, state of plants equipment and the general role of nuclear in the country's energy policy. The criteria for the economic assessment of LTO programmes include:

- production and asset portfolio;
- predictability of future electricity prices;
- need for NPP equipment upgrade and replacement;
- impact of refurbishment activities on the decennial average of the energy availability factor (EAF);
- risk and uncertainty (site-dependence, political, financial, and regulatory);
- overnight cost of refurbishment;
- $LCOE_{EO}$ – levelised cost of electricity generation after LTO activities;
- country's carbon policy and security of energy supply.

One should note that a favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original lifetime or term authorised by the regulator (or expected by the operator). Other national or organisational factors will also need to be taken into consideration. In addition an approval is required from the nuclear safety authority that confirms that the refurbished plant complies with their requirements for safe and secure operation. In this chapter, the main focus is on the economics of refurbishment.

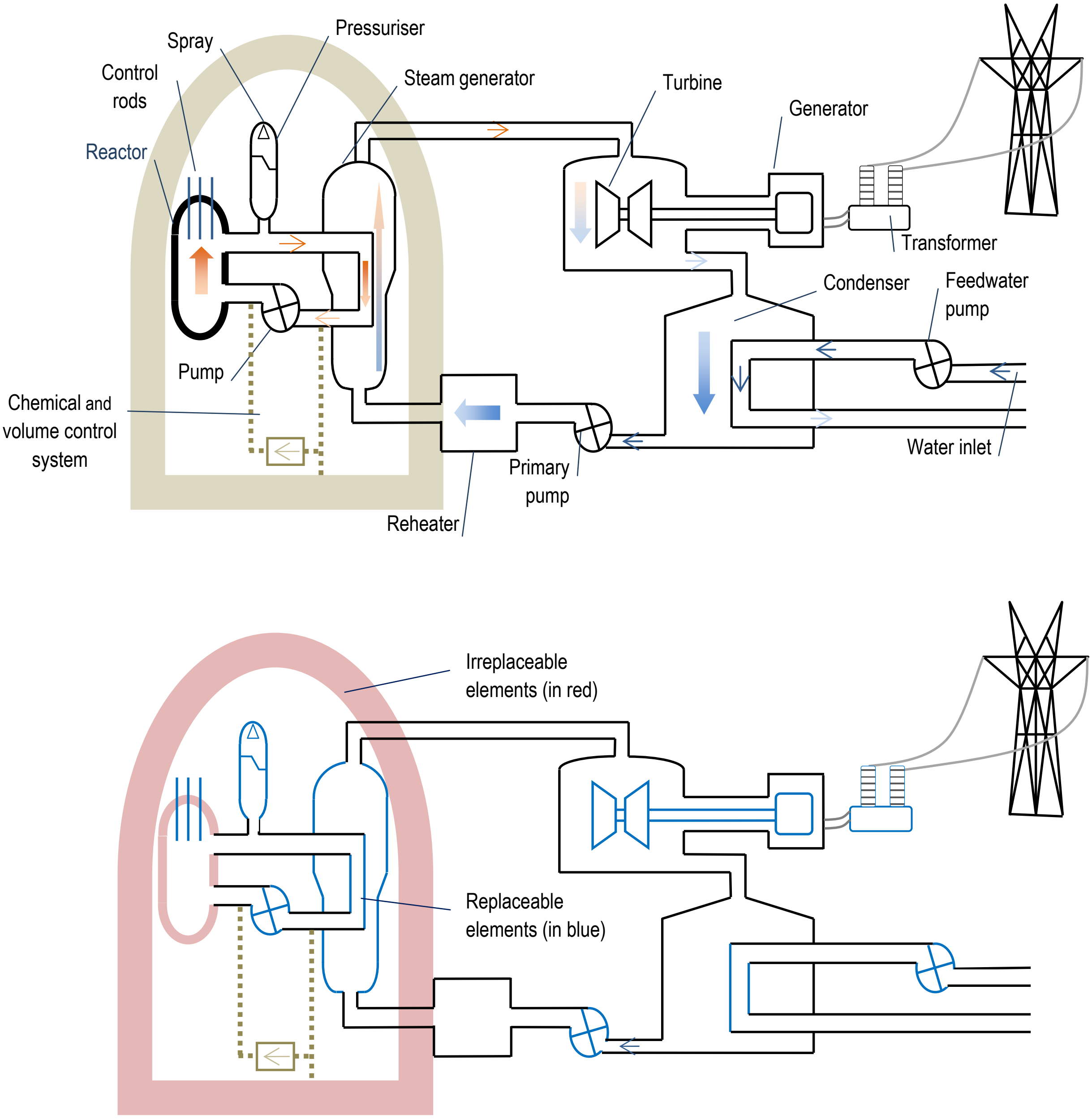
The assessment criteria and the methodology of their evaluation (described in Chapter 4) are used in Chapter 5 for country-based case studies. LTO programmes in countries that have not participated in the economic part of the study and some non-OECD countries are summarised in Chapter 6. The summary and conclusions are presented in Chapter 7.

Lifetime-limiting factors

Considerable research and development (R&D) efforts have already been conducted on material degradation of RPVs, primary piping, core internals, secondary systems, weldments, concrete structures, cable insulation, buried piping and other components.

During the operational lifetime of a nuclear reactor many of its components (heavy equipment, pipes, valves, cables, electronics, etc.) are replaced. However, there are some irreplaceable parts that constitute the critical life-limiting components, namely the RPV and the containment building (see Figure 1.2). There is an abundant literature on the lifetime management of RPVs by the IAEA (IAEA 2009a, 2009b, 2010), and by national and international research and regulatory bodies. In this section only a brief overview of key findings is presented.

Figure 1.2. General scheme (top) of a pressurised water reactor and indication of irreplaceable parts (bottom)



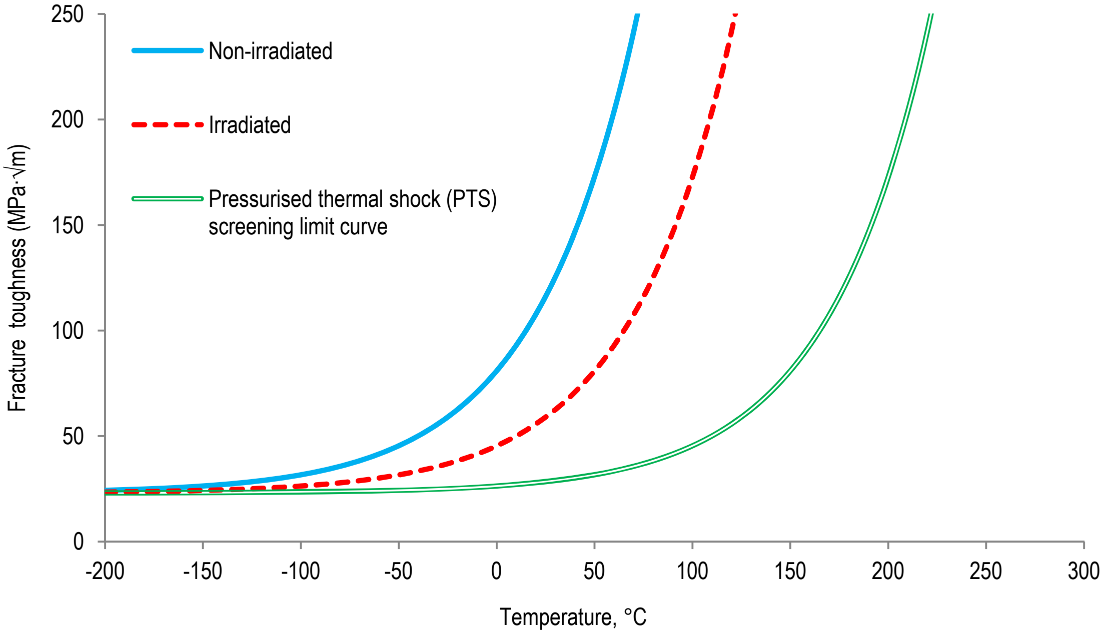
Reactor pressure vessel (RPV)

The wall of the RPV is exposed to neutron irradiation leading to embrittlement of the steel and welds in the area of the reactor core ("beltline" area). Also, it is subject to thermal ageing and fatigue.

A flaw (of a critical size) in the wall of an embrittled pressure vessel can propagate rapidly through the vessel in case of certain accidental scenarios or transients (PTS – pressurised thermal shock in accidental conditions or overpressure at low temperature), possibly resulting in a through-wall crack and jeopardising the integrity of the RPV (IAEA, 2010).

The ability of a material containing a crack to resist fracture is determined by its fracture toughness K measured in $\mathrm{MPa}\cdot\sqrt{\mathrm{m}}$. The mechanical stress in the vicinity of a crack of local curvature R is proportional to $K/\sqrt{R}$. The fracture toughness increases with temperature and decreases with irradiation time (see Figure 1.3). One of the main R&D objectives with respect to LTO of nuclear reactors is to determine the fracture toughness of irradiated materials constituting the RPV.

Figure 1.3. Illustration of the effect of irradiation on the fracture toughness



It appears that the impact of irradiation is strongly dependent on the chemical composition of the vessel material. In particular, the fracture toughness is (adversely) affected by the neutron irradiation if copper, nickel or phosphor are present in the steel.

The RPVs and welding material of older reactors (typically fabricated before 1972) sometimes had relatively high quantities of copper and phosphor that strongly affect the fracture toughness of the vessels. However, newer RPVs are made from steel that is much more resistant to irradiation damage than vessels of the first generations.

According to the R&D results, most of the vessels have sufficient safety margin below the PTS screening criterion. An example (from Lucon et al., 2009) for steel samples from Belgian reactors of first and second deployment stages is presented in Figure 1.4 and Figure 1.5. The adjusted reference temperature[2] (ART) for the Belgian RPVs increases with increasing years of operation because of embrittlement, but for all reactors ART is below the regulatory limit defined by PTS screening criteria. For the older units Doel 1, Doel 2 and Tihange 1 (Figure 1.4), the margins are about 30°C in the worst case, and while for the newer Doel 3, Doel 4, Tihange 2 and Tihange 3 (Figure 1.5) reactors the effects of irradiation damage are significantly smaller and the margin is always larger than 100°C.

However, even if the material properties are favourable to LTO, complete inspections of RPV are needed to ensure the global structural integrity of the vessel.

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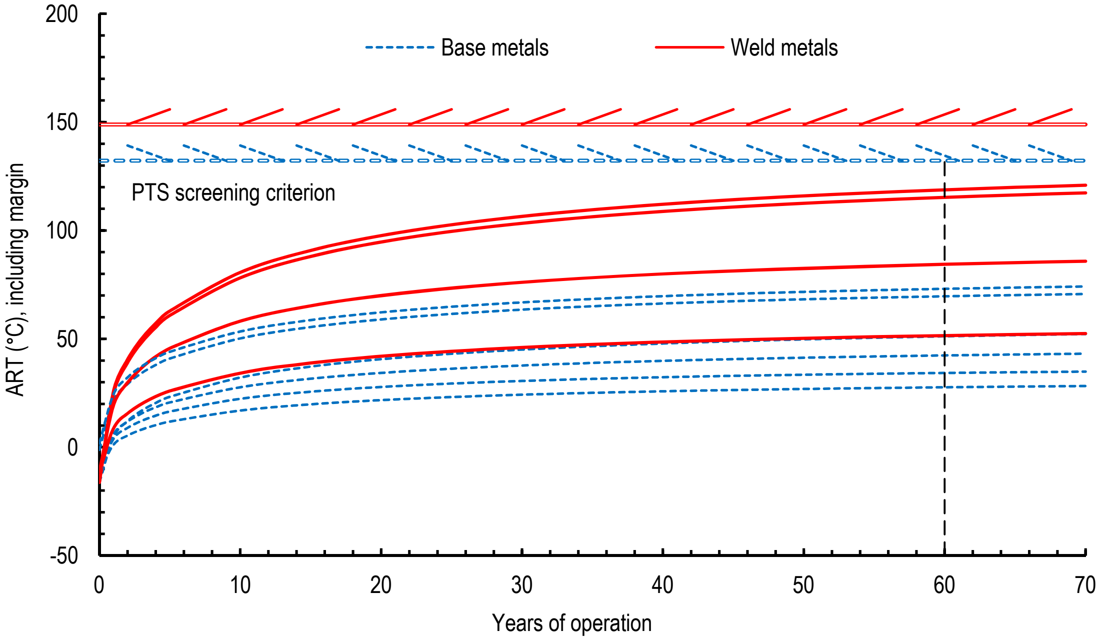
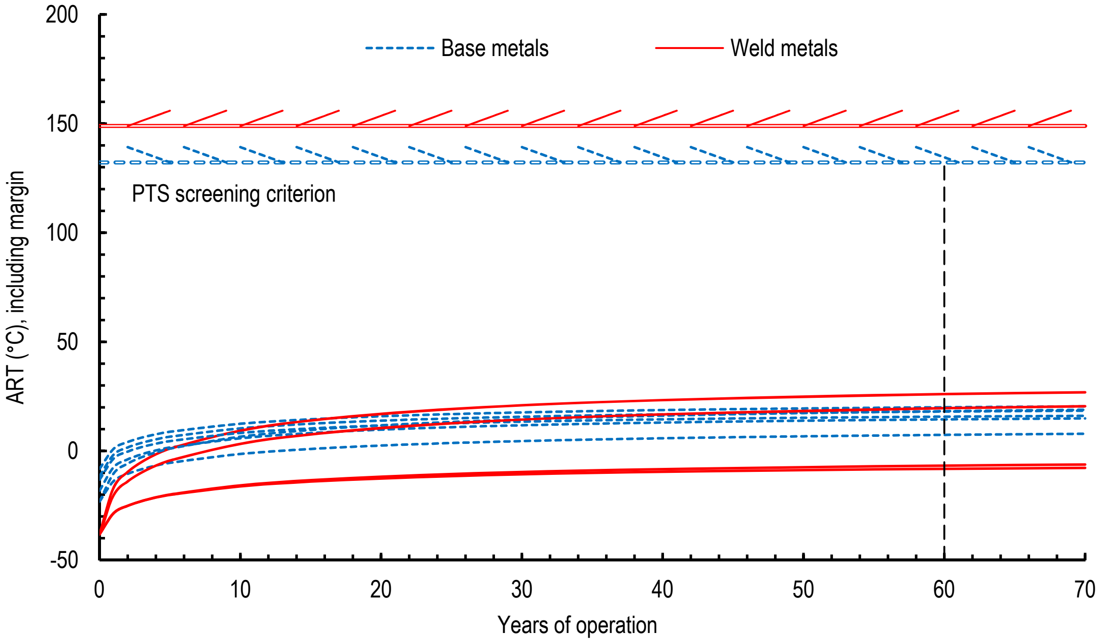
2. ART is ductile-to-brittle transition temperature calculated by adding to the non-irradiated value of RT_{NDT} (reference temperature for Nil Ductility Transition), the variation ΔRT_{NDT} caused by irradiation and a margin term that accounts for experimental uncertainties.

Figure 1.4. Adjusted reference temperature (ART) compared to pressurised thermal shock (PTS) for RPV base and weld metals from Doel 1, Doel 2 and Tihange 1 NPPs in Belgium



Note: Curves should be compared to double lines of the same type (dashed blue for base metals, red for weld metals).
Source: Lucon et al., 2009.

Figure 1.5. Adjusted reference temperature (ART) compared to pressurised thermal shock (PTS) for RPV base and weld metals from Doel 3, Doel 4 and Tihange 2 and 3 NPPs in Belgium



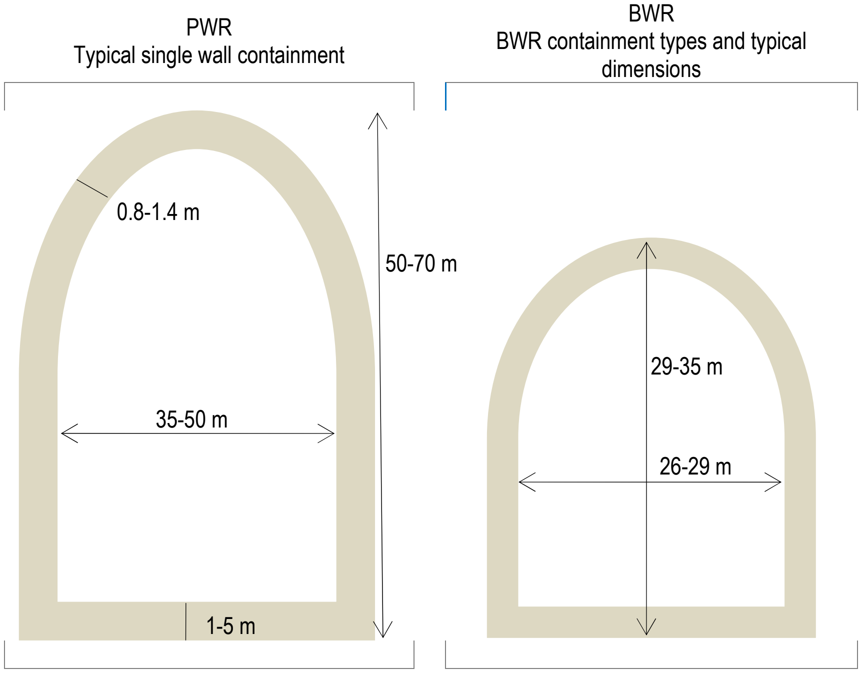
Note: Curves should be compared to double lines of the same type (dashed blue for base metals, red for weld metals).
Source: Lucon et al., 2009.

Containment

Primary containment is one of the key safety-related concrete structures in NPPs. It is the third (and final) barrier to radioactive release in the event of a severe accident (the first is the fuel cladding; the second is the RPV and the primary circuit).

Containments are large concrete or steel structures, and are typically designed to resist internal pressures of about 5 bars and temperatures of approximately 150°C in pressurised water reactors (PWRs), and about 6 bars and 170°C in BWRs – boiling water reactor (see Figure 1.6).

Figure 1.6. Schematic view of PWR and BWR containments



Source: Nuclear containments: state-of-the-art report (Fédération internationale du béton, 2001).

With respect to LTO, the containment structure and containment liner are subject to ageing management review. The purpose of these reviews is to identify age-related degradations like corrosion of concrete containment liners, corrosion of post-tensioning tendon wires, loss of pre-stressing force, concrete spalling at containment buttress, water infiltration, cracking and spalling of containment dome concrete due to freeze-thaw damage, concrete cracks due to inappropriate chemical environment, etc.

Thus, the continued operation of NPPs requires timely analysis and repair of degradations in the concrete structures. In many countries the leak tightness of containments is experimentally verified (by pressurising) during PSRs (every ten years at minimum).

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Chapter 2. Regulatory and legal requirements for long-term operation in different countries

Acceptance of an NPP for LTO must be based on evidence that the plant will comply with the "licensing basis" over the extended period of service. How this is achieved will depend on regulatory strategies in individual countries (OECD/NEA, 2012). In general, this requires an assessment of the current and projected condition of the plant and, in particular, of the systems that perform fundamental safety functions, to ensure that these systems will continue to perform their safety functions during the extended operating period. The strategy used could range from an approach that mainly addresses the impact of ageing to one that seeks changes in safety level based on the expectations for newer plants.

Typical regulatory approaches for assurance of safety in long-term operation

Licence renewal and PSRs are two basic regulatory approaches that have been adopted for authorisation of LTO of nuclear power reactors. Some countries use aspects from one or both approaches in determining whether, and under what conditions, to allow LTO (see Table 2.1).

Licence renewal

In countries where the licence is granted for a given operating period, a formal licence renewal process is used as part of a broader regulatory system. This broader system is a robust and comprehensive framework that allows safety considerations on a continuous basis. It includes elements such as ongoing technical evaluation and oversight, an onsite resident inspector programme, generic issue identification, a robust operating experience programme, and an ability to impose requirements that plants improve safety through new regulations and orders. These elements apply to all plants irrespective of their licence renewal status.

The licence renewal process itself has two tracks: one for the review of safety issues and another for review of environmental issues. A basic assumption of the licence renewal process is that "the current licensing basis" is acceptable, as supplemented for LTO to account for ageing effects. Another basic assumption is that the current regulatory process is acceptable, as supplemented for specific challenges associated with LTO.

The operator must supply to the regulator a licence renewal application which is the principal document used to both request and justify LTO. The licence renewal application is used to demonstrate that adequate safety levels will be maintained for LTO and to provide an assessment of potential environmental impacts from LTO.

The licence renewal application includes technical information to demonstrate that the intended functions of systems, structures and components will remain within the design safety margins, and the current licensing basis of the plant will remain valid throughout the planned LTO period, supplemented as necessary with additional actions and programmes required for licence renewal. An applicant must identify and analyse the ageing-related issues for certain critical systems, structures and components at the facility during the period of the renewed licence and describe how these issues will be managed during LTO.

Table 2.1. Regulatory approaches to LTO in different countries

	Licence renewal	Periodic safety review (PSR)	Comment
Belgium		Yes	In Belgium, service life (operating licence) for NPPs is set by law at 40 years. Utilities have to conduct a PSR for their operating NPPs every ten years and have to submit the PSR report to the federal regulator for nuclear control for review and approval. In the case of Tihange 1, there will be the possibility of a one-off extension of ten years of the operating licence, under the condition that the results of the next PSR for this reactor are approved by the federal regulator.
Finland		Yes	According to the Nuclear Energy Act, the operating licences are granted for a fixed term. The licence conditions may by changed during its period of validity by the government. The licence can also be revoked if the licensee is failing to comply with the licence conditions and the nuclear regulator (STUK) is given power to monitor the operation of the plants and take any measures required to ensure public safety.
France		Yes	In France, the operating licence for a nuclear reactor does not set a limit for service life. However, article 29 of the Transparency and Nuclear Safety Act (13 June 2006) requires that the operator of a nuclear reactor performs a safety review of the facility every ten years.
Hungary		Yes	According to current Hungarian regulations the operating licence is subject to a PSR, which is performed (every 10 years) as a self-assessment by the licensee under the control and approval of the regulatory body during the original design lifetime (30 years for the currently operating NPPs). The licensee has to prepare and submit to the regulatory body a licence renewal request for permitting an LTO, justifying a design lifetime, up to 20 years beyond original design lifetime.
Korea, Republic of		Yes	A PSR has to be conducted every ten years and submitted for regulatory review and approval to justify the next ten years of continued operation. The “final ten-year PSR” may also be used to request extension of the original service life by another ten years. Service life of existing designs is between 30-40 years.
Russian Federation	Yes		The operating licence is limited to the original design lifetime of the plant (30 years for the currently operating NPPs). Relicensing by the regulator (Rostekhnadzor) is a prerequisite for the extension of the operational lifetime. The duration of the licence extension is determined individually for each unit based on residual life. The licensee has to prepare and submit to the regulatory body a proposal for permitting an LTO period of which depends on revised, justified and approved longer than the original design lifetime. The Russian plants undergo constant reviews and inspections, and Rostekhnadzor can order the shutdown of the unit or take any other actions to ensure public safety.
Switzerland		Yes	In Switzerland, the service life for NPPs is not limited. Article 10 of the Nuclear Energy Ordinance (NEO) defines the principles for the design of the safety functions of NPPs. These include, in particular, single failure criterion, principles of redundancy and diversity, functional and physical separation, automation principle and conservativism in design. In the NEO and the Nuclear Energy Act it is stipulated that the licence holder shall upgrade the NPP to the extent that it is necessary in keeping with operational experience and the current state of back fitting technology, and beyond insofar as further upgrading is appropriate and results in a further reduction of the risk to human beings and the environment.
United Kingdom		Yes	In the United Kingdom, a single non-transferable licence is granted to cover the life of the nuclear site from start of construction to final decommissioning. There is no pre-determined end date for operation. Nuclear facilities are permitted to continue to operate for as long a period as the licensee can demonstrate that it is safe do so. The PSRs (conducted with a periodicity of around ten years maximum since the early 1990s) should confirm that original safety standards will be maintained, identify any life-limiting features on the plant, and demonstrate that all reasonably practicable measures to improve the plant to modern standards are being implemented. The regulator may require the licensee to carry out plant modifications that have been identified during the PSR as reasonably practicable or undertake other activities, e.g. perform additional analyses. If the plant cannot be brought sufficiently close to modern standards, the licensee may be required to cease operation. The end points of past PSRs of UK’s facilities have included all of these potential outcomes.
United States	Yes		The US Atomic Energy Act of 1954 allows the Nuclear Regulatory Commission (NRC) to issue licences for commercial power reactors to operate for up to 40 years. The NRC regulations allow the renewal of these licences for an additional period of 20 years if the reactor satisfies safety and environmental criteria. Although the licensing process does not require PSRs, the US nuclear plants undergo constant reviews and inspections and the NRC can revoke the licence or take any other actions to ensure public safety.

As part of the licence renewal application, the operator must also prepare an environmental report on the potential impact on the environment of continued plant operation. This environmental report includes a description of the action (e.g. continued operation of the plant through licence renewal), the purpose of the action, and a description of the environment affected.

The regulator performs a review of the licence renewal application, including inspections and audits as necessary. The regulator's decision to grant or deny a licence renewal is based on whether the applicant has demonstrated that the facility can be safely operated for an additional licence period with no significant adverse environmental impacts.

Periodic safety review (PSR)

In countries that have chosen the PSR approach, the operator is required to periodically perform such a review to assess the capacity of the NPP to continue operation in a safe manner. Based on an analysis of the operator's review results, the regulator can authorise the continued operation of the plant up to the end of the next PSR cycle (usually ten years). The PSR is required to *(i)* confirm the compliance of the plant with its licensing basis, and *(ii)* provide an assessment of the plant safety level with regard to modern safety standards and internationally recognised good practices. All reasonably practicable improvement measures have to be taken by the operator as a result of the review. Safety improvements can be related not only to plant design (plant modification) but also to operational issues (such as the management system and operating procedures). Thus, the PSR should not only confirm that the safety level is maintained, but should also usually result in a step-improvement of the safety level. This PSR approach, which has been applied in various countries before entering LTO, is, or will be, applied for safety assessment of LTO.

Safety level required for long-term operation

Important considerations in the definition of the acceptable level of safety during LTO include the following:

- the time period of LTO;
- the operational history and experience at the plant;
- the physical condition of the plant;
- the ageing of safety-related systems, structures and components; and
- the degree of certainty about the long-term performance of safety components.

In the licence renewal option, the starting premise is that the current licensing basis of the plant will continue to ensure safe operation during the period of LTO. This current licensing basis is dynamic in that it changes over time to account for plant modifications and operational changes. It will also be modified as part of the licence renewal process to account for ageing management activities deemed necessary to ensure safe operation during the period of LTO. In addition, routine plant changes will occur as part of the normal licensing process to support day-to-day plant operations. The goal of the licence renewal option for continued safe plant operation during the LTO period is achieved through maintaining the current licensing basis of the plant and effectively managing ageing of systems, structures, and components within the scope of licence renewal. Consideration of further safety enhancements are part of the broader regulatory framework.

The PSR option incorporates an integrated safety review of the operation of the plant to confirm safety of ongoing operation and to identify safety improvements judged to be practicable to support the period of LTO. This option uses the process of endorsing LTO as an opportunity to increase safety margins beyond their current level or to reduce risk from plant operation as far as practicable. It also seeks to apply improvements in technology and methods to correspondingly improve plant safety as part of its assessment of LTO. In addition, execution of the PSR process for LTO serves to demonstrate that the NPP will continue to maintain a high level of compliance with modern codes and standards to support extended operation.

Within the regulatory framework, "end of operation" would be determined at the end of the operating licence or when the operator is no longer able to demonstrate that the plant can be operated safely consistent with the safety basis for the plant and regulatory requirements, or when the operator opts to cease operations. In most of the cases requiring a decision with respect to "end of operation", the consideration of ageing and safety of non-replaceable components or systems is likely to be an important factor.

Scope of the regulatory assessment for long-term operation

The LTO safety assessment can include the following topics, depending on the country's regulatory framework:

- ageing management for LTO;
- environmental assessments;
- operating experience;
- safety improvements;
- security improvements; and
- emerging issues.

Ageing management for long-term operation

Ageing management addresses physical ageing that could result in degradation of systems, structures and components such that safety functionality could be impaired. Physical ageing includes a variety of degradation modes, including cracking, loss of material (e.g. corrosion, wear, etc.) and changes in material properties. Physical ageing is usually governed by the levels of stress and environmental factors such as water quality, temperature, humidity and radiation. Ageing management helps to ensure that systems, structures and components that are important to safety are capable of performing their required safety functions during the plant life. This is a broad activity that involves maintenance, surveillance, equipment qualification, in-service inspection, water chemistry control, and other plant programmes. It provides a methodical process to detect, assess and correct, as necessary, the effects of ageing. Thus, an effective ageing management programme is a key element of safe and reliable operation of NPPs during the originally planned operation time frames, as well as for periods of LTO.

A systematic process should be in place to determine which systems, structures and components should be subject to ageing management programmes. Time-limited ageing analysis may be required for major structural and safety components to assess the effects of ageing, fatigue and relaxation (creep), as well as degradation due to environmental conditions. Safety analyses which use time-limited assumptions must be updated to include additional time periods for LTO and to determine whether any additional ageing management is required.

To demonstrate safe LTO, the operator needs to develop a comprehensive ageing management programme. Ideally, the operator will have ageing data over the entire operating life that contributes to the demonstration that ageing has not reduced the effectiveness of plant systems, structures, and components below the design basis requirements. A comprehensive ageing management programme includes co-ordinating, integrating and modifying existing programmes and activities that relate to managing the ageing of systems, structures and components and developing new programmes that may be needed for LTO. These programmes and activities include inspection, monitoring and assessment, to detect and characterise degradation, and maintenance to provide timely mitigation and correction of degradation.

The operator's ageing management programmes should identify parameters to be monitored or inspected and preventive and remedial actions that may be necessary. The programme should be capable of early detection of ageing effects to reduce risks of loss of functionality of impacted systems, structures, and components. Monitoring and trending will provide better predictability of the extent of degradation and make possible timely corrective or remedial actions. It is also of importance to utilise operating experience feedback to support the conclusions that the effects of ageing will be managed adequately so that the intended functions of a system, structure or component will be maintained throughout the planned LTO period.

The implementation of an effective ageing management programme throughout the service life of the systems, structures and components requires the operator to apply a systematic approach that provides a framework for co-ordinating all activities and programmes that are needed in this process. It is essential that the operators obtain a comprehensive understanding of the plant's ageing behaviour which is the foundation for a well-functioning ageing management programme. This foundation consists of systematic data on numerous issues such as material and fabrication data, operational conditions and stressors, possible ageing mechanisms, as well as the location and consequences of ageing and failures.

Although plants may have internal programmes that assure safety in one aspect or another, one implication of LTO is to put these programmes into an environment of heightened regulatory significance and oversight, commensurate with the possibilities and significance of the degradation. The development of new or revised programmes that address LTO may therefore be needed.

The operator should review data and information collected from ageing management programmes to confirm that safety analysis assumptions, credited parameters and predictions remain valid, and that limiting criteria and required design margins continue to be met as the plant ages. The operator should be able to predict the cumulative effect of ageing on systems, structures and components over the period considered for LTO in order to decide what actions or measures need to be taken.

Ageing management for LTO should take into account credit that may be given for existing programmes (such as in-service inspection and maintenance programmes) and monitoring of ageing of non-replaceable components (such as the RPV and the containment building).

The operator should consider not only the physical ageing of systems, structures and components but also technological ageing (obsolescence) that may arise in plant systems, structures and components. The rapid changes seen in technology over the past few decades mean that some systems, structures and components can become obsolete. Therefore, the operator should manage the situation by seeking to ensure long-term availability of spare parts or by being prepared to replace obsolete equipment. In the regulatory framework of some countries, the regulator sets performance criteria for equipment, and the operator would be required to address obsolescence when the performance criteria cannot be met.

Environmental assessment

The environmental impact of LTO of an NPP may need to be assessed if such a requirement is part of the country's regulatory framework. Some countries do not consider environmental issues when evaluating LTO. For those that do, there are a variety of different approaches taken to assess environmental issues in the context of LTO. The types of issues that may be considered include all or some of the following: uranium fuel cycle impacts, management of waste, surface water quality, aquatic ecology, groundwater use and quality, terrestrial resources, threatened or endangered species, air quality, land use, human health, socio-economics, postulated accidents, decommissioning and environmental justice. Environmental issues may also involve public participation, depending on a country's regulatory framework.

Operating experience

The operator should consider operating experience from a variety of sources, both domestic and international, on a continuous basis. These sources include:

- plant-specific experience;
- experience from similar plant designs (i.e. the same class of plants);
- experience from similar materials, operating conditions and systems, structures and components; and
- relevant experience, regardless of plant type, that contributes to the judgements on acceptability for LTO (e.g. the Fukushima Daiichi accident).

Adverse operating experience which identifies ageing-related degradation can be used to identify new ageing phenomena that require ageing management during LTO, either from the perspective of new ageing mechanisms or new locations of known mechanisms.

Specific consideration of the effectiveness of ageing management programmes implemented by the operator, including past corrective actions that result in programme enhancements or additional programmes or activities, can provide objective evidence to ensure that the effects of ageing are adequately managed and will continue to be managed during the period of LTO.

Similarly, positive operating experience that identifies no ageing-related degradation has an important role in assuring safe LTO. Positive operating experience, such as that derived from first-of-a-kind or one-time examinations that have been implemented to support LTO, or similar practices, broadens the knowledge base of what is working properly in the plant and allows for refocusing of resources to areas that may be more problematic.

The operator should evaluate operating experience to derive lessons learnt and to identify any precursors of conditions that are adverse to safety. The evaluation should, where appropriate, result in clear recommendations for appropriate and timely corrective actions so that any necessary corrective action can be taken before serious conditions arise.

Safety improvements

When the objective is to assess the safety level against modern standards, the regulator may include, in the regulatory assessment, safety improvements or broader modifications to the safety approach. Improvements that may be needed can be identified based on an assessment of:

- evolution of regulations, safety objectives, and practices (nationally and internationally); and
- lessons learnt from other plants or equipment involving risk.

The comparison with more recent NPPs (nationally and internationally) can lead the regulator to take into account safety improvements that were not considered in the original licensing process (including changes that arise from events such as the

Fukushima Daiichi accident). Based on the objectives defined by the regulator for the safety improvement, the operator should develop a methodology which enables identification of areas for improvement. Examples of such changes that would enhance safety are:

- modification of the layout of the plant (such as improvement in the segregation of electrical and mechanical equipment);
- improvements that enable compliance of all safety-related systems with the single failure criterion;
- enhanced resistance to external hazards (such as earthquakes, strong winds, tsunami, floods and loss of offsite power) and internal events (such as fires, pipe breaks, and station black-out);
- improvements in redundancy, diversity and integrity of systems (such as alternate power sources), plant control facilities (such as main and emergency control rooms) and critical areas in the plant (such as spent fuel pools);
- improvements with respect to capacity to mitigate the consequences of severe accidents (including the establishment of severe accident management guidelines);
- implications from multi-units events;
- considerations related to enhancing emergency preparedness and response.

There is a general recognition that newer safety requirements should be accommodated to the extent that is reasonably practicable, taking account of the potential safety gains and costs involved. On the basis of the identified improvements, an implementation plan should be agreed between the regulator and operator to be monitored as part of the ongoing oversight process.

Countries that use the licence renewal process for LTO incorporate a regulatory system that provides a continual consideration of the need for safety enhancements as a part of the ongoing regulatory activities outside of the licence renewal process. Considerations include requirements for plant upgrades during the life of the plant (including the period of LTO). As new technical information indicating a possible safety concern is identified, the regulator reviews the potential safety concern and may conclude that existing programmes or regulations need to be revised (e.g. through back-fitting safety systems), or that new programmes or regulations are needed to assure an acceptable level of safety.

Within this regulatory system, operating experience is evaluated to determine needed changes to ensure adequate protection (i.e. safety margin), including redefining adequate protection at an enhanced level as necessary. Such changes can be achieved through rule changes, orders to operators, or written communications to all operators. In addition, during the life of the plant, an operator may request approval of licence amendments from the regulator. The amendments often involve changes to make the plant safer or more reliable. In addition, operators regularly update their licensing basis to apply newer versions of codes and standards which have been endorsed by the regulator. By regulation, the operator is required to update the plant's licensing basis on a biennial basis to ensure that the final safety analysis report contains the latest information.

Accidents, such as that at Fukushima Daiichi, provide insights into required protection at NPPs. When such significant nuclear events occur, regulators are expected to evaluate and potentially define new safety levels that operators need to achieve to continue to operate safely. Regulators may incorporate safety improvements from such operating experience through regulatory changes that apply to all operating plants regardless of their stage in operating life. If considered appropriate, regulators may incorporate these new safety improvements as part of the LTO process.

Security improvements

Older nuclear power plants may not have been designed and constructed to the same physical security standards that apply at new plants. The LTO review should examine the extent to which provisions for physical security can be augmented if such a requirement is part of the country's regulatory framework.

This review should serve to confirm that, in LTO of the plant, there would not be any impediments to implementation of security measures that may be required to respond to anticipated physical threats and risks.

As with safety improvements, some countries continually monitor the adequacy of physical plant security and require improvements, as necessary, to ensure adequacy. In such cases, there is no need for a specific reconsideration of physical plant security to support LTO.

Emerging issues

The start of the period of LTO could occur a number of years after the submission of the operator's application for authorisation. Consequently, the operator should establish a process for responding to any issues that might emerge during this intervening period.

This process will identify:

- the approach for consideration of new operating experience and research results or revisions of codes, standards and practices;
- a methodology for assessing the safety significance of differences with revised codes, standards and practices.

The safety of LTO should be kept under review by the operator throughout this period, and modifications to planned ageing management activities should be implemented as necessary to ensure safe operation during the period of LTO.

Reference

OECD/NEA (2012), *Challenges in Long-term Operation of Nuclear Power Plants – Implications for Regulatory Bodies*, OECD Publishing, Paris.

Chapter 3. Safety initiatives following the Fukushima Daiichi accident

This chapter describes the safety initiatives that have already been decided or are being considered by the member states and international organisations following the Fukushima Daiichi accident. It is important to stress that these safety initiatives or measures to increase robustness of NPPs concern **all** operating new NPPs irrespective of their age and their intention to seek authorisation for LTO beyond the period assumed in the design of the plant.

The accident that occurred at the Fukushima Daiichi NPP in Japan, following the earthquake and tsunami of 11 March 2011, renewed the political and regulatory attention in the measures needed to minimise risk and assure robust levels of nuclear safety. The response of the national regulatory authorities and international organisations was immediate. All countries with operating NPPs promptly embarked on comprehensive risk and safety assessments of the design of the NPPs in areas that were immediately evident from the Fukushima Daiichi accident. Many of the reviews included an evaluation of the site specific extreme natural hazards along with an assessment of the ability to withstand severe accidents.

Following the comprehensive risk and safety assessments performed on NPPs, it was concluded, in general, that the facilities examined offer a sufficient safety level to require no immediate shutdown of any of them. However, regulatory authorities consider that their continued operation requires an increase in their robustness to extreme situations beyond their existing safety margins, as soon as possible. It is important to note that the regulatory authorities and industry are still learning from this accident and the ongoing situation, as more information is gained from the Japanese authorities and international organisations.

Nonetheless, member states have already started implementing the lessons learnt and will continue to do so within their regulatory systems on a continuous manner, since the completion of the overall assessment of this accident may take years. Significant measures to increase robustness of plants have already been decided or are considered. Such measures include provisions of additional mobile equipment to prevent or mitigate severe accidents, installation of hardened fixed equipment, and the improvement of severe accident management, together with appropriate staff training measures. In many cases, important modifications are being prepared for the near future.

Nuclear Energy Agency

Following the Fukushima Daiichi accident a number of initiatives have been undertaken internationally to learn from the accident, to share approaches on key follow-up initiatives and finally to implement those lessons learnt to improve nuclear safety, and protect the public and the environment. Within the NEA, monitoring of the accident as it progressed began immediately and the NEA is continuing to work with its members to learn the technical and regulatory lessons from the accident (NEA, 2012).

Along those lines, on 8 June 2011, the NEA Committee on Nuclear Regulatory Activities (CNRA) hosted a forum on “The Fukushima Accident: Insights and Approaches” that brought together top regulators, and senior industry and international organisation executives to discuss and agree on some key messages in the wake of the accident. The NEA CNRA constituted the Senior-level Task Group on Impacts of the Fukushima Accident that is compiling information and synthesising common approaches for follow-up activities within the NEA regulatory community. The role of the NEA Committee on the Safety of Nuclear Installations (CSNI) with respect to the Fukushima Daiichi accident will be to work in co-operation with CNRA and the NEA Committee on Radiation Protection and Public Health (CRPPH), to address key technical areas by reviewing the accident and undertaking specific technical studies to address knowledge gaps. CRPPH is supporting Japan with regards to offsite emergency management, decontamination of areas in and around the Fukushima Daiichi NPP, and radiation protection activities.

In addition to specific work by the three committees, there are three additional lines of NEA support directly to Japan: *i)* recovery of the land and decontamination, *ii)* national reviews and stress tests and *iii)* enhancement to the regulatory infrastructure.

The Bureaux of CNRA, CRPPH, and CSNI participated in a tri-bureaux meeting in December 2011 to enhance co-operation and co-ordination between these three NEA standing technical committees (STCs) in responding to the Fukushima Daiichi accident. The three bureaux agreed on topics, issues and concerns after the Fukushima Daiichi accident that constituted the NEA integrated response. In consequence, activities have been initiated on: accident management and progression; crisis or emergency communications; reassessment of defence-in-depth; evaluating the methodologies for defining and assessing initiating internal and external events, including coupled, as well as methodologies defining the design basis criteria; reassessment of operating experience and prior opportunities to identify or address conditions that could challenge nuclear safety; radiological protection and health physics; and decontamination and recovery (onsite and offsite).

European Union (EU)

The European Council of 24/25 March 2011 requested that a comprehensive safety and risk assessment, in the light of preliminary lessons learnt from the Fukushima Daiichi accident, be performed on all EU nuclear plants. The request of the Council included "stress tests" performed at national level complemented by a European peer review. This was the first time that such a multilateral exercise covering over 140 reactors in all EU countries operating NPPs was considered.

The Commission and the European Nuclear Safety Regulators Group (ENSREG) agreed that the work on the stress tests should be carried along two parallel tracks: (*i*) a safety track to assess how nuclear installations can withstand the consequences of various extreme external events; and (*ii*) a security track to analyse security threats and incidents due to malevolent or terrorist acts.

The objectives of the peer review were to assess the compliance of the stress tests with the ENSREG specifications, to check that no important problem has been overlooked and to identify strong features, weaknesses and relevant proposals to increase plant robustness in light of the preliminary lessons learnt from Fukushima Daiichi.

The stress tests were conducted on a voluntary basis in three steps:

- Nuclear operators from 15 EU countries and 2 neighbouring countries, Switzerland and Ukraine, were asked to conduct a self-assessment and produce progress reports.
- National regulators reviewed the information supplied by operators and prepared national reports.
- Peer reviews of the national reports were conducted by national and European Commission experts.

The final report on the Peer Review of EU Stress Tests was published in May 2012 (ENSREG, 2012). On the basis of this report, action plans will be proposed before the end of 2012 by national regulators.

The peer review concluded that all countries have taken significant steps to improve the safety of their plants, with varying degrees of practical implementation. In spite of differences in the national approaches and degree of implementation, the peer review showed an overall consistency across Europe in the identification of strong features, weaknesses and possible ways to increase plant robustness in light of the preliminary lessons learnt from the Fukushima Daiichi accident. As a result of the stress tests, significant measures to increase robustness of plants have already been decided or are considered. Such measures include provisions of additional mobile equipment to prevent or mitigate severe accidents, installation of hardened fixed equipment, and the improvement of severe accident management, together with appropriate staff training measures. In many cases, important modifications were identified at the national level and these issues will be implemented in the context of the national action plans.

The peer review also identified four main areas of improvement to be considered at the European level:

European guidance on assessment of natural hazards and margins

Overall, the compliance of the European stress tests with the ENSREG specification was good with regard to compliance of the installations with their design basis for earthquake and flooding. However, there was a lack of consistency identified with respect to natural hazards assessments where significant differences exist in national approaches and where difficulties were encountered with beyond design margins and cliff-edge effects assessments.

The peer review board recommends that the Western European Nuclear Regulators Association (WENRA), involving the best available expertise from Europe, develop guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions, as well as corresponding guidance on the assessment of margins beyond the design basis and cliff-edge effects.

Periodic safety review

The peer review demonstrated the positive contribution of periodic safety reviews as an efficient tool to maintain and improve the safety and robustness of plants. In the context of the peer review, this finding is especially relevant for the protection of installations against natural hazards.

The peer review board recommends that ENSREG underline the importance of periodic safety review. In particular, ENSREG should highlight the necessity to re-evaluate natural hazards and relevant plant provisions as often as appropriate but at least every ten years.

Containment integrity

The Fukushima Daiichi accident highlighted once again the importance of the containment function, which is critical, as the last barrier to protect the people and the environment against radioactive releases resulting from a nuclear accident. This issue was already extensively considered, as a follow-up of previous accidents, and possible improvements were identified. Their expeditious implementation appears to be a crucial issue in light of the Fukushima Daiichi accident.

National regulators should consider urgent implementation of the recognised measures to protect containment integrity.

The measures to be taken can vary depending on the design of the plants. For water-cooled reactors, they include equipment, procedures and accident management guidelines to depressurise the primary circuit in order to prevent high pressure core melt, hydrogen explosions and prevent containment overpressure.

Prevention of accidents resulting from natural hazards and limiting their consequences

The Fukushima Daiichi accident has also shown that defence-in-depth should be strengthened by taking into account severe accidents resulting from extreme natural hazards exceeding the levels taken into account by the design basis and current safety requirements applicable to the plants. Such situations can result in devastation and isolation of the site, an event of long duration, unavailability of numerous safety systems, simultaneous accidents of several plants including their spent fuel pools, and the presence of radioactive releases.

National regulators should consider necessary implementation of measures allowing prevention of accidents and limitation of their consequences in case of extreme natural hazards.

Typical measures which can be considered are bunkered equipment to prevent and manage severe accident including instrumentation and communication means, mobile equipment protected against extreme natural hazards, emergency response centres protected against extreme natural hazards and contamination, rescue teams and equipment rapidly available to support local operators in long duration events.

United States

The Near-Term Task Force was established in order to conduct a systematic review of the US NRC processes and regulations to determine whether the agency should make additional improvements to its regulatory system and to make recommendations to the commission for its policy direction, after the accident at Fukushima Daiichi (NRC, 2011). The review of the Fukushima Daiichi accident for insights for reactors in the US addressed measures to protect against accidents resulting from natural phenomena, mitigating the consequence of such accidents and ensuring emergency preparedness.

The task force concluded that a sequence of events like the Fukushima Daiichi accident is unlikely to occur in a US plant based on the current regulatory approach and plant capabilities. Therefore, continued operation and continued licensing activities, including operation beyond the design life time do not pose an imminent risk to public, health and safety. However, the task force concluded that a set of recommendations would provide a more balanced application of the defence-in-depth concept using risk insights enhancing the regulatory framework. The overarching recommendations concern the following areas.

Clarifying the regulatory framework

- The task force recommends establishing a logical, systematic, and coherent regulatory framework for adequate protection that appropriately balances defence-in-depth and risk considerations.

Ensuring protection

- The task force recommends that the NRC require licensees to re-evaluate and upgrade as necessary the design-basis seismic and flooding protection of structures, systems, and components for each operating reactor.
- The task force recommends, as part of the longer term review, that the NRC evaluate potential enhancements to the capability to prevent or mitigate seismically induced fires and floods.

Enhancing mitigation

- The task force recommends that the NRC strengthen station blackout mitigation capability at all operating and new reactors for design-basis and beyond-design-basis external events.
- The task force recommends requiring reliable hardened vent designs in BWR facilities with Mark I and Mark II containments.
- The task force recommends, as part of the longer term review, that the NRC identify insights about hydrogen control and mitigation inside containment or in other buildings as additional information is revealed through further study of the Fukushima Daiichi accident.
- The task force recommends enhancing spent fuel pool make-up capability and instrumentation for the spent fuel pool.
- The task force recommends strengthening and integrating onsite emergency response capabilities such as emergency operating procedures, severe accident management guidelines, and extensive damage mitigation guidelines.

Strengthening emergency preparedness

- The task force recommends that the NRC require that facility emergency plans address prolonged station blackout and multi-unit events.
- The task force recommends, as part of the longer term review, that the NRC pursue additional emergency preparedness topics related to multi-unit events and prolonged station blackout.
- The task force recommends, as part of the longer term review, that the NRC should pursue emergency preparedness topics related to decision-making, radiation monitoring, and public education.

Improving the efficiency of NRC programmes

- The task force recommends that the NRC strengthen regulatory oversight of licensee safety performance (i.e. the reactor oversight process) by focusing more attention on defence-in-depth requirements consistent with the recommended defence-in-depth framework.

The NRC staff then made an assessment of the recommendations and proposed prioritisation into three tiers. The first tier consists of those recommendations which the staff determined should be started without unnecessary delay and for which sufficient resource flexibility, including availability of critical skill sets, exists. The second tier consists of those recommendations which could not be initiated in the near term due to factors that include the need for further technical assessment and alignment, dependence on tier 1 issues, or availability of critical skill sets. Finally, the third tier consists of those recommendations that require further staff study to support a regulatory action, have an associated shorter-term action that needs to be completed to inform the longer-term action, or are dependent on the availability of critical skill sets.

On March 2012, based on the prioritised task force recommendations, the NRC issued the first regulatory requirements for the 104 US operating reactors based on the lessons learnt at Fukushima Daiichi, which included: order for mitigation strategies to respond to extreme natural events resulting in the loss of power at plants; order for ensuring reliable hardened containment vents; order for enhancing spent fuel pool instrumentation. A Request for Information for seismic and flooding re-evaluations and walk-downs, and re-evaluations of emergency communications systems and staffing levels were also issued.

IAEA action plan

In June 2011, an IAEA Ministerial Conference on Nuclear Safety was convened to direct the process of learning and acting upon lessons following the Fukushima Daiichi accident in order to strengthen nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. The IAEA was requested to prepare an action plan (see IAEA, 2011) that defines a programme of work to strengthen the global nuclear safety framework, building on the experience and knowledge therein, including the conclusions and recommendations of the fact finding expert mission conducted in May-June 2011, which included:

- Nuclear designers and operators should appropriately evaluate and provide protection against the risks of all natural hazards, and should periodically update these arrangements.
- Defence-in-depth, physical separation, diversity and redundancy requirements should be applied for extreme external events.
- Severe long-term combinations of external events should be adequately covered in design, operations, resourcing and emergency arrangements.
- Hardened on-site emergency response centres with adequate provisions for communications, essential plant parameters, control and resources should be provided for all major nuclear facilities with severe accident potential.
- Simple effective robust equipment should be available to restore essential safety functions in a timely way for severe accident conditions. Emergency arrangements, especially for the early phases, should be designed to be robust.
- Hydrogen risks should be subject to detailed evaluation and necessary mitigation systems provided.

The action plan will be updated, as necessary, as the understanding of the accident develops and additional analysis of the root causes are being carried out. Its success in strengthening nuclear safety will depend on the commitment to implementing it in full through the co-operation and participation of member states and the involvement of many other stakeholders.

The action plan considers 12 main actions, each with corresponding sub-actions, focusing on: safety assessments in the light of the accident at Fukushima Daiichi; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organisations; IAEA Safety Standards; international legal framework; member states planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionising radiation; communication and information dissemination; and research and development.

Conclusions

Valuable experience and many lessons have been and are being learnt by member states and operators in managing NPPs under adverse conditions. Measures to strengthen the safety and robustness of NPPs have been or are being considered. Such measures include provisions for ensuring protection against extreme events and its combinations; enhancing mitigation capabilities for station blackout and loss of ultimate heat sink; strengthen mitigation capabilities for severe accidents, including installation of hardened fixed equipment; and improvement of severe accident management. The changes in regulatory requirements after the Fukushima Daiichi accident will also address strengthening emergency preparedness for long-term scenarios including multi-unit events.

The implementation of lessons learnt to improve nuclear safety concern all operating NPPs independently of their age or their intention to seek authorisation for LTO. The associated cost of the safety improvements need to be considered by the operators for the continued operation of the NPPs including a potential LTO. In the country case studies in Chapter 5, we will present the cost data for the Fukushima-related upgrades available to date.

References

NEA (2012), *Integrated NEA Fukushima Activities for Safety Enhancements (INFASE)*, OECD Publishing, Paris, France.

ENSREG (2012), *Peer Review Report: Stress Tests Performed on European Nuclear Power Plants*, ENSREG online report. Available at: www.ensreg.eu/EU-Stress-Tests.

NRC (2011), *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-term Task Force Review of Insights from the Fukushima Dai-Ichi Accident*, US NRC, 12 July 2011. Available at: http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf.

IAEA (2011), "Action Plan on Nuclear Safety", presented at the IAEA General Conference on 22 September 2011, Available at: www.iaea.org/newscenter/focus/actionplan.

Chapter 4. Economics of long-term operation: figures of merit

Assessment criteria

The economic assessment of long-term operation of NPPs should take into account various factors and parameters reflecting current and future financial conditions of operation, political and regulatory risks, state of the plants' equipment and the general role of nuclear in the country's energy policy.

One should note that a favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original lifetime or term authorised by the regulator (or expected by the operator). The final decision belongs to the nuclear safety authority to confirm that the refurbished plant complies with their requirements for safe and secure operation. In this chapter, the main focus is on the economics of refurbishment.

The development of criteria for evaluating the economics of LTO of NPPs requires consideration of both technical and economic characteristics of the refurbishment processes. From both a national and a utility's perspective, a decision on the advantages or disadvantages of continued operation of a given NPP could be made on the bases of the following figures of merit:

- production and asset portfolio;
- predictability of future electricity prices;
- need for NPP equipment upgrade and replacement;
- impact of refurbishment activities on the decennial average of the energy availability factor;
- risk and uncertainty (site-dependence, political, financial, regulatory);
- overnight cost of refurbishment;
- LCOE_{EO} – levelised cost of electricity generation after LTO activities;
- country's carbon policy and security of energy supply.

Ideally, these general characteristics should be used to assess different options that the utility or government might consider (see Figure 4.1). In this study the main focus is on the nuclear option, but other sources of electricity will be briefly discussed to put the issue of LTO into an appropriate energy policy context. The main source of data for comparisons is the recent joint study by the NEA and International Energy Agency (IEA) *Projected Costs of Generating Electricity: 2010 Edition* (IEA/NEA, 2010).

The methodology of the individual assessment of criteria is discussed below. Each general characteristic (presented above) compared in this chapter is assessed using a three-point grading system (see Table 4.1).

Figure 4.1. Economics assessment flowchart

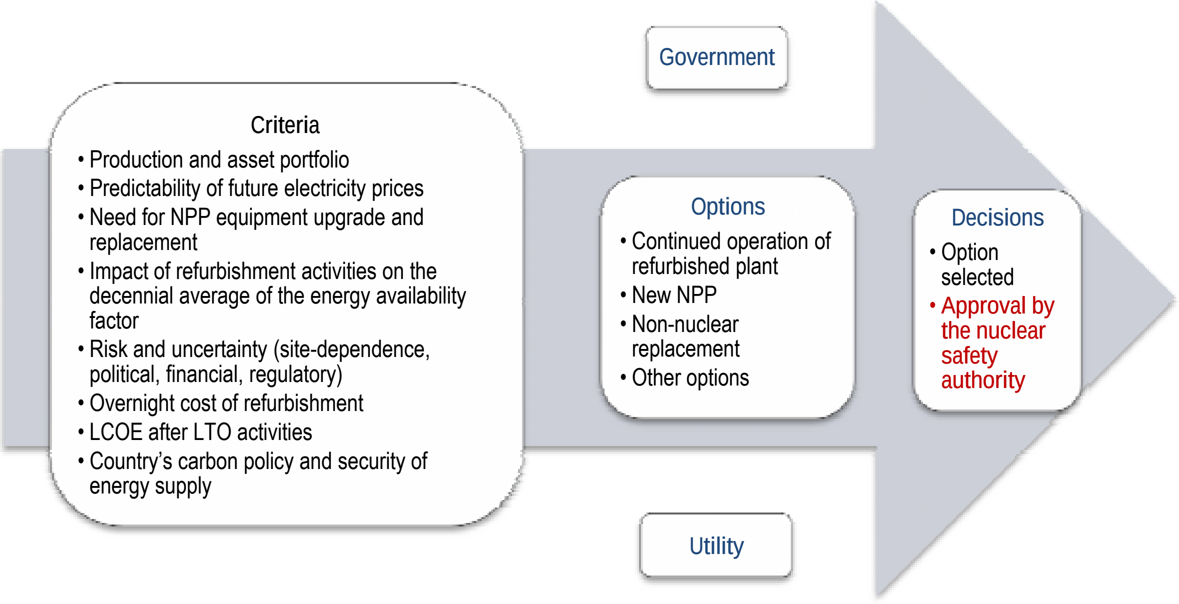


Table 4.1. Summary of the grading system used in this study for the economic assessment of LTO

Score	★★★	★★	★
Comment	Three stars is the most positive outcome for extended operation of an NPP.	Two stars is a neutral outcome for extended operation of an NPP.	One star is the least positive outcome for extended operation of an NPP.

Methodology of criteria evaluation

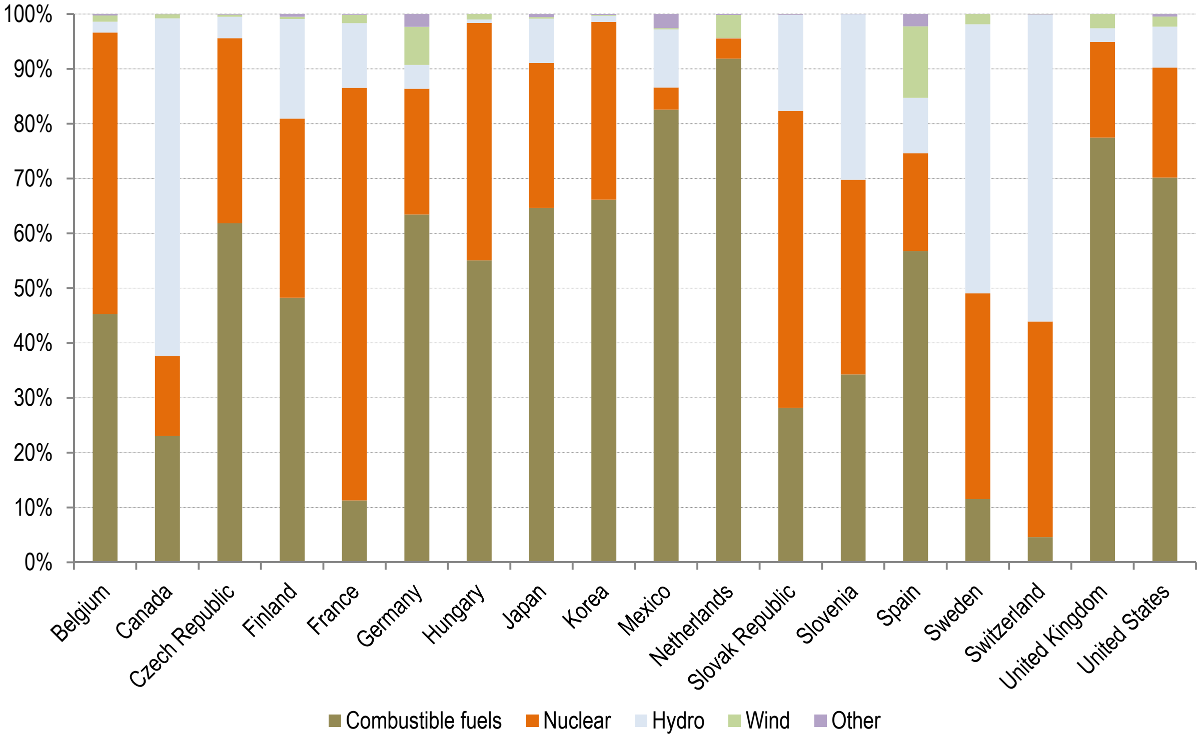
Production and asset portfolio

The share of electricity from NPPs in the national energy mix (see Figure 4.2) and the total generating capacity are important factors influencing the economics of LTO of NPPs. For a country or utility having significant installed nuclear capacity, it could be challenging to replace the existing nuclear capacity with fossil or low-carbon sources of electricity, especially given the degree of maturity and economical competitiveness of the latter. Taking into consideration the desire to move to a low carbon economy, developing or maintaining a significant share of nuclear power is presented in some countries as a reason in favour of the extended operation of NPPs.

However, a too large share of old NPPs could be a challenge in some countries if the share of intermittent must-run renewable sources of electricity increases and thus flexible production units are required as backup. Although some French and German NPPs are flexible and operate in the load-following mode (see Figure 4.3 and NEA, 2011a), this is not a general case. Moreover, in some cases the flexibility of the nuclear fleet might not be fully sufficient to deal with extreme or extended variability of intermittent power sources like wind or solar. Thus, depending on the country's energy policy, LTO activities may also require additional investment in order to improve manoeuvring capabilities of those NPPs, for which it is technically feasible.

Figure 4.2. Net electricity production and generation capacity in selected OECD countries by source in 2009 (IEA, 2011)

Net electricity production



Net electrical capacity

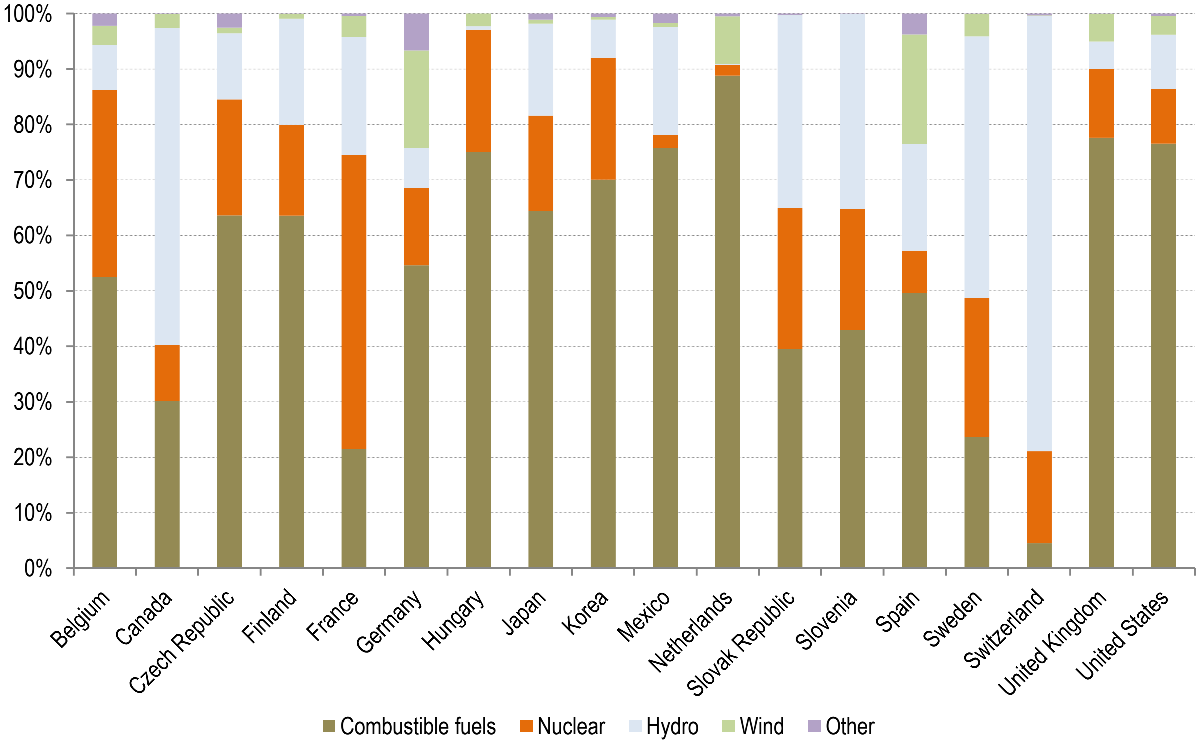
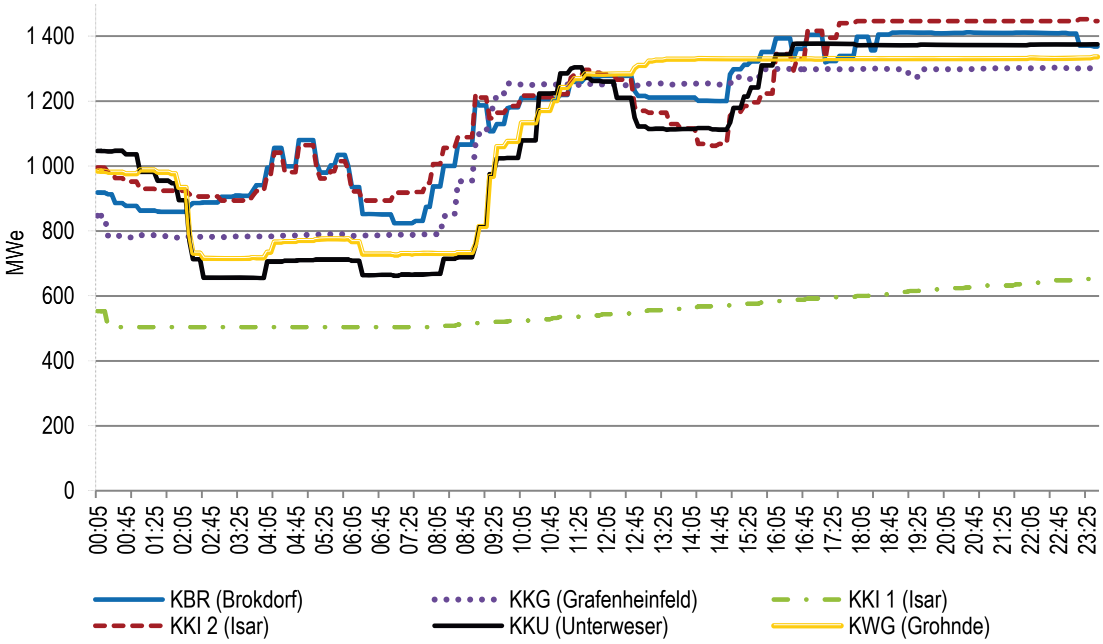


Figure 4.3. Example of load-following over 24 hours for selected German NPPs (NEA, 2001a)



Courtesy of E.ON Kernkraft.

Interconnection with neighbouring grids and availability of capacity in these countries is another important parameter. In isolated systems (e.g. islands) any changes in the energy mix has to be replaced by alternative capacity or electricity savings schemes. Low cross-border trading capacity could be a strong incentive for LTO of NPPs.

Thus, the country's mid- and long-term energy policy is important for evaluating the impact of *production and asset portfolio* on LTO of NPPs, in particular the following aspects:

- share and sources of baseload electricity in the current and future energy mix;
- manoeuvring capabilities of existing power plants and NPPs;
- cross-border electricity trading capacity and grid integration with neighbouring countries.

The evaluation of the impact of *production and asset portfolio* on LTO of NPPs is performed using the following convention:

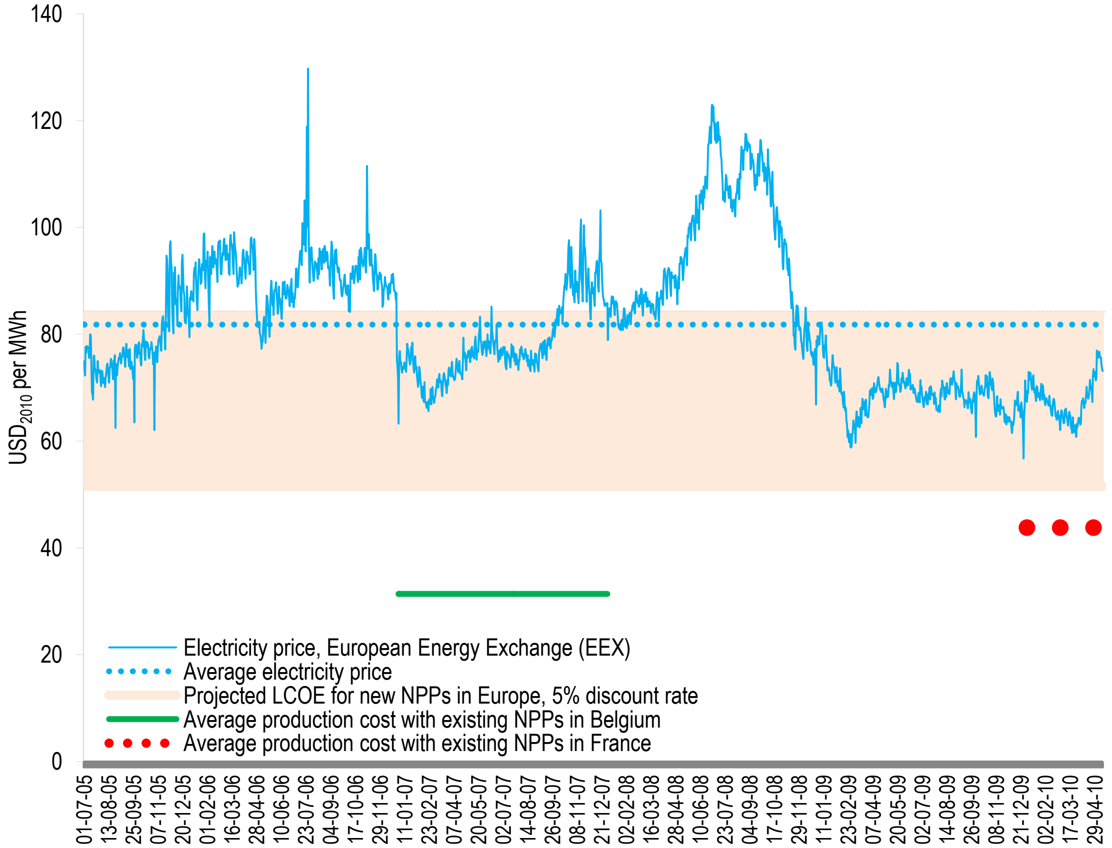
Production and asset portfolio	
If the share of nuclear generation in the electricity mix is large (more than 30%), NPPs have a potential for load-following, or the cross-border electricity capacity is limited, the score for LTO of NPPs is three stars.	★★★
If the share of nuclear generation is important (10-30%) but the remaining electricity mix is well diversified, and there is a potential for cross-border electricity trading, then the score for LTO of NPPs is two stars.	★★
If the share of nuclear generation is small (less than 10%) and the remaining part of the electricity mix is well diversified, NPPs have low potential for load-following and the cross-border electricity capacity is significant, the score for LTO of NPPs is one star.	★

Predictability of future electricity prices

Since nuclear is a technology with high-fixed cost and low-variable cost, it is preferably used as a baseload source of electricity, although some utilities in France and Germany operate some nuclear stations in the load-following mode (NEA, 2011a).

The nature of the electricity market is an important factor for the determination of future electricity prices. In liberalised electricity markets the prices of electricity are strongly volatile (see Figure 4.4). Electricity price in Figure 4.4 is a weighted average of spot, quarterly, monthly and yearly future daily price from the European Energy Exchange (EEX), where the weights are the trading volumes (largely dominated by yearly futures contracts[1]).

Figure 4.4. Electricity prices in Europe in 2005-2010



Note: Projected LCOE for new NPPs in Europe are taken from IEA/NEA, 2010.

Comparing the average electricity prices in Europe in 2005-2010 (see Figure 4.4) with projected costs of electricity generation at new NPPs (figures for LCOE for new NPPs in Europe at 5% real discount rate are taken from IEA/NEA, 2010) shows that there is a potential investment risk for utilities. According to the empirical probability distribution function shown in Figure 4.5 (calculated using the data from Figure 4.4) there is a probability of 5-10% of having electricity prices below the LCOE for new NPPs in Europe. One should note that most of the new European NPP projects considered in IEA/NEA, 2010 are first-of-a-kind Generation III/III+ nuclear power stations. In such case, the extension of the operational lifetime of existing NPPs seems to be a worthwhile option, because of smaller investments needed. For serial production of new reactors, the LCOE for nuclear is expected to be significantly decreased[2].

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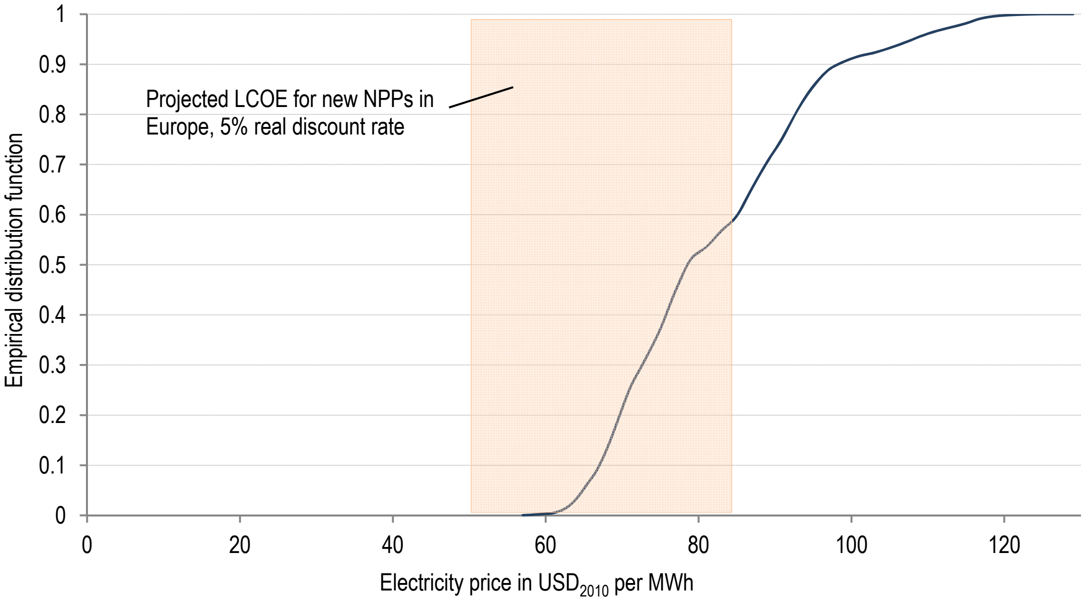
1. The trading volumes at EEX in 2005-2010 are the following: 68% are yearly electricity futures; 16% are quarterly electricity futures; 7% are monthly electricity futures; and 9% are traded at daily spot prices.
2. For example see discussion of the industrial maturity case on page 64 in NEA, 2011b.

Figure 4.5. Empirical distribution function for the data from Figure 4.4



Also, despite the apparent liberalised nature of some electricity markets, there might be regulations specific to nuclear power (e.g. "nuclear taxes") or renewables (e.g. in Germany where renewables have priority on the grid, which has led to several hours of negative prices on the German market in past years, or feed-in tariffs). In this case the nature of the market is not favourable to nuclear in general, whether LTO or new NPPs.

Regulated electricity markets are generally favourable to nuclear since the electricity prices are predictable, and the LCOE of nuclear electricity is one of the smallest among low-carbon sources. However, in the case of a significant decrease in the fossil fuel prices (e.g. significant decrease in natural gas prices in the US in 2011 following large-scale extraction of shale gas), new nuclear can become less attractive. But the capital investment of existing NPPs has already been largely amortised in most cases, and thus one can consider that LTO programmes are only marginally affected by the variation of the fossil fuel prices.

The evaluation of the impact of *predictability of future electricity prices* on LTO of NPPs is performed using the following convention:

Predictability of future electricity prices	
If the prices are predictable, and there are no plans for specific limitations/regulations restricting the operation of NPPs, the score for LTO of NPPs is three stars.	★★★
If utilities operate in a liberalised market with volatile electricity prices or in case of specific regulation/taxation in place marginally affecting the operation of NPPs, the score is two stars.	★★
If the prices are strongly volatile, or in case of special regulations or taxes that potentially will make operation of NPPs significantly less favourable in the future, the score is one star.	★

Need for NPP equipment upgrade and replacement

The obsolescence of equipment of the NPP determines, to a large extent, the investment costs needed for replacement and upgrades. In particular, the state of I&C systems is an important factor for safe and economic operation of the plant. Independently from lifetime management considerations, some utilities have invested in replacement of some equipment that became obsolete or where the spare parts supply can become critical in the future. Thus all NPPs in the world have a different degree of obsolescence of equipment.

The maintenance policies are different depending on the utilities' and the regulatory requirements. In the case when a plant's components are preventively replaced, the need for equipment upgrade and replacement would be smaller. Also, anticipated refurbishment planning and maintenance usually allows better arrangement with equipment manufacturers, and reduces the unplanned outage duration. Thus, reactors anticipating refurbishment would typically have excellent performance indicators. On the contrary, a utility postponing refurbishment and replacement might face delays in manufacturing components and need to invest significant amounts over a shorter period of time.

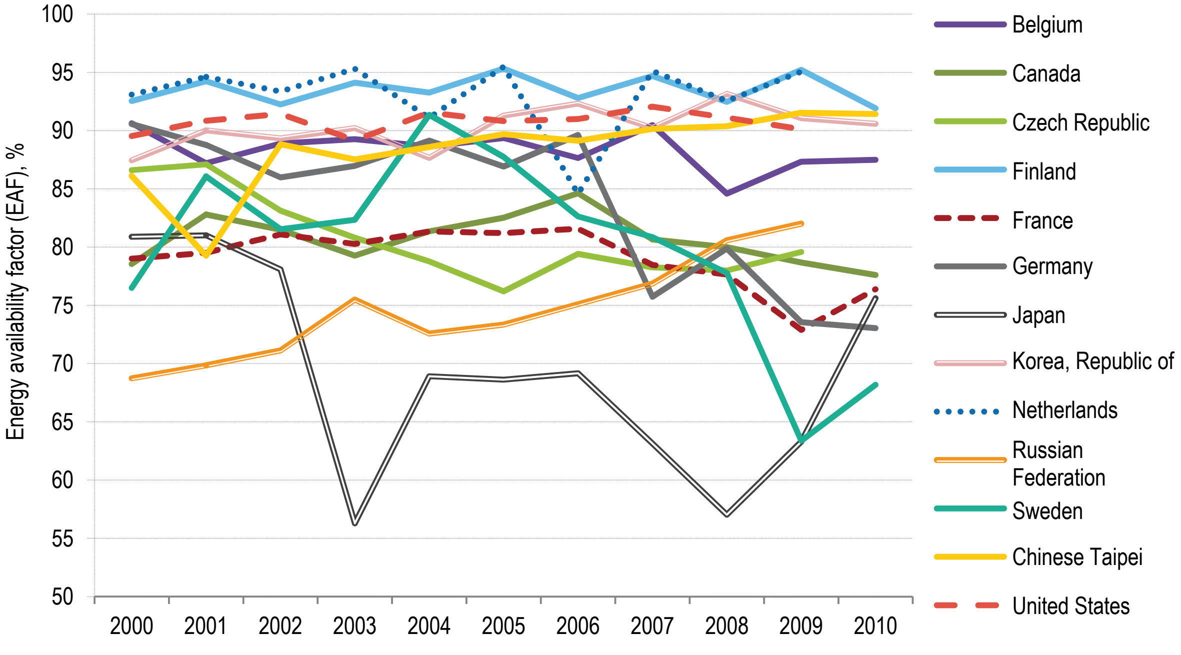
The evaluation of the impact of the *need for NPP equipment upgrade and replacement* on LTO of NPPs is performed using the following convention:

Need for NPP equipment upgrade and replacement	
If most equipment or systems of the plant are up to date the score is three stars.	★★★
If a significant part of the equipment or systems of the plant is up to date, the score is two stars.	★★
If a large part of equipment or systems of the plant are out of date, the score is one star.	★

Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)

Generally speaking, the capacity factor[3] and the EAF[4] are key drivers for baseload electricity generation costs. Although the world weighted average availability factor for all NPPs was close to 80% in 2010, the spread of the values is significant (see Figure 4.6). In OECD countries, the average outage duration was 1 422 hours (i.e. 59 days) per reactor-year in 2005-2011 (according to the IAEA PRIS).

Figure 4.6. Evolution of the EAF in selected economies, since 2000



Source: IAEA PRIS, 2010.

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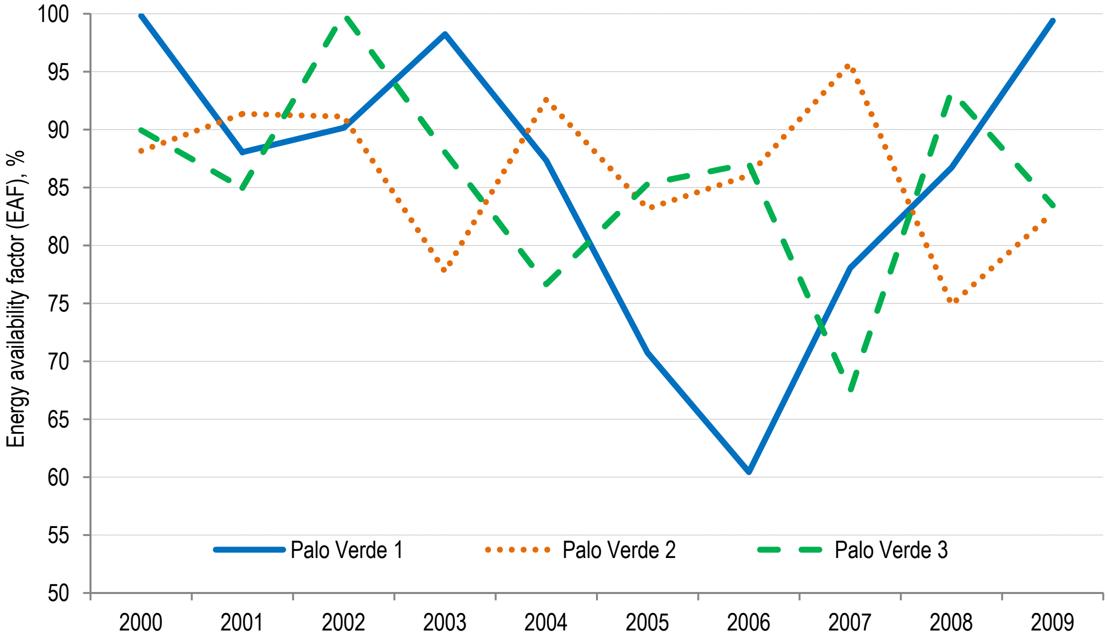
[3] Capacity factor is the ratio between the electricity supplied and reference power generation.

[4] Energy availability factor is the ratio between the electricity that could have been supplied and reference power generation.

Additional lifetime management activities (e.g. refurbishment, specific monitoring and inspections, etc.) can impact the EAF and capacity factor through extension of certain outages. An example of such impact is given in Figure 4.7 for Palo Verde NPP in the US, where steam generators, pressure vessel heads and pressurisers have been replaced recently at all three units[5]. Worsening of performance indicators as a consequence of refurbishment results in a decrease of revenue, and thus impacts LTO of NPPs. However, in certain cases, a refurbishment programme can improve the capacity factor by reducing the outage duration in the future.

Figure 4.7. EAF evolution for Palo Verde NPP (United States) that underwent a major refurbishment programme prior to its lifetime extension in 2011



Source: IAEA PRIS.

Major refurbishment usually includes replacement of major equipment components like steam generators, pressuriser (for PWR), pressure vessel heads, turbogenerator, drywell works (on some BWRs), etc. The duration of the replacement is specific for each unit. Typically, the time required to replace the steam generator is about 35-80 days. In France, the decennial safety review (that includes major refurbishment, maintenance, inspection and tests) takes about 3-6 month. Some reactors require even longer outages, for example, retubing the CANDU reactor of Embalse NPP (Argentina) is planned for about 20 months, and the same operation at Wolsong 1 (Republic of Korea) took 839 days.

Impact of refurbishment activities on the decennial average of the EAF	
If the EAF is marginally affected (less than -3%) over a ten-year period by lifetime management activities, the score is three stars.	★★★
If the EAF is slightly affected (3-6% decrease) over a ten-year period by lifetime management activities, the score is two stars.	★★
If the EAF is strongly affected (more than -6%) over a ten-year period by lifetime management activities, the score is one star.	★

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[5] In particular, note the effect on availability for Palo Verde 1. Modifications were completed in 2005, but unplanned residual issues affected availability through 2006. Palo Verde 2 made modifications in 2003 and Palo Verde 3 made modifications in 2007.

Risk and uncertainty (site-dependence, political, financial, and regulatory)

There are several risks and uncertainties that can influence the utility's decision to extend the operational lifetime of their nuclear power stations.

Political risks are usually correlated with variations of the public attitude to nuclear power. However, sometimes there are additional political risks arising, for instance, when political coalitions are formed and the policy on nuclear power is a condition for such coalition. In this case, an additional political risk could arise, independent of the general (average) public attitude to nuclear power. Also, there is a political risk when major political parties in a country have opposite views on nuclear power.

The **public attitude to nuclear power** itself is equally important. In the case of strong anti-nuclear opposition in a country, or even in neighbouring countries, the LTO of NPPs could become an important political issue.

Regulatory risks concern unforeseeable time delays in issuing authorisations and changes in the safety requirements that may occur. These requirements are subject to change due to external or internal events, security concerns and, generally speaking, they are the reflection of learning from the whole experience of the nuclear industry. For example, the design of NPPs changed after the Three Mile Island accident (namely, I&C, human-system interface, etc.). After the Fukushima Daiichi accident and the establishment of new regulatory requirements (discussed in Chapter 3) the regulatory risks are higher for older NPPs.

Financial risks are particularly important for investment-intensive projects (e.g. building nuclear power stations). In some cases this also applies to LTO programmes especially if significant investment in refurbishment and licensing is needed. The financial risk depends on several factors including the real interest rate, availability of loan guaranties, the nature of the electricity market and the future electricity prices. Particularly challenging are amortisation of refurbishment investments if the extended operation is unknown.

Finally, there are **technological risks** associated with LTO of NPPs, for example unforeseen technical issues with the plant equipment or irreplaceable components, or new knowledge on the seismic conditions of the site that could prevent continued operation of the plant.

The evaluation of various *risks and uncertainties* on LTO of NPPs is performed using the following convention:

Risks and uncertainties	
If risks are low compared to building replacement capacity the score is three stars.	★★★
If risks are moderate compared to building replacement capacity the score is two stars.	★★
If risks are significant compared to building replacement capacity the score is one star.	★

Overnight cost of refurbishment

The total cost of refurbishment is composed of several important contributions:

- cost of engineering and documentation preparation;
- cost of RPV life management (including R&D expenditures);
- cost of refurbishment of components:
  - primary pumps;
  - steam generators;
  - turbogenerator and condenser;

  - shutdown systems;
  - instrumentation and control (I&C) systems;
  - electrical systems;
  - cables;
  - other components.
- cost of the safety review;
- cost of environmental impact assessment;
- cost of licensing process;
- taxes;
- other costs.

These and others cost components are discussed in detail in IAEA, 2002. The evaluation of the impact of *overnight cost of refurbishment* on LTO of NPPs is performed using the following convention:

Overnight cost of refurbishment	
If the overnight cost of refurbishment is smaller than the investment needed to build a replacement capacity, and the utility is not limited by financing, the score is three stars.	★★★
If the overnight cost of refurbishment is comparable with the costs of building a replacement capacity, and some external funding is needed, the score is two stars.	★★
If the overnight cost of refurbishment is significantly higher than the costs of building an alternative (non-nuclear) generating capacity, and it can only be covered by external funds, the score is one star.	★

Levelised cost of electricity generation after long-term operation activities

The levelised cost of electricity (LCOE) includes the initial investment in construction of the plant, its operation and maintenance (O&M), fuel and carbon costs, and also provisions for decommissioning.

In order to be able to operate beyond the term originally defined by the regulatory body or originally assumed by the operator, additional investment is needed. Since the plant is modified due to refurbishment, the O&M and fuel costs might change (especially for power uprate performed at the same time with lifetime extension). Also, the extended operation might lead to some adjustments in provisions for decommissioning. All these costs are discounted over the extension period and divided by the levelised electricity generation, yielding the levelised cost of electricity during the extended operation – LCOE_{EO}.

LCOE and LCOE_{EO} are important characteristics of the economics of current and extended operation. The details on their calculation are given in the following subsections.

Calculation of LCOE

The general formula for LCOE used (see IEA/NEA, 2010) for all sources of electricity reads:

$$\text{LCOE}=\frac{\sum_{t=-t_C}^{\text{Lifetime}}\frac{(\text{Investment}_t+\text{O\&M}_t+\text{Fuel}_t+\text{Carbon}_t+\text{Decommissioning}_t)}{(1+r)^t}}{\sum_{t=1}^{\text{Lifetime}}\left(\frac{\text{Electricity}_t}{(1+r)^t}\right)}$$

The subscript "t" denotes the year in which the electricity production takes place or the expenses are made:

t_C: Construction duration

Electricity_t: The amount of electricity produced in year "t"

r: Annual discount rate

Investment_t: Investment cost in year "t"

$\text{O\&M}_t$: Operations and maintenance cost in year "t"

Fuel_t: Fuel cost in year "t"

Carbon_t: Carbon cost in year "t"

Decommissioning_t: Decommissioning cost in year "t"

In the case of nuclear the LCOE is largely dominated by fixed costs (see Table 4.2), especially for large discount rates. O&M costs are also significant, and the share of the fuel costs is considerably smaller for nuclear than for other thermal plants. The carbon costs are considered zero for NPPs since they do not emit CO_2 in operation.

Table 4.2. Structure of nuclear electricity generation cost (based on IEA/NEA, 2010)

	5% real discount rate	10% real discount rate
Total investment cost	58.6%	75.6%
Operation and maintenance	25.2%	14.9%
Fuel costs*	16.0%	9.5%
Carbon costs	0.0%	0.0%
Decommissioning	0.3%	0.0%

* Fuel costs comprise the costs of the full nuclear fuel cycle including spent fuel reprocessing or disposal (IEA/NEA, 2010).

Calculation of LCOE_{EO} after refurbishment and lifetime extension

The formula for LCOE_{EO} corresponding to the period of extended operation reads:

$$\text{LCOE}_{EO}=\frac{\sum_{t=-t_R}^{t_{EO}}\frac{\left(\text{Refurbishment}_t+\text{O\&M}_t^{EO}+\text{Fuel}_t^{EO}+\text{Decommissioning}_t^{EO}\right)}{(1+r)^t}}{\sum_{t=1}^{t_{EO}}\left(\frac{\text{Electricity}_t^{EO}}{(1+r)^t}\right)}$$

where:

t_R: Refurbishment duration

t_{EO}: Duration of extended operation

$\text{Electricity}_t^{EO}$: The amount of electricity produced in year "t", after refurbishment

r: Annual discount rate

Refurbishment_t: Refurbishment cost in year "t"

$\text{O\&M}_t^{EO}$: Operations and maintenance cost after refurbishment, in year "t"

Fuel_t^{EO}: Fuel cost after refurbishment, in year "t"

$\text{Decommissioning}_t^{EO}$: Decommissioning cost associated with refurbishment in year "t"

In several aspects it is different from the original LCOE:

- The refurbishment investment starts before the end of the original lifetime and takes t_R years. This investment includes all costs associated with the refurbishment process. This cost is discussed in more detail earlier in this chapter. All costs are discounted over the total period of extended operation t_{EO}.
- Following refurbishment, the O&M costs could change, and hence a dedicated value is introduced.
- Fuel utilisation could be improved following refurbishment of the plant (especially I&C), and thus a dedicated variable Fuel_t^{EO} is introduced.
- Since NPPs do not emit CO_2 during operation, it is not taken into account in LCOE_{EO}.
- Provision for decommissioning should normally be done during the original lifetime of the plant. However, some adjustments would possibly be needed following the refurbishment process, and thus a dedicated flux $\text{Decommissioning}_t^{EO}$ is introduced.

Values of parameters

The following set of generic parameters will be used in most of the case studies in Chapter 5:

- currency unit: USD of the year 2010;
- the real discount rates considered for this study are 3% and 8%;
- two durations of extensions are considered: 10 years and 20 years;
- all cash-flows are discounted to the year 2012.

Evaluating the score

Ideally, LCOE_{EO} should be compared with levelised costs of electricity generation with alternative sources of electricity, including replacement of NPP capacity, prices of imported electricity, etc. The evaluation of the impact of levelised cost of electricity generation on LTO of NPPs is performed using the following convention:

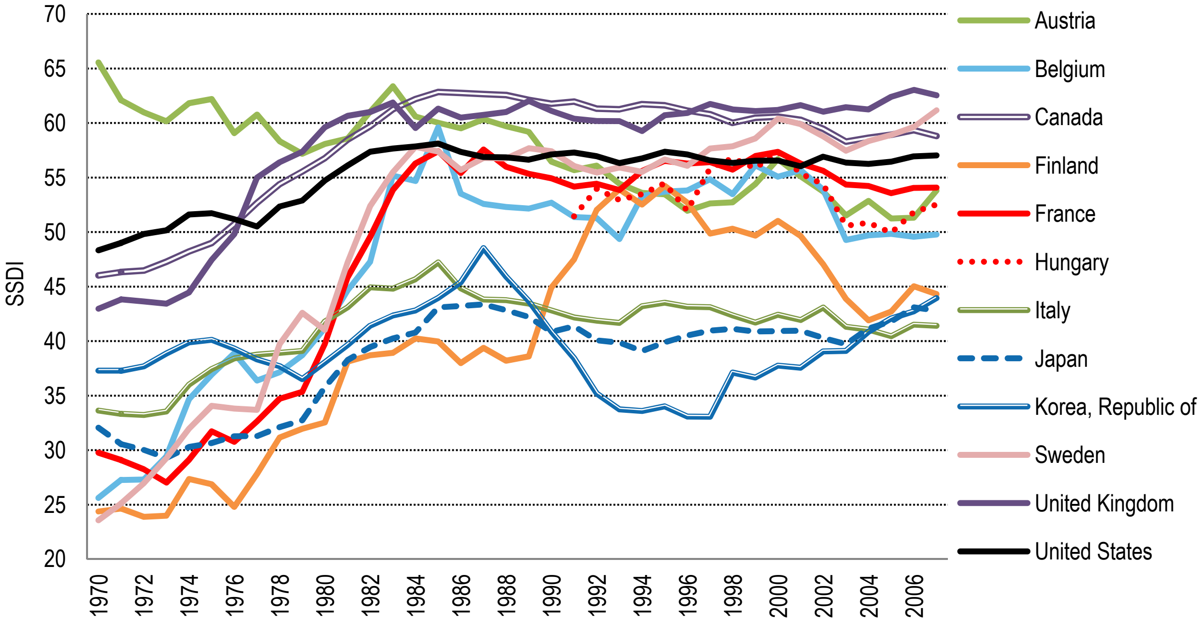
Levelised cost of electricity generation	
If the LCOE_{EO} is lower than projected costs of electricity (replacement plant, imports, etc.) the score is three stars.	★★★
If the LCOE_{EO} is comparable to projected costs of electricity the score is two stars.	★★
If the LCOE_{EO} is higher than projected costs of electricity the score is one star.	★

Country's carbon policy and security of energy supply

This criterion is an assessment of the role of the country's carbon policy and the role of nuclear energy in the security of energy supply. Some countries have to reduce their carbon footprint in order to meet mid- and long-term goals and commitments. The recent study (NEA, 2011b) showed that introducing a carbon pricing mechanism would strongly improve the competitiveness of NPPs in general and LTO programmes in particular.

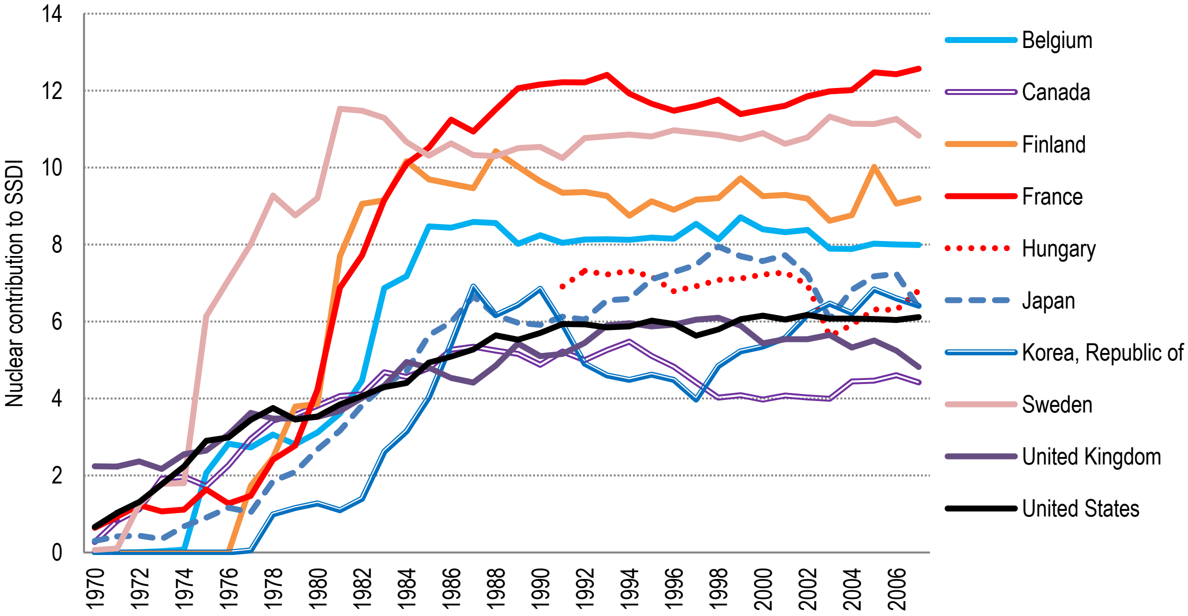
The security of energy supply is an important political issue for many OECD countries with NPPs and considering extension of their operational lifetime. In some countries, the contribution of nuclear energy to the country's level of security of supply is significant. In a recent OECD/NEA study *The Security of Energy Supply and the Contribution of Nuclear Energy* (NEA, 2010a), a composite index measuring the level of the security has been developed – Simplified Supply and Demand Index (SSDI). It is composed of three weighted contributions taking into account the degree of diversity and supply origin of different energy carriers, the efficiency of energy consumption by main economical sectors, and the state of the electricity generation infrastructure. The SSDI takes its values from 0 to 100 interpreting, respectively, poor and perfect state of the security of supply. In the study, the SSDI has been calculated for selected OECD countries (see Figure 4.8).

Figure 4.8. Evolution of SSDI in selected OECD countries



Together with other important factors like diversification of the energy mix and improvement of energy intensities, nuclear energy contributed significantly to improvement of the security of energy supply in OECD countries (see Figure 4.9).

Figure 4.9. The contribution of nuclear energy to SSDI for selected OECD countries



The evaluation of the impact of *country's carbon policy and security of energy supply* on LTO of NPPs is performed using the following convention:

Country's carbon policy and security of energy supply	
If there is a strong national policy on reducing CO_2 emissions or if there is a carbon pricing mechanism in place, and the contribution of nuclear power to security of energy supply is considered important, the score is three stars.	★★★
If there is a national policy on reducing CO_2 emissions but nuclear electricity is not counted as a carbon-free source of electricity, or if there are no immediate intention to introduce carbon taxes, the score is two stars.	★★
If there are no binding policies on reducing CO_2 emissions, and nuclear energy is not seen as an important factor of security of energy supply, the score is one star.	★

Summary of the methodology

The methodology of the economic assessment of NPP LTO programmes is summarised in Table 4.3.

Table 4.3 Summary of assessment methodology

	★★★ Most positive outcome for LTO	★★ Neutral outcome for LTO	★ Least positive outcome for LTO
Production and asset portfolio	If the share of nuclear generation in the electricity mix is large (more than 30%), NPPs have a potential for load-following, or the cross-border electricity capacity is limited, the score for LTO of NPPs is three stars.	If the share of nuclear generation is important (10-30%) but the remaining electricity mix is well diversified, and there is a potential for cross-border electricity trading, then the score for LTO of NPPs is two stars.	If the share of nuclear generation is small (less than 10%) and the remaining part of the electricity mix is well diversified, NPPs have low potential for load-following and the cross-border electricity capacity is significant, the score for LTO of NPPs is one star.
Predictability of future electricity prices	If the prices are predictable, and there are no plans for specific limitations/regulations restricting the operation of NPPs, the score for LTO of NPPs is three stars.	If utilities operate in a liberalised market with volatile electricity prices or in case of specific regulation/taxation in place marginally affecting the operation of NPPs, the score is two stars.	If the prices are strongly volatile, or in case of special regulations or taxes that potentially will make operation of NPPs significantly less favourable in the future, the score is one star.
Need for NPP equipment upgrade and replacement	If most equipment or systems of the plant are up to date the score is three stars.	If a significant part of the equipment or systems of the plant is up to date, the score is two stars.	If a large part of equipment or systems of the plant are out of date, the score is one star.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	If the EAF is marginally affected (less than -3%) over a ten-year period by lifetime management activities, the score is three stars.	If the EAF is slightly affected (3-6% decrease) over a ten-year period by lifetime management activities, the score is two stars.	If the EAF is strongly affected (more than -6%) over a ten-year period by lifetime management activities, the score is one star.
Risk and uncertainty (site-dependence, political, financial, regulatory)	If risks are low compared to building replacement capacity the score is three stars.	If risks are moderate compared to building replacement capacity the score is two stars.	If risks are significant compared to building replacement capacity the score is one star.
Overnight cost of refurbishment	If the overnight cost of refurbishment is smaller than the investment needed to build a replacement capacity, and the utility is not limited by financing, the score is three stars.	If the overnight cost of refurbishment is comparable with the costs of building a replacement capacity, and some external funding is needed, the score is two stars.	If the overnight cost of refurbishment is significantly higher than the costs of building an alternative (non-nuclear) generating capacity, and it can only be covered by external funds, the score is one star.
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	If the $LCOE_{EO}$ is lower than projected costs of electricity (replacement plant, imports, etc.) the score is three stars.	If the $LCOE_{EO}$ is comparable to projected costs of electricity the score is two stars.	If the $LCOE_{EO}$ is higher than projected costs of electricity the score is one star.
Country's carbon policy and security of energy supply	If there is a strong national policy on reducing CO_2 emissions or if there is a carbon pricing mechanism in place, and the contribution of nuclear power to security of energy supply is considered important, the score is three stars.	If there is a national policy on reducing CO_2 emissions but nuclear electricity is not counted as a carbon-free source of electricity, or if there are no immediate intention to introduce carbon taxes, the score is two stars.	If there are no binding policies on reducing CO_2 emissions, and nuclear energy is not seen as an important factor of security of energy supply, the score is one star.

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Chapter 5. Assessment of long-term operation programmes in selected NEA countries: case studies

In this chapter, past and ongoing LTO programmes in different OECD/NEA countries are discussed in detail.

Belgium

There are seven operating nuclear power reactors in Belgium. The oldest unit was built in 1969 and the newest in 1978. The operational lifetime of Belgian reactors is limited by law to 40 years. The law of 2003 announced a gradual nuclear phase-out, with nuclear reactors shutdown at the end of their original lifetime. This law also foresaw the possibility of lifetime extensions but only in the case that no sufficient replacement production capacity would be available at the end of the originally foreseen operational lifetime of the existing NPPs.

Table 5.1 Nuclear power plants in Belgium

Unit name	Type	Model	Site – location	Latest reference unit power (net), MWe	Grid date (DD/MM/YY)
Doel 1	PWR	WE (2 loops)	Delta of river near seacoast	433	28/08/1974
Doel 2	PWR	WE (2 loops)	Delta of river near seacoast	433	21/08/1975
Doel 3	PWR	WE (3 loops)	Delta of river near seacoast	1 006	23/06/1982
Doel 4	PWR	WE (3 loops)	Delta of river near seacoast	1 039	08/04/1985
Tihange 1	PWR	Framatome (3 loops)	Inland near a river	962	07/03/1975
Tihange 2	PWR	WE (3 loops)	Inland near a river	1 008	13/10/1982
Tihange 3	PWR	WE (3 loops)	Inland near a river	1 046	15/06/1985

Source: IAEA PRIS.

Several commissions ("AMPERE" in 1999, "Energy 2030" in 2005) have analysed the Belgian nuclear energy policy and various scenarios.

More recently a study was undertaken by the GEMIX commission in 2008-2009, which was updated, by GEMIX 2 that started its work in 2011. At the end of 2011, the DG Energy of the Ministry of Economic Affairs was also charged to make an Infrastructure Study of the Electrical Supply with the horizon of 2017 in order to allow the current Belgian government to reach a final decision.

The first study by GEMIX was commissioned by the Royal Decree of 28 November 2008. The objective of the GEMIX study was to analyse costs and benefits of energy policy scenarios meeting several requirements:

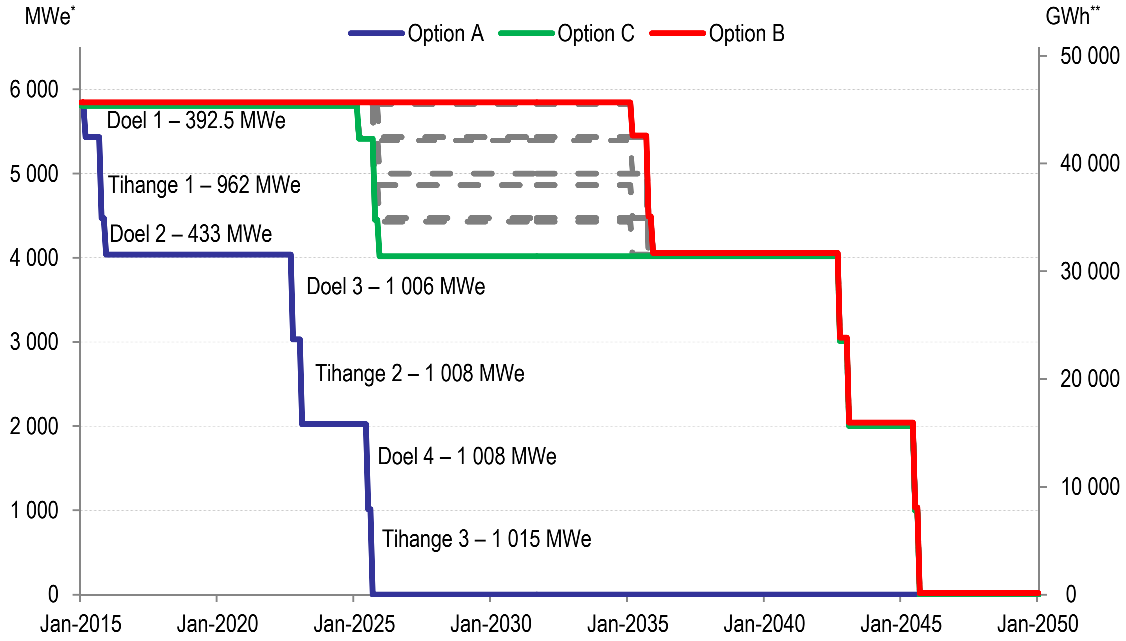
- security of energy supply;
- economical competitiveness;
- CO_2 objectives with respect to the framework of the Energy-Climate Package 20/20.

Three policy measures were envisaged for nuclear power (see Figure 5.1):

- Option A: unchanged application of the 2003 act (i.e. phase out without lifetime extension).
- Option B: possible lifetime extension of the nuclear park to 60 years.
- Option C: delay the closure of Doel 1, Doel 2 and Tihange 1 with a decennial reassessment and to reassess in 10 years to see whether a further extension from 50 to 60 years would still have added value. The newer units Doel 3, Doel 4, Tihange 2, and Tihange 3 would be extended to a maximum of 60 years.

When considering lifetime extension options, an economical profitability of a ten-year extension was required.

Figure 5.1. Scenarios envisaged by GEMIX group



* Installed capacity in 2008.

** Net generation based on an availability rate of 88%.

The operator has estimated that the lifetime investment costs for the oldest units Doel 1, Doel 2 and Tihange 1 would be about EUR$_{2007}$ 900 million[1] (USD$_{2010}$ 1.19 billion) for a total net electrical output of 1 828 MWe (i.e. the specific overnight cost of LTO is about USD$_{2010}$ 650/kWe). This is considerably smaller than the investment needed to build an alternative capacity, for which the specific overnight costs are (according to IEA/NEA, 2010):

- about USD$_{2010}$ 2 600/kWe for supercritical coal plant (of capacity 750 or 1 100 MWe);
- about USD$_{2010}$ 1 100-1 280/kWe for a combined-cycle gas turbine (CCGT) plant (of capacity 400-850 MWe);
- about USD$_{2010}$ 5 530/kWe for a new NPP;

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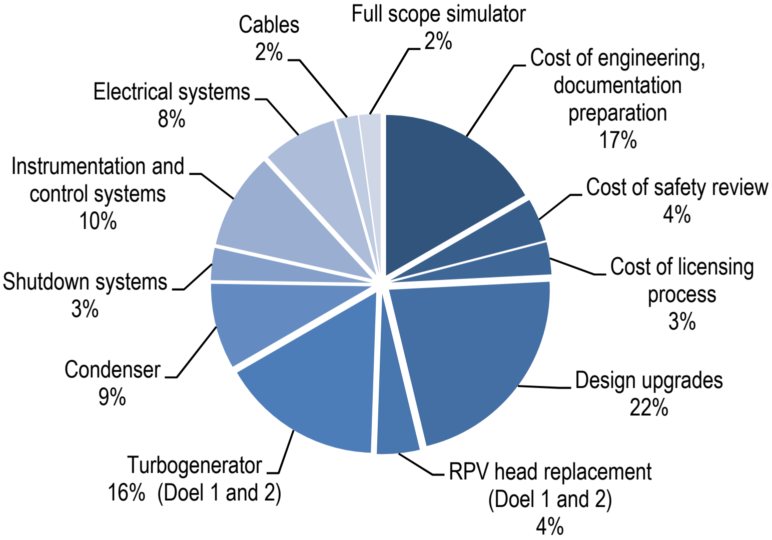
1. About EUR$_{2012}$ 100 million out of this investment cost is needed in order to take into account modifications required following the stress tests carried out in 2011 after the Fukushima Daiichi accident.

- USD_{2010} 2 500-2 700/kWe for an onshore wind turbine (capacity 2 or 6 MWe), and about USD_{2010} 6 250/kWe for an offshore wind turbine (3.6 MWe).

Figure 5.2. Cost decomposition of the LTO process for Doel 1, Doel 2 and Tihange 1



Without lifetime extension of existing NPPs one would already need to replace 700-800 MWe by 2014. Despite an increase in production costs at NPPs, alternative options seem to require significant investment leading to even higher production costs, or they conflict with the security of energy supply/CO_2 objectives. The GEMIX group recommended in 2009:

- Delaying the shutdown of the three oldest nuclear reactors (Doel 1, 2 and Tihange 1) by ten years.
- Re-evaluating the situation in ten years in order to assess the added value of a further extension of the operating lifetime by ten years.
- Delaying the closure of the more recent reactors (Doel 3, Doel 4, Tihange 2 and Tihange 3) by 20 years.

In 2007, Doel 1, Doel 2 and Tihange 1 produced 14 274 GWh (gigawatt-hour) of electric power. Using the last known cost data from Belgian utilities (Table 5.2) and considering an LTO lifetime investment of USD_{2010} 650/kWe, one can calculate the $LCOE_{EO}$. The results are given in Table 5.3 for 10- and 20-year licence extension periods, and for 3% and 8% real interest rates.

Table 5.2. Production cost of Belgian NPPs in 2007

	EUR_{2007} per MWh	USD_{2010} per MWh
Amortisation	0.40-1.10	0.59-1.63
Operation and maintenance	14.20	21.00
Fuel cost	4.05	5.99
Provision for decommissioning	3.01	4.45
Total	21.70-22.40	32.12-33.15

Table 5.3. Calculation of LCOE_{EO} for the oldest Belgian NPPs

(in USD_{2010}/MWh)

Extended operation period	Discount rate	Levelised investment cost in LTO	O&M costs	Fuel cost	Provision for decommissioning	Total
10 years	3%	9.83	21	6	4.45	41.25
10 years	8%	11.90	21	6	4.45	43.35
20 years	3%	5.60	21	6	4.45	37.00
20 years	8%	8.12	21	6	4.45	39.60

According to the calculation of LCOE_{EO} given in Table 5.3, the cost of electricity generation at the oldest NPPs in Belgium might increase (on a cost basis of 2007) by 11-19% for a 20-year lifetime extension and by about 25-30% for a 10-year extension. Despite this increase, the LCOE_{EO} is considerably below the levelised costs of electricity generation with alternative sources.

As a result of the GEMIX 1 proposal, the Belgian government decided in 2009 to follow the recommendation of GEMIX to postpone the shutdown of the three oldest reactors by ten years. Before this decision was turned into a special law, it was dismissed by the government in 2010. The new government, which was installed in December 2011, decided that the law of 2003 would in principle be carried out if adequate power could be secured from other sources and prices would not rise quickly. In July 2012, the government also received the infrastructure study of the DG Energy of the Ministry of Economic Affairs.[2]

The final decision which was taken is that:

- Doel 1 and 2 will be stopped after 40 years of operation according to the original law.
- Tihange 1 will have an LTO extension of ten years.
- The lifetime of the four reactors of the more recent type, Doel 3 and 4 as well as Tihange 2 and 3 is limited to 40 years. The possibility, foreseen in the law of 2003, to operate longer than originally foreseen, in case of shortage of supply, is suppressed.
- At the same time the government also decided that the operator should sell the production of Tihange 1 at cost plus conditions to new entrants in the market.

The argument for giving an extension to Tihange 1 was based on the lower LTO cost and a possible shortage of supply. In Doel 1 and 2, the turbogenerator and reactor vessel head had to be replaced leading to higher costs, while in Tihange the impact of the post-Fukushima stress tests resulted in higher costs than in Doel. The motivation behind the global decision was to confirm the nuclear phase-out.

In Figure 5.3 and Figure 5.4 the estimates of LCOE_{EO} for existing NPPs in Belgium (Table 5.3) are compared to LCOE with alternative sources: gas, coal, new nuclear and wind. The overnight capital costs and O&M costs for these alternative sources were taken from IEA/NEA, 2010. The price of coal is assumed to be USD_{2010} 90 per metric ton, and the assumption for the long-term gas prices is USD_{2010} 7/Mmbtu (million metric British thermal units).

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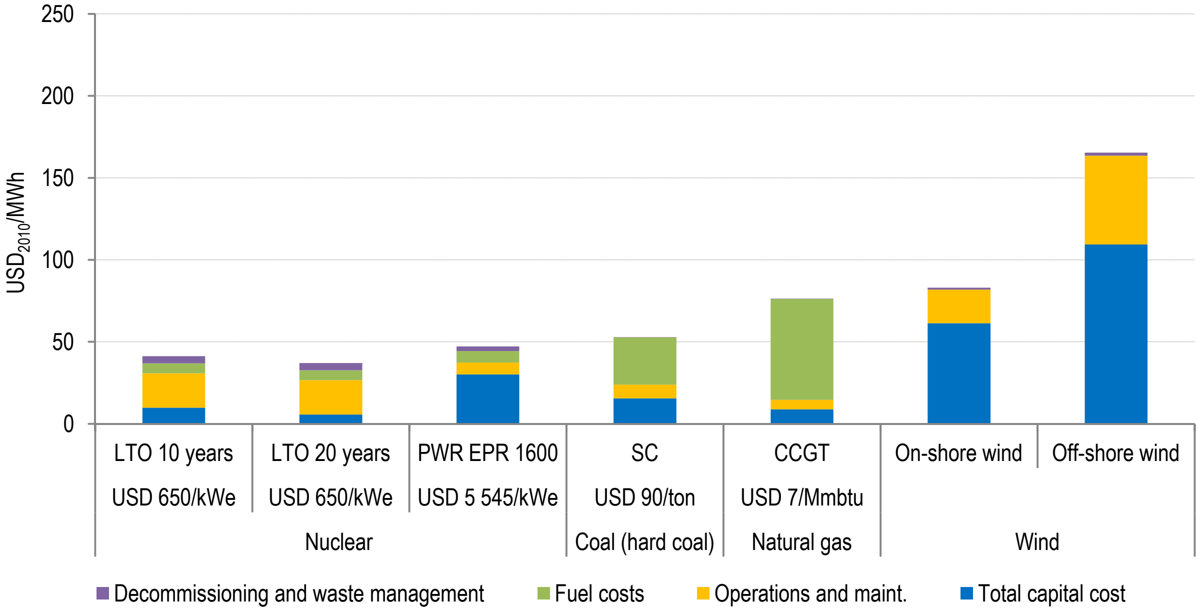
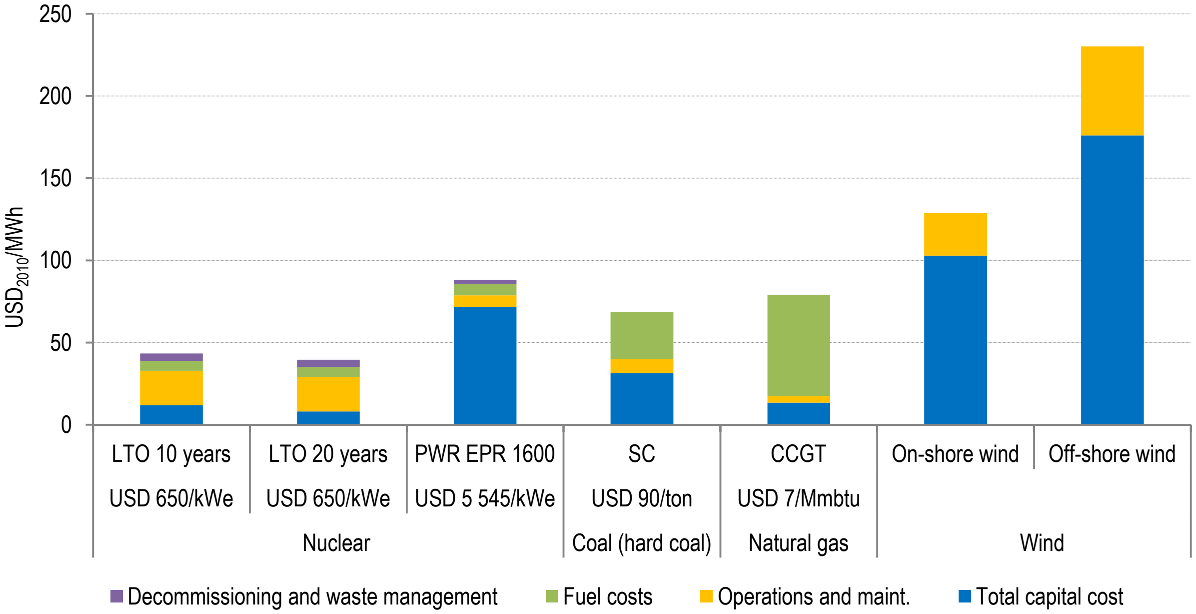
[2] In parallel with an update of GEMIX 1.

Figure 5.3. Projected costs of electricity generation in Belgium, at 3% real discount rate



Note: CCGT = Combined-cycle gas turbine. PWR = Pressurised water reactor; EPR = European pressurised reactor; SC = Supercritical.

Figure 5.4. Projected costs of electricity generation in Belgium, at 8% real discount rate



Note: CCGT = Combined-cycle gas turbine. PWR = Pressurised water reactor; EPR = European pressurised reactor; SC = Supercritical.

The summary of the assessment of the LTO programme in Belgium (using the methodology from Chapter 4) is provided in Table 5.4. LTO of the oldest Belgian NPPs (Doel 1, Doel 2 and Tihange 1) clearly appears to be attractive from the economical, environmental and security of supply viewpoints. However, political decisions have been very important, and have taken priority over the economic arguments from the LTO process.

Table 5.4. Assessment results for the NPP LTO programme in Belgium

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★	The share of nuclear generation in the national electricity mix is large (about 51% in 2009). The remaining part is mainly generated by gas-fired power plants and coal power plants. Belgian NPPs do not operate in the load-following mode. Belgium is very well connected to the transmission networks of neighbouring countries, and several new interconnection projects are currently being developed.
Predictability of future electricity prices	★	The electricity market in Belgium is liberalised. There are specific taxes in place (about USD_{2010} 6.5/MWh) that strongly affect the economic profitability of NPPs.
Need for NPP equipment upgrade and replacement	★★	A significant part of plant equipment is up to date. Steam generators have been replaced at most of the Belgian NPPs.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★/★★★	In 2000-2010, the EAF was slightly affected by refurbishment activities (e.g. steam generator replacement).
Risk and uncertainty (site-dependence, political, financial, regulatory)	★	Political risks are high. For example, in 2011 several political parties negotiating to form a new governmental coalition agreed that the 2003 nuclear phase-out law closing Doel 1, Doel 2 and Tihange 1 by 2015 and the others by 2025 should be implemented if adequate power could be secured from other sources and prices would not rise unduly. The final decision of July 2012 confirms that the evolution of the political opinion strongly intervenes in the final decision.
Overnight cost of refurbishment	★★★	The overnight cost of refurbishment of the oldest Belgian NPPs is about USD_{2010} 650/kWe. This is significantly lower than projected investment costs in CCGT (more than USD_{2010} 1 100/kWe), coal plant (more than USD_{2010} 2 500/kWe) or renewables.
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	★★★	The $LCOE_{EO}$ is about USD_{2010} 41-43/MWh for a 10-year lifetime extension and about USD_{2010} 37-39/MWh for a 20-year lifetime extension, for a real discount rate of 3-8%. This is significantly below the projected costs of electricity generation with alternative sources.
Country's carbon policy and security of energy supply	★★	- Belgium has a strong national policy on reducing the CO_2 emissions from electricity generation. - Nuclear power used was considered as part of the solution. - Carbon taxes are expected to be introduced. - Nuclear still plays a significant role in the security of energy supply in Belgium (see Figure 4.8 and Figure 4.9).

Finland

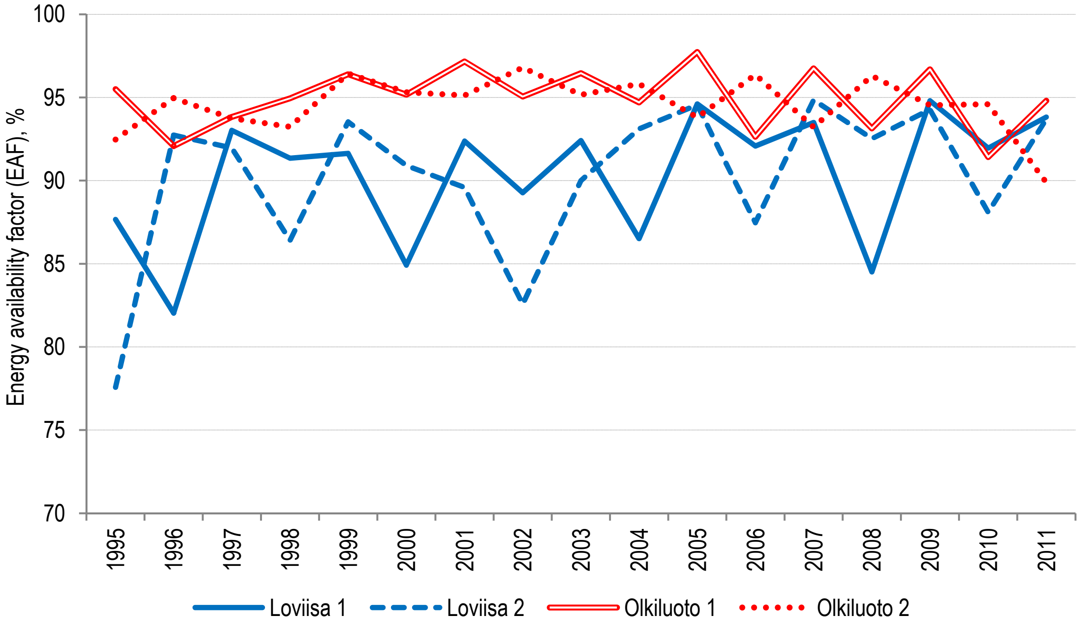
Finland has four operating nuclear reactors (see Table 5.5) that have produced about 22.3 TWh (terawatt-hour) in 2011. This represents 26% of the total electricity supply. A new unit (a European pressurised reactor [EPR] of 1 600 MWe) is currently under construction at Olkiluoto site, and two additional large reactors are envisaged (these might add another 3 000 MWe of installed power).

Table 5.5. Operating NPPs in Finland

Unit name	Type	Model	Site – location	Latest gross electrical power, MWe	Grid data (DD/MM/YY)	Long-term operation
Loviisa 1	PWR	VVER-440/V-213	Seacoast	520	08/02/1977	Licence extension until 2027
Loviisa 2	PWR	VVER-440/ V-213	Seacoast	520	04/11/1980	Licence extension until 2030
Olkiluoto 1	BWR	BWR-2500	Seacoast	910	02/09/1978	
Olkiluoto 2	BWR	BWR-2500	Seacoast	910	18/02/1980	

Nuclear reactors in Finland were subject to important modernisation programmes and power uprates discussed below. Despite these extensive maintenance programmes, the EAF of all four operating NPPs in Finland remained very high, among the highest in the world (see Figure 5.5).

Figure 5.5. The EAF of operating NPPs in Finland



Source: IAEA PRIS.

The first power uprate of the BWR at Olkiluoto 1 and 2 in 1983-1984 increased the electric output from 660 to 710 MWe. Between 1995 and 1998, a second modernisation programme for Olkiluoto 1 and 2 (MODE) involved some 40 major projects. In both units, the steam separator, generator and main transformer were replaced, and the turbine island has been modernised. As a result of the implementation of the MODE programme, the electric output increased from 710 MWe to 840 MWe. Further upgrades in 2005-2006 of the turbine island of Olkiluoto 1 and 2 (Turbine Island Modernisation project – TIMO) were performed during the annual outage. As a result, the power output increased from 840 to 860 MWe at both units.

Finally, the most recent modernisation project of Olkiluoto 1 and 2 in 2010-2011 improved the efficiency of the plant by adding another 20 MWe at each unit without any increase in energy consumption. The cost of this modernisation programme is estimated at EUR 160 million.

Loviisa NPP hosts two VVER-440/V-213 reactors. It should be noted that this is not a standard design since these units have a containment and I&C system that was supplied by western companies. The plant modernisation in 1997-2002 resulted in power uprates of Loviisa 1 and 2 from 440 MWe to 496 MWe.

The operating licence for both units has been renewed for a 50-year lifetime – Loviisa 1 to 2027 and Loviisa 2 to 2030. The pressure vessel of Loviisa 1 was heat annealed in 1996. In Loviisa 2, the critical weld in the RPV has fewer chemical impurities than the one in Loviisa 1, and thus annealing of the Loviisa 2 RPV may not be necessary even for the extended lifetime.

There are several ongoing lifetime management activities at Loviisa NPP, and the possibility of further electric power uprates by process optimisation is currently been examined. The main results of the feasibility study (TEHO2) conducted in 2010-2011 showed that:

- the turbine island can be modified to adapt to the new power level;
- the generator could be the bottle neck, since a new generator would require foundation modifications;
- ensuring the currently licensed lifetime (50 years) will require an extensive investment programme.

The conclusion of the TEHO2 study was that the reactor power increase should be postponed due to the risk of production losses, and thus the main focus in the near future is on increasing the plant's efficiency. Lifetime extension to 60 years will be taken into account in the coming investments in the framework of the LOMO2 programme. The general aim of the LOMO2 programme is:

- to ensure continuous safety enhancement of the Loviisa NPP, especially concerning environmental hazards;
- to increase gross power up to the existing generator limit power of 536 MWe (2x268 MWe), by increasing the operating efficiency;
- to decrease energy consumption of the plant;
- to ensure excellent performance indicators of the plant.

Safety improvements are the highest priority projects, and post-Fukushima studies and stress-tests results will be taken into account, with a key focus on back-up for the final ultimate heat sink (cooling towers), securing additional transportable pumps and electricity sources, ensuring protection against high sea water level and fuel storage for safety diesels, and finally improving severe accident management systems. In addition to safety improvements, a significant number of plant components are planned to be replaced or improved – I&C, low- and high-pressure turbine, pumps, transformers, etc.

Table 5.6. Assessment results for the NPP LTO programme in Finland

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	The share of nuclear generation in the national electricity mix is important (about 26% in 2011), and is expected to rise significantly in the coming years with the completion of Olkiluoto 3 and construction of two more reactors. On the other hand, Loviisa 1 and 2 are approaching the term of their licence. The Finnish grid is very well integrated with the neighbouring countries.
Predictability of future electricity prices	★★★	To a large extent, the electricity prices will be driven by the costs of electricity generation with new NPPs.
Need for NPP equipment upgrade and replacement	★★★	The NPP's equipment is up to date.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★★	The impact of refurnishing activities on the EAF is marginal. According to IAEA PRIS, the ten-year average of the EAF for Loviisa 1 and 2 is, respectively, 91.43% and 90.98%, and for Olkiluoto 1 and 2 it is 95.13% and 94.67%.
Risk and uncertainty (site-dependence, political, financial, regulatory)	★★/★★★	Although some political risk is preset, it is low if compared to some other countries.
Overnight cost of refurbishment	N/A	Finland has an ongoing nuclear programme.
LCOE_{EO} – levelised cost of electricity generation after LTO activities	N/A	
Country's carbon policy and security of energy supply	★★★	There is a strong national policy on CO_2 reduction in place. Development of nuclear power will allow significant reduction of electricity and gas import.

N/A = Not available.

France

France has 58 operating nuclear reactors (see Table 5.7), all owned and operated by Electricité de France (EDF), resulting in a total installed capacity of about 63 130 MWe. In 2010, they generated almost 408 TWh of electricity (about 74.16% of the total electricity production in France).

The French nuclear fleet was mainly commissioned during the period 1980-1990. About 80% of the total installed capacity was commissioned during a ten-year period. Thus, the fleet of nuclear reactors in France is relatively young (26 years on average).

The initial design lifetime was 40 years. However, according to the French regulatory framework, there is theoretically no time limit for NPP operation. Every ten years, the French Nuclear Safety Authority (ASN) performs a PSR consisting of conformity checks and safety reassessments. It aims to improve the compliance of operating nuclear plants with safety standards, and to reassess these standards based on feedback and new knowledge. The safety standards reassessed in this way are then set until the next re-examination. The objectives are established by the ASN (which monitors compliance), while the utility (EDF) proposes solutions to meet them and implements them after obtaining the approval of the ASN. If the safety review is satisfactory, the ASN gives the authorisation to continue operation for ten more years.

In France, 34 reactors of the PWR-900 series obtained a licence extension of 10 years in 2002, and 20 units of the PWR-1300 series were granted a 10-year licence extension in 2006, providing that some modifications during the outage after 20 years of operation are performed (see Table 5.7). Further extension of the operating licence (from 30 to 40 years) is currently being considered: Tricastin 1 and Fessenheim 1 were granted a 10-year licence extension in 2011, and Bugey 2 in 2012, providing that EDF implements the prescriptions of the ASN.

Table 5.7. Operating NPPs in France

Unit name	Type	Model	Site – location	Latest reference unit power (net), MWe	Grid date (DD/MM/YY)	# Next periodic inspection (ten years)
Belleville 1	PWR	P'4 REP 1300	Inland near a river	1 310	14/10/1987	3
Belleville 2	PWR	P'4 REP 1300	Inland near a river	1 310	06/07/1988	3
Blayais 1	PWR	CP1	Seacoast	910	12/06/1981	3
Blayais 2	PWR	CP1	Seacoast	910	17/07/1982	3
Blayais 3	PWR	CP1	Seacoast	910	17/08/1983	3
Blayais 4	PWR	CP1	Seacoast	910	16/05/1983	3
Bugey 2	PWR	CP0	Inland near a river	910	10/05/1978	4
Bugey 3	PWR	CP0	Inland near a river	910	21/09/1978	3
Bugey 4	PWR	CP0	Inland near a river	880	08/03/1979	4
Bugey 5	PWR	CP0	Inland near a river	880	31/07/1979	4
Cattenom 1	PWR	P'4 REP 1300	Inland near a lake	1 300	13/11/1986	3
Cattenom 2	PWR	P'4 REP 1300	Inland near a lake	1 300	17/09/1987	3
Cattenom 3	PWR	P'4 REP 1300	Inland near a lake	1 300	06/07/1990	3
Cattenom 4	PWR	P'4 REP 1300	Inland near a lake	1 300	27/05/1991	2
Chinon B1	PWR	CP2	Inland near a river	905	30/11/1982	3
Chinon B2	PWR	CP2	Inland near a river	905	29/11/1983	3
Chinon B3	PWR	CP2	Inland near a river	905	20/10/1986	3
Chinon B4	PWR	CP2	Inland near a river	905	14/11/1987	3
Chooz B1	PWR	N4 REP 1450	Inland near a river	1 500	30/08/1996	2

Table 5.7. Operating NPPs in France *(continued)*

Unit name	Type	Model	Site – location	Latest reference unit power (net), MWe	Grid date (DD/MM/YY)	# Next periodic inspection (ten years)
Chooz B2	PWR	N4 REP 1450	Inland near a river	1 500	10/04/1997	2
Civaux 1	PWR	N4 REP 1450	Inland near a river	1 495	24/12/1997	2
Civaux 2	PWR	N4 REP 1450	Inland near a river	1 495	24/12/1999	2
Cruas 1	PWR	CP2	Inland near a river	915	29/04/1983	3
Cruas 2	PWR	CP2	Inland near a river	915	06/09/1984	3
Cruas 3	PWR	CP2	Inland near a river	915	14/05/1984	3
Cruas 4	PWR	CP2	Inland near a river	915	27/10/1984	3
Dampierre 1	PWR	CP1	Inland near a river	890	23/03/1980	4
Dampierre 2	PWR	CP1	Inland near a river	890	10/12/1980	4
Dampierre 3	PWR	CP1	Inland near a river	890	30/01/1981	3
Dampierre 4	PWR	CP1	Inland near a river	890	18/08/1981	3
Fessenheim 1	PWR	CP0	Inland near a river	880	06/04/1977	4
Fessenheim 2	PWR	CP0	Inland near a river	880	07/10/1977	4
Flamanville 1	PWR	P4 REP 1300	Seacoast	1 330	04/12/1985	3
Flamanville 2	PWR	P4 REP 1300	Seacoast	1 330	18/07/1986	3
Golfech 1	PWR	P'4 REP 1300	Inland near a river	1 310	07/06/1990	2
Golfech 2	PWR	P'4 REP 1300	Inland near a river	1 310	18/06/1993	2
Gravelines 1	PWR	CP1	Seacoast	910	13/03/1980	4
Gravelines 2	PWR	CP1	Seacoast	910	26/08/1980	3
Gravelines 3	PWR	CP1	Seacoast	910	12/12/1980	3
Gravelines 4	PWR	CP1	Seacoast	910	14/06/1981	3
Gravelines 5	PWR	CP1	Seacoast	910	28/08/1984	3
Gravelines 6	PWR	CP1	Seacoast	910	01/08/1985	3
Nogent 1	PWR	P'4 REP 1300	Inland near a river	1 310	21/10/1987	3
Nogent 2	PWR	P'4 REP 1300	Inland near a river	1 310	14/12/1988	3
Paluel 1	PWR	P4 REP 1300	Seacoast	1 330	22/06/1984	3
Paluel 2	PWR	P4 REP 1300	Seacoast	1 330	14/09/1984	3
Paluel 3	PWR	P4 REP 1300	Seacoast	1 330	30/09/1985	3
Paluel 4	PWR	P4 REP 1300	Seacoast	1 330	11/04/1986	3
Penly 1	PWR	P'4 REP 1300	Seacoast	1 330	04/05/1990	3
Penly 2	PWR	P'4 REP 1300	Seacoast	1 330	04/02/1992	2
St. Alban 1	PWR	P4 REP 1300	Inland near a river	1 335	30/08/1985	3
St. Alban 2	PWR	P4 REP 1300	Inland near a river	1 335	03/07/1986	3
St. Laurent B1	PWR	CP2	Inland near a river	915	21/01/1981	3
St. Laurent B2	PWR	CP2	Inland near a river	915	01/06/1981	3
Tricastin 1	PWR	CP1	Inland near a river	915	31/05/1980	4
Tricastin 2	PWR	CP1	Inland near a river	915	07/08/1980	4
Tricastin 3	PWR	CP1	Inland near a river	915	10/02/1981	4
Tricastin 4	PWR	CP1	Inland near a river	915	12/06/1981	3

If no further permits are granted, and the lifetime of the French fleet is limited to 40 years, it would be necessary to build about 5 000 MWe/year (assuming an availability factor of 80%) of capacity starting from 2019 and for a period of 10 years.

EDF's plan for refurbishment of the main components is summarised below[3]. Most of the components are refurbished after 30 years of operation, and will be spread over a 3- to 5-year period around the 30th anniversary of the plant:

- ***Steam generators***: globally scheduled to be completed before the end of 2025 for 1 300 MWe plants. Steam generators of 20 reactor units of the 900 MWe fleet have been replaced between 1990 and 2010.
- ***Turbines***: replacement of the rotors before 2020 for CP1 units (see Table 5.7).
- ***Generators***: first rewinding of the stators before 2020, second rewinding to be planned later.
- ***Main power transformers***: before the end of 2025.
- ***Other components***: around the 30th anniversary of the unit (depending on the results of the ageing analysis).

As a result of the complementary safety assessment conducted in France after the Fukushima Daiichi accident, ASN considered that the facilities examined offer a sufficient level of safety, requiring no immediate shutdown of facilities. At the same time, ASN considered that the continued operation of the facilities require that their robustness to extreme situations needed to be reinforced. The main requirements are:

- to reinforce the protection of NPPs against external hazards (earthquake, flooding, etc.);
- to reinforce water and electricity supply;
- to limit the radioactive releases in the event of a severe reactor accident (no significant and long-term contamination);
- to reinforce crisis management at the plant and at national level (human and material resources).

The key additional measures in France are:

- to identify and establish a "hard core" approach to material and organisational measures designed to ensure control of the basic safety functions in extreme situations;
- to create a Nuclear Rapid Response Force (FARN) that will be able to intervene within 24 hours to support operational teams.

A significant part of these measures were already considered by EDF within the framework of the LTO operations, but will be brought forward. The remaining part of the initial investment in the construction of NPPs is described in the 2012 report "French Court of Audits". As a reminder, the total investment is estimated at EUR_{2010} 118.2 billion:

- construction: EUR_{2010} 83.2 billion;
- financial interest: EUR_{2010} 12.8 billion;
- cost of decommissioning[4]: EUR_{2010} 18.4 billion; and
- cost of last cores, EUR_{2010} 3.8 billion.

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[3] This plan was defined before the accident at Fukushima Daiichi, and a significant number of actions were already envisaged.

[4] With respect to PWR-type reactors, provisions were made for all 58 operational units, on the basis of an estimated amount of EUR_{2010} 291/kWe for all decommissioning operations, excluding management of decommissioning waste. These provisions are taken into account in the capital amortisation.

According to the same report by the French Court of Audits, the combined O&M and fuel cost was EUR_{2010} 11 billion during the year 2010 (including EUR_{2010} 1.7 billion of investment) for the entire fleet, or about USD_{2010} 37.5/MWh. The total **investment** in all the fleet until 2025 is about EUR_{2011} 55 billion or approximately EUR_{2011} 875/kWe (USD_{2010} 1 090/kWe[5]) consisting of:

- Investment in refurbishment and safety upgrades (i.e. LTO investment), performance improvement and maintenance: EUR_{2011} 50 billion.
- The total cost of post-Fukushima additional measures is estimated at EUR_{2011} 10 billion. Approximately half of the additional measures were already forecasted within the LTO programme, in order to allow operating up to 60 years. Thus, the post-Fukushima impact on the French LTO programme resulted in about 10% increase of the initially planned LTO investment.

Since 1 July 2007, the French electricity sales and supply market has been fully liberalised. According to NOME Law (entered into force on 7 December 2010), the utility operating all French NPPs (EDF) will have to provide its competitive suppliers with up to 100 TWh per year (representing about 25% of the total nuclear generation in France), in accordance with the economic conditions of nuclear production. The regulated access to historical nuclear energy (ARENH – Accès Régulé à l'Électricité Nucléaire Historique) is set by a governmental decree following a legal option from the energy regulatory commission (CRE – Commission de régulation de l'énergie) for the first three years then beginning in 2013 by proposal by the CRE. The ARENH price was set at EUR_{2011} 40/MWh for 2011, 2nd semester, and has been set at EUR_{2011} 42/MWh (USD_{2011} 54/MWh) starting from 1 January 2012. The French Court of Auditors assessed the electricity generation cost by various methods in relation to the cost of using the nuclear assets, see Table 5.8.

Table 5.8. Cost calculations by the French Court of Audits, 2012

(in USD_{2010}/MWh[1])

	O&M expenses	Cost of using nuclear assets	Total
Account cost[2]	38.4	5.8	44.2
« Champsaur » Commission[3]	35.9	7.9	43.8
Complete accounting cost for generation[4]	31.0	22.1	52.7
Current economic cost[5]	38.5	27.0	65.6

1. The conversion from the currency unit used in the French Court of Audits, 2012 (EUR_{2010}) to USD_{2010} was performed by the OECD/NEA Secretariat using the annual average exchange rate.

2. The “accounting cost” approach is consistent with the accounting of the company which is defined in order to calculate an operating profit. It takes into account amortisation of the fleet but does not consider neither interest on the invested capital, nor the impact of inflation. It estimates the total cost of production by summing operating expenses, maintenance and amortisation. Amortisation is calculated on the initial investment in current currency.

3. The “Champsaur commission” approach “aims to set a tariff for electricity generation” says the report. It is essentially based on an accounting method taking into account the amortisation of the fleet, but considering an interest on the residual share of the capital which is not amortised in the accounts. This residual share is calculated without taking into account the impact of inflation.

4. The “full accounting cost of production” approach is also based on an accounting logic. It takes into account amortisation of the fleet, interest on the non amortised part of capital and inflation effect on the value of the fleet. The inflation effect reflects partially to the increased cost of a replacement fleet compared to the initial investment (it does not reflect the rise of construction costs, well above inflation). Moreover, in this method, maintenance and refurbishment costs are considered as capital assets, like the initial investments, rather than operating costs.

5. The “current economic cost” approach is based on an economic logic for the calculation of the cost of electricity generation. It takes into account operating and maintenance expenses, and the cost of the invested capital. This capital cost is no longer based on an accounting method as in the previous approaches. It takes the form of an economic rent, which considers a refund and interest (including risk) of capital. In the present case, the rate of interest on capital is 7.8%.

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[5] Since this investment is planned over a significant interval of time, a long-term conversion factor was used: EUR 1 = USD 1.25.

Taking into account LTO and post-Fukushima maintenance programmes, these values were increased by 10-15% (see Table 5.9).

Table 5.9. LTO and post-Fukushima cost impact on the generation costs calculated by the French Court of Audits, 2012

	2010 value	Mean value from 2011 to 2025	% increase
Maintenance expenses	USD 2.25 billion[1]	USD 4.9 billion[1]	
Cost of electricity generation (in USD_{2010}/MWh[1])			
Account cost	44.2	50.6	+15%
« Champsaur » commission	43.8	50.2	+15%
Current economic cost	65.6	71.8	+10%

1. The conversion from the currency unit used in the French Court of Audits, 2012 (EUR_{2010}) to USD_{2010} was performed by the OECD/NEA Secretariat using the annual average exchange rate.

Using the above assumption on the overnight cost of LTO programme cost, and using the data available for O&M and fuel costs, the OECD/NEA Secretariat has calculated the levelised cost of electricity generation after refurbishment. The results are given in Table 5.10 for a 10- and 20-year extension of operation, and for 3% and 8% real discount rates. The calculation of the levelised cost given in Table 5.10 below assumes an overnight investment cost of EUR_{2011} 55 billion over the period 2011-2025 and a payback period beginning in 2026, although part of this investment programme is necessary for the operation of the fleet before 2025.

The $LCOE_{EO}$ is about USD_{2010} 51-71/MWh for a 10-year lifetime extension and about USD_{2010} 41-57/MWh for a 20-year lifetime extension, for a real discount rate of 3-8%. For comparison, the LCOE for a gas-fired CCGT plant with specific construction cost of USD_{2010} 1 100/kWe would be about USD_{2010} 87/MWh for a gas price of USD 7/Mmbtu, and the LCOE for renewable sources is significantly higher (see IEA/NEA, 2010).

Table 5.10. Calculation of $LCOE_{EO}$ for French NPPs

(in USD_{2010}/MWh)

Extended operation period	Discount rate	Levelised investment cost in LTO	O&M costs	Fuel costs	Total
10 years	3%	23.41	19.98	7.57	50.97
10 years	8%	43.45	19.98	7.57	71.00
20 years	3%	13.42	19.98	7.57	40.98
20 years	8%	26.69	19.98	7.57	57.25

The summary of assessment results of the LTO programme in France (using the methodology from Chapter 4) is provided in Table 5.11. Continued operation of French NPPs is clearly attractive from the economical and environmental viewpoints and would allow France to maintain its high level of energy independence and security of energy supply.

Table 5.11. Assessment results for the NPP LTO programme in France

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	The share of nuclear generation in the electricity mix is significant (75%) and leads to: - Use operational and effective tools as they are in good condition. - Maintain the industrial sector of nuclear energy (which is highly qualified, and represents a lot of jobs). - Spread investment over time to renew the fleet. French NPPs can operate at load following and can partially contribute to manage the intermittency of renewable energy production. There is no regulatory lifetime limit to the operation of NPPs.
Predictability of future electricity prices	★★★	The NOME Act gives a regulated price for nuclear production.
Need for NPP equipment upgrade and replacement	★★ to ★★★ over the fleet	The ten-year safety reassessment process leads to steady progress independent of lifetime management. Furthermore, refurbishment programmes have already begun before it reached 40 years of operation, so there is incentive to operate the reactors as long as the new components are operational. Moreover, there are long-term investments that have already been programmed (some contracts are already signed with the suppliers (SG replacement, I&C ...), and identified by the French Court of Auditors. Nevertheless, as in many other European countries, additional equipment upgrades are likely to be required by the regulator to increase the NPP safety level in view of LTO. As a conclusion, even if the refurbishment programme is significant, it is managed with anticipation.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★★	For the moment, the EAF is marginally affected (less than 3%) over a ten-year period by lifetime management activities, whereas the refurbishment programme is ongoing. EDF is making every effort to minimise the impact: - First, total outage duration is optimised between outages for the ten-year inspection, and outages due to maintenance. - At the scale of the French fleet, there is an optimisation effect on the maintenance duration, and also an optimisation in the planning of operations.
Risk and uncertainty (site-dependence, political, financial, regulatory)	Globally ★★	Technological risk: the risk is managed (R&D, US experience, optimisation of the management of operation of NPPs) (★★★). Financial risk: according to the NOME act, refurbishment shall be included in the electricity price and, consequently, there should be no financial risk (★★★). Regulatory risk: ASN asked EDF to set up a programme that consists of studying two main issues: ageing management, especially for non-replaceable components, and improvement of safety level in comparison with new NPPs safety objectives. EDF will conduct the appropriate studies. ASN should take up a position on ageing management of the main non-replaceable components by 2015. ASN's definitive position on the ability of each reactor to be operated beyond 40 years will be given on a reactor by reactor basis, starting in 2019 (★★). Public acceptance risk: there is a risk of public acceptability regarding the nuclear energy in general, not particularly LTO. A risk always exists in the case of a new event in an NPP around the world (★★★).
Overnight cost of refurbishment	★★★ (★★ on a strict overnight cost point of view)	Overnight cost of refurbishment is lower than the overnight cost of replacement either by new reactors (currently EPRs) or some other capacity. In any case, it makes no sense to consider the share of the investment independently from the cost of production (in the case of CGT, for example, fuel cost is much higher than nuclear fuel). Refurbishment financing is likely to be included in the electricity price, according to the NOME Act.
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	★★★	The electricity generation cost of refurbished NPPs is lower than LCOE of any other replacement capacities according to the 2010 IEA/NEA report (Europe region and discount rate less than 10%). The French Court of Auditors assessed the electricity generation cost of refurbished NPPs between USD_{2010} 50 and 72/MWh depending on the method of calculation. The government of France chose a method taking into account the part of the capital initially invested which has already been paid, and the new investments in the current fleet. A decree shall define the method that will be implemented by the regulator to settle the price. It will be released by the end of 2013.
Country's carbon policy and security of energy supply	★★★	In France there is a very strong commitment for reducing CO_2 emissions and nuclear energy is a very low CO_2 producer. Nuclear power also contributes to: security of energy supply; national balance of trade; an efficient electricity generation.

Hungary

Hungary has four operating nuclear reactors owned by the state utility Paks NPP Ltd., a member of MVM holding. The four VVER-440 reactors (PWR reactor) were built during 1982-1987 (see Table 5.12), with an original design lifetime of 30 years. Paks 1 is expected to obtain a licence extension before the end of 2012.

Table 5.12. NPPs in Hungary

Unit name	Type	Model	Site – location	Latest reference unit power (net), MWe	Grid date (DD/MM/YY)	Projected end of operational lifetime	Implementation of severe accident management	Expected lifetime extension
Paks 1	PWR	VVER V-213	Inland near a river	473	28/12/1982	2012	2011	20
Paks 2	PWR	VVER V-213	Inland near a river	473	06/09/1984	2014	2012	20
Paks 3	PWR	VVER V-213	Inland near a river	473	28/09/1986	2016	2013	20
Paks 4	PWR	VVER V-213	Inland near a river	473	16/08/1987	2017	2014	20

Continuous upgrading of the plant has resulted in good production and safety indicators. In 1996-2002, several important safety improvement measures were taken (for a total budget of about USD 300 million):

- emergency and accident management improvement;
- increased reliability of safety systems;
- decreased equipment usage;
- supporting of operational staff;
- improved earthquake protection;
- improved fire safety;
- reconstruction of the reactor protection system;
- installation of the unit and back-up control room's emergency iodine filtering system;
- vibration absorber under the steam generator;
- strengthening of the walls around the I&C equipment;
- supporting bridge of the localisation towers.

Another key measure for LTO of the Paks NPP is the implementation of severe accident management (SAM). The implementation period for this programme is 2011-2014, and the total budget is about EUR 100 million and it includes:

- Installation of passive autocatalytic hydrogen recombiners (PARs) into the containment to preserve the integrity of the containment. The required installed capacity has been identified, which is sufficient for neutralisation of the generated hydrogen volume.
- Construction of a reactor cavity flooding system with external cooling of the reactor vessel, which aims at preventing interaction of the corium with the concrete in the event of a severe accident. Reactor vessel cooling is necessary to avoid corium escaping from the reactor vessel.

- Reinforcement of the spent fuel pool pipelines and installation of quick action valves to mitigate the risk of emptying the spent fuel pool.
- Installation of accident monitoring system.
- Autonomous power supply for the safety valves of the pressuriser.

There are two main steps of the Paks LTO programme. The first step is the development of the ELTO (Extended Lifetime Operation) programme and establishment of the conditions for and justifications of LTO. It has to be submitted for one or more units of the NPP at least 4 years before expiration of the design life and after 20 years of operation. The next step is a licence application that requires successful completion of the ELTO programme. It has to be submitted for each individual unit separately at least one year before expiration of the design life.

The first unit of Paks NPP is expected to obtain the licence extension before the end of 2012.

The total overnight investment in refurbishment of all four units at Paks NPP is about EUR_{2011} 930 million with larger expenses expected in 2012-2015 (see Figure 5.6).

Figure 5.6. Expenses profile for the Paks NPP refurbishment programme after 2010

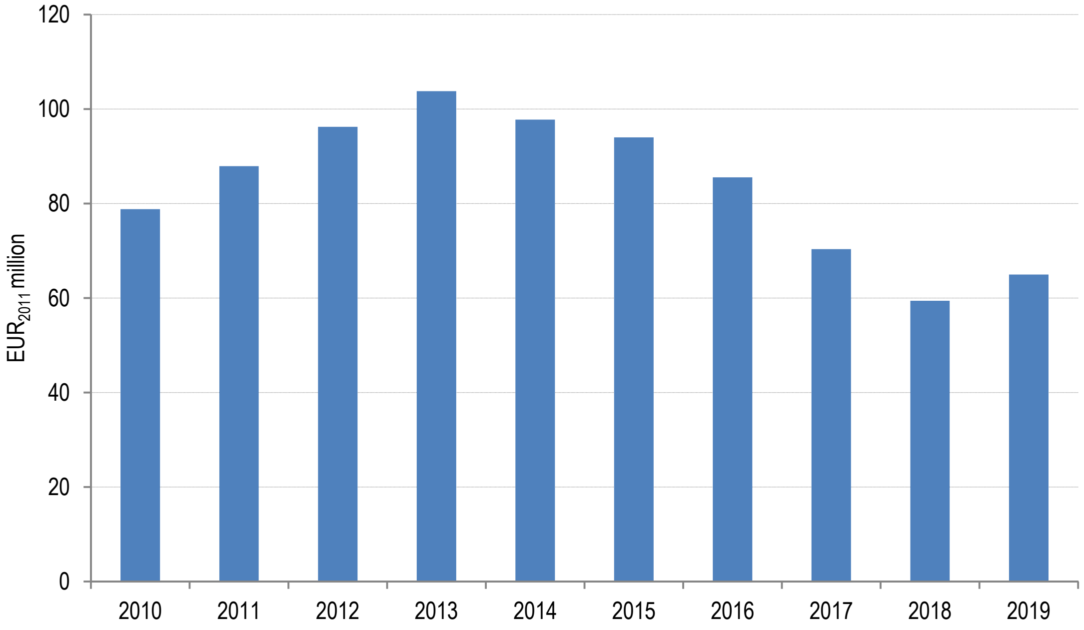
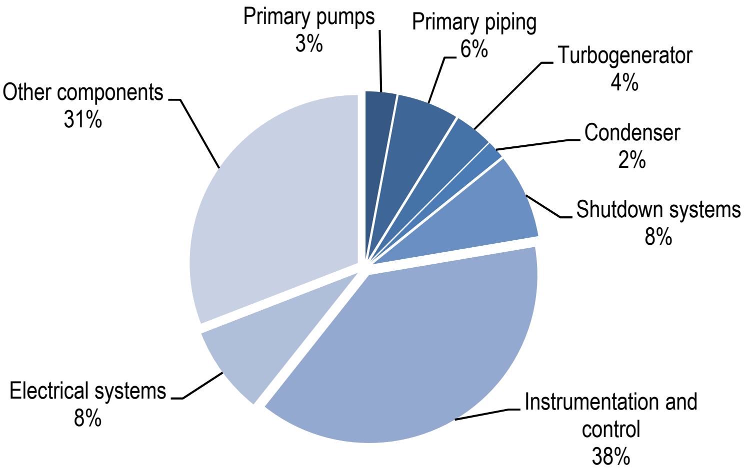


Table 5.13. Overnight investment in Paks NPP LTO

Costs attributable to LTO	Overnight costs EUR_{2011}	Overnight costs USD_{2010}	Expected expenses schedule
Overnight investment in refurbishment, including cost of engineering and documentation preparation	930 million	1 290 million	2012-2020
Implementation of post-Fukushima corrective actions	80-150 million	111-208 million	2012-2017
Total	1 010-1 080 million	1 400-1 498 million	
Specific overnight investment in LTO	533-570/kWe	740-792/kWe	

About 15% of this amount (i.e. about EUR_{2011} 125 million) is attributable to engineering and documentation preparation. The share of different components in the overnight investment in refurbishment is shown in Figure 5.7. The main investment is in I&C refurbishment.

Figure 5.7. Cost decomposition of Paks NPP refurbishment



The complementary safety review after the Fukushima Daiichi accident concluded that the units at Paks NPP are satisfactorily protected against key events and no immediate measures are needed. However, some improvements have been suggested, especially:

- improved protection against external events;
- amendment of existing plant procedures;
- provision of existing and alternative electrical power supplies;
- provision of existing and alternative cooling;
- mitigation of the consequences of severe accidents.

The total cost of these corrective actions is about EUR_{2011} 80-150 million, for all four units. These corrective actions will be implemented during 2012-2017.

The total cost of the LTO programme (2011-2020) for all four units of the Paks NPP is thus projected to be about EUR_{2011} 1 010-1 080 million (see Table 5.13). The effect of Fukushima on the LTO programme of Paks NPP represents about 10-17% increase of initially planned investment.

The specific investment costs for the Paks NPP LTO are thus USD_{2010} 740-792/kWe. This is considerably smaller than the investment needed to build an alternative capacity, for which the specific overnight costs are:

- approximately USD_{2010} 1 100/kWe for a CCGT plant;
- about USD_{2010} 1 940/kWe for a lignite plant;
- USD_{2008} 5 195/kWe for a new NPP (according to IEA/NEA, 2010).

The O&M costs are expected to decrease by about 10% after the refurbishment, and the fuel costs are assumed to remain the same as before the refurbishment. Using these data and the overnight costs in refurbishment, the LCOE_{EO} for the extended operation can be calculated following the methodology described in Chapter 4. It is assumed that the original investment in construction is already paid off, and no other costs should be included.

The results are summarised in Table 5.14. Comparing these results with the projected costs of electricity generation with alternative sources (nuclear, thermal or renewables) one can conclude that the $LCOE_{EO}$ for continued operation of Paks NPP is significantly lower than the LCOE for alternative sources. For example, the cost of electricity generation with a new NPP in Hungary is projected to be USD_{2008} 81.7/MWh at 5% real discount rate (IEA/NEA, 2010).

Table 5.14. Calculation of $LCOE_{EO}$ for Paks NPP

(in USD_{2010}/MWh)

Discount rate	Levelised investment cost	O&M costs before refurbishment	O&M costs after refurbishment	Fuel cost	Total
3%	6.67-7.13	20.2	18.38	4.48	29.52-29.98
8%	10.18-10.87	20.2	18.38	4.48	33.03-33.72

The summary of assessment results of the LTO programme in Hungary (using the methodology from Chapter 4) is provided in Table 5.15. LTO of Paks NPP clearly appears to be an economically profitable option consistent with Hungarian national policies on CO_2 emissions reduction and improving the security of energy supply.

Table 5.15. Assessment results for the NPP LTO programme in Hungary

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	The share of nuclear generation in the national electricity mix is large (about 42%). The remaining part is mainly generated by coal (18.4%), gas (32.5%) and renewables (7%). Hungary has a 750 kV transmission line with Ukraine, and 400 kV lines to Austria, the Slovak Republic, Slovenia, Serbia and Romania, and several 220 kV lines to Austria and Ukraine.
Predictability of future electricity prices	★★★	The prices are predictable, the volatility is low, and there is no intention to restrict the use of NPPs.
Need for NPP equipment upgrade and replacement	★★	A significant part of equipment is up to date.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★	In 2001-2011, the EAF was slightly affected by refurbishment activities, primarily because of I&C system refurbishment activities.
Risk and uncertainty (site-dependence, political, financial, regulatory)	★★★	- NPP LTO programmes and new builds are supported by all parties of the parliament. - Public support to nuclear is strong. - Regulatory risks, financial risks and technological risks are low.
Overnight cost of refurbishment	★★★	The overnight cost of refurbishment of Paks NPP is USD_{2010} 740-792/kWe, significantly lower projected investment costs in CCGT in Hungary (about USD_{2010} 1 100/kWe), or a lignite plant (about USD_{2010} 1 940/kWe).
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	★★★	The $LCOE_{EO}$ is less than USD_{2010} 30/MWh at 3% real discount rate and less than USD_{2010} 34/MWh at 8% discount rate. This is significantly below the costs of electricity generation with alternative sources.
Country's carbon policy and security of energy supply	★★/★★★	- Hungary has a strong national policy on reducing the CO_2 emissions from electricity generation (from current 370 g CO_2/kWh to approximately 200 g CO_2/kWh). - Nuclear power is considered as a carbon-free source of electricity. - There is no immediate intention to introduce carbon taxes. - Nuclear plays a significant role in the security of energy supply in Hungary.

Republic of Korea

The Korean fleet of NPPs is relatively new (see Table 5.16). In 2011, Korean NPPs produced more than 147 TWh that represented about 30% of national electricity generation. The remaining part is almost entirely supplied by thermal plants using imported coal and natural gas.

Table 5.16. Operating NPPs in the Republic of Korea

Unit name	Type	Model	Operator	Grid date (DD/MM/YY)	Installed capacity (MWe)	Long-term operation
Kori 1	PWR	WH	KHNP	26/06/1977	587	Ten-year lifetime extension (until 18/06/2017)
Kori 2	PWR	WH F	KHNP	22/04/1983	650	
Kori 3	PWR	WH F	KHNP	22/01/1985	950	
Kori 4	PWR	WH F	KHNP	15/11/1985	950	
Shin Kori 1	PWR	OPR-1000	KHNP	04/08/2010	1 000	
Shin Kori 2	PWR	OPR-1000	KHNP	28/01/2012	1 000	
Shin Wolsong 1	PWR	OPR-1000	KHNP	27/01/2012	950	
Ulchin 1	PWR	France CPI	KHNP	07/04/1988	950	
Ulchin 2	PWR	France CPI	KHNP	14/04/1989	1 000	
Ulchin 3	PWR	OPR-1000	KHNP	06/01/1998	1 000	
Ulchin 4	PWR	OPR-1000	KHNP	28/12/1998	1 000	
Ulchin 5	PWR	OPR-1000	KHNP	18/12/2003	1 000	
Ulchin 6	PWR	OPR-1000	KHNP	07/01/2005	679	
Wolsong 1	PHWR	CANDU 6	KHNP	31/12/1982	700	Ten years (in progress)
Wolsong 2	PHWR	CANDU 6	KHNP	01/04/1997	700	
Wolsong 3	PHWR	CANDU 6	KHNP	25/03/1998	700	
Wolsong 4	PHWR	CANDU 6	KHNP	21/05/1999	1 000	
Yonggwang 1	PWR	WH F	KHNP	05/03/1986	950	
Yonggwang 2	PWR	WH F	KHNP	11/11/1986	950	
Yonggwang 3	PWR	OPR-1000	KHNP	30/10/1994	1 000	
Yonggwang 4	PWR	OPR-1000	KHNP	18/07/1995	1 000	
Yonggwang 5	PWR	OPR-1000	KHNP	19/12/2001	1 000	
Yonggwang 6	PWR	OPR-1000	KHNP	16/09/2002	1 000	

Note: KHNP = Korea Hydro and Nuclear Power Company, Ltd.; PHWR = Pressurised heavy water reactor.

In the Republic of Korea, the licence renewal period of operating NPPs is ten years. Utilities have to conduct a PSR for its operating NPPs every ten years and submit PSR reports for regulatory review and approval.

The safety evaluation report on Wolsong 1 (CANDU-6, 660 MWe) was submitted in December 2009. The refurbishment activities of Wolsong 1 included the complete retubing of the reactor (the first time for a CANDU-6), and took 839 days to complete. Then, Wolsong 1 was reconnected to the electrical grid on 18 July 2011. The safety evaluation report on Wolsong 1 was also submitted in December 2009, and the licence renewal is expected to be approved by 2012.

In June 2006, the KHNP submitted to the regulator the safety evaluation report for continued operation of Kori 1 (PWR, 587 MWe) and the Ministry of Education, Science and

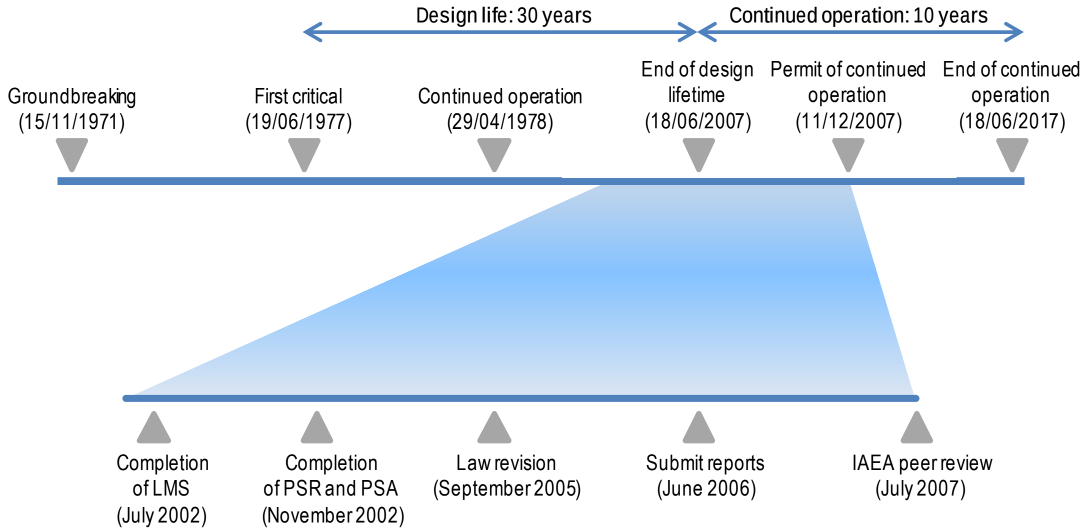
Technology (MEST) officially permitted its continued operation on 11 December 2006. The oldest NPP (Kori 1) is currently in the middle of the ten-year extended operation (see Figure 5.8). The process included three phases:

- Phase I (1993-1996) Feasibility Study:
  - feasibility evaluation method and techniques;
  - Phase II planning.
- Phase II (1997-2001) Detail Evaluation and Engineering:
  - Kori 1 detail inspection and residual life evaluation;
  - documentation for licence renewal;
  - planning for lifetime extension.
- Phase III (2001-2008) Replacement and Maintenance:
  - implementation;
  - advanced technology development.

Phases I and II included: development of the ageing management programme and fire protection; fire hazard and safe shutdown analysis; probabilistic safety assessment; evaluation of core damage frequency due to Kori 1 internal events; evaluation of risk due to Kori 1 fire; flood and seismic events; and environmental qualification.

As part of Phase III, a mandatory, rolling ten-year PSR has been done by KHNP, based on the IAEA recommendations (Safety Series No. 50-SG-O12 [NS-G-2.10]). As a result of this PSR, 40 recommendations were issued.

Figure 5.8. Milestones of the Kori 1 NPP



Note: LMS = Life-cycle management system; PSA = Probabilistic safety assessment; PSR = Periodic safety review.

The refurbishment programme during operation included:

- condenser and feed water heater replacement (1988);
- low pressure turbine replacement (1997): stress corrosion cracking;
- steam generator replacement (1998): alloy600 → alloy690;

- plant process control system upgrade (1998): analog → digital;
- main transformer replacement (2002): internal insulation disable.

Recent refurbishment for continued operation includes:

- main generator, exciter and isolated phase busduct replacement (2005);
- reactor coolant pump internal and motor replacement (2005);
- installation of alternate AC diesel generator to reinforce protection in the event of station blackout (2006);
- motor control centre, main steam isolation valve, heating, ventilating and air conditioning, feed pump replacement or reinforcement, etc.

For the economic estimates, the operator has considered three scenarios corresponding to the extension of the operational lifetime by 10, 20 and 30 years. The corresponding investment needed was estimated at:

- USD 185.9 million (for a 10-year extension);
- USD 233 million (for a 20-year extension); and
- USD 490 million (for a 30-year extension).

Using these assumptions, the operator obtained the following projections for the levelised cost of electricity:

- USD 26.28/MWh for 10 years of continued operation;
- USD 25.27/MWh for 20 years; and
- USD 30.32/MWh for 30 years.

Thus, according to the operator's estimates, the LCOE_{EO} is optimal for a 20-year extension, and continued operation is economically more interesting than building a new NPP. The actual investment in the continued operation of Kori 1 (587 MWe) is about USD 290 million, i.e. about USD 500/kWe (see Figure 5.9). The expenses schedule is presented in Figure 5.10.

Figure 5.9. Cost decomposition of the Kori 1 refurbishment programme

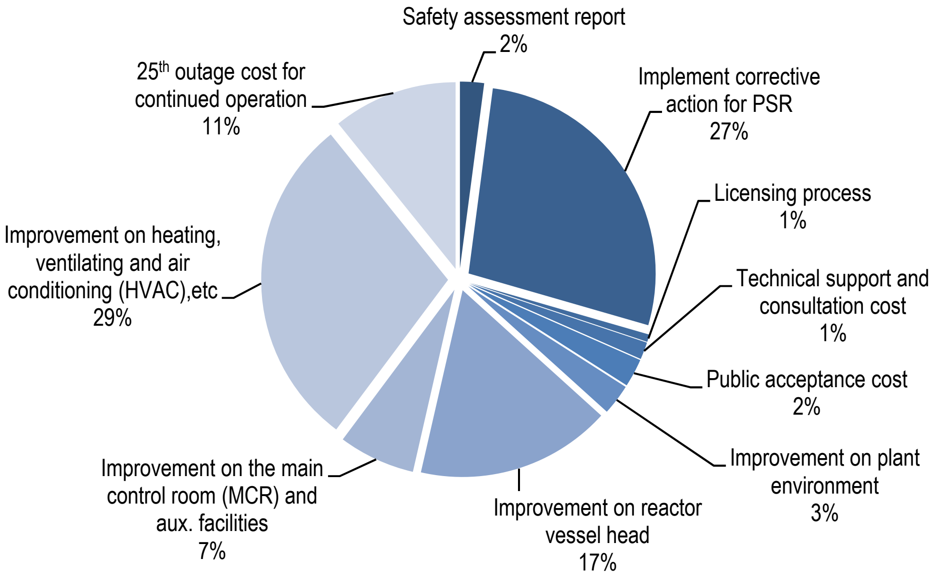
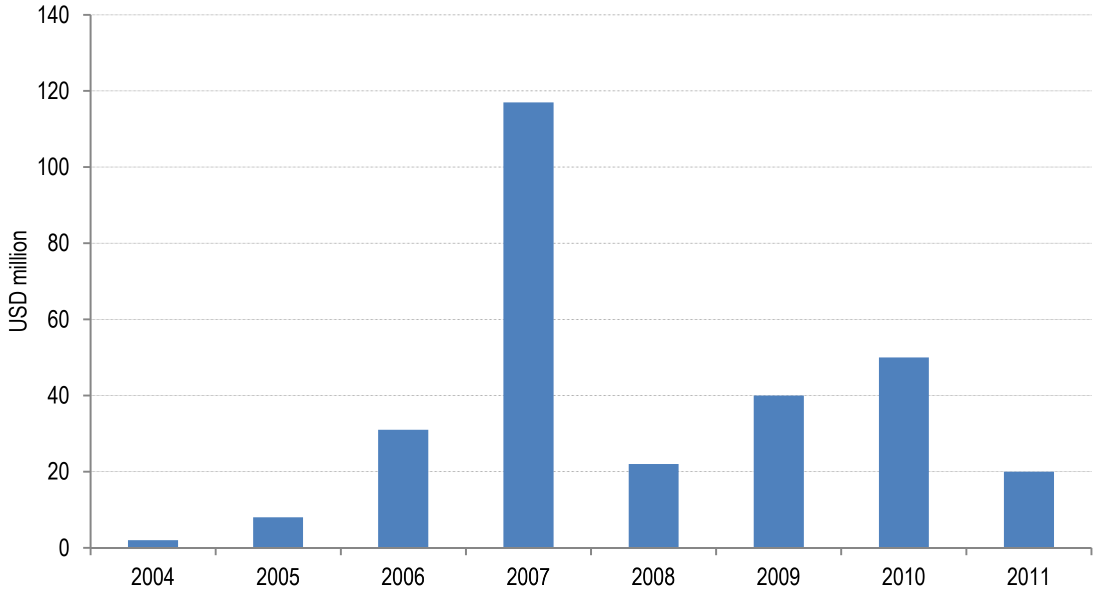
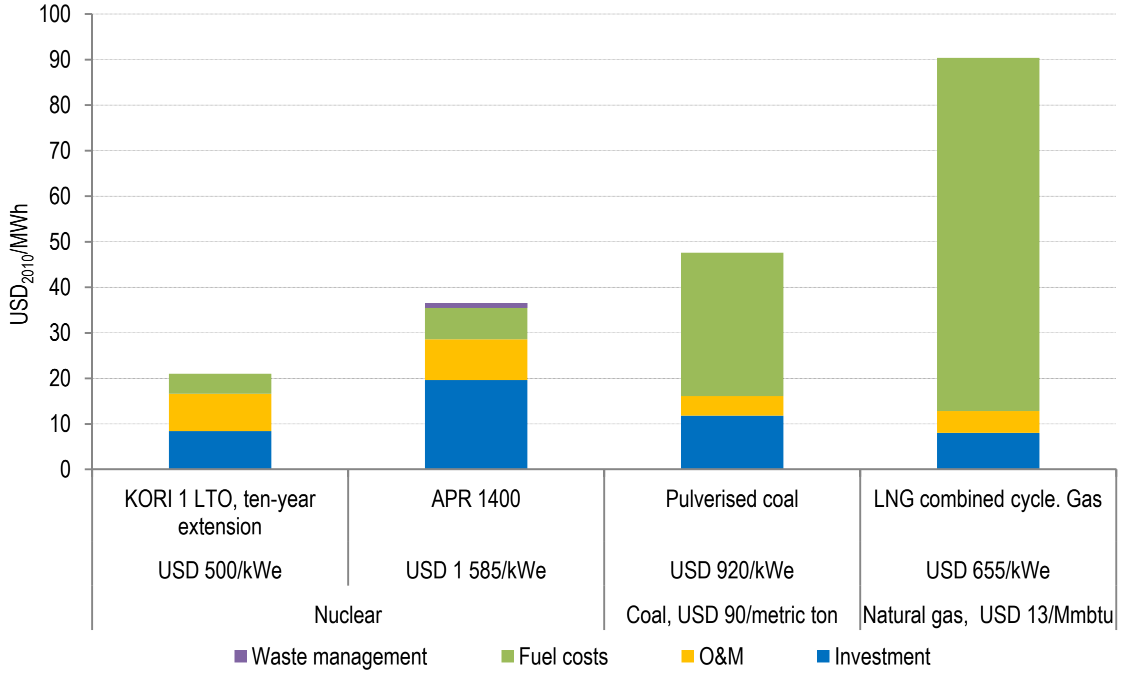


Figure 5.10. Expenses profile for the Kori 1 refurbishment programme



Using the assumption of: *(i)* USD 500/kWe for the overnight costs of Kori 1 refurbishment; *(ii)* USD 8.25/MWh for O&M costs after refurbishment; and *(iii)* USD 4.38/MWh for the fuel costs; the LCOE for extended operation can be calculated following the methodology described in Chapter 4. The result for 8% real discount rate is provided in Figure 5.11, in comparison with alternative sources (new NPPs, coal and gas). The assumption for the price of natural gas is USD 13/Mmbtu and for coal USD 90 per metric ton. Within these assumptions, the LCOE for extended operation of Kori 1 appears smaller that the LCOE for alternative sources of power.

Figure 5.11. Comparison of Kori 1 LCOE with projected LCOE for alternative sources



Note: APR = Advanced pressurised reactor; LNG = Liquefied natural gas.

Right after the Fukushima Daiichi accident, KHNP carried out its own safety reviews of all 21 units in operation and received a special safety review by a government-organised team of experts outside the company. The results of the reviews showed that Korean NPPs were safe from natural disasters such as earthquakes and tsunamis. Also, the IAEA IRRS (Integrated Regulatory Review Service) on Korean regulatory bodies found that Korea's response to the Fukushima Daiichi accident was timely and effective, and that Korean NPPs maintained the best possible safety. Nevertheless, KHNP has established 56 short- and long-term improvements plans to enhance the safety of NPPs currently in operation against serious natural disasters. These plans are being broadly implemented not only in the operating plants but also in the plants under construction. Over USD 1 billion will be invested by 2015 in post-Fukushima upgrades.

Nuclear power plays a major role in the security of energy supply in the Republic of Korea. The Republic of Korea showed an important increase of SSDI (see Chapter 4) at the beginning of the 1980s (see Figure 4.8). The total energy demand in the Republic of Korea has been growing very fast since the mid-1970s, as a consequence of the economic growth. The first sharp increase in the energy demand (from 1982 to 1987) was satisfied by the introduction of NPPs. Because of it, the SSDI rose during this period. Between 1987 and 1997, the Korean economy was growing at a very high rate, and the corresponding energy demand was essentially covered by fossil sources of power. Since 2000, the increase in the energy demand in the Republic of Korea has stabilised. A continuous increase of SSDI since 1996 may be explained by an important increase in nuclear power generation that was multiplied by a factor of more than 2.5 between 1994 and 2006. Today, the contribution of nuclear power to Korean electricity production is considerable, see Figure 4.9.

The summary of assessment results of the LTO programme at Kori 1 (using the methodology from Chapter 4) is provided in Table 5.17. LTO of the Kori 1 NPP clearly appears to be an economically profitable option consistent with Korean national policies on CO_2 emissions reduction and improving the security of energy supply.

Table 5.17. Assessment results for the NPP LTO programme in the Republic of Korea

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	Nuclear energy represents about 31% of electricity generation in the Republic of Korea. The remaining part of the electricity mix (coal, gas, oil and hydro) is well diversified. There is practically no cross-border electricity capacity.
Predictability of future electricity prices	★★/★★★	Utilities operate in a liberalised market and there is no plan for specific limitations restricting the operation of NPPs.
Need for NPP equipment upgrade and replacement	★★★	Most of the equipment and systems are up to date in Korean NPPs.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	Wolsong 1 (CANDU): ★ Kori 1 (PWR): ★★★	The EAF is marginally affected by LTO activities. However, in the case of Wolsong unit 1 (CANDU), refurbishment activities had long outages due to replacement of pressure tubes.
Risk and uncertainty (site-dependence, political, financial, regulatory)	★★	Regulatory and financial risks are low, but there are moderate political and public acceptance risks.
Overnight cost of refurbishment	★★★	LTO overnight investment is about USD 500/kWe (including the ~10% increase due to post-Fukushima measures). This is significantly below the costs of building a replacement capacity.
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	★★★	The levelised cost of electricity generation after lifetime extension is more competitive than projected costs of electricity (replacement, imports).
Country's carbon policy and security of energy supply	★★	Nuclear energy greatly contributes to the security of energy supply. There is currently no carbon pricing mechanism.

Switzerland

Switzerland has five operating nuclear power reactors at four sites (see Table 5.18). In 2010, they generated 25.3 TWh of electricity, or more than 40% of the country's electricity needs.

Large nuclear plants (Gösgen and Leibstadt NPPs) and many of the large hydroelectric dams are co-shared by Swiss utilities. Utilities with part-ownership of Gösgen and/or Leibstadt are AEW Energy, Axpo (formerly NOK), BKW (Bernische Kraftwerke), CKW (Centralschweizerische Kraftwerke – majority owned by Axpo), EGL (since recently 100% owned by Axpo), Alpiq (formerly ATEL and EOS), EWB (Energie Wasser Bern) as well as the city of Zürich.

The notion of "operational lifetime" of NPPs does not exist in Switzerland, according to the Swiss Federal Nuclear Energy Act of 2003. Nuclear plants are allowed to operate as long as they satisfy the safety criteria defined by the Swiss Federal Nuclear Energy Act and the Swiss Federal Nuclear Safety Inspectorate (ENSI). The plants can be operated as long as the utility owning the reactor is willing to invest to meet the safety criteria. The power plants of Beznau (unit 1 and 2), Gösgen and Leibstadt have unlimited operating licences.

In December 2009, the Federal Department of the Environment, Transport, Energy and Communications (DETEC) granted an unlimited operating licence to the operator of Mühleberg, BKW-FMB Energy Ltd. This decision was overturned by the Federal Administrative Court (FAC) on 1 March 2012. According to this decision, the Mühleberg NPP is allowed to operate until 28 June 2013. The operator of the Mühleberg NPP has lodged an appeal against this decision at the Federal Supreme Court (FSC) in Lausanne. The FSC confirmed the decision of the FAC at the end of April 2012. To continue operation after June 2013, a long-term plant life management plan, approved by the authorities, needs to be in place.

Table 5.18. Operating NPPs in Switzerland

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)
Beznau 1	PWR	WH (2 loops)	Inland near a river	365	17/07/1969
Beznau 2	PWR	WH (2 loops)	Inland near a river	365	23/10/1971
Goesgen	PWR	PWR (3 loops)	Inland near a river	985	02/02/1979
Leibstadt	BWR	BWR-6	Inland near a river	1 190	24/05/1984
Muehleberg	BWR	BWR-4	Inland near a river	373	01/07/1971

According to the stress tests recently conducted by ENSI, the safe operation of Swiss NPPs is currently assured. Thus, NPPs in Switzerland will most probably continue their operation for a significant length of time, and the end date for their operation cannot be predicted.

Nuclear energy plays a crucial role in the security of energy supply during the whole year but especially in the winter months, when there is less hydropower available and the nuclear share of domestic production can be as high as 60%. During the winter months, Switzerland is a net importer of electricity. Except for 3% of the electricity coming from (waste burning) thermal plants, Switzerland has practically no other source of fully predictable base load power other than nuclear plants.

The Swiss electricity market is strongly interconnected with the European market. A new Electricity Supply Act came into force on 1 January 2009. The market is to be liberalised in two phases: *(i)* for larger consumers with an annual electricity consumption of more than 100 000 kWh. These 50 000 or so companies account for slightly more than half of Switzerland's total electricity consumption; *(ii)* following a transitional period of five years, the market will then be fully liberalised from 2014, giving private households the freedom to switch to another supplier, should they wish.

After the Fukushima Daiichi accident, ENSI took a number of measures in order to verify the level of safety of Swiss NPPs. The safety reassessments focused on the design of Swiss NPPs in respect of earthquakes, external flooding and the combination of both events, as well as the loss of emergency power supply and loss of ultimate heat sink for the safety and auxiliary systems and the spent fuel pool cooling.

Some immediate measures were ordered, including setting up an external storage facility for emergency equipment, and plant-specific connections and back-fitting of feed lines for the external supply of the spent fuel pools. The external storage facility is a former ammunitions depot of the Swiss Army at Reitnau in the canton Aargau. This depot is a bunker located at high altitude, thus naturally protected from flooding. The equipment stored at Reitnau is transportable by helicopter to any of the NPP locations in Switzerland within approximately one hour.

Also, Swiss operators were asked to take part in the EU stress test. On the basis of reviews conducted to date, the international EU-ENSREG review team and ENSI concluded that Swiss NPPs demonstrate a high level of protection against the impacts of earthquakes, flooding and other natural hazards, as well as loss of electrical power and ultimate heat sink. However, a number of improvement measures have been suggested by ENSI and the utilities.

Capital amortisation for Swiss NPPs is approximately linear over 50 years. It can be assumed that about 25% of the initial investment currently remains. However, future investments increase the capital costs again and therefore capital amortisation is re-evaluated yearly.

It is not quite straightforward to attribute the investments to LTO as Swiss plants are refurbished on a regular basis (due to the requirement of the Swiss Nuclear Act) over all their lifetime. In the past and in the upcoming years, there were and still will be major investments in the nuclear island, safety systems, I&C but also conventional systems and components such as turbogenerators and condensers, which were deemed necessary to maintain a smooth operation with high capacity factors at least until 50 years lifetime.

The specific future investment in NPP refurbishment and maintenance (approximately doubling the specific LTO investment) i.e. USD_{2010} 980-1 300/kWe is smaller than the investment needed to build an alternative capacity, for which the specific overnight costs at the plant's level are (according to IEA/NEA, 2010):

- approximately USD_{2010} 1 600/kWe for a CCGT plant (net capacity 395 MWe);
- about USD_{2010} 3 700/kWe for wind turbines[6] (net capacity 6 MWe).

Thermal plants are very difficult to put into operation, as there is strong opposition. Construction of coal plants seems almost impossible in Switzerland. Construction of CCGT plants could be done, however the economics are currently unfavourable compared to neighbouring countries, mainly due to the CO_2-compensation regulations, forcing utilities to compensate a large part of the emissions with Swiss projects, which are challenging to implement since the carbon footprint of the electricity sector is already very low.

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[6] The overnight investment cost of building wind turbines have decreased since the time when the NEA/IEA, 2010 study was conducted.

Hydropower capacity has already reached its maximum. At best, about 500 MWe (3 TWh/a) of hydro capacity could theoretically be added in Switzerland only under remarkable ecological losses.

The O&M costs at Swiss NPPs are in the range of CHF 12-24/MWh (Swiss francs) (O&M and personnel costs). Fuel costs: CHF 3.5-5/MWh, excluding provisions for waste management and decommissioning that are about CHF 7.5-14/MWh. The specific investment attributable to LTO is estimated at about USD_{2010} 490-650/kWe, and (approximately) represents half of the total future investment in refurbishment and improvement. Using these data, the LCOE can be calculated assuming a 10- or 20-year extended operation. The result is given in Table 5.19.

Table 5.19. Calculation of LCOE_{EO} for Swiss NPPs

(in USD_{2010}/MWh)

Extended operation period	Discount rate	Levelised investment cost in LTO	Other future investment	O&M costs	Fuel cost	Decommissioning and waste management provisions	Total
10 years	3%	6.3-8.4	6.3-8.4	11.5-23	3.35-4.8	7.2-13.4	34.7-58
10 years	8%	6.9-9.2	6.9-9.2	11.5-23	3.35-4.8	7.2-13.4	35.5-60
20 years	3%	3.2-4.2	3.2-4.2	11.5-23	3.35-4.8	7.2-13.4	28.5-50
20 years	8%	3.5-4.6	3.5-4.6	11.5-23	3.35-4.8	7.2-13.4	29.0-50

Table 5.20. Assessment results for the NPP LTO programme in Switzerland

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	Switzerland is a special case, because nuclear share is large, but there are practically no fossil fuel-fired power plants – nuclear supplies the bulk of the base load electricity.
Predictability of future electricity prices	★★	After the Fukushima Daiichi accident, the Swiss government decided that existing NPPs should not be replaced by new NPPs. Due to the very challenging task of replacing the large share with non-nuclear capacity, the existing plants capacity will still be needed for some time (positive for LTO). At the same time, the Swiss electricity market is strongly influenced by neighbouring countries such as France and Germany.
Need for NPP equipment upgrade and replacement	★★/★★★	Most equipment and components of Swiss plants are up to date (taking into account already running projects).
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★★	LTO related work is expected to have a very low or almost no impact on the average EAF. Most long outages have to be planned for maintenance and refurbishment even without LTO activities.
Risk and uncertainty (site-dependence, political, financial, regulatory)	★/★★	In general, risks for LTO are moderate compared to other sources (including a strategy based on more imports).
Overnight cost of refurbishment	★★	Costs are relatively high, but most of the projects are already planned and ongoing.
LCOE_{EO} – levelised cost of electricity generation after LTO activities	★★★	The impact of LTO related activities is relatively low and comparable to current costs. The costs are not expected to exceed USD_{2010} 70/MWh in any scenario.
Country's carbon policy and security of energy supply	★★★	Switzerland is currently developing a new "Energy Strategy 2050", which will have a big impact on carbon policy and security of supply. The Federal Council is placing emphasis on increased energy savings (energy efficiency), the expansion of hydropower and new renewable energies, and, if necessary, on fossil fuel-based electricity production (cogeneration facilities, gas-fired combined-cycle power plants) and imports.

United States

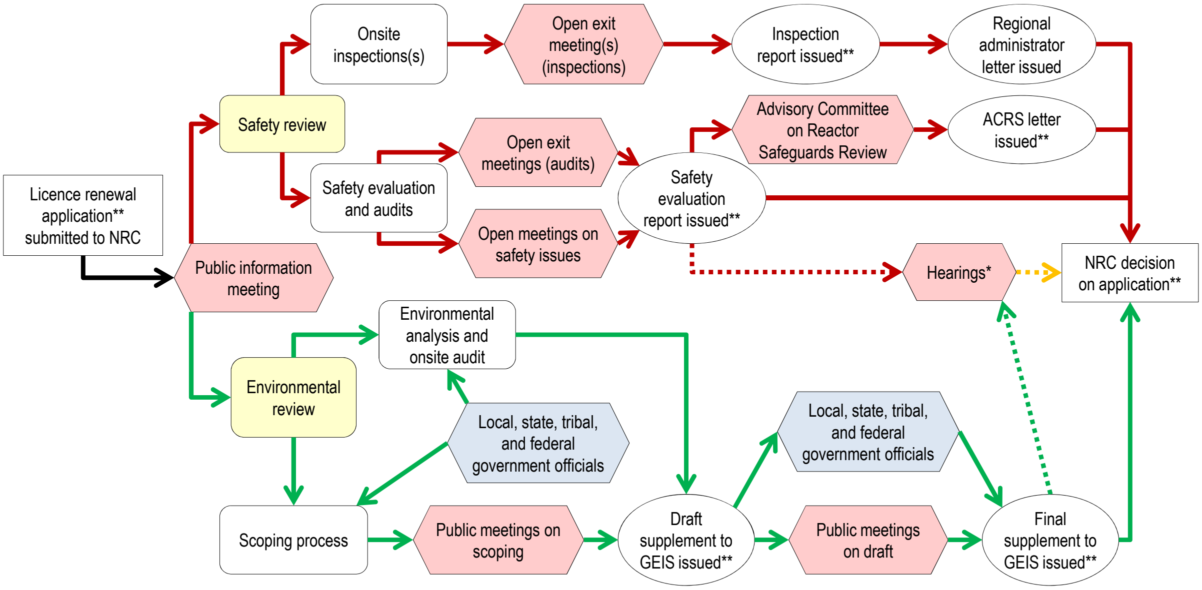
There are 104 operating nuclear reactors in the US, operated by a number of utilities (see Table 5.21). The US Atomic Energy Act of 1954 allows the NRC to issue licences for commercial power reactors to operate for up to 40 years (NRC, 2006). Also, the NRC regulations allow the renewal of these licences for an additional period of 20 years if the reactor satisfies safety and environmental criteria.

The oldest plants in the US are 42 years old, and the average age of the fleet is 31 years old. Before the implementation of lifetime extension programmes started (in 1998), 12 plants in the US have been closed since 1987, most of them for economic reasons:

- La Crosse (1987);
- Shoreham (1989);
- Rancho Seco (1989);
- Fort St. Vrain (1989);
- Yankee Rowe (1991);
- Trojan (1992);
- San Onofre 1 (1992);
- Millstone unit 1 (1995);
- Connecticut Yankee (1996);
- Maine Yankee (1996);
- Big Rock Point (1997);
- Zion unit 1 and 2 (1998).

Since 2000, the renewal of the operating licence in the US is a well established process involving a safety review, an environmental review and an overall licence review. The whole process is summarised in Figure 5.12. This process takes about 22 months if no hearing is required, and 30 months if it is required.

Figure 5.12. A flowchart of the licence renewal process in the United States



* If a request for hearing is granted. ** Available at www.nrc.gov.
Source: NRC, 2006.

As of July 2012, 73 of 104 US plants have 20-year licence extensions to 60 years (see Table 5.21). The NRC is currently reviewing applications for 13 more units. In addition, more letters of intent have been sent by utilities. Only the newest US unit (15 years old) has no letter of intent. The schedule of US NPP licences expiring is given in Figure 5.13.

Figure 5.13. Number of US NPP licences expiring (as of 2011)

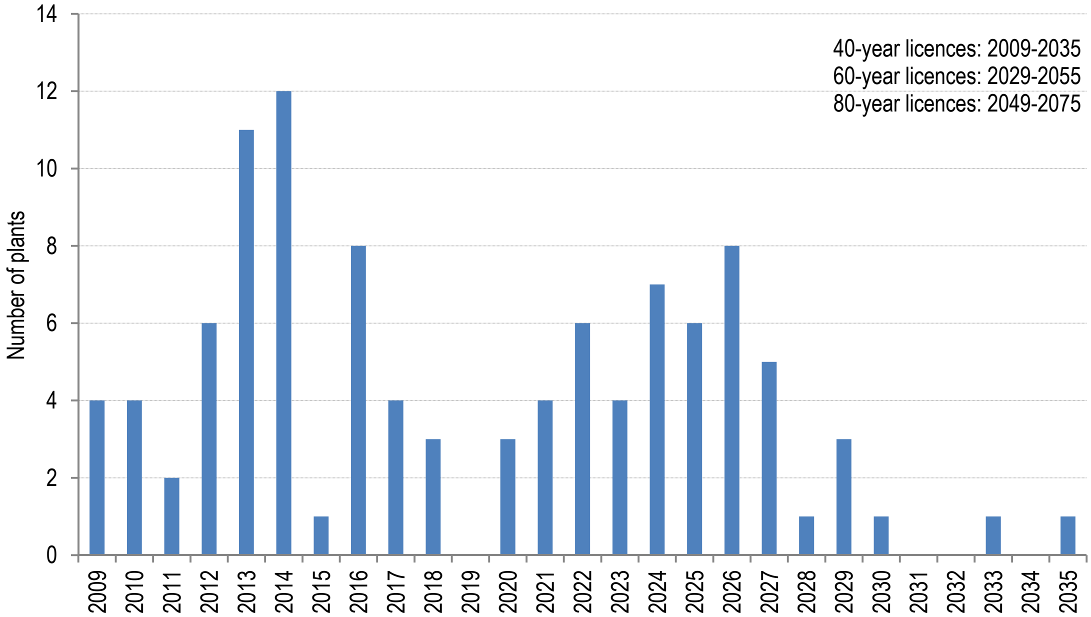


Table 5.21. Operating NPPs in the United States, June 2012

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Lifetime extension (years)	Owner
Arkansas One 1	PWR	B&W (L-loop) DRYAMB	Inland near a river	842	17/08/1974	20	Entergy Arkansas Inc.
Arkansas One 2	PWR	CE (2 loops) DRYAMB	Inland near a river	993	26/12/1978	20	Entergy Arkansas Inc.
Beaver Valley 1	PWR	W (3 loops)	Inland near a river	892	14/06/1976	20	PPL Susquehanna, LLC
Beaver Valley 2	PWR	W (3 loops)	Inland near a river	885	17/08/1987	20	Ohio Edison Co.
Braidwood 1	PWR	W (4 loops)	Inland near a lake	1 178	12/07/1987		Exelon Corporation
Braidwood 2	PWR	W (4 loops) DRYAMB	Inland near a lake	1 152	25/05/1988		Exelon Corporation
Browns Ferry 1	BWR	BWR-4 (Mark 1)	Inland near a river	1 093	15/10/1973	20	Tennessee Valley Authority
Browns Ferry 2	BWR	BWR-4 (Mark 1)	Inland near a river	1 104	28/08/1974	20	Tennessee Valley Authority
Browns Ferry 3	BWR	BWR-4 (Mark 1)	Inland near a river	1 105	12/09/1976	20	Tennessee Valley Authority
Brunswick 1	BWR	BWR-4 (Mark 1)	Inland near a river	938	04/12/1976	20	Progress Energy Carolinas, Inc.
Brunswick 2	BWR	BWR-4 (Mark 1)	Inland near a river	920	29/04/1975	20	Progress Energy Carolinas, Inc.
Byron 1	PWR	W (4 loops) DRYAMB	Inland near a river	1 164	01/03/1985		Exelon Corporation
Byron 2	PWR	W (4 Loops) DRYAMB	Inland near a river	1 136	06/02/1987		Exelon Corporation

Table 5.21. Operating NPPs in the United States, June 2012 *(continued)*

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Lifetime extension (years)	Owner
Callaway 1	PWR	W (4 loops) DRYAMB	Inland near a river	1 190	24/10/1984		Ameren UE, Union Electric Company
Calvert Cliffs 1	PWR	CE (2 loops) DRYAMB	Seacoast	855	03/01/1975	20	Constellation Energy Nuclear Group, LLC
Calvert Cliffs 2	PWR	CE (2 loops) DRYAMB	Seacoast	850	07/12/1976	20	Constellation Energy Nuclear Group, LLC
Catawba 1	PWR	W (4 loops) ICECND	Inland near a lake	1 129	22/01/1985	20	North Carolina Electric Membership Corp.
Catawba 2	PWR	W (4 loops) ICECND	Inland near a lake	1 129	18/05/1986	20	North Carolina Municipal Power Agency No.1
Clinton 1	BWR	BWR-6 (Mark 3)	Inland near a lake	1 065	24/04/1987		Exelon Corporation
Columbia	BWR	BWR-5 (Mark 2)	Inland near a river	1 131	27/05/1984	20	Energy Northwest
Comanche Peak 1	PWR	W (4 loops) DRYAMB	Inland near a lake	1 209	24/04/1990		Luminant Generation Company LLC
Comanche Peak 2	PWR	W (4 loops) DRYAMB	Inland near a lake	1 158	09/04/1993		Luminant Generation Company LLC
Cooper	BWR	BWR-4 (Mark 1)	Inland near a river	774	10/05/1974	20	Nebraska Public Power District
Crystal River 3	PWR	B&W (L-loop)	Seacoast	860	30/01/1977		Progress Energy Florida, Inc.
Davis Besse 1	PWR	B&W (R-loop)	Inland near a lake	894	28/08/1977		Cleveland Electric Illuminating Co.
Diablo Canyon 1	PWR	W (4 loops)	Seacoast	1 122	11/11/1984		PG&E Corporation
Diablo Canyon 2	PWR	W (4 loops)	Seacoast	1 118	20/10/1985		PG&E Corporation
Donald Cook 1	PWR	W (4 loops) ICECDN	Inland near a lake	1 009	10/02/1975	20	American Electric Power Company, Inc.
Donald Cook 2	PWR	W (4 loops) ICECND	Inland near a lake	1 060	22/03/1978	20	American Electric Power Company, Inc.
Dresden 2	BWR	BWR-3 (Mark 1)	Inland near a river	867	13/04/1970	20	Exelon Corporation
Dresden 3	BWR	BWR-3 (Mark 1)	Inland near a river	867	22/07/1971	20	Exelon Corporation
Duane Arnold 1	BWR	BWR-4 (Mark 1)	Inland near a river	601	19/05/1974	20	NextEra Energy Resources, LLC
Enrico Fermi 2	BWR	BWR-4 (Mark 1)	Inland near a lake	1 106	21/09/1986		DTE Energy Co.
Farley 1	PWR	W (3 loops)	Inland near a river	851	18/08/1977	20	Alabama Power Company
Farley 2	PWR	W (3 loops) DRYAMB	Inland near a river	860	25/05/1981	20	Alabama Power Company
Fitzpatrick	BWR	BWR-4 (Mark 1)	Inland near a lake	855	01/02/1975	20	Entergy Nuclear Operations, Inc.
Fort Calhoun 1	PWR	CE (2 loops)	Inland near a river	478	25/08/1973	20	Omaha Public Power District
Grand Gulf 1	BWR	BWR-6 (Mark 3)	Inland near a river	1 251	20/10/1984		Systems Energy Resources, Inc
H.B. Robinson 2	PWR	W (3 loops) DRYAMB	Inland near a lake	724	26/09/1970	20	Progress Energy Carolinas, Inc.
Hatch 1	BWR	BWR-4 (Mark 1)	Inland near a river	876	11/11/1974	20	Georgia Power Co.
Hatch 2	BWR	BWR-4 (Mark 1)	Inland near a river	883	22/09/1978	20	Georgia Power Co.
Hope Creek 1	BWR	BWR-4 (Mark 1)	Inland near a river	1 191	01/08/1986	20	PSEG Power, Inc.
Indian Point 2	PWR	W (4 loops) DRYAMB	Inland near a river	1 022	26/06/1973		Entergy Nuclear Operations, Inc.
Indian Point 3	PWR	W (4 loops) DRYAMB	Inland near a river	1 040	27/04/1976		Entergy Nuclear Operations, Inc.

Table 5.21. Operating NPPs in the United States, June 2012 *(continued)*

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Lifetime extension (years)	Owner
Kewaunee	PWR	W (2 loops) DRYAMB	Inland near a lake	556	08/04/1974	20	Dominion Generation
LaSalle 1	BWR	BWR-5 (Mark 2)	Inland near a lake	1 118	04/09/1982		Exelon Corporation
LaSalle 2	BWR	BWR-5 (Mark 2)	Inland near a lake	1 120	20/04/1984		Exelon Corporation
Limerick 1	BWR	BWR-4 (Mark 2)	Inland near a river	1 130	13/04/1985		Exelon Corporation
Limerick 2	BWR	BWR-4 (Mark 2)	Inland near a river	1 134	01/09/1989		Exelon Corporation
McGuire 1	PWR	W (4 loops) ICECND	Inland near a lake	1 100	12/09/1981	20	Duke Energy Corp.
McGuire 2	PWR	W (4 loops) ICECND	Inland near a lake	1 100	23/05/1983	20	Duke Energy Corp.
Millstone 2	PWR	COMB CE DRYAMB	Seacoast	869	09/11/1975	20	Dominion Resources, Inc.
Millstone 3	PWR	W (4 loops) DRYSUB	Seacoast	1 233	12/02/1986	20	Dominion Resources, Inc.
Monticello	BWR	BWR-3	Inland near a river	572	05/03/1971	20	Xcel Energy
Nine Mile Point 1	BWR	BWR-2 (Mark 1)	Inland near a lake	621	09/11/1969	20	Constellation Energy Nuclear Group, LLC
Nine Mile Point 2	BWR	BWR-5 (Mark 2)	Inland near a lake	1 143	08/08/1987	20	Constellation Energy Nuclear Group, LLC
North Anna 1	PWR	W (3 loops)	Inland near a lake	903	17/04/1978	20	Virginia Electric Power Co.
North Anna 2	PWR	W (3 loops)	Inland near a lake	972	25/08/1980	20	Virginia Electric Power Co.
Oconee 1	PWR	B&W (L-loop)	Inland near a lake	846	06/05/1973-	20	Duke Energy Corp.
Oconee 2	PWR	B&W (L-loop)	Inland near a lake	846	05/12/1973	20	Duke Energy Corp.
Oconee 3	PWR	B&W (L-loop)	Inland near a lake	846	18/09/1974	20	Duke Energy Corp.
Oyster Creek	BWR	BWR-2 (Mark 1)	Seacoast	614	23/09/1969	20	Exelon Corporation
Palisades	PWR	CE (2 loops) DRYAMB	Inland near a lake	778	31/12/1971	20	Entergy Nuclear Operations, Inc.
Palo Verde 1	PWR	CE (2 loops) DRYAMB	Inland near a lake	1 311	10/06/1985	20	Arizona Public Service Co.
Palo Verde 2	PWR	COMB CE80 DRYAMB	Inland near a lake	1 314	20/05/1986	20	Arizona Public Service Co.
Palo Verde 3	PWR	COMB CE80 DRYAMB	Inland near a lake	1 317	28/11/1987	20	Arizona Public Service Co.
Peach Bottom 2	BWR	BWR-4 (Mark 1)	Inland near a river	1 122	18/02/1974	20	Exelon Corp. (50%) PSEG Power (50%)
Peach Bottom 3	BWR	BWR-4 (Mark 1)	Inland near a river	1 112	01/09/1974	20	Exelon Corp. (50%) PSEG Power (50%)
Perry 1	BWR	BWR-6 (Mark 3)	Inland near a lake	1 240	19/12/1986		Cleveland Electric Illuminating Co.
Pilgrim 1	BWR	BWR-3 (Mark 1)	Seacoast	685	19/07/1972	20	Entergy Nuclear Operations, Inc.
Point Beach 1	PWR	W (2 loops) DRYAMB	Inland near a lake	512	06/11/1970	20	NextEra Energy Resources, LLC
Point Beach 2	PWR	W (2 loops) DRYAMB	Inland near a lake	515	02/08/1972	20	NextEra Energy Resources, LLC
Prairie Island 1	PWR	W (2 loops) DRYAMB	Inland near a river	560	04/12/1973	20	Xcel Energy
Prairie Island 2	PWR	W (2 loops) DRYAMB	Inland near a river	554	21/12/1974	20	Xcel Energy
Quad Cities 1	BWR	BWR-3 (Mark 1)	Inland near a river	882	12/04/1972	20	Exelon (75%), MidAmerican Energy (25%)

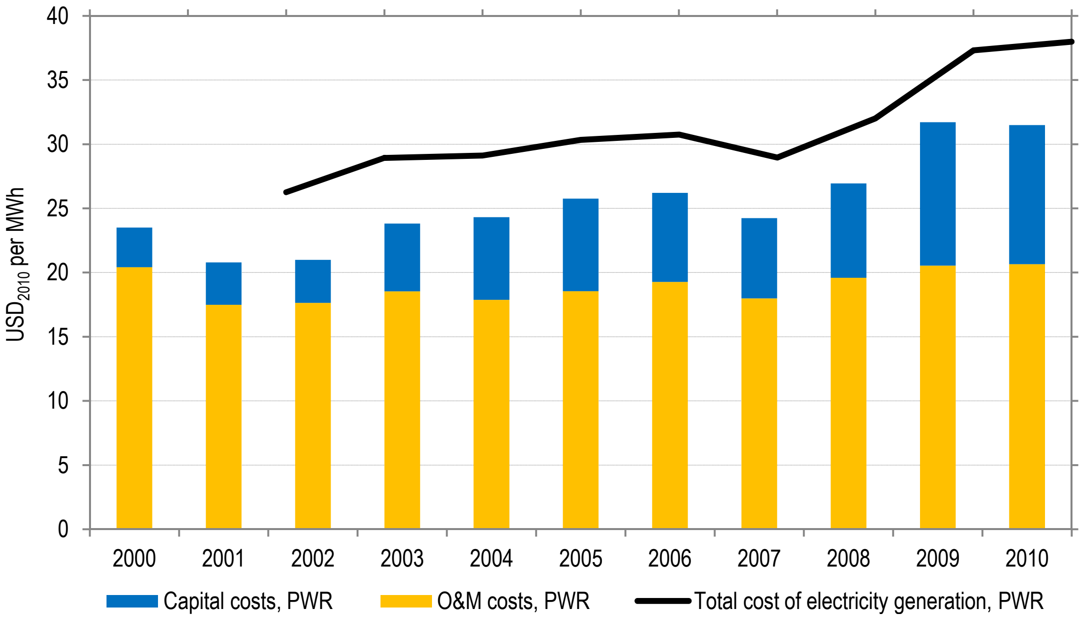
Table 5.21. Operating NPPs in the United States, June 2012 *(continued)*

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Lifetime extension (years)	Owner
Quad Cities 2	BWR	BWR-3 (Mark 1)	Inland near a river	892	23/05/1972	20	Exelon (75%), MidAmerican Energy (25%)
R.E. Ginna	PWR	W (2 loops)	Inland near a lake	580	02/12/1969	20	Constellation Energy Nuclear Group, LLC
River Bend 1	BWR	BWR-6 (Mark 3)	Inland near a river	974	03/12/1985		Entergy Gulf States Inc.
Salem 1	PWR	W (4 loops) DRYAMB	Inland near a river	1 174	25/12/1976	20	PSEG Power, Inc.
Salem 2	PWR	W (4 loops) DRYAMB	Inland near a river	1 158	03/06/1981	20	PSEG Power, Inc.
San Onofre 2	PWR	CE (2 loops) DRYAMB	Seacoast	1 070	20/09/1982		Southern California Edison Co.
San Onofre 3	PWR	CE (2 loops) DRYAMB	Seacoast	1 080	25/09/1983		Southern California Edison Co.
Seabrook 1	PWR	W (4 loops) DRYAMB	Seacoast	1 247	29/05/1990		NextEra Energy Resources, LLC
Sequoyah 1	PWR	W (4 loops) ICECND	Inland near a river	1 152	22/07/1980		Tennessee Valley Authority
Sequoyah 2	PWR	W (4 loops) ICECND	Inland near a river	1 126	23/12/1981		Tennessee Valley Authority
Shearon Harris 1	PWR	W (3 loops) DRYAMB	Inland near a lake	900	19/01/1987	20	Progress Energy Carolinas, Inc.
South Texas 1	PWR	W (4 loops)	Inland near a river	1 280	30/03/1988		NRG Energy, Inc.
South Texas 2	PWR	W (4 loops) DRYAMB	Inland near a river	1 280	11/04/1989		NRG Energy, Inc.
St. Lucie 1	PWR	COMB CE DRYAMB	Seacoast	839	07/05/1976	20	Florida Power and Light Co.
St. Lucie 2	PWR	COMB CE DRYAMB	Seacoast	839	13/06/1983	20	Florida Power and Light Co.
Surry 1	PWR	W (3 loops) DRYSUB	Seacoast	839	04/07/1972	20	Dominion Resources, Inc.
Surry 2	PWR	W (3 loops) DRYSUB	Seacoast	799	10/03/1973	20	Dominion Resources, Inc.
Susquehanna 1	BWR	BWR-4 (Mark 2)	Inland near a river	1 239	16/11/1982	20	PPL Corporation
Susquehanna 2	BWR	BWR-4 (Mark 2)	Inland near a river	1 190	03/07/1984	20	PPL Corporation
Three Mile Island 1	PWR	B&W (L-loop)	Inland near a river	805	19/06/1974	20	Exelon Corporation
Turkey Point 3	PWR	W (3 loops) DRYAMB	Seacoast	693	02/11/1972	20	Florida Power and Light Co.
Turkey Point 4	PWR	W (3 loops) DRYAMB	Seacoast	693	21/06/1973	20	Florida Power and Light Co.
Vermont Yankee	BWR	BWR-4 (Mark 1)	Inland near a river	620	20/09/1972	20	Entergy Nuclear Operations, Inc.
Virgil C. Summer 1	PWR	W (3 loops) DRYAMB	Inland near a lake	966	16/11/1982	20	South Carolina Electric and Gas Co.
Vogtle 1	PWR	W (4 loops) DRYAMB	Inland near a river	1 150	27/03/1987	20	Georgia Power Co.
Vogtle 2	PWR	W (4 loops) DRYAMB	Inland near a river	1 152	10/04/1989	20	Georgia Power Co.
Waterford 3	PWR	CE (2 loops)	Inland near a river	1 168	18/03/1985		Entergy Louisiana Inc.
Watts Bar 1	PWR	W (4 loops) ICECND	Inland near a river	1 123	06/02/1996		Tennessee Valley Authority
Wolf Creek	PWR	W (4 loops)	Inland near a lake	1 160	12/06/1985	20	Kansas City Power and Light Co.

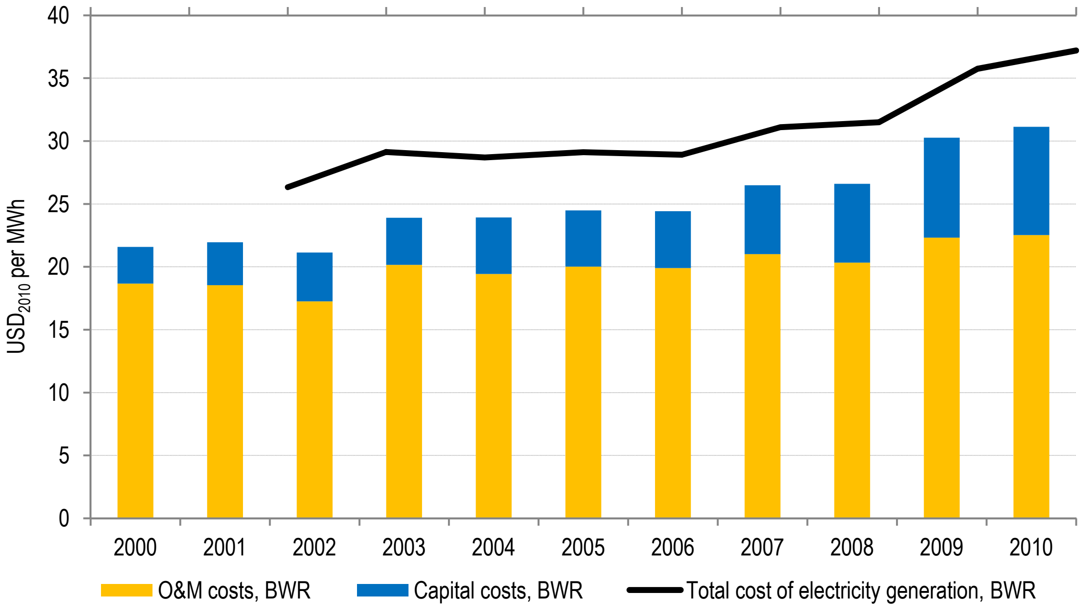
The costs of electricity generation at NPPs in the US are divided in three usual categories: Capital, O&M and fuel costs (see Figure 5.14).

Figure 5.14. Evolution of costs of electricity generation at US NPPs, in constant USD$_{2010}$

Pressurised water reactor (PWR) in the United States



Boiling water reactor (BWR) in the United States



According to the Electric Utility Cost Group (EUCG), the nuclear industry average **capital costs** were USD$_{2010}$ 10.00/MWh in 2010. This includes the costs associated with capital improvements and modifications made during the year including design and installation costs in addition to equipment costs. Other miscellaneous capital additions such as facilities, computer equipment, moveable equipment and vehicles are also included. These capital costs do not include allowance for funds used during construction (interest and depreciation). US capital costs include power uprates, which are different from other refurbishment costs because they are offset by increased revenue. To date, 6 440 MWe have been added through power uprates of existing plants, and about 6 000 MWe uprate potential remains available.

Nuclear industry average **O&M costs** were USD_{2010} 21.36/MWh in 2010. These costs are the costs associated with all operations and maintenance[7], and the average **fuel costs** were USD_{2010} 6.34/MWh. This includes the waste fund fee, uranium, enrichment, conversion, and fabrication.

It should be noted that there is no incremental refurbishment needed for a typical NPP to operate for more than 40 years. The investment in maintenance and capital improvements (i.e. refurbishment) needed to reach 40 years is most often adequate to operate for 60 years. The evolution of capital refurbishment costs for US PWRs and BWRs is given in Figure 5.14. One can note an increase of the capital costs over the last several years, reflecting investment in refurbishment and upgrades.

One can also note an increase of these costs after 2000 (when the lifetime extension programmes started to be initiated), mainly because of capital improvement.

Regarding other costs attributable to the LTO programme, one should mention the **cost of licence renewal,** which is typically in the range of USD 15-20 million, including the NRC review fees and utility support of the NRC review process. This includes the engineering studies, environmental studies, preparation of the licence renewal application, and cost of the NRC review process, but does not include the cost of litigation if intervention is successful as well as NRC's Atomic Safety and Licensing Board hearings if required. The vast majority of licence renewal projects have not involved litigation.

According to the Electric Power Research Institute (EPRI) survey on costs of refurbishment, the investment costs (in LTO) are likely to be about USD 750/kWe. A wide variability of responses for all choices indicates significant levels of uncertainty. The figure of USD 750/kWe, at 5% discount rate and a 20-year timeframe is consistent with the current US spending rate on capital improvement.

As a conservative assumption for the LCOE_{EO} estimation, the values of USD 750/kWe and USD 1 000/kWe are used for the overnight capital investment required for the refurbishment of US plants. Using the current values for the O&M and fuel costs (see Figure 5.14), the LCOE during the 20-year period of extended operation can be calculated (see Table 5.22). It is assumed that the original instruction investment in construction is already paid off after 40 years of operation.

Table 5.22. Calculation of LCOE_{EO} in the United States, for a 20-year lifetime extension

Discount rate	Assumption on the LTO investment, USD_{2010}/kWe	Levelised investment cost, USD_{2010}/MWh	O&M costs USD_{2010}/MWh	Fuel cost USD_{2010}/MWh	Total USD_{2010}/MWh
3%	750	7.06	21.36	6.34	34.76
	1 000	9.41	21.36	6.34	37.11
8%	750	12.89	21.36	6.34	40.59
	1 000	17.19	21.36	6.34	44.89

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[7] Including chemistry, radiation, preventive maintenance, corrective maintenance, surveillance testing, non capital improvements, planning and scheduling, operations, housekeeping/ facilities, fuel management, plant engineering, design engineering, licensing, security, emergency planning, nuclear safety assess, QA and QC, training, records management, human resources, insurance, labour and payroll.

Comparison with other cases

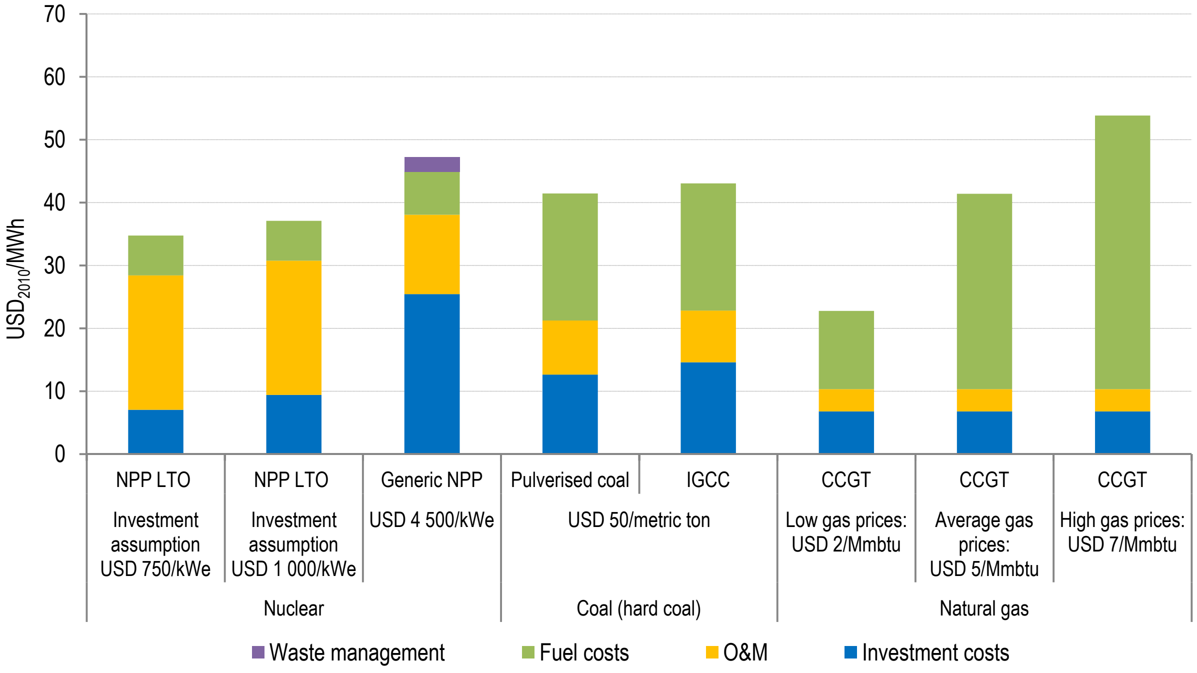
Nuclear plants in the US have been the lowest cost baseload electricity source after hydro for the past several years. This success is based on high capacity factors for the nuclear plants and a relatively stable fuel price. Drops in electricity demand and extremely low natural gas prices have challenged the business case for new nuclear and some proposed large uprate projects in recent years.

In Figure 5.15 and Figure 5.16, the estimates of LCOE_{EO} for existing NPPs in the US (Table 5.22) are compared to LCOE with alternative sources: gas, coal and new nuclear. The overnight capital costs and O&M costs were taken from (IEA/NEA, 2010). For a new NPP, an overnight investment of USD$_{2010}$ 4 500/kWe was assumed. The price of coal is assumed to be USD$_{2010}$ 50 per metric ton. Three cases of natural gas prices[8] were considered: low costs (USD$_{2010}$ 2/Mmbtu), average case (USD$_{2010}$ 5/Mmbtu) and high case scenario (USD$_{2010}$ 7/Mmbtu).

Except for extremely low long-term prices of natural gas of USD$_{2010}$ 2/Mmbtu, the extended operation of existing NPPs has the lowest levelised costs of electricity generation.

The US Energy Information Administration[9] provides even higher estimates for the electricity generation costs (at WACC [weighted average cost of capital] equal to 7.4%) with non-nuclear sources than those estimated in Figure 5.15 and Figure 5.16 (e.g. USD$_{2009}$ 63-125/MWh for natural gas-fired plants, and USD$_{2009}$ 94-136/MWh for coal-fired power plants).

Figure 5.15. Projected costs of electricity generation with alternative sources in the United States, at 3% real discount rate



Note: CCGT = Combined-cycle gas turbine; IGCC = Integrated gasification combined cycle.

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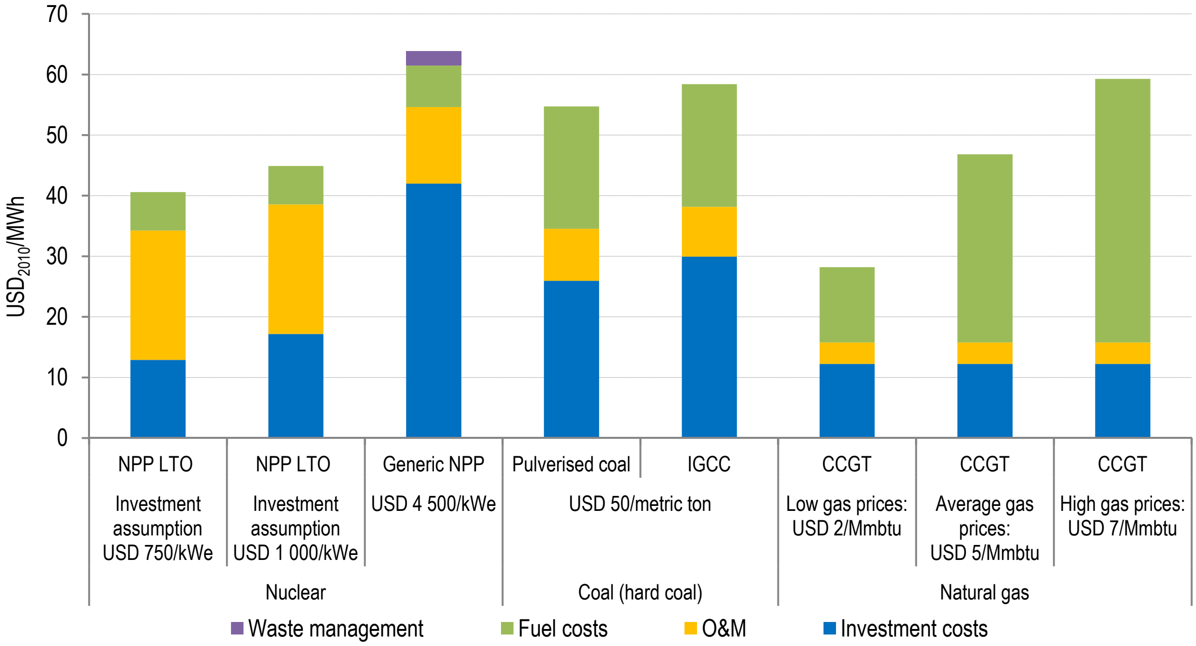
[8] The IEA assumptions ("Current Policies Scenario") for the natural gas import price in the United States in the *World Energy Outlook 2011* (IEA, 2011) is USD$_{2010}$ 6.1/Mmbtu in 2015, USD$_{2010}$ 7.0/Mmbtu in 2020, USD$_{2010}$ 7.7/Mmbtu in 2025 and USD$_{2010}$ 8.4/Mmbtu in 2030.

[9] www.eia.gov/oiaf/aeo/electricity_generation.html.

Figure 5.16. Projected costs of electricity generation with alternative sources in the United States, at 8% real discount rate



Note: CCGT = Combined-cycle gas turbine; IGCC = Integrated gasification combined cycle.

Table 5.23. Assessment results for the NPP LTO programme in the United States

	Score (★, ★★ or ★★★)	Comment
Production and asset portfolio	★★★	Nuclear energy represents about 20% of US electricity generation. Several large US utilities have significantly higher shares of nuclear in their energy mix (e.g. Exelon and Entergy); however, areas served by these companies have non-nuclear electricity sources from other providers.
Predictability of future electricity prices	★★	Drops in electricity demand and extremely low natural gas prices challenge the predictability of future electricity prices.
Need for NPP equipment upgrade and replacement	★★★	Most of the equipment in US NPPs is up to date.
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★/★★★	In a large majority of cases the EAF is marginally affected by LTO activities. The average EAF in 2000-2011 for plants that went through the licence extension process is 90.63%, compared to the average EAF over the same period of time for NPPs of less than 30 years old: 91.12%. However, in some cases (e.g. Crystal River NPP and San Onofre NGS) refurbishment activities can lead to long unplanned outages and performance issues.
Risk and uncertainty (site-dependence, political, financial, regulatory)	★★★	The regulatory process is well established. 72 reactors of 104 have been granted a lifetime extension to 60 years (as for June 2012).
Overnight cost of refurbishment	★★★	According to the EPRI survey, the upper bound of the LTO overnight investment is in the range USD 750-1 000/kWe. This is significantly below the costs of alternatives except for gas-fired power plants.
LCOE_{EO} – levelised cost of electricity generation after LTO activities	★★/★★★	The levelised cost of electricity generation after the lifetime extension is highly competitive, except for very low long-term gas prices (about USD 3/Mmbtu).
Country’s carbon policy and security of energy supply	★★	There is no immediate intention to introduce carbon tax. However, nuclear power plays an important role in ensuring carbon-free supply of electricity.

Further plans for lifetime extension

Many nuclear plants in the US are planning to apply for a second extension (from 60 to 80 years) in order to operate beyond 60 years. The first nuclear plant to reach 60 years of age will be in 2029. Research is currently underway to determine the effects of ageing on important systems, structures and components. According to a recent utility survey (conducted by EPRI among 10 executives representing 57 units):

- more than 60% of responses considered there was >75% chance to operate to 80 years;
- one third are estimated as having 25-75% chance;
- about 5% gave <25% chance.

The systems likely to prevent 80-year operations (from 60 years) are mainly reactors' internals, general design obsolescence, RPV and containment/torus. The events likely to prevent operation up to 80 years (from 60 years) primarily include security or terrorism, cooling water availability, loss of public or board of director's confidence.

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Chapter 6. Summary of LTO programmes for selected countries that have not participated in the questionnaire

Russian Federation

The Russian Federation has 33 operating nuclear reactors of different types (VVER/PWR, RBMK[1], fast breeder reactors [FBR] – see Table 6.1) that have produced about 173 TWh in 2011 of the total 1 052 TWh of electricity generated, i.e. about 16.4%. The remaining part was generated at thermal power plants (713 TWh) and hydro plants (165 TWh).

Generally, the original lifetime (licence) of Russian nuclear reactors was 30 years. Several reactors of different technology and designs (VVER-440, VVER-1000, RBMK and sodium-cooled BN-600) have obtained a 15- to 25-year extension of their original design lifetime of 30 years.

The older PWR/VVER-440 reactors have obtained a 15-year extension, and larger VVER-1000 have obtained a 25-year lifetime extension.

The RBMK reactors (LWGR) have all been modernised after the Chernobyl accident. Among the most important modifications:

- the fuel enrichment was increased from 1.8% to 2.4% (to avoid instability in certain low-power configurations);
- instrumentation and control was improved;
- shutdown systems were reinforced and SCRAM time was reduced.

These modifications and refurbishment allowed extending the operating licence for 15-20 years (depends on the unit, see Table 6.1).

The Beloyarsky 3 fast neutron reactor (BN-600) was upgraded and recently obtained a 15-year licence extension.

Little information is available on the costs and modernisation of different units. For example, regarding the most recent LTO programmes, the refurbishment of Novovoronezh 5 unit (first series of VVER-1000) took more than a year and cost (Rossijskaja gazeta, 2012) around RUB 14 billion (new Russian rubles) – about USD_{2010} 460 million or USD_{2010} 485/kWe.

After the accident at Fukushima Daiichi, additional measures have been taken to enhance the capability of Russian NPPs to resist to external events. For example, an additional 66 mobile diesel generators, 35 large mobile pumps and 80 mobile pumps were delivered to NPPs before June 2012.

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[1] RBMKs are light-water graphite-moderated reactors (LWGR).

Table 6.1. Operating NPPs in the Russian Federation

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Projected end of operational lifetime	Extension of operational lifetime (years)
Balakovo 1	PWR	VVER V-320	Inland near a river	950	28/12/1985	28/12/2015	
Balakovo 2	PWR	VVER V-320	Inland near a river	950	08/10/1987	08/10/2017	
Balakovo 3	PWR	VVER V-320	Inland near a river	950	25/12/1988	25/12/2018	
Balakovo 4	PWR	VVER V-320	Inland near a river	950	11/04/1993	04/11/2023	
Beloyarsky 3 (BN-600)	FBR	BN-600	Inland near a lake	560	08/04/1980	08/04/2010	15
Bilibino 1	LWGR	EGP-6	Inland near a river	11	12/01/1974	12/01/2004	15
Bilibino 2	LWGR	EGP-6	Inland near a river	11	30/12/1974	30/12/2004	15
Bilibino 3	LWGR	EGP-6	Inland near a river	11	22/12/1975	22/12/2005	15
Bilibino 4	LWGR	EGP-6	Inland near a river	11	27/12/1976	27/12/2006	15
Kalinin 1	PWR	VVER V-338	Inland near a lake	950	09/05/1984	09/05/2014	
Kalinin 2	PWR	VVER V-338	Inland near a lake	950	03/12/1986	03/12/2016	
Kalinin 3	PWR	VVER V-320	Inland near a lake	950	16/12/2004	16/12/2034	
Kalinin 4	PPWR	VVER V-320	Inland near a lake	950	24/11/2011	24/11/2041	
Kola 1	PWR	VVER V-230	Seacoast	411	29/06/1973	29/06/2003	15
Kola 2	PWR	VVER V-230	Seacoast	411	08/12/1974	08/12/2004	15
Kola 3	PWR	VVER V-213	Seacoast	411	24/03/1981	24/03/2011	25
Kola 4	PWR	VVER V-213	Seacoast	411	11/10/1984	11/10/2014	
Kursk 1	LWGR	RBMK-1000	Inland near a lake	925	19/12/1976	19/12/2006	15
Kursk 2	LWGR	RBMK-1000	Inland near a lake	925	28/01/1979	28/01/2009	15
Kursk 3	LWGR	RBMK-1000	Inland near a lake	925	17/10/1983	17/10/2013	
Kursk 4	LWGR	RBMK-1000	Inland near a lake	925	02/12/1985	02/12/2015	
Leningrad 1	LWGR	RBMK-1000	Seacoast	925	21/12/1973	21/12/2003	15
Leningrad 2	LWGR	RBMK-1000	Seacoast	925	11/07/1975	11/07/2005	15
Leningrad 3	LWGR	RBMK-1000	Seacoast	925	07/12/1979	07/12/2009	20
Leningrad 4	LWGR	RBMK-1000	Seacoast	925	09/02/1981	09/02/2011	20
Novovoronezh 3	PWR	VVER V-179	Inland near a river	385	27/12/1971	27/12/2001	15
Novovoronezh 4	PWR	VVER V-179	Inland near a river	385	28/12/1972	28/12/2002	15
Novovoronezh 5	PWR	VVER V-187	Inland near a river	950	31/05/1980	31/05/2010	25
Rostov 1	PWR	VVER V-320I	Inland near a river	950	30/03/2001	30/03/2031	
Rostov 2	PWR	VVER V-320I	Inland near a river	950	18/03/2010	18/03/2040	
Smolensk 1	LWGR	RBMK-1000	Inland near a river	925	09/12/1982	09/12/2012	
Smolensk 2	LWGR	RBMK-1000	Inland near a river	925	31/05/1985	31/05/2015	
Smolensk 3	LWGR	RBMK-1000	Inland near a river	925	17/01/1990	17/01/2020	

Ukraine

Ukraine has 15 operating nuclear power reactors, all PWRs (13 VVER-1000 and 2 smaller VVER-440) producing almost half of domestically generated electric power.

Little information is available on the costs of refurbishment of Ukrainian NPPs. Sometimes a generic cost of USD 300/kWe is quoted (Tarakanov, 2012). On 26 April 2012, the Prime Minister of Ukraine Mr Mykola Azarov stated that the modernisation of one unit requires about UAH 4 billion (Ukrainian hryvnia) – about USD 500/kWe. Regarding the refurbishment cost of Rovno 1 and 2, the president of the plant operator noted that more than USD 300 million has been invested in the modernisation of Rovno 1 and 2 since 2004[2].

Table 6.2. Operating NPPs in Ukraine

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Projected end of operational lifetime (DD/MM/YY)	Extension of operational lifetime
Khmelnitski 1	PWR	VVER V-320	Inland near a lake	950	31/12/1987	31/12/2017	
Khmelnitski 2	PWR	VVER V-320	Inland near a lake	950	07/08/2004	07/08/2034	
Rovno 1	PWR	VVER V-213	Inland near a river	381	31/12/1980	31/12/2010	31/12/1930
Rovno 2	PWR	VVER V-213	Inland near a river	376	30/12/1981	30/12/2011	31/12/1931
Rovno 3	PWR	VVER V-320	Inland near a river	950	21/12/1986	21/12/2016	
Rovno 4	PWR	VVER V-320	Inland near a river	950	10/10/2004	10/10/2034	
South Ukraine 1	PWR	VVER V-302	Inland near a lake	950	31/12/1982	31/12/2012	LTO programme in progress.
South Ukraine 2	PWR	VVER V-338	Inland near a lake	950	06/01/1985	06/01/2015	LTO programme in progress.
South Ukraine 3	PWR	VVER V-320	Inland near a lake	950	20/09/1989	20/09/2019	LTO programme in progress.
Zaporozhe 1	PWR	VVER V-320	Inland near a river	950	10/12/1984	10/12/2014	LTO programme in progress.
Zaporozhe 2	PWR	VVER V-320	Inland near a river	950	22/07/1985	22/07/2015	LTO programme in progress.
Zaporozhe 3	PWR	VVER V-320	Inland near a river	950	10/12/1986	10/12/2016	
Zaporozhe 4	PWR	VVER V-320	Inland near a river	950	18/12/1987	18/12/2017	
Zaporozhe 5	PWR	VVER V-320	Inland near a river	950	14/08/1989	14/08/2019	
Zaporozhe 6	PWR	VVER V-320	Inland near a river	950	19/10/1995	19/10/2025	

Ukraine participated in the European stress tests that were conducted after the Fukushima Daiichi accident. As a result of the stress tests, some potential safety improvements have been identified (SNRI, 2011) and have to be considered by utilities:

- Implementation of the hydrogen concentration monitoring system in containment for beyond design basis accidents.
- Reliability increase of emergency power supply system under station blackout (mobile diesel generators).
- Additional seismic investigations of NPP sites and assurance of seismic resistance of equipment, piping, buildings and structures important to safety.
- Detailed analysis of severe accidents and development of severe accident management guides;

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[2] www.nuclear.ru/eng/press/nuclear_power/2118746.

- Measures on severe accident management during ex-vessel stage.
- Provision of instrumentation before and after accidents.
- Modernisation of NPP radiation monitoring systems.
- Implementation of a closed-circle television system for fire/explosion hazardous and non-serviced rooms.

In addition to the above safety improvement measures, the following improvements have been identified from the stress test results:

- Assurance of operability of essential service water loads under loss of water in the spray ponds as a result of tornado.
- A series of measures aimed at assurance of long-term (up to 72 hours) residual heat removal from the core and spent fuel pool under station blackout and/or loss of ultimate heat sink:
  - make-up of secondary systems using mobile facilities;
  - make-up of spent fuel pools.
- Emergency make-up of primary systems with boric water are under consideration (for compensation of potential loss of primary coolant).
- Development of severe accident management guides for spent fuel pools.
- I&C upgrade to ensure the proper work under severe accident conditions.

The above measures were included into the "Comprehensive Safety Improvement Program" defined by the government of Ukraine on the 7 December 2011[3]. According to this programme, UAH 12.5 billion (i.e. about USD 1.5 billion) would be required to implement the safety improvements.

The London based European Bank for Reconstruction and Development (EBRD) has initiated a funding programme[4] for all 15 operating nuclear power units in Ukraine to bring them in line with internationally accepted safety standards and Ukrainian requirements (see EBRD, 2012). The EBRD has evaluated this programme at EUR 1.45 billion (i.e. about USD 140/kWe).

United Kingdom

Three types of reactors are currently operating in the United Kingdom: gas-cooled MAGNOX and advanced gas-cooled reactors (AGR) and one PWR (see Table 6.3). Several new-build projects are underway.

In the UK, a single non-transferable licence is granted to cover the life of the nuclear site from start of construction to final decommissioning. There is no pre-determined end date for operation. Nuclear facilities are permitted to continue to operate for as long a period as the licensee can demonstrate that it is safe do so.

The PSRs (conducted with a periodicity of around ten years maximum since the early 1990s) should confirm that original safety standards will be maintained, identify any life-limiting features on the plant, and demonstrate that all reasonably practicable measures to improve the plant to modern standards are being implemented. The forward PSR programmes in the UK are summarised in Figure 6.1.

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[3] Cabinet of Ministers Decree #1270, 7 December 2011.

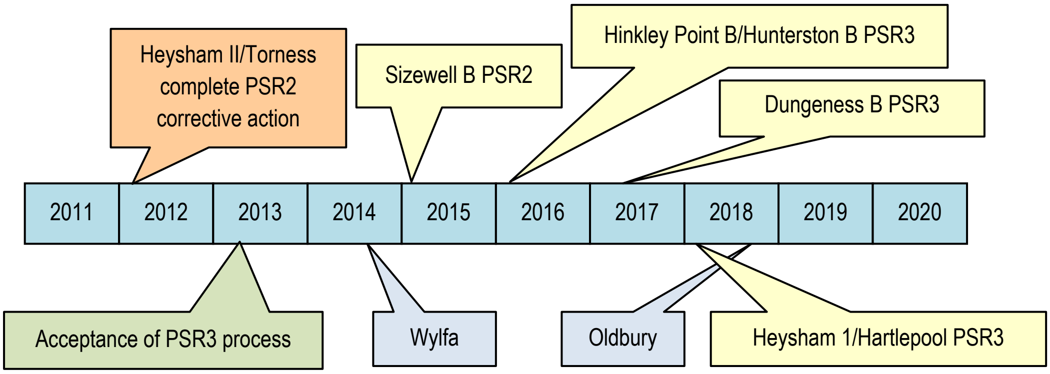
[4] Expected to be approved in September 2012.

The regulator may require the licensee to carry out plant modifications that have been identified during the PSR as reasonably practicable or undertake other activities, e.g. perform additional analyses. If the plant cannot be brought sufficiently close to modern standards, the licensee may be required to cease operation. The end points of past PSRs of UK's facilities have included all of these potential outcomes.

Table 6.3. Operating NPPs in the United Kingdom

Unit name	Type	Model	Site – location	Latest reference unit power (net)	Grid date (DD/MM/YY)	Initial accounting lifetime	First review	Second review	Scheduled closure date
Dungeness B1	GCR	AGR	Seacoast	520	03/04/1983	35 years	1997	2007	2018
Dungeness B2	GCR	AGR	Seacoast	520	29/12/1985		1997	2007	2018
Hartlepool A1	GCR	AGR	Seacoast	595	01/08/1983	35 years	1998	2008	2019
Hartlepool A2	GCR	AGR	Seacoast	595	31/10/1984		1998	2008	2019
Heysham A1	GCR	AGR	Seacoast	585	09/07/1983	35 years	1998	2008	2019
Heysham A2	GCR	AGR	Seacoast	575	11/10/1984		1998	2008	2019
Heysham B1	GCR	AGR	Seacoast	620	12/07/1988	35 years	1999	2009	2023
Heysham B2	GCR	AGR	Seacoast	620	11/11/1988		1999	2009	2023
Hinkley Point B1	GCR	AGR	Seacoast	435	30/10/1976	40 years	1996	2006	2016
Hinkley Point B2	GCR	AGR	Seacoast	435	05/02/1976		1996	2006	2016
Hunterston B1	GCR	AGR	Seacoast	430	06/02/1976	40 years	1996	2006	2016
Hunterston B2	GCR	AGR	Seacoast	430	31/03/1977		1996	2006	2016
Sizewell B	PWR	SNUPPS	Seacoast	1 188	14/02/1995	40 years	1999	2009	2035
Torness 1	GCR	AGR	Seacoast	600	25/05/1988	35 years	1999	2009	2023
Torness 2	GCR	AGR	Seacoast	605	03/02/1989		1999	2009	2023
Wylfa 1	GCR	MAGNOX	Seacoast	490	24/01/1971		1996	2004	September 2014

Figure 6.1 Forward PSR programme in the United Kingdom



The operating lifetime of Wylfa Magnox plant

The Nuclear Decommissioning Authority (NDA) announced in August 2012 that Wylfa has received permission from the Office for Nuclear Regulation (ONR) to transfer fuel between its reactors, enabling electricity generation to continue until September 2014, nearly four years beyond its original closure date of December 2010.

The site will continue to use one reactor, enabled through the transfer of partially used fuel from reactor 2 to reactor 1. Reactor 2 was shut down in April 2012 because of limited fuel stocks, notably since Magnox fuel is no longer manufactured. This process was successfully carried out at the NDA's Oldbury Magnox site, which ceased generation in February 2012.

The operating lifetime of EDF Energy's nuclear power plants

EDF Energy owns and operates the eight remaining NPPs in the UK (for details see EDF, 2011).

EDF Energy's eight operational nuclear plants in the UK have a total capacity of 8.7 GWe (gigawatt electric). The potential lifetime of each NPP is determined primarily by its ability to maintain safety procedures in accordance with its nuclear site licence with regard to both technical and financial aspects. Any decision by EDF Energy to extend the operating life of an NPP beyond its initially scheduled closure date would be based, in large part, on a combination of economic factors and the engineering studies on technical processes and safety issues. Lifetime extensions will require the consent of the NDA if the extension results in an increase in the costs of performing decommissioning requirements as defined in the Nuclear Liabilities Funding Agreement, signed when British Energy was restructured.

The accounting lives and corresponding current scheduled closure dates of the EDF Energy's existing power plants are shown in Table 6.3.

EDF Energy's strategy is to seek life extensions for all its UK nuclear power stations where it is safe and commercially viable to do so. A lifetime programme has been implemented.

EDF Energy expects to secure life extensions of 20 years for Sizewell B, the only PWR in the UK, and an average of seven years for the AGR fleet: advanced gas-cooled reactor technology is unique to the UK and the 14 reactors have already been granted life extensions of 10 years or more beyond their original accounting lives of 25 years.

The life extension decision is made by EDF Energy only after a detailed analysis and review that considers, first and foremost, safety, followed by technical viability, economics and social impacts.

With a large proportion of generating capacity due to shut down within the next ten years, coupled with a need to decarbonise electricity generation, the UK government is pursuing an energy policy which is designed to provide clean, secure and affordable electricity for Britain.

As a result of planned reforms to the UK electricity market, the introduction by the UK government of a carbon price floor from 2013 will provide greater long term certainty about the price of carbon and the value of low carbon generation. EDF Energy is continuing to invest heavily in its UK nuclear plants to maintain performance and to deliver life extensions. Carbon price support helps strengthen the case for this investment which ensures that the plants continue to deliver much needed low carbon electricity.

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Chapter 7. Summary and conclusions

In 2011, 289 reactors in the world were older than 25 years, and only 45 new units were connected to the grid in 2000-2011. Without life extensions, nuclear capacity would thus fall dramatically in the next decade, especially if the construction of new nuclear power plants also slows as a result of the Fukushima Daiichi accident. Refurbishments and LTO of existing NPPs are therefore important to the competitiveness of the nuclear industry in OECD countries as these existing NPPs are able to produce baseload power at low and stable costs.

Licence renewal and PSR are the two basic regulatory approaches that have been adopted for authorisation of LTO of nuclear power reactors. Some countries use aspects from one or both approaches in determining whether, and under what conditions, to allow LTO.

The aim of the OECD/NEA project "Economics of Long-term Operation of Nuclear Power Plants" was to collect and analyse technical and economic data on the upgrade and lifetime extension experience in OECD countries. It did this with assistance from a working group of experts from eight countries; a questionnaire sent to members and published information. The overall conclusions follow:

- The analysis presented in this report shows that LTO of NPPs has significant economic advantages for most utilities envisaging LTO programmes.
- The multi-criteria approach provides a valuable method for assessing the range of issues important in any decisions related to LTO, since the criteria identified allow consideration of national issues and priorities, which should be included in the decision-making process.
- The OECD/NEA Ad Hoc Expert Group on the Economics of Long-term Operation of Nuclear Power Plants recommends that the following criteria could guide the decision on the advantages or disadvantages of continued operation of a given NPP:
    - production and asset portfolio;
    - predictability of future electricity prices;
    - need for NPP equipment upgrade and replacement;
    - impact of refurbishment activities on the decennial average of the energy availability factor;
    - risk and uncertainty (site-dependence, political, financial, regulatory);
    - overnight cost of refurbishment;
    - $LCOE_{EO}$ – levelised cost of electricity generation after LTO activities;
    - country's carbon policy and security of energy supply.

An assessment of LTO programmes in selected OECD countries using a simple three-grade ranking system (see Table 4.3 for details) was performed, the results are summarised in Table 7.1.

Table 7.1. Summary of the economic assessment of LTO programmes in selected OECD countries

	Belgium	Finland	France	Hungary	Korea, Republic of	Switzerland	United States
Production and asset portfolio	★★	★★★	★★★	★★★	★★★	★★★	★★★
Predictability of future electricity prices	★	★★★	★★★	★★★	★★/★★★	★★	★★
Need for NPP equipment upgrade and replacement	★★	★★★	★★/★★★	★★	★★★	★★★	★★★
Impact of refurbishment activities on the decennial average of the energy availability factor (EAF)	★★/★★★	★★★	★★★	★★	Wolsong 1 (CANDU): ★ Kori 1 (PWR): ★★★	★★★	★★/★★★
Risk and uncertainty (site-dependence, political, financial, regulatory)	★	★★/★★★	★★	★★★	★★	★/★★	★★★
Overnight cost of refurbishment	★★★	N/A	★★/★★★	★★★	★★★	★★	★★★
$LCOE_{EO}$ – levelised cost of electricity generation after LTO activities	★★★	N/A	★★★	★★★	★★★	★★★	★★/★★★
Country's carbon policy and security of energy supply	★★	★★★	★★★	★★/★★★	★★	★★★	★★

Note: Score "★" is the least positive outcome of that criterion for NPP LTO and score "★★★" is the most positive outcome for NPP LTO.

N/A = Not available.

- A favourable outcome of the economic assessment does not necessarily mean that the plant can continue operation beyond the original term authorised by the regulator (or expected by the operator). An authorisation from the nuclear safety authority is required, confirming that the reactors continue to meet the licensing basis.
- The changes in regulatory requirements after the Fukushima Daiichi accident primarily concern reinforcement of protection against extreme events, dealing with accident management in potentially harsh environment, long-duration loss of power or cooling functions and accidents affecting multiple units at the same time.
- These changes apply to all operational NPPs regardless of their intentions on LTO. Based on the information available to date, there are no additional Fukushima regulatory requirements related to LTO only.
- Currently, LTO programmes cost in the range of USD_{2010} 500-1 100/kWe (see Table 7.2), as reported by the licensees, depending on the extent of prior refurbishments and additional regulatory requirements or other plant performance improvements (like power uprates).

Table 7.2. Cost summary of LTO and refurbishment programmes in selected countries

Country	Specific investment in LTO	Comment
Belgium	USD_{2010} 650/kWe	Including ~11% increase due to post-Fukushima measures.
France	USD_{2010} 1 090/kWe	Including all investments from 2011 to 2025: maintenance, refurbishment, safety upgrades, performance improvement; and ~10% increase due to post-Fukushima measures.
Hungary	USD_{2010} 740-792/kWe	Including 10-17% increase due to post-Fukushima measures.
Korea, Republic of	USD 500/kWe	Including ~10% increase due to post-Fukushima measures.
Switzerland	USD_{2010} 490-650/kWe	Specific future investment in NPP refurbishment and maintenance (approximately the double of the specific LTO investment) is USD_{2010} 980-1 300/kWe.
United States	About USD_{2010} 750/kWe	EPRI survey data and current spending on capital improvement.
Russian Federation*	About USD_{2010} 485/kWe	Data for Novovoronezh 5 unit (first series of VVER-1000: V-187).
Ukraine*	About USD 300-500/kWe	Public statements by Energoatom and the Ukrainian Prime Minister.

* These countries did not participate in the study.

- The preliminary estimates of the economic impact of post-Fukushima modifications are about 10-17% of the initially projected LTO investment.
- Factors that affect the economics of LTO include replacement of obsolete equipment, safety upgrades to current standards and the ageing of irreplaceable components such as RPV or containment building.
- In most of the cases, the continued operation of NPPs for at least ten more years is profitable[1] even taking into account the additional costs of post-Fukushima modifications. The $LCOE_{EO}$ are likely to be significantly smaller than the projected electricity generation costs with alternative sources. Currently, the $LCOE_{EO}$ for the countries considered in this study[2] is in the range of USD_{2010} 30-58/MWh in the case of continued operation for 20 additional years and in the range of USD_{2010} 30-71/MWh in the case of continued operation for 10 additional years.
- The LTO programmes remain cost effective compared to alternative, nuclear and non-nuclear, replacement sources. In the US, the LTO decision could be more marginal if the prices of natural gas remain extremely low for a long period of time. However, projections from the forecasting agencies indicate that prices are expected to rise.
- Despite the economic attractiveness of LTO, there are several risks and uncertainties that can influence the utilities' decision to extend the operational lifetime of NPPs such as public acceptance, changes in national policies or security concerns.

The OECD/NEA Ad Hoc Expert Group on the Economics of Long-term Operation of Nuclear Power Plants recommends that:

- A multi-criteria approach should be used for the assessment of LTO of NPPs, since they allow the various factors, both quantitative and qualitative, to be included.
- Stakeholders should learn from the experiences and assessments of other countries.

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1. In some countries there are additional taxes or special situations that affect the overall profitability of nuclear.
2. Estimates for Belgium, France, Hungary, Republic of Korea, Switzerland and the United States.

- Given that there is a lack of public knowledge on the extent of the refurbishment and upgrading that accompanies a decision to extend the operational lifetime of a reactor, it would be valuable for industry to provide more detailed information to the public and other stakeholder groups on the extensive and demanding nature of an LTO programme.
- It is good practice to anticipate the safety requirements regarding ageing management and safety margin improvements throughout the plant lifetime. In this regard, ongoing monitoring programmes are important and continuous replacement programmes should be carried out.
- An effective ageing management programme is a key element of safe and reliable operation of NPPs during the originally planned operation time frames, as well as for periods of LTO. LTO of NPPs could be a key element in the decarbonising of electricity generation since they maintain low carbon sources of baseload electricity which cannot easily be replaced by other low-carbon technologies.
- Further work should be undertaken to establish a more complete technical basis for decisions on LTO beyond the currently demonstrated periods.

Appendix 1. Glossary

AGR	Advanced gas-cooled reactor
ARENH	Accès régulé à l'électricité nucléaire historique
ART	Adjusted reference temperature
ASN	French Nuclear Safety Authority: Autorité de sûreté nucléaire
BWR	Boiling water reactor
CCGT	Combined-cycle gas turbine
CNRA	NEA Committee on Nuclear Regulatory Activities
CRPPH	NEA Committee on Radiation Protection and Public Health
CSNI	NEA Committee on the Safety of Nuclear Installations
EAF	Energy availability factor
EBRD	European Bank for Reconstruction and Development
EDF	Electricité de France
EEX	European Energy Exchange
ELTO	Extended lifetime operation
ENSI	Swiss Federal Nuclear Safety Inspectorate
ENSREG	European Nuclear Safety Regulators Group
EPR	European pressurised reactor
EPRI	Electric Power Research Institute
EU	European Union
FAC	Swiss Federal Administrative Court
FBR	Fast breeder reactors
FSC	Swiss Federal Supreme Court
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
I&C	Instrumentation and control
KHNP	Korea Hydro and Nuclear Power Company, Ltd
kWe	Kilowatt electric
LCOE	Levelised cost of electricity generation
LCOE_{EO}	Levelised cost of electricity generation during the extended operation (i.e. after LTO activities)
LTO	Long-term operation

LWGR	Light-water graphite-moderated reactors
MAGNOX	Magnesium alloy graphite moderated gas-cooled uranium oxide reactor
Mmbtu	Million metric British thermal units
MWh	Megawatt-hour
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NEO	Nuclear Energy Ordinance
NPP	Nuclear power plant
NRC	United States Nuclear Regulatory Commission
O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PHWR	Pressurised heavy water reactor
PRIS	IAEA Power Reactor Information System
PSR	Periodic safety review
PTS	Pressurised thermal shock
PWR	Pressurised water reactor
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy (light-water graphite-moderated reactor)
R&D	Research and development
RPV	Reactor pressure vessel
SSDI	Simplified Supply and Demand Index
TWh	Terawatt-hour
US	United States
VVER	Russian pressurised water reactor

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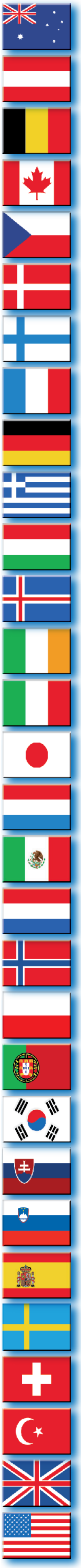
OECD/NEA PUBLISHING, 2 rue André-Pascal, 75775 PARIS CEDEX 16
ISBN 978-92-64-99205-4



The Economics of Long-term Operation of Nuclear Power Plants

Refurbishment and long-term operation (LTO) of existing nuclear power plants (NPPs) today are crucial to the competitiveness of the nuclear industry in OECD countries as existing nuclear power plants produce baseload power at a reliable cost. A number of nuclear power plants, most notably 73 units in the United States (up to 2012), have been granted lifetime extensions of up to 60 years, a development that is being keenly watched in other OECD countries. In many of these (e.g. France, Switzerland), there is no legal end to the operating licence, but continued operation is based on the outcomes of periodic safety reviews.

This study analyses technical and economic data on the upgrade and lifetime extension experience in OECD countries. A multi-criteria assessment methodology is used considering various factors and parameters reflecting current and future financial conditions of operation, political and regulatory risks, the state of the plants' equipment and the general role of nuclear power in the country's energy policy.

The report shows that long-term operation of nuclear power plants has significant economic advantages for most utilities envisaging LTO programmes. In most cases, the continued operation of NPPs for at least ten more years is profitable even taking into account the additional costs of post-Fukushima modifications, and remains cost-effective compared to alternative replacement sources.

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ISBN 978-92-64-99205-4