EDITORIAL NOTE

ANNEX IX. EXAMPLE OF ROADMAP TEMPLATE APPLICATION TO REGIONAL AND GLOBAL ANALYSES

IX.1. APPROACHES TO THE AGGREGATION OF ROADMAPS

For the construction of regional and global roadmaps based on national roadmaps, it is necessary to be able to correctly aggregate data from the initial national roadmaps, i.e. to combine them. In general, aggregation is understood as combination, summation and consolidation of system performance parameters and indicators on some basis to obtain generalized aggregate data.

Aggregation is considered a transformation of a model or combination of diverse models into one model with fewer variables and constraints, i.e. an aggregated model that gives an approximate (in comparison with the originals) but easier to use description of a process or object under study. In both cases, the essence of aggregation resides in combining homogeneous elements into larger ones. When aggregating, it is extremely important to take into account the structure of elements to be combined. In some cases, it is necessary to analyse the possibility of aggregation and the adjustment of the original model parameters. When constructing roadmaps, aggregation is necessary because no roadmap can accommodate the whole variety of real resources in an evolving system of resources, links and other specific elements.

In the process of aggregation, when moving from the lower to the higher stage of a model, characteristics, parameters and performance indicators are combined in one way or another, and their total number is decreased. At the same time, some information can be lost, since it may be necessary to conduct calculations approximately, i.e. on the basis of approximate patterns. Therefore, when aggregating, it is always necessary to compare the benefits of reducing calculations with the disturbance caused by the loss of a piece of information. It is especially difficult to perform aggregation in dynamic models, because the ratio of elements entering the enlarged group changes with time, and structural heterogeneity can arise.

A discrepancy between the results of the initial model and the aggregated model is called aggregation error and its reduction is one of the main requirements for the implementation of optimal aggregation.

It should be noted that the structure of data representation in the roadmap template is such that it facilitates simpler data aggregation and creation of combined or aggregated roadmaps based on individual roadmaps. Within the roadmap template, the aggregation procedure can be performed in several ways: (a) the direct summation of data of the same type presented in different roadmap template sections prepared for different countries; and (b) the formation of simplified, typical models of national roadmaps followed by the development, with the same model assumptions, of the aggregated roadmap for a group of countries using the averaged parameters of reactor technologies. In both cases, it is necessary to take into account a number of general provisions for developing the initial roadmaps. Requirements that have to be met when preparing national roadmaps, which are planned to be combined into regional or global roadmaps, are the following:

(a) The overall time horizon and a way to divide it into separate time intervals should be the same in all national roadmaps that are to be combined. Otherwise, additional calculations will be required to bring the data from the original roadmaps defined in arbitrary timescales into a unified timescale, which may reduce the accuracy of the original data presentation.

(b) It is desirable that the initial roadmaps represent the reactor park in an even, unified form that will make it possible, when aggregating, to describe the final reactor park with the same generalized set of reactor types and thereby minimize the nomenclature of reactors specified in the aggregated model. If this proves impossible, then the reactors that cannot find a partner for combination should appear in the generalized roadmap independently and the corresponding material flows for them will not need to be combined with those for other reactors; all material flows for this reactor type will be present in the integrated roadmap in the same form as they are present in the initial roadmap. If some types of reactor can be combined, then it is possible to reflect the material flows in the aggregated roadmap for the respective types of reactors either by mechanically adding the corresponding material flows from national roadmaps or by determining the most appropriate average parameters of reactors and their fuel supply parameters in the aggregated roadmap with subsequent calculations of all necessary material flows in the aggregated model based on these average reactor parameters. It should be noted that the average parameters in this case should be chosen in such a way as to reproduce, with the smallest deviations, the data obtained by the simple mechanical adding of material flows for individual roadmaps.

(c) To create a balanced aggregated roadmap, it is necessary that all sections of the original national roadmaps be of the same type in content and equally structured.

(d) It is advisable to present all data on material flows in different initial national roadmaps in the same units, in order to avoid the need to bring them to the same units of measurement during aggregation.

(e) It seems advisable that all initial model assumptions should be the same for different initial national roadmaps (taking or not taking into account initial fuel inventories, final fuel discharges, supply side specifications of supply—demand balances etc.). It is obvious that the more roadmaps for individual countries are planned to be combined, the simpler the model assumptions should be, so as not to overload the aggregation procedure with irrelevant details.

(f) When combining roadmaps in the roadmap template, particular attention should be given to the sections 'Provide services/Transfer out materials' and 'Secondary supply/Transfer in materials', since they reflect possible interrelationships of a given country with other countries, including those that can be part of the combined initial roadmaps. In the latter case, when constructing an aggregated roadmap, it is necessary to avoid double accounting for information of the same type that can be contained in roadmaps of different countries.

(g) The existence of a free market for certain nuclear fuel cycle products or services or, on the contrary, the presence of commercial or political restrictions, can and should be reflected in the supply side of the aggregated roadmaps. If there are constraints, they should be taken into account for each nuclear fuel cycle product or service in the supply–demand balance.

(h) An aggregated roadmap representation as a Gantt chart, combined with a tabular data representation, which details all the material flows and the possible structure of nuclear fuel cycle services and products, contains comprehensive information on the supply and demand sides. This information can be used as a base to build various graphs and dependencies to make the tabular data representation more easily perceivable but, at the same time, somewhat roughen the original detailed data representation. Therefore, the most appropriate type of graphical tabular data representation should be selected based on the problem context in each particular case.

(i) Special care should be taken when building aggregated roadmaps where the initial roadmap features a closed nuclear fuel cycle, which suggests spent nuclear fuel reprocessing and fissile material recycling. In this case, the fuel supply structure of a country's NES with a closed nuclear fuel cycle can significantly change if it suggests importing spent nuclear fuel to this country from other countries followed by reprocessing this spent nuclear fuel and using fissile materials extracted from it.

(j) Following these principles, it is possible to integrate not only national but also regional roadmaps. A correctly constructed aggregated roadmap is a useful tool that shows possible opportunities for cooperation between countries and directions for enhancing the sustainability of the NES through the implementation of new and more effective collaboration agreements.

IX.2. EXAMPLE OF THE BOTTOM-UP AGGREGATION OF METRICS

IX.2.1. Summary for the roadmapping exercise fromthe 11th INPRO Dialogue Forum

An example of bottom-up aggregation is based on the materials developed at the 11th INPRO Dialogue Forum Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems held in October 2015. Participants filled in a questionnaire serving as a simplified prototype template for the ROADMAPS collaborative project. The following metrics were included in this simplified country level template:

- Country profile;
- National prospects for nuclear energy capacity and growth until the end of the century;
- National prospects for NES collaboration strategy until the end of the century;
- Technology options of interest to the country to enhance nuclear energy sustainability.

Subsequently, the metrics have been further developed, amended and included into the final roadmap template.

The responses to the questionnaire for a simplified country level template from 38 participants from 21 Member States were collected, analysed and integrated. Template time frames were identified as current, short term (2016–2035), medium term (2036–2055) and long term (2056–2100). The information provided was either (a) an official plan, or (b) a scenario study or expert opinion. Country profiles provided short descriptions of national prospects for nuclear energy size and growth, NES collaboration strategy and preferable technology options to the end of the century. National prospects for nuclear energy capacity and growth until the end of the century indicated visions for development of NESs. The 'nuclear energy size' option was identified as: no nuclear, small (0–10 GW(e)), medium (10–50 GW(e)), and large (>50 GW(e)). Nuclear energy growth taking into account decommissioning was identified as: decreasing, stabilization including replacement of units, small growth (below 0.1 GW(e)/year), medium growth (between 0.1 and 0.5 GW(e)/year) and significant growth (>0.5 GW(e)/year). National prospects for NES collaboration strategy included:

- National indigenous technology development and international cooperation;
- Single bilateral agreements;
- Multilateral agreements;
- Multiple bilateral agreements.

The technology option set of interest to the country to enhance nuclear energy sustainability was somewhat different from the set indicated in Section 3 and 4, namely:

- Current base nuclear energy option, representing once-through thermal reactors;
- Safe disposal of spent nuclear fuel;
- Higher reactor outlet temperatures to open new energy markets;
- Once-through breed and burn;
- Limited recycling of used nuclear fuel to reduce waste;

— Fast breeder reactors (breeding ratio ≥ 1) and a closed fuel cycle;
— Minor actinide transmutation;
— Thorium based closed fuel cycle.

Each of the options above is supposed to be the final end state for an NES, but some may also be an intermediate step in technology deployment on the way to another end state. Deployment of some technologies may be limited to a few countries, but associated benefits may be realized by other countries through collaborative instruments. Deployment of new technologies may impact economics and may also require modification to the approaches to safety, security, physical protection, proliferation resistance and/or waste management.

Analysis of the questionnaires gave an idea how to represent country level roadmaps and how to aggregate them into global roadmaps. According to the suggestion for a bottom-up approach, simplified country level roadmaps were aggregated to global group roadmaps for technology holders (five countries), technology users (seven countries) and newcomers (nine countries). The aggregated roadmaps had the same structure as country level roadmaps. Roadmaps for country groups can help harmonize different countries' intentions and resources and facilitate cooperation towards enhanced NES sustainability. Summaries of the aggregation of the simplified country level roadmaps into country group roadmaps are provided in the following sections.

IX.2.2. Metrics aggregation for technology holder countries

The entries for the technology holder countries are summarized as a roadmap template in Fig. IX.1–IX.3.

IX.2.2.1. Summary of 'national prospects for nuclear energy capacity and growth'

Most entries provided information on nuclear energy capacity and growth as an official plan for the short term and as a scenario study or expert opinion for the medium and long terms.

For technology holder countries, the trend is moving from medium and large capacity in the short term to large capacity in the medium and long term. Significant growth was identified in most countries; however, one response indicated stabilization of the nuclear capacity.

IX.2.2.2. Summary of 'NES collaboration strategy until the end of the century'

As in the previous case, most entries provided information on their NES collaboration strategy as an official plan for the short term and as a scenario study or expert opinion for the medium and long terms.

Among the entries, collaboration comprising bilateral, multilateral and multiple bilateral agreements is perceived to be very important (with a total of 44, 45 and 52 entries in the short, medium and long terms, respectively) for NES function including front end activities, NPP operation and back end activities. National development received slightly less priority (total of 36, 31 and 31 entries in the short, medium and long terms, respectively) with a decreasing trend by the end of the century (see Fig. IX.3 (a)).

The priorities in the short term are collaborations on:

— Obtaining and producing uranium (8);
— Converting and enriching uranium(7);
— NPP design (7);
— Fabricating and obtaining fuel (6);
— Reprocessing spent nuclear fuel (5);
— NPP operation (4);
— Storing spent nuclear fuel (4);

— Disposing HLW and spent nuclear fuel (3).

In the medium and long term the priorities for collaboration are similar; however, back end activities received more importance:

— Obtaining and producing uranium (9 in medium term, 9 in long term);
— Converting and enriching uranium (7, 7);
— Fabricating and obtaining fuel (7, 7);
— Reprocessing spent nuclear fuel (6, 7)
— NPP design (5, 6);
— Storing spent nuclear fuel (5, 6);
— NPP operation (4, 5);
— Disposing HLW and spent nuclear fuel (2, 5).

Multiple bilateral agreements are the leader among collaboration strategies with a range of 20–22 entries for the considered period. Multilateral and bilateral agreements are less frequent with a range of 10–13 entries in the short and medium terms, and tending to increase in the long term (to 15–16 entries). In most entries, several NES collaboration strategies were applied simultaneously (see Fig. IX.3 (b)).

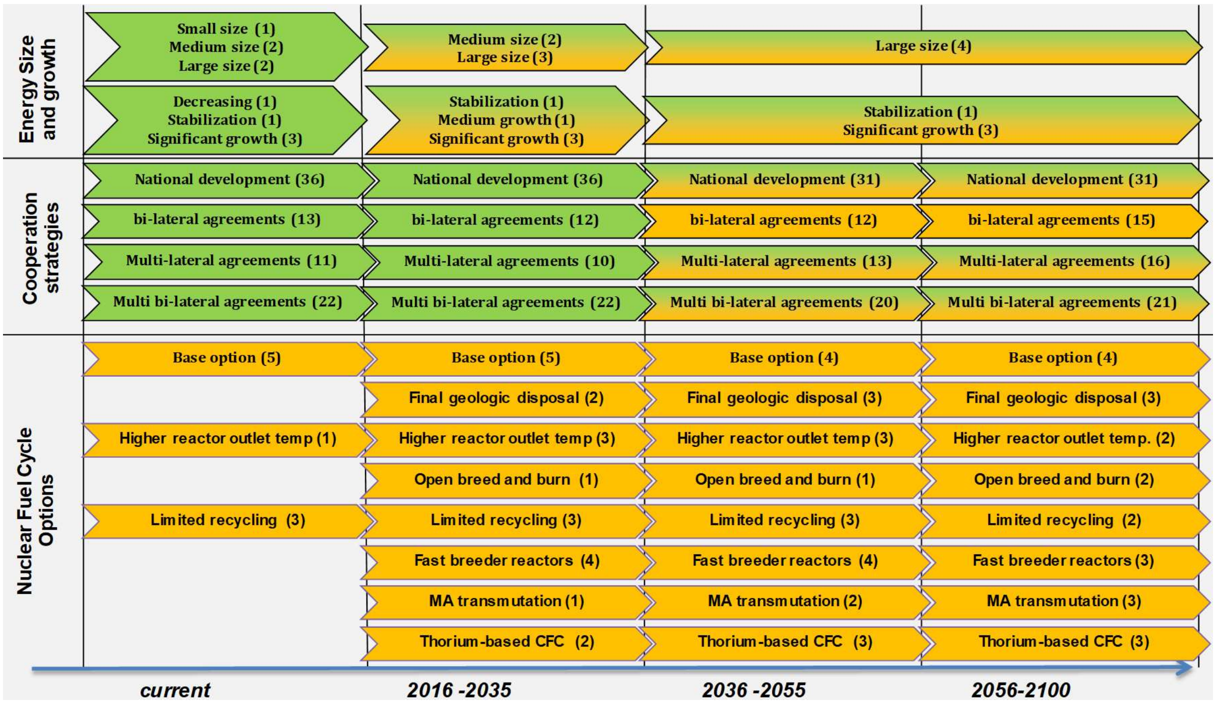


FIG. IX.1. Simplified chart for summary of technology holder countries. Green indicates official plans and yellow shading indicates expert opinion . Legend: MA — minor actinide; CFC — closed fuel cycle.

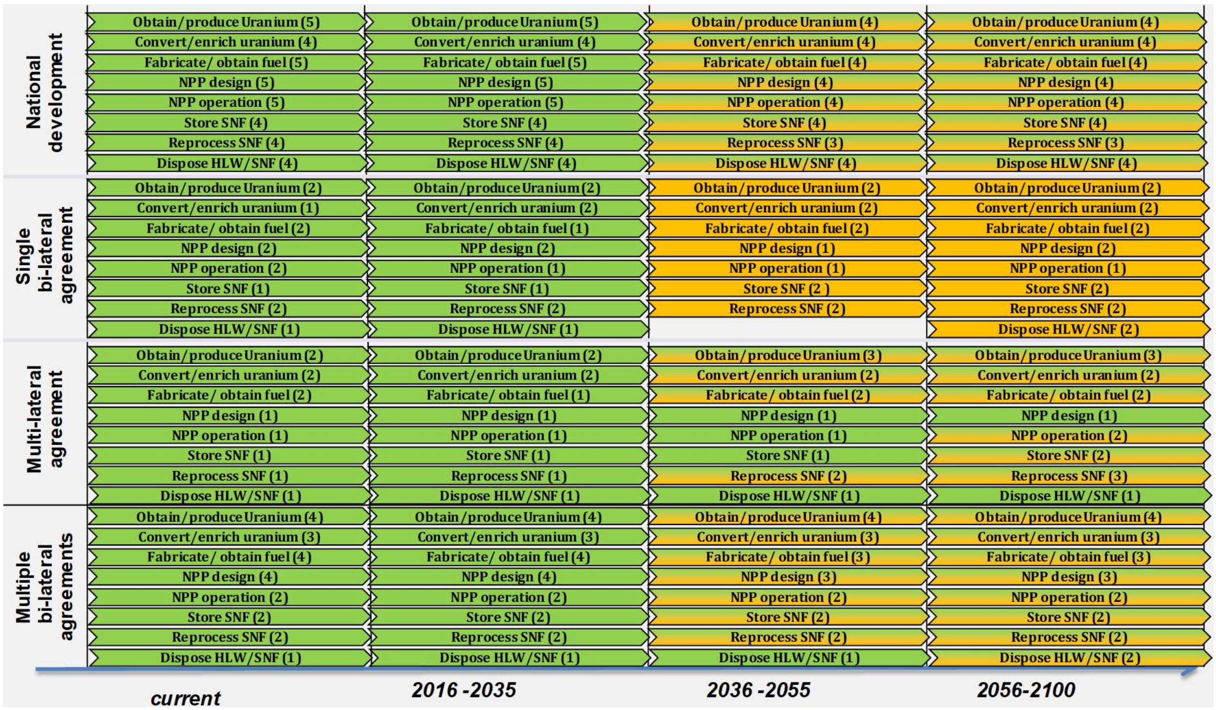
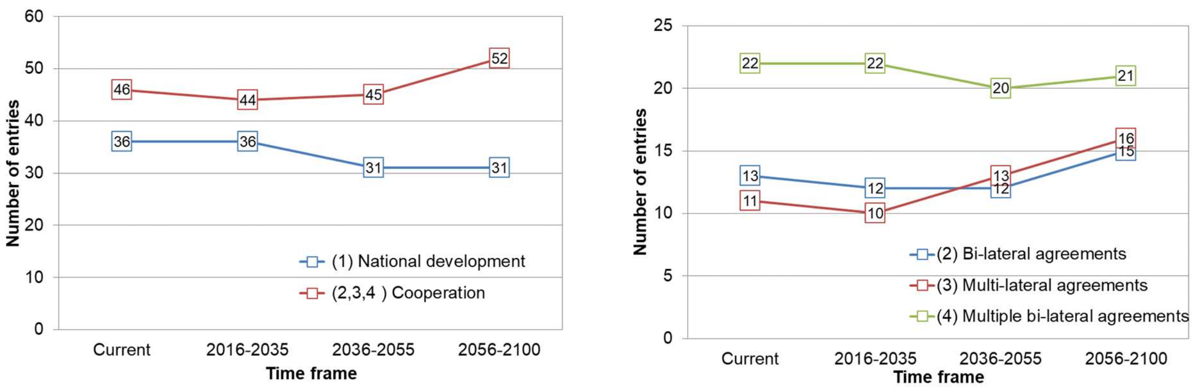


FIG. IX.2. Simplified chart for summary of technology holder countries. Green indicates official plans and yellow indicates expert opinion. Legend: SNF — spent nuclear fuel.



(a) (b)

FIG. IX.3. National development and cooperation options for the technology holder countries, showing (a) planned rates of national development and cooperation and (b) preferences for different types of agreement.

IX.2.2.3. Summary of 'preferable options to enhance nuclear energy sustainability for the countries'

For technology holder countries, Option A (Base nuclear energy option) continues to be the most preferable option during the century with a slight decline by the end of the century. Options C (higher reactor outlet temperatures to open new energy markets) and D (once-through breed and burn) also contribute, but with a lower number of entries for the whole period. Option E (limited recycling of used fuel) is slightly decreasing in the long term. This decrease may be real or it may just be due to respondents who did not fill out the information corresponding to the long term column. Option F (fast breeder reactors with breeding ratio ≥ 1) and a closed fuel cycle) comes second after the base option in the short and medium term and becomes equal with other options in the long term. Options G (minor actinide transmutation) and H (thorium based closed fuel cycle) have one and two entries, respectively, in the short term, indicating a slowly increasing rate during the medium term and reaching three entries by the end of the century. Option B (safe disposal of spent nuclear fuel) has as small a number of entries as the G and H options, whereas this option should complete any other option.

IX.2.3. Metrics aggregation for technology user countries

The entries for the technology user countries are summarized in Figs IX.4–IX.6. As in the case of technology holder countries, most entries provided information on nuclear energy capacity and growth and on NES collaboration strategies as an official plan for the short term and as a scenario study or expert opinion for the medium and long terms.

IX.2.3.1. Summary of 'national prospects for nuclear energy size and growth'

For the technology user countries, a small capacity of nuclear energy appears to be preferred in the short, medium and long terms, with very limited medium scale in the long term. Stabilization and small growth were identified in most countries during the whole period until the end of the century.

IX.2.3.2. Summary of 'NES collaboration strategy until the end of the century'

Entries gave a similar importance to collaboration strategies (including bilateral, multilateral and multiple bilateral agreements) and national development in the short term. In the medium and long term, cooperation has significant growth (32 and 42 entries in the medium and long terms, respectively), while reliance on national development is decreasing (20, 16 and 16 entries in the short, medium and long terms, respectively; see Fig. IX.6 (a)). The priorities in the short term are collaborations on:

— NPP design (7);
— Fabricating and obtaining fuel (6);
— Reprocessing spent nuclear fuel (3);
— NPP operation (2);
— Obtaining and producing uranium (2);
— Converting and enriching uranium (2);
— Storing spent nuclear fuel (1);
— Disposing HLW and spent nuclear fuel (0).

In the medium term, NPP design, fabricating and obtaining fuel, and storing spent nuclear fuel share the first place, with seven entries each. In the long term, disposing HLW and spent nuclear fuel (11) moves to the first place, with the next priority being reprocessing spent nuclear fuel (7), NPP design (6), storing spent nuclear fuel (6) and fabricating and obtaining fuel (5), as follows:

— NPP design (7 in the medium term, 6 in the long term);
— Storing spent nuclear fuel (7, 6);
— Fabricating and obtaining fuel (7, 5);
— Reprocessing spent nuclear fuel (3, 7);
— Disposing HLW and spent nuclear fuel (2, 11);
— NPP operation (2, 2);
— Converting and enriching uranium (2, 3);

— Obtaining and producing uranium (2, 2).

Multilateral agreements are the leader among collaboration strategies (10, 12 and 15 entries in the short, medium and long terms, respectively). Bilateral agreements take the second place (8) in the short term and the last place (12) in the long term. The multiple bilateral agreements strategy has the lowest number of entries (5) in the short term and the same number of entries (15) as the leader in the long term (see Fig. IX.6 (b)).

IX.2.3.3. Summary of 'preferable options to enhance nuclear energy sustainability for the countries'

For technology user countries, Option A (Base nuclear energy option) is steadily preferred during the whole period.

Option C (higher reactor outlet temperatures to open new energy markets) appears only in the long term, and Option D (once-through breed and burn) shows a low rate starting from two entries in the short term and finishing with three entries in the long term. Unlike in the technology holder group of countries, Option E (limited recycling of used fuel) has only one entry in the short term, three entries in the medium term and four entries in the long term. Option F (fast breeder reactors with breeding ratio ≥ 1 and a closed fuel cycle) appears only in the medium term (two entries) and the long term (three entries). There is some slowly growing interest in Option G (minor actinide transmutation) during the considered period. Option H (thorium based closed fuel cycle) has only one response in the medium and long term. Option B (safe disposal of spent nuclear fuel) has significant interest, being the second preferred option after Option A (base nuclear energy option).

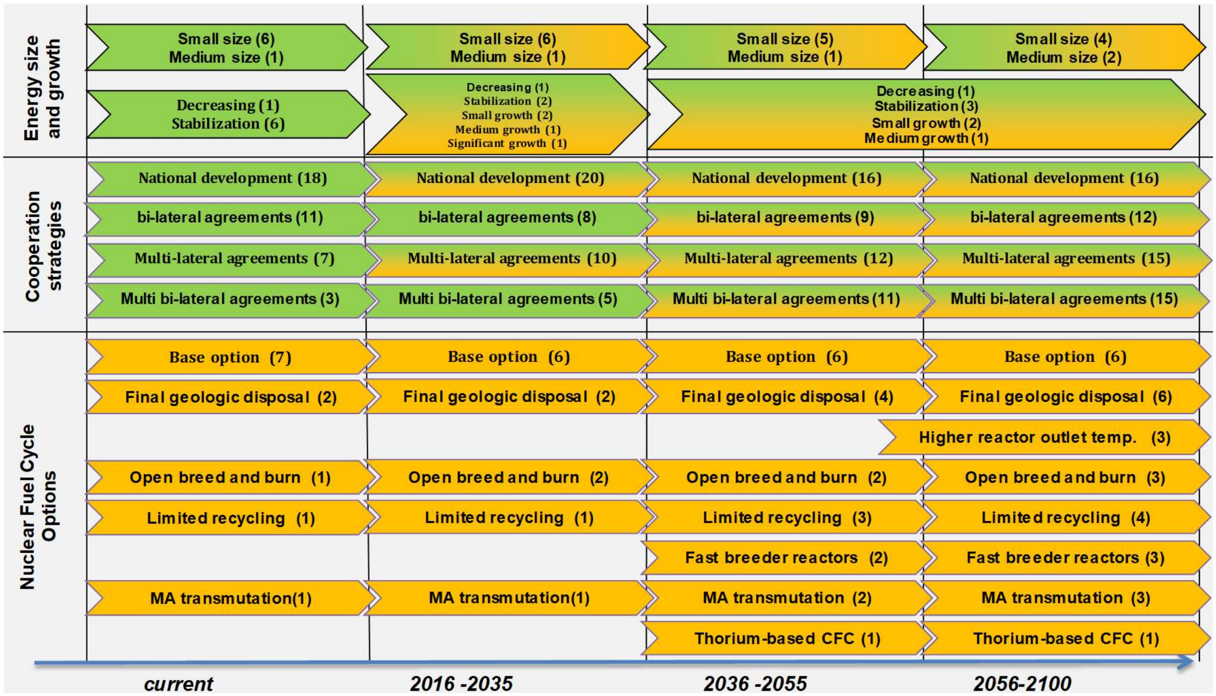


FIG. IX.4. Simplified chart for summary of technology user countries. Green indicates official plans and yellow indicates expert opinion. Legend: MA — minor actinide; CFC — closed fuel cycle.

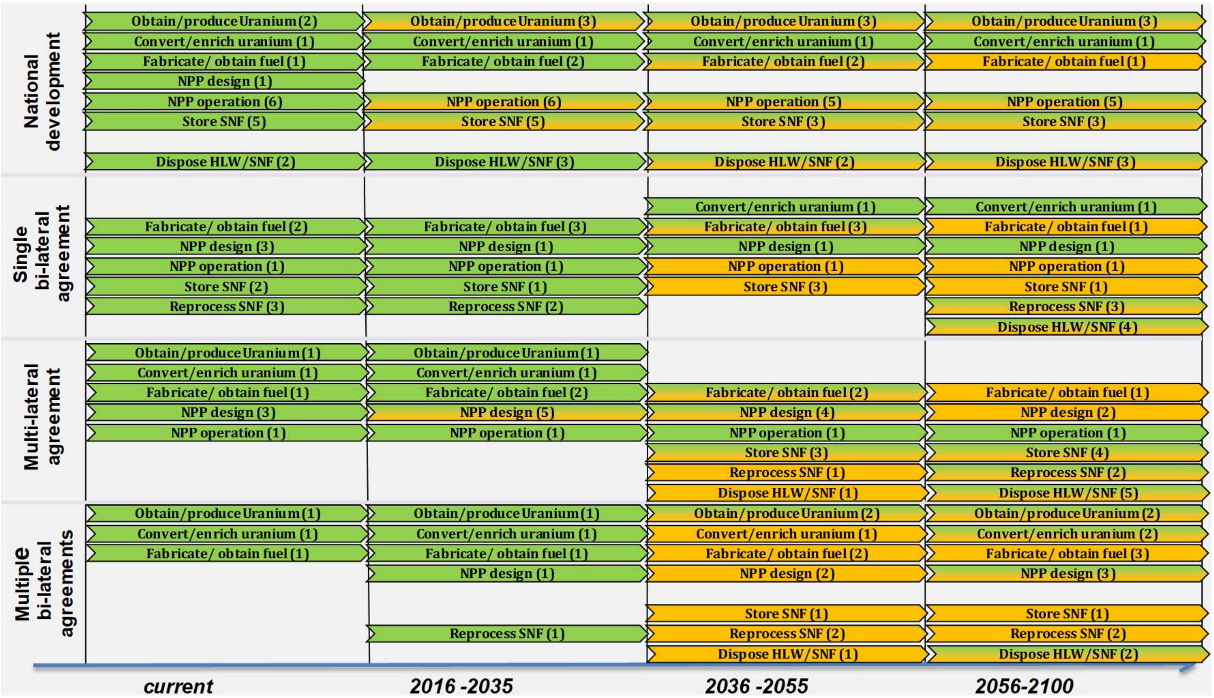
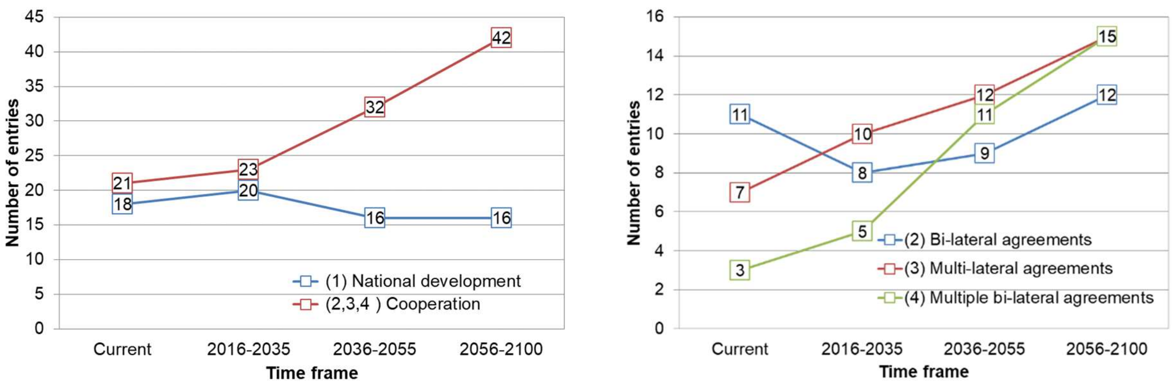


FIG. IX.5. Simplified chart for summary of technology user countries. Green indicates official plans and yellow indicates expert opinion. Legend: SNF — spent nuclear fuel.



(a) *(b)*

FIG. IX.6. National development and cooperation options for the technology user countries, showing (a) planned rates of national development and cooperation and (b) preferences for different types of agreement.

IX.2.4. Metrics aggregation for newcomer countries

The entries for newcomer countries are summarized in Figs IX.7–IX.9. Most entries provided information on nuclear energy capacity and growth and on NES collaboration strategies as an official plan for the short term and as a scenario study or expert opinion for the medium and long terms.

IX.2.4.1. Summary of 'National prospects for nuclear energy capacity and growth until the end of the century'

For newcomer countries, as in the case of the technology user countries, small capacity is preferred in the short and medium term. However, contrary to the technology user countries, medium capacity enjoys a similar preference to the small in the long term. Growth also looks more optimistic than in technology user countries. Medium and small growth was identified in most newcomer countries until the end of the century. More significant growth was identified in one response.

IX.2.4.2. Summary of 'NES collaboration strategy until the end of the century'

Among the respondents, collaboration is perceived to be very important (43, 55 and 58 entries in the short, medium and long terms, respectively). National development received less priority (16, 26 and 28 entries in the short, medium and long terms, respectively; see Fig. IX.9 (a)).

The priorities in the short term are collaborations on:

- Fabricating and obtaining fuel (8);
- NPP design (8);
- NPP operation (7);
- Converting and enriching uranium (7);
- Storing spent nuclear fuel (5);
- Obtaining and producing uranium (5);
- Disposing HLW and spent nuclear fuel (3).

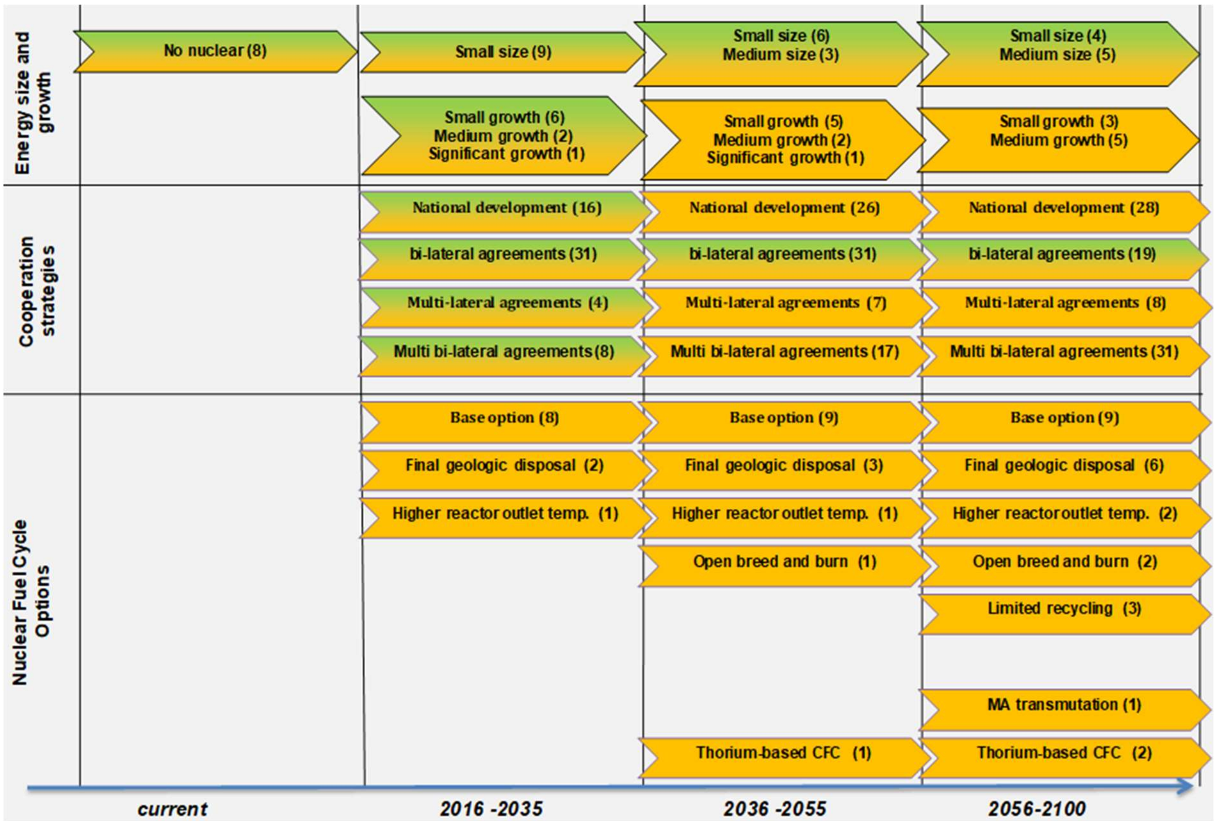


FIG. IX.7. Simplified chart for summary of newcomer countries. Green indicates official plans and yellow indicates expert opinion. Legend: MA — minor actinide; CFC — closed fuel cycle.

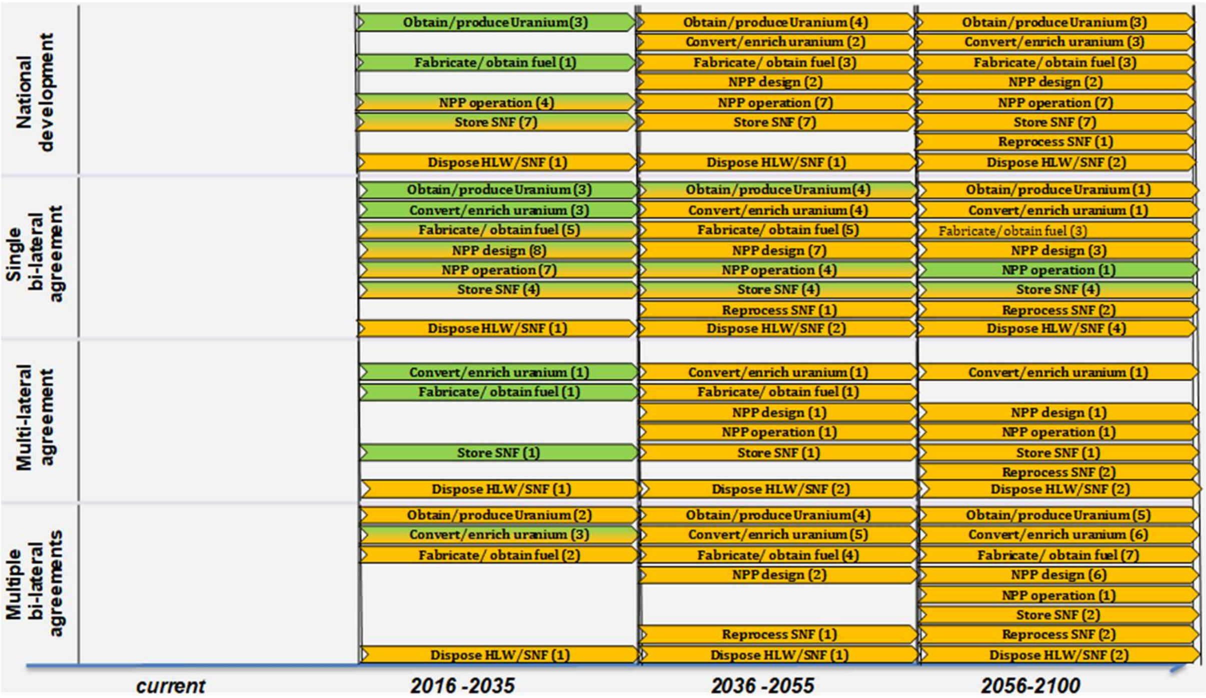
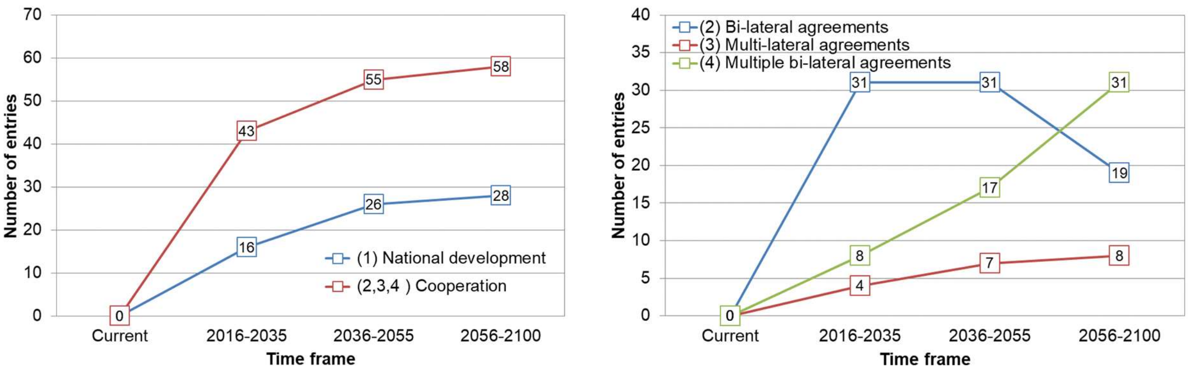


FIG. IX.8. Simplified chart for summary of newcomer countries. Green indicates official plans and yellow indicates expert opinion.



(a) *(b)*

FIG. IX.9. National development and cooperation options for the newcomer countries, showing (a) planned rates of national development and cooperation and (b) preferences for different types of agreement.

In the short term, collaborations for reprocessing spent nuclear fuel were not considered of interest.

In the medium and long terms, NPP design (10) and fabricating and obtaining fuel (10) are in first place, whereas disposing HLW and spent nuclear fuel and storing spent nuclear fuel received less importance:

— Fabricating and obtaining fuel (10 in medium term, 10 in the long term);
— NPP design (10, 10);

— Converting and enriching uranium (10, 8);
— Obtaining and producing uranium (8, 6);
— Disposing HLW and spent nuclear fuel (5, 8);
— Storing spent nuclear fuel (5, 7);
— NPP operation (5, 3);
— Reprocessing spent nuclear fuel (2, 6).

Bilateral agreements are the leader among collaboration strategies (31entries in both the short and medium terms), with significant reduction to 19 entries in the long term. Multiple bilateral agreements take the second place (8, 17) in the short and medium terms and become the leader (31) in the long term. Multilateral agreements received the lowest number of entries (4, 7, 8) for the short, medium and long terms, respectively, over the whole period (see Fig. IX.9 (b)).

IX.2.4.3. Summary of 'preferable options to enhance nuclear energy sustainability'

For newcomer countries Option A (base nuclear energy option) is steadily preferred during the whole period, as in the cases of the technology holder and technology user countries. Options C (higher reactor outlet temperatures to open new energy markets) and D (once-through breed and burn) show a low preference, starting from one response in the short term and medium term and finishing with two entries in the long term. Option E (limited recycling of used fuel) appears only in the long term with three entries. There is no interest for Option F (fast breeder reactors (breeding ratio ≥ 1) and a closed fuel cycle). There is minor interest for Options G (minor actinide transmutation) and H (thorium based closed fuel cycle) by the end of the period. Option H (thorium based closed fuel cycle) has only one response in the medium term and two in the long term. Option B (safe disposal of spent nuclear fuel) has received significant interest, with the number of entries for this option taking the second place after Option A (base nuclear energy option).

IX.3. APPLICATION OF ROADMAP TEMPLATE TO GAINS SCENARIOS

This section provides the results of the trial application of the roadmap template to GAINS scenarios including cross-cutting analysis using roadmap templates for NG1, NG2 and NG3 groups (nuclear group 1, nuclear group 2 and nuclear group 3), regarding cooperation in the nuclear fuel cycle with the indication of key developments, events and relevant metrics.

IX.3.1. Overview of the GAINS INPRO collaborative project

The INPRO collaborative project has developed an analytical framework for evaluating transition scenarios to future sustainable NESs and conducted sample analyses GAINS [IX.1]. The framework includes a set of elements helping interested Member States to model national and regional NESs, taking into account the potential of technical innovation and various forms of cooperation.

Long term projections for nuclear power evolution were considered the starting point of NES modelling. Different types of NES architectures were defined in the framework, these being: homogeneous BAU scenarios based on PWRs and HWRs operated in a once-through fuel cycle; scenarios for a closed fuel cycle using thermal and fast reactors (BAU-FR) for comparison with the BAU scenarios; and innovative scenarios for thorium fuel and for minor actinide utilization in accelerator driven systems or molten salt reactors.

A specific feature of the framework is a heterogeneous world model comprising groups of non-personified, non-geographical countries with differing fuel cycle strategies. The next element is a metric for transition scenario analyses and evaluations based on the concept of key indicators. The GAINS framework includes a collection of data for the material flow analysis of nuclear energy scenarios comprising existing and conceptual reactor designs and related nuclear fuel cycle technologies. A material flow analysis method and economic tools developed by the IAEA and in some Member States were analysed and applied for NES simulations.

IX.3.2. Purpose of the roadmap

The roadmap template is used to integrate the results of the GAINS collaborative project. The main purpose of this case study is to apply the roadmap template to the GAINS heterogeneous scenario based on the introduction of the BAU+FR scenario for the illustration of regional cross-cutting analysis. The study identified savings in time and resources on the way to a more sustainable regional and global NES that could be achieved through innovative technologies and cooperation among country groups. The analysis provides a balance of nuclear materials and services for technology holder and user countries.

IX.3.3. Metrics on nuclear energy position and development for NG1, NG2 and NG3 countries

This section presents the analysis of metrics on nuclear energy position and development for NG1, NG2 and NG3 countries. Time frames were identified as current, short term (current year to 2030), medium term (2031–2050) and long term (2051–2100). Table IX.3 provides colour codes for associated time frames.

TABLE IX.1. TIME FRAMES IDENTIFIED IN THE STUDY

Current	Current year (c.y.)
Short term	c.y.–2030
Medium term	2031–2050
Long term	2051–2100

The study considers three country groups: NG1 recycles spent nuclear fuel and pursues a fast reactor programme; NG2 directly disposes of spent fuel or sends it for reprocessing to NG1 countries and NG3 sends spent nuclear fuel to NG1 or NG2 countries. Nuclear energy production for each group in the nominal case of the moderate and high GAINS scenarios of nuclear energy demand are summarized in Fig. IX.10. The global growth curves from the GAINS publication [IX.1] start with current global nuclear electricity generation as of 2008, with growth to 2100. After 2100, the generation level is held at 2500 GW(e)/year for the moderate case and 5000 GW(e)year for the high case. In the nominal case the shares of nuclear energy generation in groups related to total nuclear energy generation by the year 2100 are 40% for NG1, 40% for NG2 and 20% for NG3.

Nuclear Energy Size , GWyear				
	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
NG1	149	285/333	455/682	1000/2000
NG2	149	285/333	455/682	1000/2000
NG3	0	30/34	90/136	500/1000
World total	298	600/700	1000/1500	2500/5000

FIG. IX.10. Scenarios of nuclear energy generation for moderate and high GAINS demands.

Domestic technology options of NG1 consist of the once-through nuclear fuel cycle during the whole century with transition to the complete recycling of spent fuel in the medium and long term and final geological disposal facilities for highly radioactive waste in the long term. Domestic technology options of NG2 include the once-through nuclear fuel cycle for all time frames and final geological disposal facilities for spent fuel in the long term. The group NG3 has no plans to build, operate or manage fuel recycling facilities or permanent geological disposal facilities for highly radioactive waste (Table IX.4).

TABLE IX.2. DOMESTIC TECHNOLOGY OPTIONS

National technology options/country group classification	Once-through nuclear fuel cycle	Complete recycle of spent nuclear fuel	Final geological disposal of all wastes
NG1	Current	Medium term	Long term
	Short term	Long term	
	Medium term		
	Long term		
NG2	Current		Long term
	Short term		
	Medium term		
	Long term		

Access of user groups to the technology options of the technology holder group is schematically illustrated in Fig. IX.11. The groups NG2 and NG3 have access to the following technology options of NG1: once-through nuclear fuel cycle; complete recycle of spent fuel; and final geological disposal of all wastes. Additionally, the group NG3 has access to the options including once-through nuclear fuel cycle and final geological disposal of spent nuclear fuel of NG2.

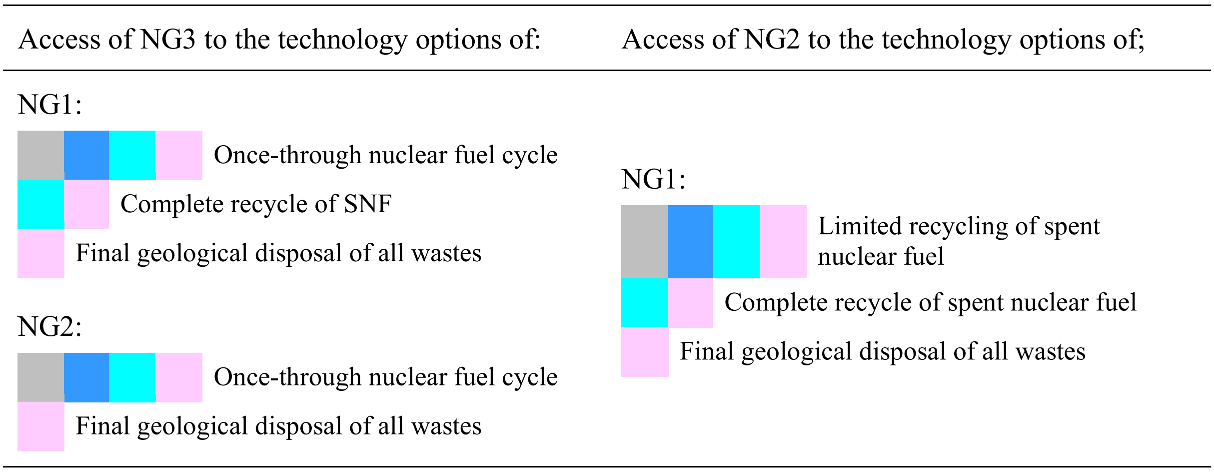


FIG. IX.11. Access of the user group to the technology options of the holder group

Domestic reactor and fuel cycle technologies and deployment time frames in different country groups are given in Fig. IX.12. The NES of NG1 countries combines a once-through cycle based on LWRs and a closed cycle based on break-even FRs (breeding ratio ~1) with reprocessing of LWR spent fuel for recycle in FRs. Domestic fuel cycle technologies of NG1 include uranium and plutonium fuel fabrication, wet and dry spent nuclear fuel storage, spent nuclear fuel reprocessing and geological disposal of HLW. The NG2 NES is based on LWRs and HWRs operated in the once-through fuel cycle. The fuel cycle of NG2 countries includes uranium fuel fabrication, wet and dry spent nuclear fuel storage and geological disposal of spent nuclear fuel. The countries of NG3 use an NES based on LWRs with the necessary LWR infrastructure, but without infrastructure for spent nuclear fuel reprocessing and geological disposal of HLW.

Domestic Technology	c.y.	c.y. – 2030	2031 – 2050	2051 – 2100
LWR	NG1/NG2/NG3	NG1/NG2/NG3	NG1/NG2/NG3	NG1/NG2/NG3
HWR	NG2	NG2	NG2	NG2
FR		NG1	NG2	NG3
Uranium fuel fabrication	NG1/NG2	NG1/NG2	NG1/NG2	NG1/NG2
Plutonium fuel fabrication		NG2	NG2	NG2
Wet SNF storage	NG1/NG2/NG3	NG1/NG2/NG3	NG1/NG2/NG3	NG1/NG2/NG3
Dry SNF storage	NG1/NG2	NG1/NG2	NG1/NG2	NG1/NG2
Aqueous SNF reprocessing		NG1	NG1	NG1
Advanced SNF reprocessing		NG1	NG1	NG1
Geological disposal				NG1/NG2

FIG. IX.12. Domestic reactor and nuclear fuel cycle technologies and deployment time frames in different country groups. Legend: SNF – spent nuclear fuel.

Table IX.5 compiles a collaboration matrix on the nuclear fuel cycle. NG1 is a provider of front end services including uranium conversion and enrichment, fuel fabrication and back end services such as storage of spent nuclear fuel, reprocessing of spent nuclear fuel and disposal of HLW. NG2 provides services including uranium conversion and enrichment, fuel fabrication and back end services for the storage and disposal of spent nuclear fuel. Group NG3 uses front end and back end services provided by NG1 and NG2 groups. The group NG3 obtains fabricated fuel from NG2 and NG1 and exports its spent fuel for either recycle or disposal. The group NG2 cooperates with NG1 to recycle fuel in NG1 and to geologically dispose highly radioactive waste in the form of reprocessing waste.

TABLE IX.3. COLLABORATION MATRIX ON NUCLEAR FUEL CYCLE

		Service provider	
		NG1	NG2
Service user	NG3	Conversion of uranium Enrichment of uranium Fabrication of fuel Storage of spent nuclear fuel Reprocessing of spent nuclear fuel Dispose of HLW	Conversion of uranium Enrichment of uranium Fabrication of fuel Storage of spent nuclear fuel Disposal of spent nuclear fuel
	NG2	Reprocessing of spent nuclear fuel Disposal of HLW	

IX.3.4. Key developments to enhance sustainability for NG1, NG2 and NG3 countries

A cross-matching of service provision and usage for NG1, NG2 and NG3 for the short, medium and long terms is given in Fig. IX.13. The NG3 group follows a strategy to limit infrastructure investments in the NES. NG1 and NG2 would need to augment their fuel cycle infrastructure to support this strategy.

In the short term, NG1 and NG2 groups sell LWRs to the NG3 and provide fresh fuel for LWRs. The NG3 group purchases LWRs and obtains on-time front end services from NG1 and NG2. In the short term, NG3 sends its spent nuclear fuel back to NG1 and NG2, which take it back during this term, so that the service supply by NG1 and NG2 match the service usage by NG3.

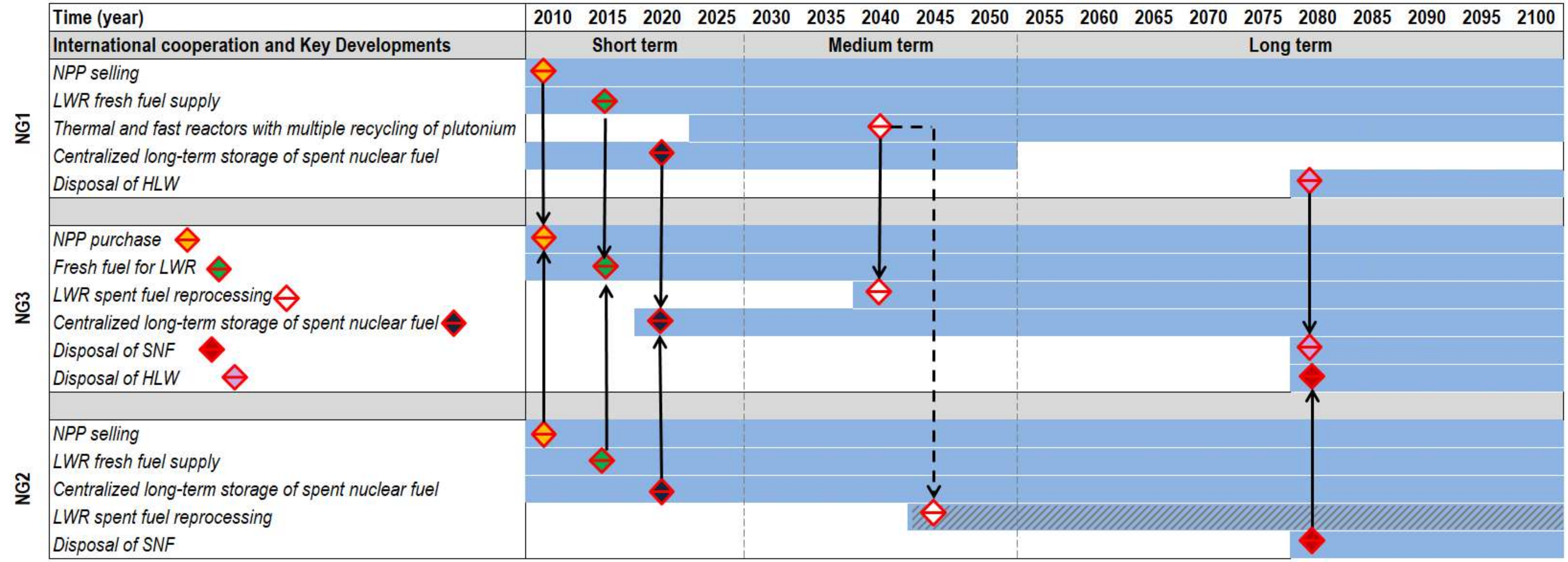


FIG. IX.13. Cross- matching of services provision and usage for NG1, /NG2 and /NG3. Legend: SNF — spent nuclear fuel.

In the medium term, NG1 deploys and manages recycling facilities and offers spent nuclear fuel reprocessing services for NG3 and NG2. This goes in line with the NG3 back end strategy for recycling spent nuclear fuel abroad during this period. NG2 could also send its spent nuclear fuel for reprocessing to the NG1 as a possible option.

In the long term, the NG1 and NG2 groups plan to build, operate and manage permanent geological facilities for highly radioactive waste in the form of used fuel for NG2 and reprocessing waste for NG1. Both groups provide HLW disposal service for NG3.

The commissioning of nuclear fuel cycle facilities for FRs can be considered key tasks that are consistent with key developments and enhance the sustainability of the NES in NG1. A high cost of electricity would potentially be found during the phase of introduction of innovative technologies. Considerations of future system benefits could possibly counter a potential loss in economics of a first of a kind unit.

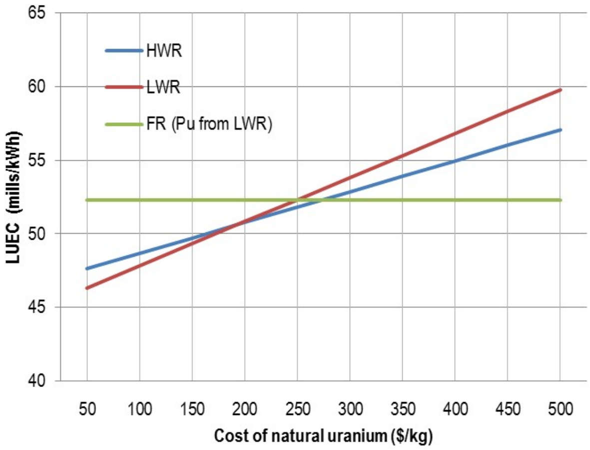


FIG. IX.14. LCOE depending on natural uranium cost for LWR, HWR and FR.

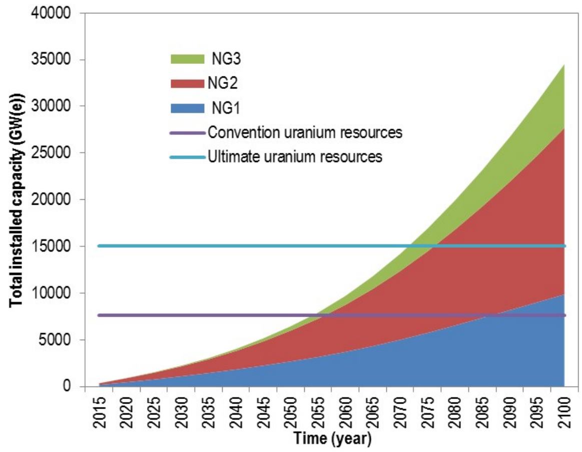


FIG. IX.15. Total cumulative uranium usage and comparison with projected resources.

In the field of economics, the relationship between the unit cost of electricity for thermal and FRs is important. Figure IX.14 gives the LCOE depending on natural uranium cost for LWR, HWR and FRs based on Ref. [IX.2]. Under the assumptions in that reference, the levelized unit electricity cost for FRs reaches the level of electricity cost from LWRs and HWRs at a natural uranium cost of about 250 US $/kg U. The timing of this event depends on the demand growth for LWRs and HWRs and the associated exhaustion of uranium at a cost of less than 250 US $/kg U. This is the time when the cumulative natural uranium demand is compared with projected conventional resources (17 Mt of identified and undiscovered resources according to the Red Book 2016 [IX.3]). The detailed analysis of cumulative uranium demand performed in Section 4 shows that all conventional uranium resources would be exhausted by 2070 (Fig. IX.15). The more ambitious development task for an NES is to provide essential economic advantages in the energy sector that can be solved through R&D and institutional arrangements.

IX.3.5. Cross-cutting analysis of reactor fleet and nuclear fuel cycle for NG1, NG2 and NG3 countries

A cross-cutting analysis using the roadmap template was performed for the NG1, NG2 and NG3 groups regarding cooperation in the nuclear fuel cycle.

IX.3.5.1. Reactor fleet and energy production

The world reactor fleet is composed of three reactor types, namely LWR, HWR and FR. NG2 uses LWRs and HWRs operated in a once-through fuel cycle. A closed fuel cycle strategy in NG1 is based on LWRs and FRs. NG3 introduces LWRs in a once-through mode from the beginning of the considered time period.

The reactor fleet in each group by reactor type is shown in Fig. IX.16. The world nuclear power generation splits in half between NG1 and NG2 from thermal reactors at the beginning of the time horizon. The overall growth curves retain a 6% share for HWRs with the other 94% split between the LWRs and FRs. The total fast reactor energy generation during a year is constrained at 10 GW(e)/year in 2030 and 400 GW(e)/year in 2050 in accordance with the high case scenario of the GAINS framework. To obtain the required reactor capacity in GW(e), these numbers are divided by the load factor of 0.85.

Total installed capacity, GW(e)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
LWR NG3	7	17	27	36	55	87	119	152	214	322	430	538	646	754	862	970	1077	1185
LWR NG2	187	237	282	328	385	477	571	664	769	906	1044	1183	1321	1460	1598	1737	1876	2014
HWR NG2	24	31	38	44	53	66	80	95	111	136	160	185	210	234	259	284	308	333
LWR NG1	212	270	320	366	383	404	433	461	503	584	666	741	801	847	880	903	919	925
FR NG1			2	8	54	135	210	286	362	439	516	601	700	812	935	1069	1208	1358
Total, GW(e)	**430**	**555**	**669**	**782**	**929**	**1169**	**1413**	**1658**	**1959**	**2386**	**2817**	**3247**	**3677**	**4106**	**4534**	**4962**	**5389**	**5816**

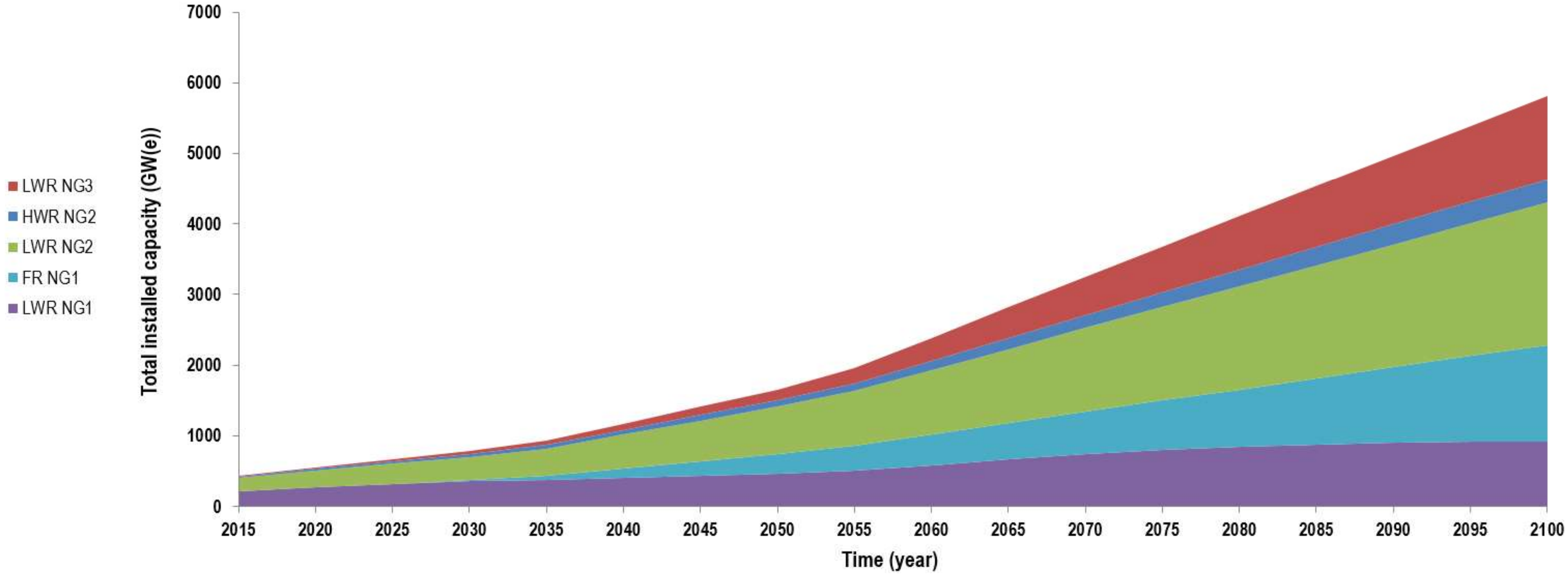


FIG. IX.16. Reactor fleet in NG1, NG2 and NG3 by reactor type.

IX.3.5.2. Data preparation

Input data for nuclear fuel cycle front end and back end requirements were prepared using the MESSAGE tool [IX.4]. The MESSAGE multiregional model was constructed for developing long term scenarios under different conditions for cooperation among countries. General characteristics of the thermal and FRs used in scenario simulations were taken from the GAINS project [IX.1]. The once-through fuel cycle consists of steps in uranium mining, conversion, enrichment, depleted uranium storage, fuel fabrication, NPP operation, spent nuclear fuel storage at the NPP and spent nuclear fuel long term storage. A combined once-through fuel cycle based on LWRs and an FR has all front end and back end facilities, including a spent nuclear fuel reprocessing facility for the separation of plutonium and storage for minor actinides, uranium and radioactive waste.

Outputs of the model include year by year data on power production, nuclear material resources, discharged fuel, radioactive waste and minor actinides, and nuclear fuel cycle services. These data were aggregated by five year periods for each group for input into the roadmap and for the performance of cross-cutting comparisons and analyses.

IX.3.5.3. Uranium consumption

The cumulative natural uranium demand for all NG groups is presented in Fig. IX.16. All NGs are assumed to have equal access to the natural uranium market. The cumulative consumption is around 17 million tonnes by 2070, and this amount is comparable with available conventional natural uranium at a price of less than US $250/kg U as estimated in Ref. [IX.3].

Uranium requirements	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Uranium requirements NG1, ktHM																		
Uranium requirements for LWR (annual)	43	55	63	71	71	79	86	89	100	115	130	141	153	160	164	167	167	168
Uranium requirements for LWR (cumulative)	174	450	749	1087	1441	1821	2235	2681	3150	3696	4314	4997	5738	6526	7338	8167	9001	9846
Total annual requirements (NG1)	**43**	**55**	**63**	**71**	**71**	**79**	**86**	**89**	**100**	**115**	**130**	**141**	**153**	**160**	**164**	**167**	**167**	**168**
Total cumulative requirements (NG1)	**174**	**450**	**749**	**1087**	**1441**	**1821**	**2235**	**2681**	**3150**	**3696**	**4314**	**4997**	**5738**	**6526**	**7338**	**8167**	**9001**	**9846**
Uranium requirements NG2, ktHM																		
Uranium requirements for LWR	37	48	56	65	82	100	119	134	154	179	204	229	256	281	306	331	361	387
Uranium requirements for HWR	4	5	6	7	8	10	12	14	17	21	24	28	32	35	39	43	46	50
Uranium requirements for LWR (cumulative)	152	393	657	962	1333	1799	2354	2997	3719	4567	5536	6631	7854	9212	10692	12296	14040	15928
Uranium requirements for HWR (cumulative)	16	40	67	99	136	183	240	308	387	484	599	732	883	1052	1240	1446	1670	1913
Total annual requirements (NG2)	**41**	**53**	**62**	**71**	**90**	**110**	**131**	**148**	**171**	**200**	**228**	**257**	**287**	**317**	**345**	**374**	**408**	**437**
Total cumulative requirements (NG2)	**167**	**433**	**724**	**1061**	**1469**	**1982**	**2595**	**3305**	**4107**	**5051**	**6135**	**7363**	**8737**	**10264**	**11932**	**13742**	**15710**	**17840**
Uranium requirements NG3, ktHM																		
Uranium requirements for LWR	2	4	6	7	12	19	24	30	47	68	87	106	126	145	164	183	204	224
Uranium requirements for LWR (cumulative)	6	24	49	82	131	213	323	462	655	954	1350	1841	2430	3117	3899	4776	5753	6833
Total annual requirements (NG3)	**2**	**4**	**6**	**7**	**12**	**19**	**24**	**30**	**47**	**68**	**87**	**106**	**126**	**145**	**164**	**183**	**204**	**224**
Total cumulative requirements (NG3)	**6**	**24**	**49**	**82**	**131**	**213**	**323**	**462**	**655**	**954**	**1350**	**1841**	**2430**	**3117**	**3899**	**4776**	**5753**	**6833**

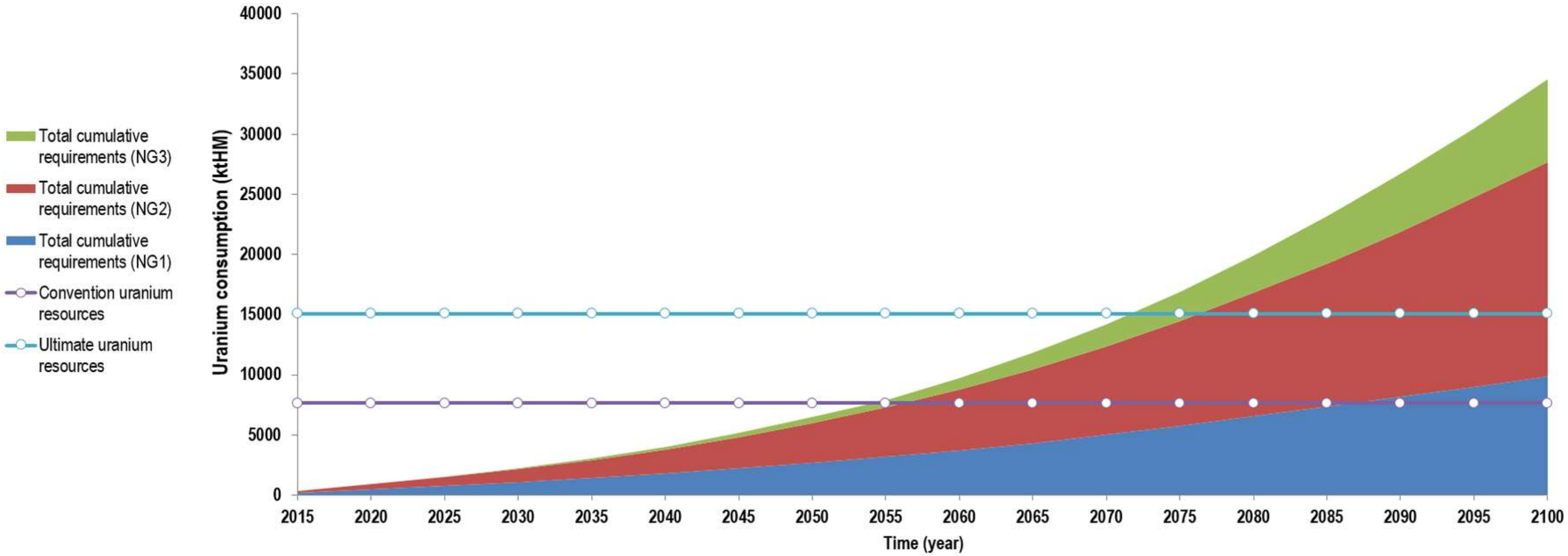


FIG. IX.17. Cumulative natural uranium demand for all NG groups.

IX.3.5.4. Fuel fabrication

According to the analysed scenario, NG1 and NG2 groups have front end fuel cycle facilities, including enrichment and/or fuel fabrication for LWRs, HWRs and FRs. The NG3 group obtain LWR fresh fuel from NG1 and NG2. Figure IX.17 shows annual LWR fuel fabrication in NG1 and NG2 and the LWR fuel export/import between groups. The fuel flows and fuel demands are balanced as:

- The NG3 fuel import matches the fuel export from NG1 and NG2.
- The fuel demand for NG3 balances with the fuel supply from NG1 and NG2.

Material shipments between regions are in line with import/export flows.

Fuel fabrication requirements NG1	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Fuel fabrication requirements NG1, ktHM																		
Fuel fabrication requirements for LWR	4.45	5.88	6.80	7.70	7.84	8.62	9.41	9.94	10.69	12.42	14.10	15.46	16.68	17.65	18.14	18.48	18.46	18.89
Fuel fabrication requirements for FR	0.00	0.00	0.05	0.17	1.21	2.80	4.29	5.80	7.32	8.84	10.38	12.09	14.07	16.32	18.80	21.47	24.39	27.36
Total, ktHM	**4.45**	**5.88**	**6.86**	**7.87**	**9.05**	**11.42**	**13.71**	**15.74**	**18.01**	**21.27**	**24.48**	**27.55**	**30.75**	**33.97**	**36.95**	**39.95**	**42.85**	**46.25**
NG1 Export commitments																		
Export, ktHM	**0**	**0**	**0**	**0**	**1**	1	1	2	3	4	5	6	7	8	9	10	11	12
NG1 export to NG3	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33	12.42
	-0.12	-0.22	-0.31	-0.41	-0.69	-1.03	-1.35	-1.67	-2.61	-3.75	-4.82	-5.89	-6.99	-8.05	-9.11	-10.17	-11.33	-12.42
Fuel fabrication requirements NG2, ktHM																		
Fuel fabrication requirements for LWR	3.88	5.15	6.04	6.94	8.68	10.70	12.77	14.61	16.53	19.35	22.12	24.91	27.74	30.71	33.43	36.16	39.50	42.44
Fuel fabrication requirements for HWR	3.58	4.63	5.58	6.54	7.76	9.80	11.89	13.97	16.44	20.02	23.67	27.32	30.97	34.62	38.27	41.92	45.57	49.22
Total, ktHM	**7.47**	**9.78**	**11.63**	**13.48**	**16.44**	**20.51**	**24.66**	**28.58**	**32.96**	**39.38**	**45.79**	**52.23**	**58.72**	**65.33**	**71.71**	**78.08**	**85.07**	**91.67**
NG2 Export commitments																		
Export, ktHM	**0.12**	**0.22**	**0.31**	**0.41**	**0.69**	**1.03**	**1.35**	**1.67**	**2.61**	**3.75**	**4.82**	**5.89**	**6.99**	**8.05**	**9.11**	**10.17**	**11.33**	**12.42**
NG2 export to NG3	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33	12.42
	-0.12	-0.22	-0.31	-0.41	-0.69	-1.03	-1.35	-1.67	-2.61	-3.75	-4.82	-5.89	-6.99	-8.05	-9.11	-10.17	-11.33	-12.42
Fuel fabrication requirements NG3,ktHM																		
Fuel fabrication requirements for LWR	0.23	0.44	0.63	0.81	1.38	2.06	2.70	3.34	5.22	7.51	9.63	11.77	13.98	16.10	18.22	20.34	22.66	24.83
	-0.23	-0.44	-0.63	-0.81	-1.38	-2.06	-2.70	-3.34	-5.22	-7.51	-9.63	-11.77	-13.98	-16.10	-18.22	-20.34	-22.66	-24.83
Total, ktHM	**0.23**	**0.44**	**0.63**	**0.81**	**1.38**	**2.06**	**2.70**	**3.34**	**5.22**	**7.51**	**9.63**	**11.77**	**13.98**	**16.10**	**18.22**	**20.34**	**22.66**	**24.83**
NG3 Import																		
Import,ktHMU	**0.23**	**0.44**	**0.63**	**0.81**	**1.38**	**2.06**	**2.70**	**3.34**	**5.22**	**7.51**	**9.63**	**11.77**	**13.98**	**16.10**	**18.22**	**20.34**	**22.66**	**24.83**
NG3 import from NG1	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33	12.42
NG3 import from NG2	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33	12.42
Total supply, ktHM	**0.23**	**0.44**	**0.63**	**0.81**	**1.38**	**2.06**	**2.70**	**3.34**	**5.22**	**7.51**	**9.63**	**11.77**	**13.98**	**16.10**	**18.22**	**20.34**	**22.66**	**24.83**
Balance: (NG3 import from NG1) + (NG3 import from NG2) - (NG1 export to NG3) - (NG2 export to NG3)																		
Balance 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Balance: (NG3 demand) -(NG3 import from NG1) - (NG3 import from NG2)																		
Balance 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

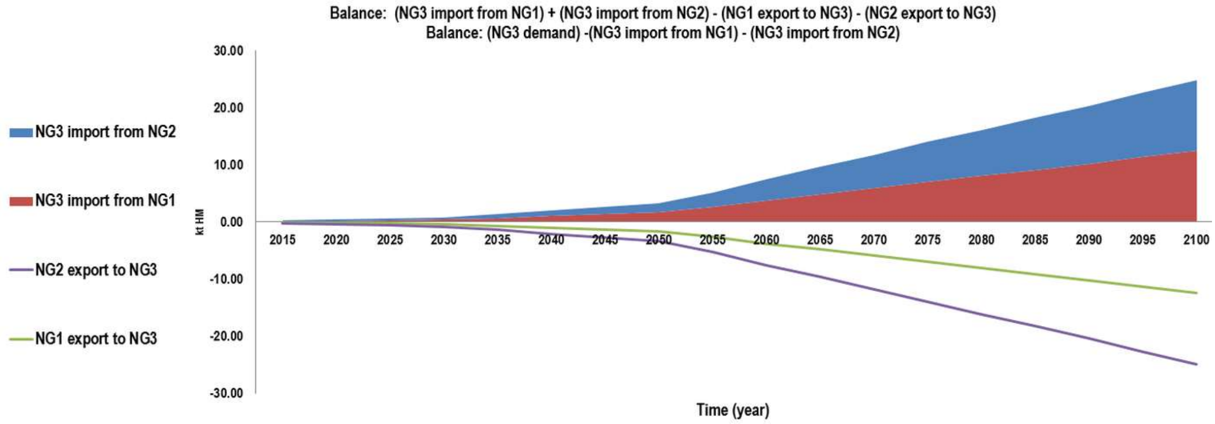


FIG. IX.18. Fuel fabrication for all NG groups.

IX.3.5.5. Spent nuclear fuel storage

Country groups discharge spent fuel from LWRs, HWRs and FRs. However, only LWR spent nuclear fuel is moved between groups. Spent nuclear fuel requirements for LWRs and LWR spent fuel movement between regions are integrated in Fig. IX.18. The NG3 group returns spent fuel to NG1 for reprocessing and to NG2 for storing and disposal. An average annual group export/import balance is kept at zero. The amount of spent fuel returned from NG3 to NG1 and NG2 equals the amount of spent fuel obtained by these groups from NG3, the nuclear material transfer being balanced in the model.

SNF Requirements NG1	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SNF discharge for LWR NG1	4.18	5.31	6.29	7.20	7.85	8.27	9.09	9.64	10.03	11.52	13.21	14.73	16.07	17.22	17.82	18.25	18.39	18.87
SNF discharge for FR NG1																		
Long term Storage LWR NG1	102.68	127.01	147.76	136.36	99.11	63.91	31.95	5.73	0.00									
Long term Storage FR NG1																		
Long term Storage LWR NG3	0.00	0.13	0.69	1.72	3.22	5.27	8.60	13.52	19.74	10.70	0.90	0.11		0.02	0.02	0.11		0.87
Total long term storage for NG1 SNF, ktHM	**102.68**	**127.01**	**147.76**	**136.36**	**99.11**	**63.91**	**31.95**	**5.73**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
NG1 take back commitments																		
Take back, ktHM	**0.12**	**0.12**	**0.22**	**0.31**	**0.41**	**0.69**	**1.03**	**1.35**	**1.67**	**2.61**	**3.75**	**4.82**	**5.89**	**6.99**	**8.05**	**9.11**	**10.17**	**11.33**
NG1 take back from NG3	0.12	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33
	-0.12	-0.12	-0.22	-0.31	-0.41	-0.69	-1.03	-1.35	-1.67	-2.61	-3.75	-4.82	-5.89	-6.99	-8.05	-9.11	-10.17	-11.33
SNF Requirements NG2																		
SNF discharge for LWR NG2	3.67	4.65	5.55	6.44	7.87	9.68	11.75	13.59	15.21	17.85	20.61	23.40	26.24	29.20	31.93	34.65	37.99	40.94
SNF discharge for HWR NG2	3.58	4.63	5.58	6.54	7.76	9.80	11.89	13.97	16.44	20.02	23.67	27.32	30.97	34.62	38.27	41.92	45.57	49.22
Long term Storage LWR NG2	84.20	102.81	124.29	150.24	180.67	216.77	261.64	316.07	380.73	453.00	536.92	634.35	745.60	871.04	1011.42	1165.60	1333.40	1516.28
Long term Storage HWR NG2	53.33	70.53	90.83	115.90	145.45	179.42	222.17	275.36	338.60	411.76	500.93	608.34	734.01	877.92	1040.09	1220.50	1419.17	1636.08
Long term Storage LWR NG3	0.00	0.13	0.69	1.72	3.22	5.27	8.60	13.52	20.03	28.42	41.08	59.04	82.30	111.03	145.16	184.59	229.33	279.51
Total long term storage for NG2 SNF, ktHM	**137.53**	**173.34**	**215.12**	**266.14**	**326.13**	**396.19**	**483.82**	**591.43**	**719.33**	**864.76**	**1037.85**	**1242.69**	**1479.61**	**1748.97**	**2051.50**	**2386.10**	**2752.57**	**3152.36**
NG2 take back commitments																		
Take back, ktHM	**0.12**	**0.12**	**0.22**	**0.31**	**0.41**	**0.69**	**1.03**	**1.35**	**1.67**	**2.61**	**3.75**	**4.82**	**5.89**	**6.99**	**8.05**	**9.11**	**10.17**	**11.33**
NG2 take back from NG3	0.12	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33
	-0.12	-0.12	-0.22	-0.31	-0.41	-0.69	-1.03	-1.35	-1.67	-2.61	-3.75	-4.82	-5.89	-6.99	-8.05	-9.11	-10.17	-11.33
SNFRequirements NG3																		
SNF discharge for LWR																		
NG3 shipment																		
Shipment of colled NG3 SNF to NG1 and NG2	**0.23**	**0.23**	**0.44**	**0.63**	**0.81**	**1.38**	**2.06**	**2.70**	**3.34**	**5.22**	**7.51**	**9.63**	**11.77**	**13.98**	**16.10**	**18.22**	**20.34**	**22.66**
NG3 return to NG1	0.12	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33
NG3 returnto NG2	0.12	0.12	0.22	0.31	0.41	0.69	1.03	1.35	1.67	2.61	3.75	4.82	5.89	6.99	8.05	9.11	10.17	11.33
Balance: (NG1/2 take back from NG3) - (NG3 return to NG1/2)																		
Balance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Requrement: (NG1 long term LWR SNF storage) + (NG3 long term LWR SNF storage)																		
Requiriment 1	102.68	127.14	148.45	138.08	102.32	69.18	40.55	19.24	19.74	10.70	0.90	0.11	0.00	0.02	0.02	0.11	0.00	0.87
Requrement: (NG2 long term LWR SNF storage) + (NG3 long term LWR SNF storage)																		
Requiriment 2	84.20	102.94	124.98	151.97	183.89	222.04	270.24	329.59	400.75	481.42	578.00	693.39	827.91	982.07	1156.57	1350.19	1562.73	1795.79

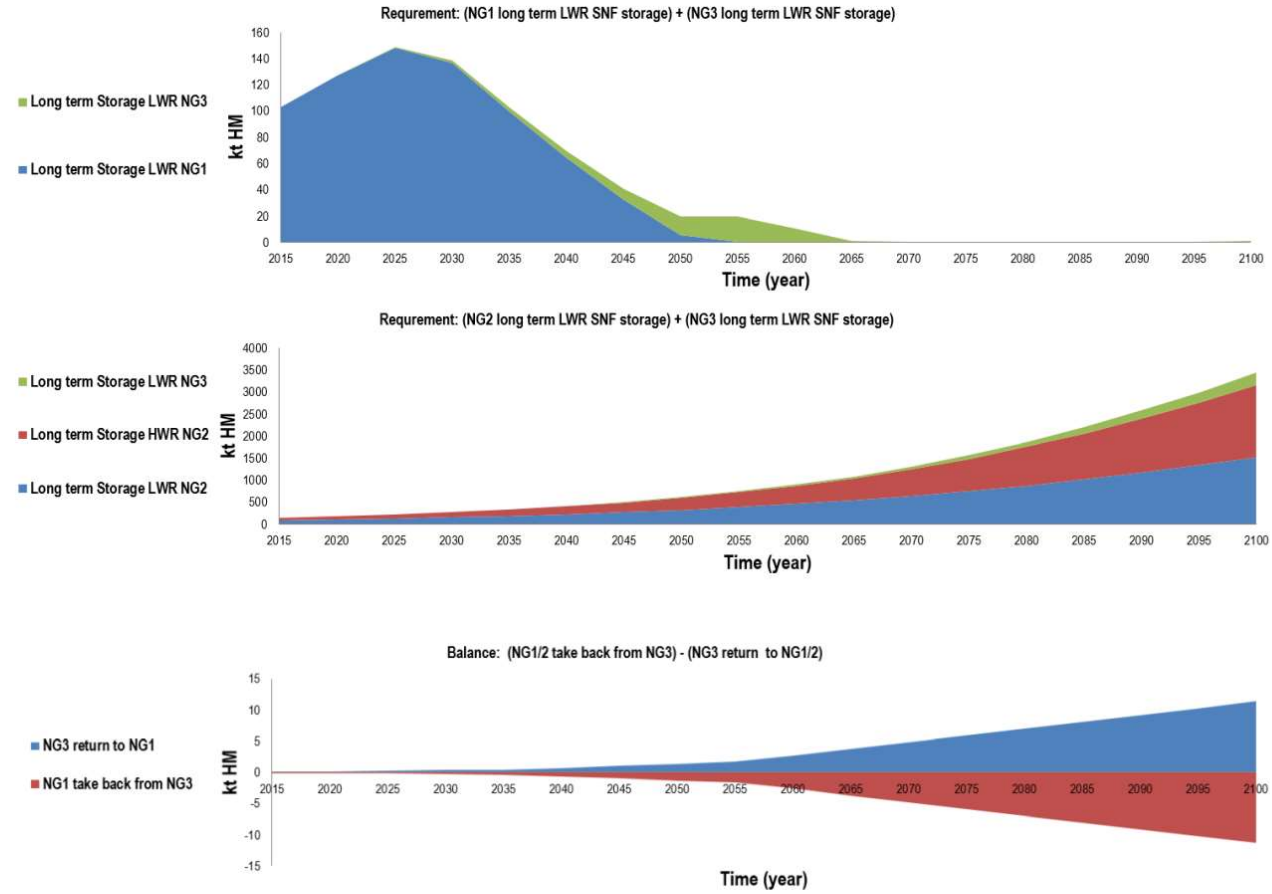


FIG. IX.19. Spent nuclear fuel storage for all NG groups. Legend: SNF — spent nuclear fuel.

Spent fuel accumulation in NG1 long term storage includes spent nuclear fuel from both NG1 and NG3. Shipment of NG3 spent fuel does not significantly impact on long term storage owing to its reprocessing and recycling. The available spent fuel inventory will not be completely used by 2085. NG2 steadily increases spent fuel accumulation, and additional storage facilities need to be built for NG3 spent fuel. It could be noted that, although the energy generation from HWRs is less than that from LWRs, the accumulation of HWR spent fuel is comparable with that of LWR spent fuel.

IX.3.5.6. Spent nuclear fuel reprocessing

Figure IX.19 shows the annual reprocessing load for spent nuclear fuel from LWRs and FRs. It is assumed that reprocessing facilities will operate at full capacity over their lifetime. The LWR reprocessing capacities are optimized for using spent nuclear fuel from NG1 and NG3. Minor surplus of spent nuclear fuel from NG3 is in long term storage.

SNF reprocessing requirements for NG1, ktHM	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
LWR SNF reprocessing requirement for NG1			0.63	2.04	11.67	15.11	15.11	15.11	14.82	9.82	11.22	12.85	14.37	15.88	17.06	17.71	18.17	18.32
LWR SNF reprocessing requirement for NG3									0.29	5.29	3.91	4.02	5.08	6.19	7.23	8.22	9.48	10.11
FR SNF reprocessing requirement for NG1					0.21	1.50	2.98	4.48	5.98	7.50	9.02	10.57	12.32	14.33	16.60	19.11	21.85	24.73
Total, ktHM	**0**	**0**	**1**	**2**	**12**	**17**	**18**	**20**	**21**	**23**	**24**	**27**	**32**	**36**	**41**	**45**	**49**	**53**
Supply																		
Reprocessing capacity, ktHM	**0**																	
LWR reprocessing capacity			0.63	2.04	11.67	15.11	15.11	15.11	15.11	15.11	15.12	16.87	19.44	22.06	24.30	25.93	27.65	28.43
FR reprocessing capacity					0.21	1.50	2.98	4.48	5.98	7.50	9.02	10.57	12.32	14.33	16.60	19.11	21.85	24.73
Total reprocessing capacity, ktHM	**0**	**0**	**1**	**2**	**12**	**17**	**18**	**20**	**21**	**23**	**24**	**27**	**32**	**36**	**41**	**45**	**49**	**53**
SNFannual import from NG3																		
Balance: (LWR reprocessing capacity - LWR reprocessing requirement)																		
Balance 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Balance: (Total reprocessing capacity -total reprocessing requirement)																		
Balance 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

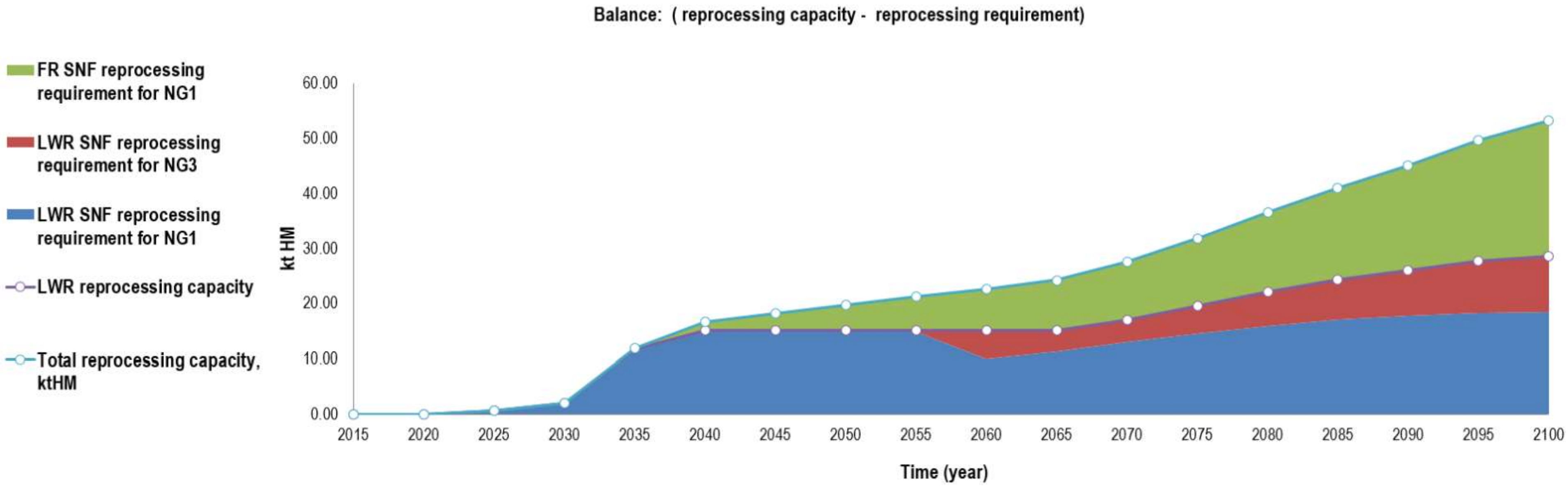


FIG. IX.20. Spent nuclear fuel reprocessing. Legend: SNF — spent nuclear fuel.

IX.3.6. Progress monitoring

Monitoring of progress towards enhanced NES sustainability was performed using normalized indicators (per unit of energy produced), characterizing the enhancements in uranium utilization, needs for enrichment and spent nuclear fuel reprocessing services, as well as regarding plutonium and spent nuclear fuel accumulation in long term storage.

Figure IX.20 shows the normalized uranium utilization in NG1 and globally. Uranium utilization in NG1 improves due to the introduction of FRs using MOX fuel. As the share of FRs in the total reactor mix increases, the consumption of uranium per unit of energy produced decreases. Globally, uranium utilization improves to a lesser degree because of the smaller share of FRs in the global nuclear energy mix in comparison with the NG1 nuclear energy mix.

Transition to the NES comprising FRs in NG1 produces a positive effect not only on uranium utilization, but also on the amount of uranium enrichment required per unit of energy produced. The result in normalized SWU is shown in Fig. IX.21. The global result shows steady improvement as FRs are introduced, but the improvement is not as significant as for NG1.

Figure IX.22 shows the annual reprocessing load for spent nuclear fuels from LWRs and FRs per unit of energy produced. The requirement for LWR spent nuclear fuel reprocessing rises and correlates with the fast reactor introduction speed change. The requirement for fast reactor spent nuclear fuel reprocessing increases monotonically along with the fast reactor capacity increase.

The values for normalized quantities of spent nuclear fuel are shown in Fig. IX.23. The LWR spent fuel in NG1 can be significantly reduced by the introduction of FRs. The NG1 long term storage values are a combination of the spent nuclear fuel produced in NG1 and spent nuclear fuel transported from NG3. Owing to reprocessing, this amount is reduced to the minimum by the middle of the century and stabilized on this level by the end of the century. The global long term storage values are a combination of storage in the NG1, NG2 and NG3, with a dip in the value when reprocessing is working off the excess inventory of the cooled spent LWR fuel, followed by rising values as the total inventory of spent fuel in NG2 grows.

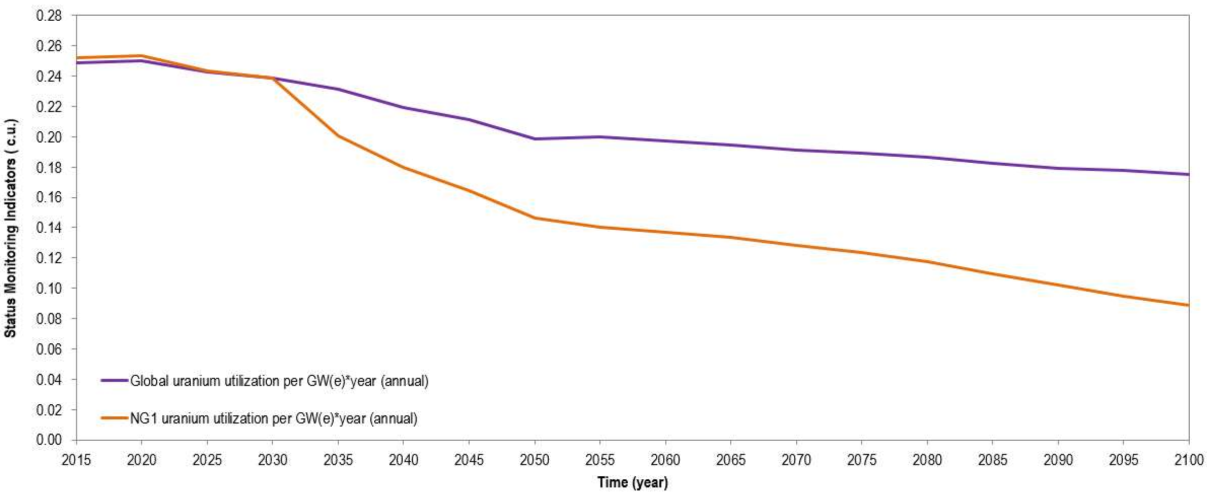


FIG. IX.21. Normalized uranium utilization in NG1 and globally.

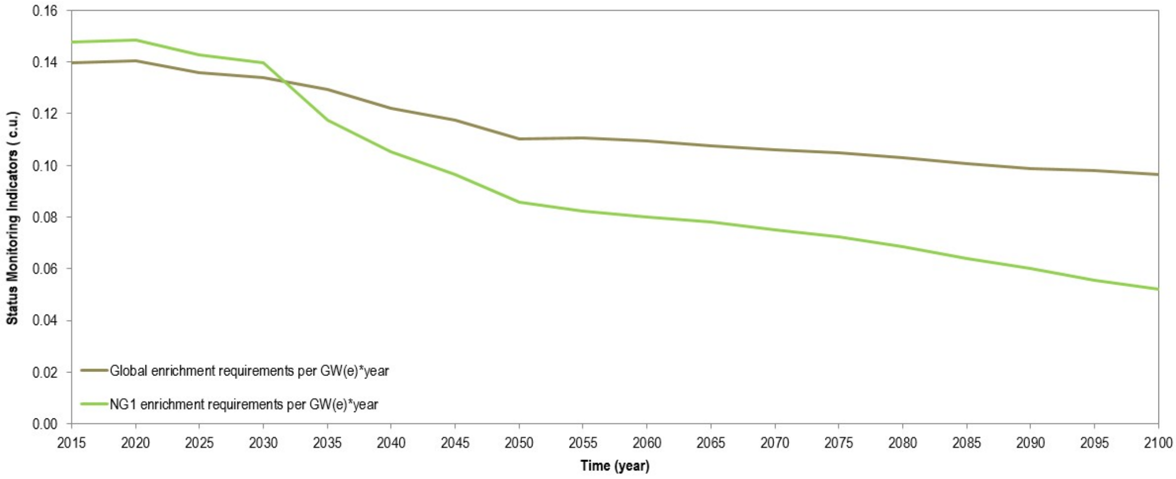


FIG. IX.22. Normalized enrichment requirements in NG1 and globally.

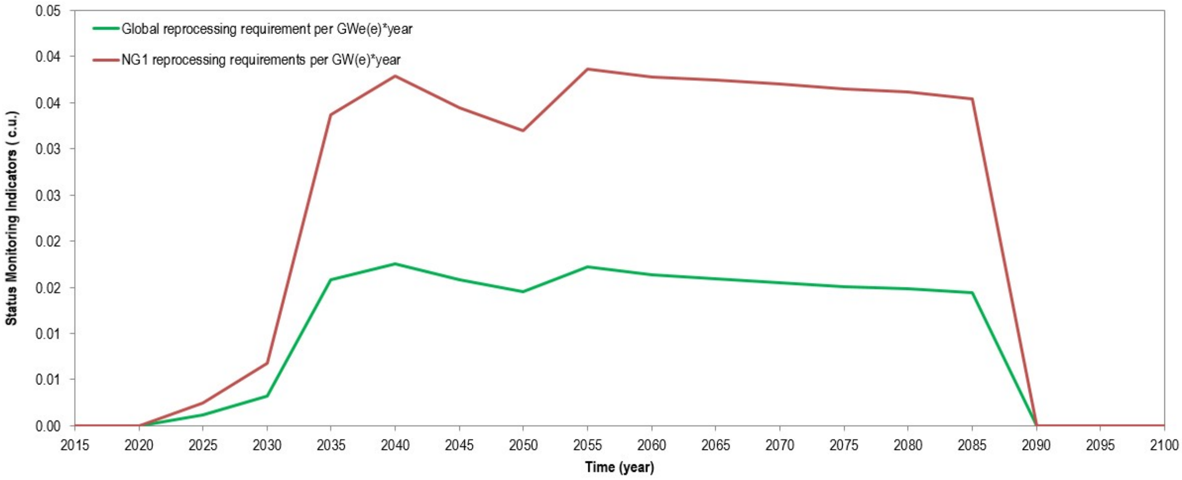


FIG. IX.23. Annual reprocessing load for spent nuclear fuels from LWRs and FRs per unit of energy produced.

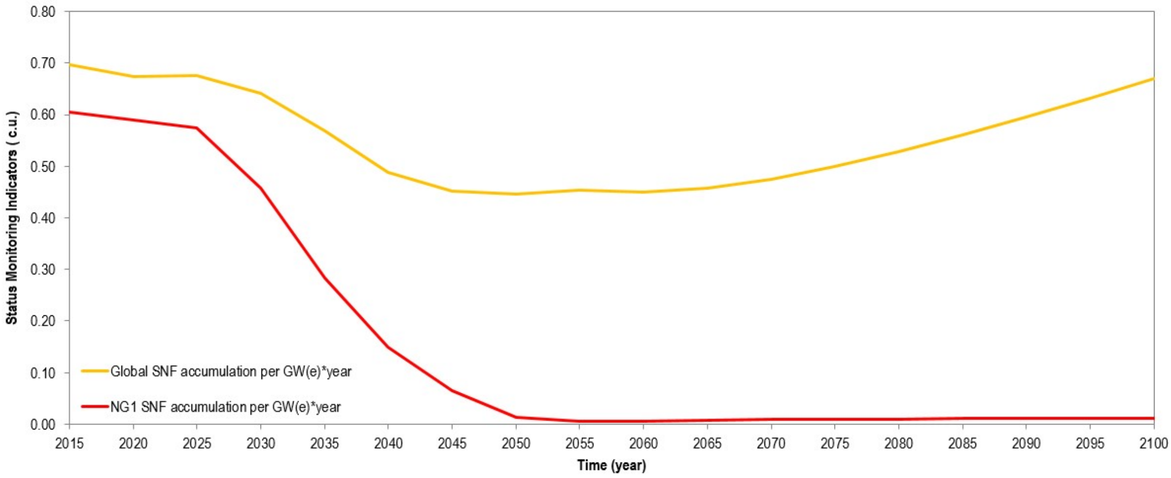


FIG. IX.24. Normalized quantities of spent nuclear fuel in NG1 and globally. Legend: SNF — spent nuclear fuel.

IX.3.7. Summary

The consolidated roadmap for the three NGs is presented in Fig. IX.24. Multilevel representation illustrates the main elements of roadmaps including nuclear power, technology options, the reactor fleet and the nuclear fuel cycle, cooperation with other countries and key developments. The groups operate synergistically with one another creating the global architecture of the NES. The NES of NG1 countries is based on two component NESs (LWRs and FRs). The development and demonstration of fast reactor technology will be achieved by the end of the century. The deployment of FRs and their incorporation on a commercial scale is planned by the end of the century. NG1 has enrichment, fuel fabrication and reprocessing facilities. This group offers front end and back end services, including spent nuclear fuel reprocessing and final disposal of HLW without plutonium. Increased levelized unit electricity cost for FRs during the introduction phase returns to the level of LWR levelized unit electricity cost and less, as conventional uranium resources are exhausted. NG2 countries have significant experience in LWR and HWR operation and the necessary infrastructure for fuel fabrication and storage of discharged fuel. This group offers services related to the once-through fuel cycle and has access to the options of the nuclear fuel cycle back end services from NG1. NG3 relies on cooperation with the NG1 and NG2 countries in the front end and back end of the fuel cycle. This group obtains fresh fuel and sends spent fuel abroad for either recycling or disposal.

Cross-cutting analysis shows the balanced shipment of services and nuclear material flows between groups. The study identified savings in time and resources achieved through the introduction of innovative technologies and cooperation among country groups. Collaboration between country groups and access to the complete recycle of spent fuel could facilitate the minimizing of the spent nuclear fuel accumulation and the associated waste disposal. An important sociopolitical and economic benefit for non-NG1 countries shipping spent nuclear fuel to NG1 would be the reduced requirements for long term spent fuel storage and the ultimate disposal of waste. Such requirements could essentially be limited to short term spent fuel storage for cooling before shipment. Reduced requirements will be transformed into reduced costs for long term spent fuel storage and final disposal.

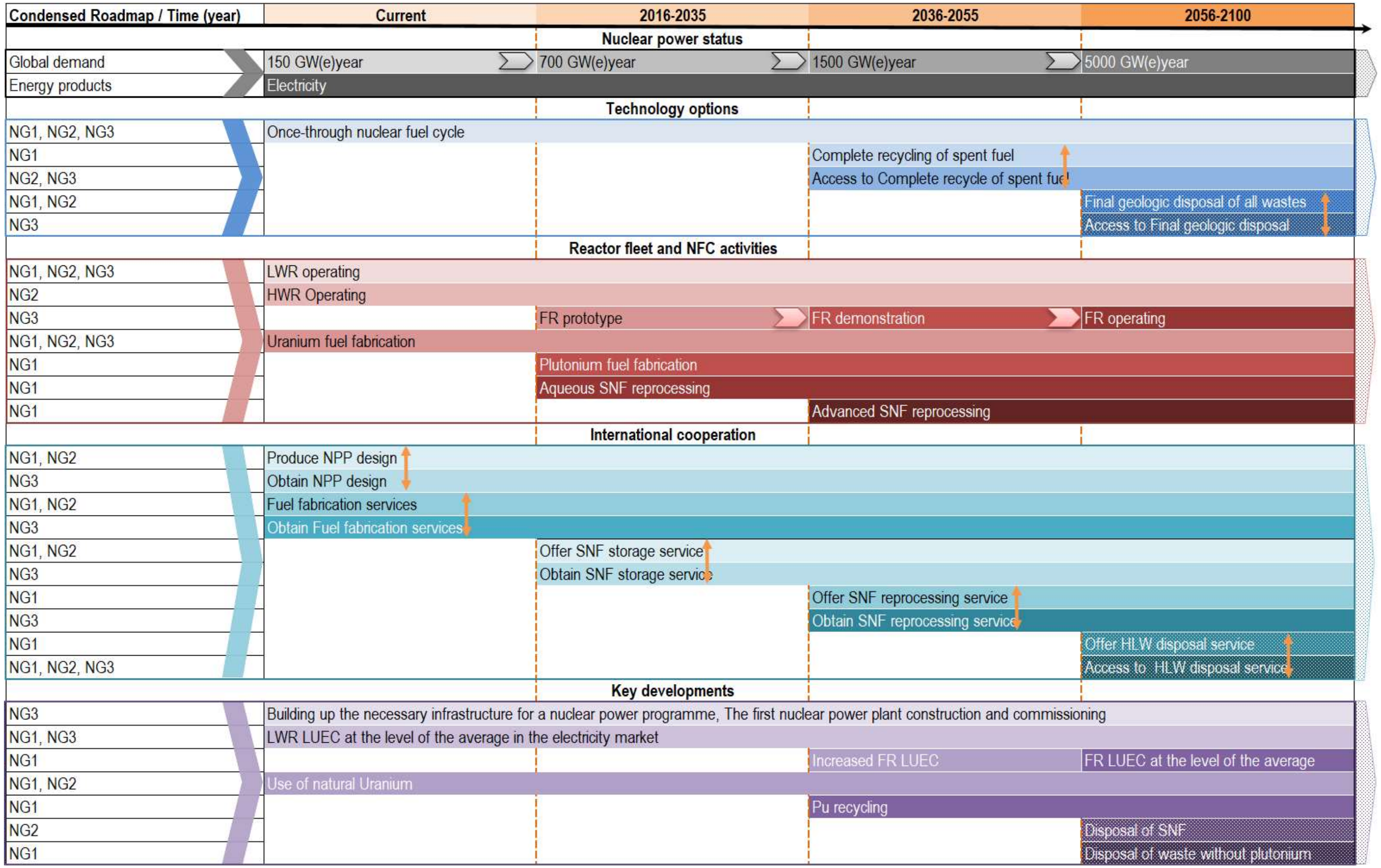


FIG. IX.25. Major elements of global (NG1+NG2+NG3) roadmap template. Legend: SNF — spent nuclear fuel; LUEC — levelized unit electricity cost.

Even if fission products are returned to the countries where they were generated, their volume will be substantially smaller compared with the volume of the spent fuel before reprocessing and, additionally, proliferation concerns will not exist for storage or final disposal of such waste. Collaboration among groups could also result in more effective utilization of resources in the global NES. Natural uranium resources could be saved through cooperation, and all countries could also benefit from costs of natural uranium that were lower in the longer term. Spent nuclear fuel, a waste to non-NG1 countries, could serve as a resource to NG1 by providing additional fissile material during a transition to large scale nuclear energy generation, perhaps helping to avoid or delay the development of FRs with high breeding ratios.

IX.4. APPLICATION OF ROADMAP TEMPLATE TO THE GLOBAL NES

This section presents the results of a trial roadmap template application to a global nuclear fuel cycle infrastructure examination to provide an illustration of a medium term global evolutionary NES deployment scenario and to evaluate supply–demand balances for the most essential nuclear fuel cycle products and services considering a given projection of nuclear power growth and nuclear reactor fleet evolution. The study is based on a combined application of an energy planning tool, open access databases and informational and statistical sources on nuclear power and the nuclear fuel cycle, which were used to populate the ROADMAPS-ET (which is a spreadsheet realization of the roadmap template with data processing options).

IX.4.1. Purpose of the roadmap

IX.4.1.1. Scope of the study

Supply–demand balances for the nuclear fuel cycle front end and back end products and services (uranium mining, milling, conversion and enrichment, fuel fabrication, spent nuclear fuel storage and reprocessing, plutonium production) at the global level were evaluated within this study. The nuclear power global situation up to 2015 was reconstructed based on the information and data from various sources on resources, production, consumption, and import and export of fresh and spent fuel, as well as on the history of nuclear reactor and nuclear fuel cycle facility commissioning and decommissioning. A scenario analysis of evolutionary NES deployment in the medium term perspective up to 2050 was carried out using an energy planning tool assuming that present day development trends would be conserved. To streamline the perception of the results represented in ROADMAPS-ET, a five year aggregation was implemented for the whole projection period.

The global nuclear reactor fleet currently includes a mix of different technologies, reflecting various concepts developed in the early years of nuclear power. Figure IX.25 shows the dominance of PWRs, including WWERs, and boiling water reactors (BWRs), both in number and in generating capacity. The remainder of the global nuclear reactor fleet in commercial operation in 2015 was composed of HWRs, older generation GCRs and advanced GCRs, LWGRs and one FR, BN-600[1].

Within the study, all nuclear reactors currently operating worldwide have been combined into seven reactor types: PWR, BWR, GCR, advanced GCR, WWER, LWGR and HWR. For the PWR and BWR, in addition to uranium oxide fuel, mixed uranium–plutonium oxide fuel (one third MOX fuel loading into the core with a 7% plutonium content) was considered. This approach has been widely used in different studies involving the NFCSS (VISTA) IAEA software tool [IX.5]. Data on the history of the nuclear reactors and nuclear fuel cycle facility

[1] The BN-800 sodium-cooled fast reactor with a total electrical power of 880 MW was built at the Beloyarsk Nuclear Power Station, in Zarechny, Sverdlovsk Oblast, the Russian Federation, and reached its full power production in August 2016.

commissioning and decommissioning were gathered according to available open access statistical data.

Despite the fact that this study considers the period beyond 2035 — a timeframe in which the new Generation IV reactor designs may be commissioned, making essential changes in the nuclear fuel cycle — it was decided to leave aside such prospects and make only a conservative evaluation and examination of the evolutionary NES deployment scenario.

To provide a correct evaluation of actual scales of nuclear material flows in the global nuclear fuel cycle, the most suitable ‘average’ nuclear reactor and fuel parameters were preidentified and used for each of the aggregated reactor types (tails assay and feed enrichment, burnup, efficiency, load factor, plutonium content, spent nuclear fuel reprocessing share etc.). To find appropriate parameters, the relevant identification problem was solved to determine the scales of natural uranium, conversion and enrichment requirements (using data published in the detailed WNA study [IX.6]), spent nuclear fuel annual production and cumulative volume, and plutonium balance (using data presented in a series of IAEA publications, e.g. Refs [IX.7, IX.8]). Evaluations were carried out according to the following steps:

— To determine the expected evolution of the global nuclear reactor fleet, the structure of the evolutionary NES was optimized using a global nuclear fuel cycle model developed within MESSAGE [IX.4].
— Based on the IAEA Power Reactor Information System and the Integrated Nuclear Fuel Cycle Information Systems, the initial data for the MESSAGE model were gathered.
— The specific costs of nuclear fuel cycle services were taken from an NEA/OECD report [IX.9].
— Based on the determined trends, a global roadmap was elaborated using ROADMAPS-ET to represent in a unified form the supply–demand balances on the nuclear fuel cycle front end and back end products and services.

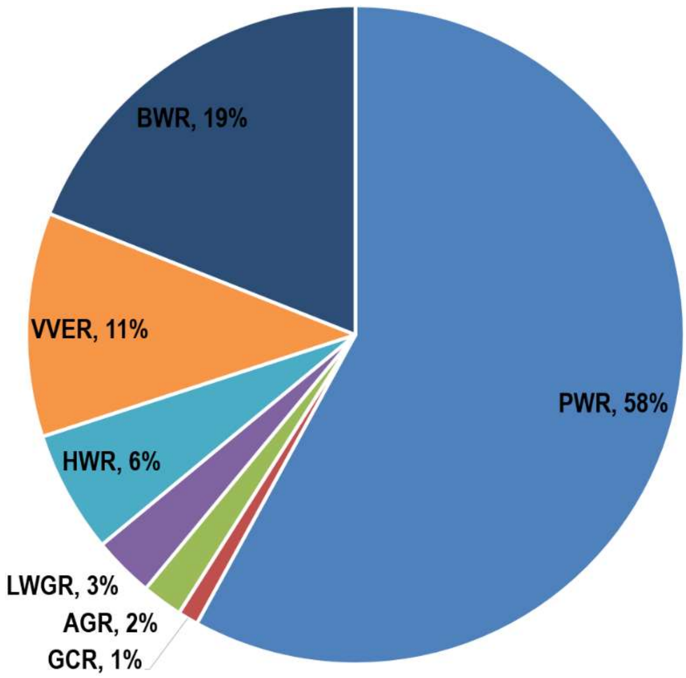


FIG. IX.26. The structure of the world's nuclear fleet (as of 2015).

IX.4.1.2. Nuclear fuel cycle infrastructure in the world

The nuclear fuel cycle includes uranium ore mines, facilities for the fine purification of extracted uranium, uranium conversion and enrichment plants, fuel fabrication plants, NPPs where fuel burning provides generation of thermal and electrical energy, spent nuclear fuel reprocessing plants to extract secondary fissile materials and to convert radioactive waste into a suitable form for permanent disposal, and waste repository sites.

The nuclear fuel cycle front end is intended for nuclear fuel fabrication and includes the following steps: uranium ore mining, ore enrichment, uranium extraction and purification, uranium conversion, uranium enrichment and fabrication of fuel elements and fuel assemblies. The nuclear fuel cycle back end starts with discharging spent nuclear fuel from the reactor, holding it in special at-reactor pools and then in away-from-reactor dry or wet storage facilities, followed by radiochemical reprocessing or geological disposing.

The front end nuclear fuel cycle products and services market is international in nature: uranium mining, milling, conversion and enrichment as well as fuel fabrication are carried out by a limited number of countries that offer their services competitively to other countries; however, some commercial and political restrictions apply on these markets. Worldwide uranium conversion and enrichment services are provided by several companies; about 15 companies offer nuclear fuel fabrication services [IX.10].

The largest conversion plants operate in Canada, France, the Russian Federation, the United Kingdom and the United States of America. France, Germany, the Netherlands, the Russian Federation, the United Kingdom and the United States of America own the largest enrichment plants. Although most uranium conversion and enrichment facilities are concentrated in a few OECD countries and in the Russian Federation, about 20 countries have the capability to fabricate fuel using uranium provided by such sources. Only Argentina, China, France, the Russian Federation, the United Kingdom and the United States of America possess the whole processing chain of nuclear fuel fabrication for LWR reactors on a commercial scale [IX.10].

The nuclear fuel cycle back end is also international to a different degree: France, the Russian Federation and the United Kingdom have practice in the management of foreign spent nuclear fuel. Four countries operate large spent nuclear fuel reprocessing facilities: France, Japan, the Russian Federation and the United Kingdom. At the same time, only France and the United Kingdom operate commercial scale (more than 1000 t HM per year) reprocessing plants. Table IX.6 shows the status of global nuclear fuel cycle infrastructure, giving capacities for nuclear fuel cycle facilities in commercial operation worldwide.

The main trends in the nuclear fuel cycle area are discussed below. Nowadays, the degree of governmental influence in setting short and medium term strategies for nuclear fuel cycle development continuously decreases, and they are readdressed to the implementation of market oriented strategies on the part of individual market actors.

The continuing trend towards a growing imbalance in the number of countries consuming and supplying nuclear fuel cycle products and services, and purely economic reasons (a high unit cost of nuclear fuel cycle services at a relatively low demand rate), give rise to transnational associations in the field of nuclear technology and the nuclear fuel cycle: the scale effect makes it reasonable to create large scale nuclear fuel cycle facilities.

The market of nuclear materials and nuclear fuel cycle services is becoming more open, especially in terms of conducting business transactions on the transfer of nuclear fuel cycle technology and facilities. Overall, nuclear fuel cycle facilities are currently acquiring primary importance while previously reactor technologies were more in focus.

TABLE IX.4. GLOBAL COMMERCIAL NUCLEAR FUEL CYCLE FACILITIES' ANNUAL CAPACITY (ESTIMATIONS)

Nuclear fuel cycle segment	Overall capacity (approx.)
Uranium production	56 000 t U
Conversion	60 000 t U
Enrichment	55 000 t SW
Fuel fabrication	
LWR	14 000 t HM
MOX	500 t HM
HWR	4 300 t HM
Spent nuclear fuel reprocessing	5 300 t HM
Spent nuclear fuel storage facilities	
At-reactor spent nuclear fuel storage facilities	160 000 t HM
Wet away-from-reactor spent nuclear fuel storage facilities	75 000 t HM
Dry away-from-reactor spent nuclear fuel storage facilities	160 000 t HM

IX.4.1.3. Model assumptions

Within this study, the following projections of global NES capacities were assumed: 430 GW(e) in 2020, 598 GW(e) in 2030 and 898 GW(e) in 2050 [IX.11]. The nuclear reactor fleet capacity growth was specified by the commissioning of new capacity and the replacement of retired capacities. The prospective evolutionary NES structure and nuclear fuel supply options were identified using the global NES scenario model developed within MESSAGE. The purpose was to reveal the main development trends taken into account so that they would be presented using ROADMAPS-ET for a global nuclear fuel cycle infrastructure examination.

Firstly, the LWR share increasing in global nuclear power is supposed: new builds of LWRs (PWRs, BWRs, and WWERs) are expected, and new LWRs will replace advanced GCRs, GCRs and LWGRs as these plants are decommissioned without plans for future commissioning. It is assumed that PWR, BWR and WWER relative shares in the LWR nuclear reactor fleet will be preserved. Secondly, a slight increase in MOX fuel consumption by LWRs is assumed relative to today's use of MOX fuel in PWRs and BWRs. Owing to this, the uranium oxide and MOX fuelled reactors were separated into two groups (PWR, BWR and PWR-MOX, BWR-MOX) which are represented individually in the roadmap. Since this case study was focused only on general evolutionary trends associated with nuclear fuel cycle infrastructure sufficiency, no other reactors were considered here owing to their small share in the global nuclear reactor fleet and their minor potential impact on nuclear material flows in the global nuclear fuel cycle.

Annual data on global reactor fleet evolution obtained using the MESSAGE model were aggregated according to the given assumptions and NES structure evolution is shown in Fig. IX.26 as it was incorporated into ROADMAPS-ET. These data represent an expert opinion rather than official data. Figure IX.27 includes both a Gantt chart of nuclear reactor fleet evolution demonstrating in figures the total installed capacity of each reactor type and an excel stacked area chart presenting the traditional visual form of nuclear reactor fleet evolution widely used in different applied energy planning studies.

Total installed capacity	2015	2020	2025	2030	2035	2040	2045	2050
AGR	7	7	5	1				
GCR	1	1						
LWGR	11	10	7	3	1			
HWR	24	25	27	31	32	35	37	40
VVER	45	51	57	61	62	64	66	68
BWR	63	70	75	84	86	113	155	180
BWR-MOX	12	24	33	38	40	43	47	49
PWR	215	218	266	342	385	453	496	512
PWR-MOX	12	24	33	38	40	43	47	49
Total, GW	391	430	502	598	646	752	848	898

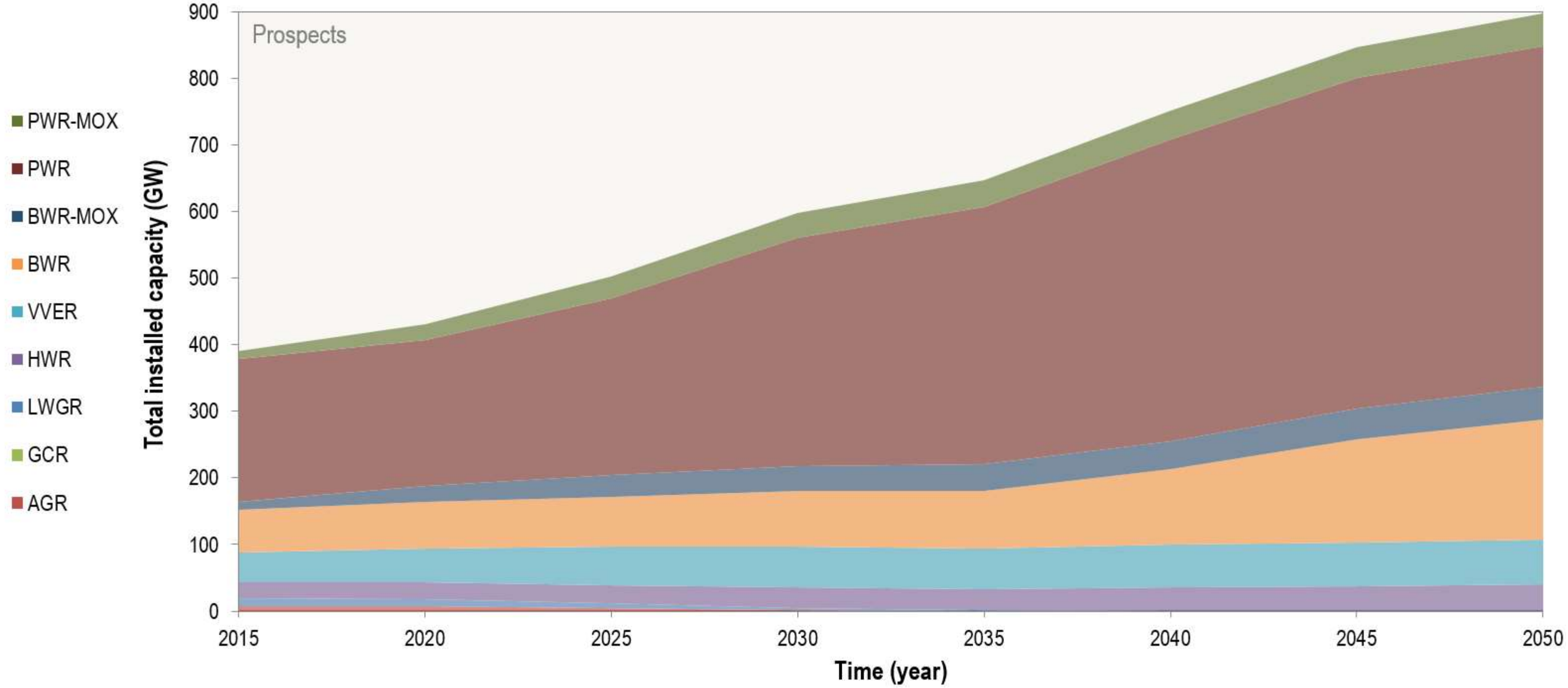


FIG. IX.27. Evolution of nuclear reactor fleet. Legend: AGR — advanced GCR. White colour used for numbers in upper part of the figure is to indicate that expert opinions rather that official data are reflected here.

IX.4.2. Supply–demand balances for nuclear fuel cycle products and services

This section presents the supply–demand balances for nuclear fuel cycle front end and back end products and services at the global level using ROADMAPS-ET. The supply–demand balances for the nuclear fuel cycle front end were evaluated for the uranium mining and milling, conversion, enrichment and fuel fabrication steps. Meanwhile, for the nuclear fuel cycle back end, supply–demand balances were evaluated for the spent nuclear fuel storage and reprocessing stages, including plutonium accumulation issues.

IX.4.2.1. Uranium mining and milling

Currently, it is commonly recognized that the world's reasonably assured resources of uranium are sufficient to ensure nuclear fuel for 50–60 years and that known resources of uranium may satisfy reactor requirements to well beyond 2035. The worldwide reserves of natural uranium are non-uniformly spread, with about 85% of all global uranium reserves being located in eight countries: more than 55% of reasonably assured resources and inferred uranium resources are found in Australia, Canada and Kazakhstan and 30% are found in Uzbekistan, Namibia, Niger, the Russian Federation and South Africa. Canada and the Russian Federation, which have well developed nuclear power programmes, are among the countries occupying a prominent place in uranium mining. Other countries with large scale nuclear power programmes either do not produce uranium at all (e.g. western European countries and Japan) or their uranium production is much lower than consumption (the United States of America). Uranium production presently takes place in more than 15 countries. Several new projects are at various stages of readiness in some of the producing countries and in more than 25 potential newcomer countries [IX.3, IX.12].

Because a nuclear renaissance was anticipated, exploration for new uranium deposits was activated and supported by the growth of production and the rise of the uranium price, and this led to increased uranium mining profitability. The countries mining natural uranium have made efforts to increase the processing chain and produce a uranium stockpile. However, presently depressed uranium prices have reduced uranium exploration activities and the opening of new mines. Moreover, in some cases, current mines have even stopped production. However, it is still expected that uranium production will rise over the next ten years.

Figure IX.27 demonstrates the supply–demand balance for uranium mining and milling and shows both primary and secondary supply options.[2] Primary supply includes current, under development, planned and prospective supply pipeline[3] mines; secondary supply assumes commercial inventories, government inventories, re-enrichment of depleted uranium and others (according to the evaluations presented in Ref. [IX.6]).

[2] It was assumed that 1 tonne of plutonium is equivalent to 75 Mt U, 75 tonnes of conversion and 52 000 separative work units [IX.6].

[3] The term 'supply pipeline' refers to uncategorized supply such as the development of early stage projects, the resurrection of cancelled and deferred projects and unexpected mine life extensions at existing operations [IX.6].

Uranium requirements	2015	2020	2025	2030	2035	2040	2045	2050
Uranium requirements for AGR	1500	1500	1071	193				
Uranium requirements for GCR	225	113						
Uranium requirements for LWGR	1844	1744	1241	570	168			
Uranium requirements for HWR	5393	5728	6068	6966	7191	7865	8315	8989
Uranium requirements for VVER	6112	6858	7665	8203	8281	8660	8831	9144
Uranium requirements for BWR	10257	11397	12211	13676	14075	18431	25263	29252
Uranium requirements for BWR-MOX	1979	3907	5298	6187	6512	7001	7652	7978
Uranium requirements for PWR	35004	35493	43230	55681	62752	73790	80699	83336
Uranium requirements for PWR-MOX	1977	3907	5298	6187	6512	7001	7652	7978
Total, tU	64292	70647	82081	97663	105491	122748	138412	146677
				Supply				
Primary supply, tU	56000	67000	76000	84000	92000	97000	102000	102000
Current	55000	50000	40000	30000	30000	30000	30000	30000
Under development	1000	15000	17000	10000	10000	10000	10000	10000
Planned		2000	7000	6000	6000	6000	6000	6000
Prospective			6000	6000	6000	6000	6000	6000
Supply pipline			6000	32000	40000	45000	50000	50000
Secondary supply, tU	18000	17000	18000	17000	13000	7500	3500	2000
Secondary supply (all sources)	18000	17000	18000	17000	13000	7500	3500	2000
Total supply, tU	74000	84000	94000	101000	105000	104500	105500	104000
				Surplus (supply - demand)				
Surplus, tU	9708	13353	11919	3337	-491	-18248	-32912	-42677

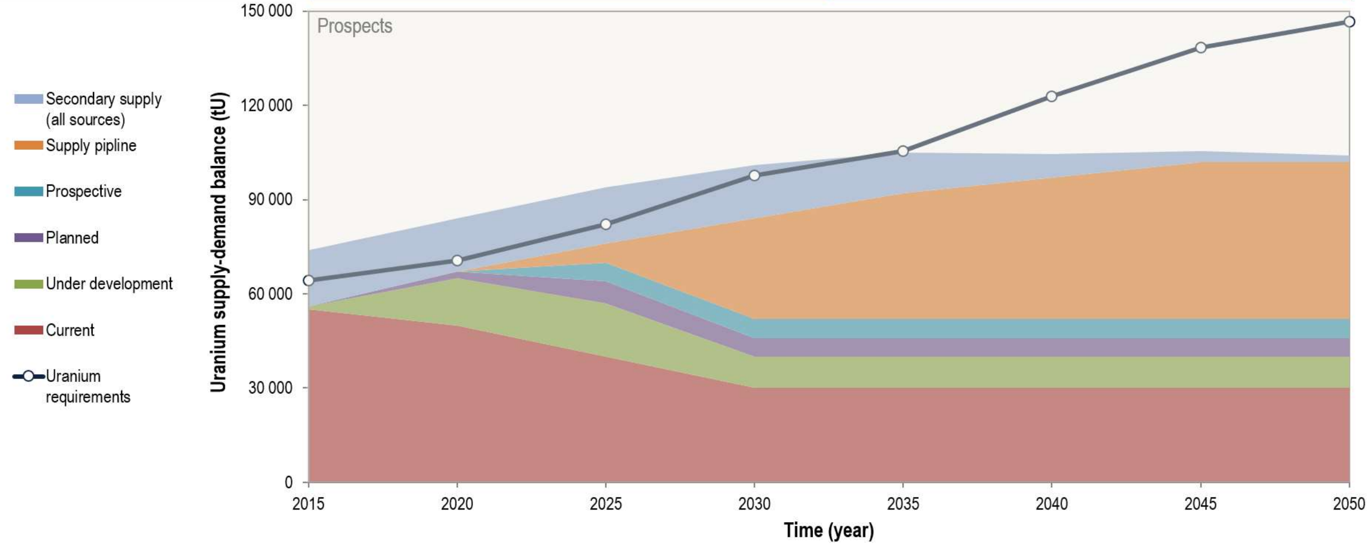


FIG. IX.28. Supply–demand balance for uranium mining and milling. Legend: AGR — advanced GCR.

Underfeeding of enrichment plants could provide substantial amounts of uranium to the market in the period up to 2025: the WNA report [IX.6] estimates that underfeeding may contribute between 5700 and 8000 t U/yr to world markets up to 2025 (typical Western tails assays are 0.22%; in the Russian Federation tails assays are normally 0.10%).

Overall, current annual uranium demand is about 65 000 Mt U while total primary production is approximately 56 000 Mt U and secondary supply provides 18 000 t U. Obviously, both current and planned primary and secondary supply options can meet the uranium demand up to 2035 and, within this balance, secondary supply options keep their importance, although their role is slowly becoming less significant. It is expected that uranium demand growth, together with a restricted contribution of secondary supply sources, will require additional uranium production for the considered evolutionary NES deployment scenario beyond 2035 (development of both new mines and 'supply pipeline' projects) so that uranium demand can be met.

IX.4.2.2. Uranium conversion

The uranium conversion segment consists of a small number of domestic companies producing UO_2 for reactors using natural uranium and uranium hexafluoride (UF_6) for reactors fuelled with enriched uranium. Canada, China, France, the Russian Federation, the United Kingdom and the United States of America operate commercial plants for the conversion of U_3O_8 to UF_6 using a dry fluoride volatility process (in the USA) and a wet process (in the other countries) [IX.12]. UF_6 conversion represents more than 90% of overall conversion requirements covered at the moment by five primary suppliers: Cameco Corporation (Canada), China National Nuclear Corporation (China), AREVA (France), Rosatom (the Russian Federation) and ConverDyn (United States of America) [IX.13], which were taken into account in the roadmap.

Secondary supply sources (commercial and governmental inventories, re-enrichment of depleted uranium and others) reduce the need for primary UF_6 conversion services and, according to Ref. [IX.13], currently provide slightly more than 12 000 Mt U for UF_6 conversion.

Figure IX.28 presents the supply–demand balance for UF_6 conversion services to demonstrate both primary and secondary supply options in comparison with UF_6 conversion requirements. Because of different factors that influence the market, the correct modelling of the supply side is rather difficult, and therefore it was represented only by nameplate capacities within the roadmap.

Conversion requirements	2015	2020	2025	2030	2035	2040	2045	2050
Conversion requirements for AGR	1500	1500	1071	193				
Conversion requirements for GCR	225	113						
Conversion requirements for LWGR	1844	1744	1241	570	168			
Conversion requirements for HWR								
Conversion requirements for VVER	6112	6858	7665	8203	8281	8660	8831	9144
Conversion requirements for BWR	10257	11397	12211	13676	14075	18431	25263	29252
Conversion requirements for BWR-MOX	1979	3907	5298	6187	6512	7001	7652	7978
Conversion requirements for PWR	35004	35493	43230	55681	62752	73790	80699	83336
Conversion requirements for PWR-MOX	1977	3907	5298	6187	6512	7001	7652	7978
Total, tU	58899	64919	76013	90697	98300	114882	130097	137688
Supply								
Primary supply, tU	59100	62100	65100	67100	67100	67100	67100	67100
Areva	15000	15000	15000	15000	15000	15000	15000	15000
Cameco	12500	12500	12500	12500	12500	12500	12500	12500
ConverDyn	15000	15000	15000	15000	15000	15000	15000	15000
Rosatom	12500	12500	12500	12500	12500	12500	12500	12500
CNNC	4000	7000	10000	12000	12000	12000	12000	12000
Others	100	100	100	100	100	100	100	100
Secondary supply, tU	12500	12500	12500	12500	10000	0	0	0
Secondary supply (all sources)	12500	12500	12500	12500	10000			
Total supply, tU	71600	74600	77600	79600	77100	67100	67100	67100
Surplus (supply - demand)								
Surplus, tU	12701	9681	1587	-11097	-21200	-47782	-62997	-70588

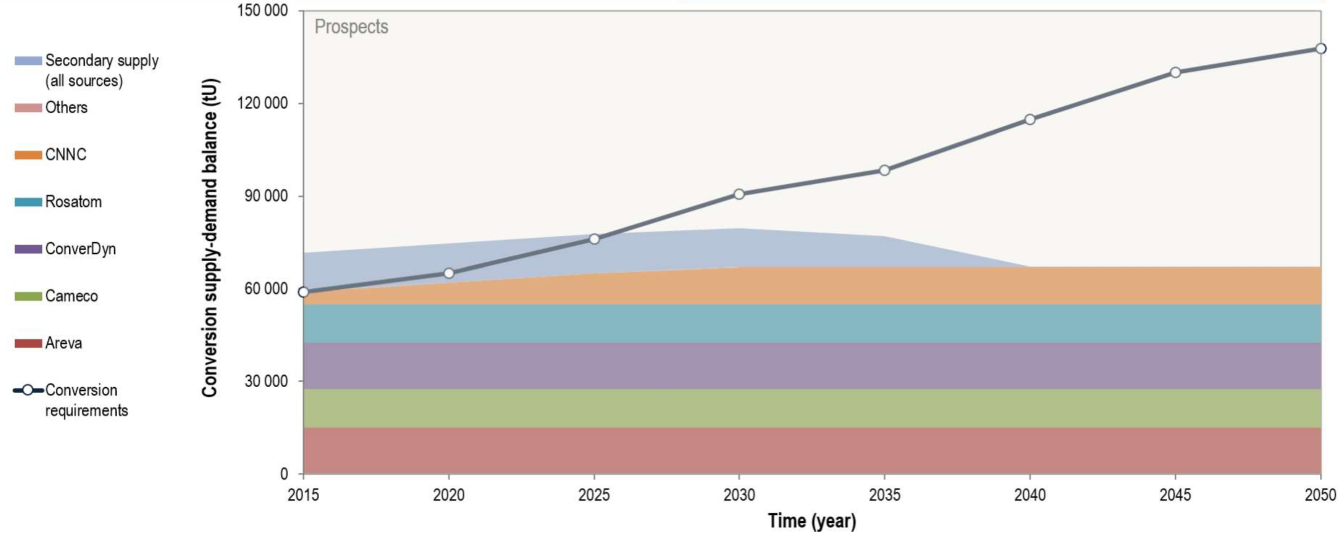


FIG. IX.29. Supply–demand balance for uranium conversion. Legend: AGR — advanced GCR.

The overall current annual UF_6 conversion capacity is about 60 000 t U/year and overall current requirements for conversion services are also close to this value. An examination of the roadmap shows that the UF_6 conversion segment is currently sufficiently supplied and a slight growth of UF_6 conversion capacity is required to meet demand growth until 2025 for the considered scenario in which nuclear energy expands. Additional UF_6 conversion capacities will be needed in more aggressive scenarios.

IX.4.2.3. Uranium enrichment

Uranium enrichment capacities are involved in primary natural uranium enrichment, the enrichment of tails to the natural uranium level, the enrichment of reprocessed uranium and, potentially, the enrichment of blend stock for high enriched uranium. The specific feature of this nuclear fuel cycle service is that it allows the final nuclear fuel cost to be optimized by selecting an appropriate level of tails assays (underfeeding or overfeeding), which, in particular, may lead to a situation when, in spite of the apparent excess of supply over demand, the uranium enrichment capacities may be practically exhausted. Owing to this, it is impossible to take into account all technological factors and market restrictions specifying actual enrichment capacities to model the supply side, and therefore this study considers only nameplate capacities of the following major primary enrichment service suppliers: the CNNC (China), AREVA (France), Rosatom (the Russian Federation) and URENCO (Europe and the United States of America) [IX.6, IX.14].

Figure IX.29 shows the supply–demand balance for enrichment services representing both primary and secondary supply options in comparison with the enrichment requirements. The overall enrichment capacity is currently about 60 million SWU per year and at present the overall requirements are approximately 50 million SWU per year. A surplus of enrichment capacity over the demand has led to the postponement of some new projects and the use of the existing capacity for underfeeding.

The potential excess of the global enrichment capacity over demand will be observed until 2025. This allows the existing enrichment capacities to be used for underfeeding. Additional enrichment capacities are also likely to be needed in more aggressive scenarios. Among the reasons for extending enrichment capacities, it is necessary to mention the general growth of nuclear power capacities, increased LWR share and fuel burnup, extended cycle length and decreased tails enrichment. All these measures are aimed at saving natural uranium and, hence, result in an increased demand for enrichment services. The prospective growth of uranium enrichment capacities is expected to be provided by gas centrifuges with evolutionary improvements to existing centrifuge technology. In view of the potential nuclear proliferation threats associated with uranium enrichment facilities, the issues related to the internationalization and application of multilateral approaches to this nuclear fuel cycle step are generally addressed.

Enrichment requirements	2015	2020	2025	2030	2035	2040	2045	2050
Enrichment requirements for AGR	785	785	561	101				
Enrichment requirements for GCR								
Enrichment requirements for LWGR	1265	1196	851	391	115			
Enrichment requirements for HWR								
Enrichment requirements for VVER	5940	6664	7448	7971	8047	8415	8581	8886
Enrichment requirements for BWR	8232	9147	9800	10976	11296	14793	20276	23478
Enrichment requirements for BWR-MOX	1588	3136	4252	4966	5227	5619	6142	6403
Enrichment requirements for PWR	28095	28487	34696	44690	50365	59224	64770	66886
Enrichment requirements for PWR-MOX	1587	3136	4252	4966	5227	5619	6142	6403
Total, t SW	47491	52551	61861	74060	80277	93670	105910	112055
Supply								
Primary supply, t SW	58500	67070	67070	67070	67070	67070	67070	67070
Rosatom	26500	29000	29000	29000	29000	29000	29000	29000
Areva	7000	7500	7500	7500	7500	7500	7500	7500
CNNC	5700	10700	10700	10700	10700	10700	10700	10700
URENCO	19200	19700	19700	19700	19700	19700	19700	19700
Others	100	170	170	170	170	170	170	170
Secondary supply, t SW	2000	2000	2000	2000	2000	2000	2000	2000
Secondary supply (all sources)	2000	2000	2000	2000	2000	2000	2000	2000
Total supply, t SW	60500	69070	69070	69070	69070	69070	69070	69070
Surplus (supply - demand)								
Surplus, t SW	13009	16519	7209	-4990	-11207	-24600	-36840	-42985

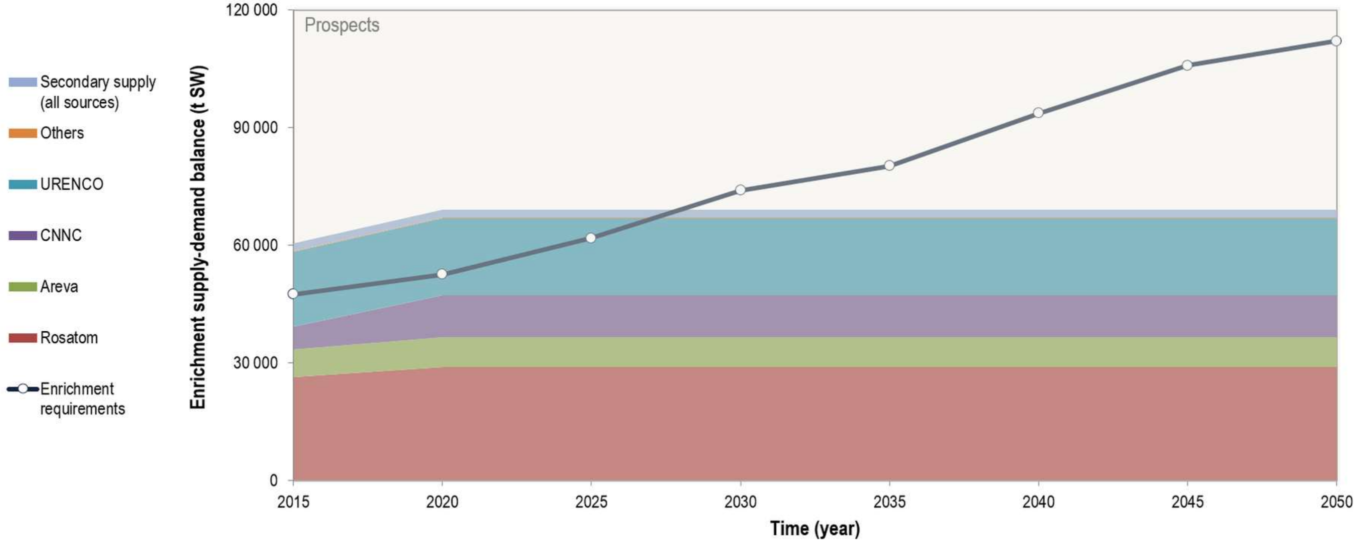


FIG. IX.30. Supply–demand balance for uranium enrichment. Legend: AGR — advanced GCR.

IX.4.2.4. Fuel fabrication

The fuel fabrication market does not provide a compatible high-tech product to be used as nuclear fuel for any reactor type; on the contrary, the final product, i.e. fabricated nuclear fuel, is individual and produced for specific reactor types. Currently, owing to market pressure, companies are forced to close down unprofitable plants in order to improve fuel fabrication efficiency, and they are seeking to develop and commercialize fuel assemblies for other reactors than those for which they have traditionally fabricated fuel. This is accompanied by consumers' intentions to diversify nuclear fuel suppliers to improve fuel supply assurance. As a result, it has become routine to strengthen and extend the international cooperation supported by the development of competitive edge, further optimize fuel fabrication technology and fulfil orders for manufacturing individual components. Competition on principally new segments of the nuclear fuel market is growing fast. Increasing fuel burnup along with other measures provide a reduction of uranium consumption per unit of energy generation, which is the main final target for this nuclear fuel cycle segment. There is a growing demand for the use of reprocessed uranium; possibilities are being investigated for a gradual transition to advanced nuclear fuel cycles, which would require additional activities to improve fuel assemblies [IX.6, IX.16].

Within the roadmap, all the existing fuel fabrication plants (supply side) were combined into four groups: UOX LWR fuel fabrication plants, MOX LWR fuel fabrication plants, HWR fuel fabrication plants and others. Figure IX.30 shows the supply–demand balance for fuel fabrication services, where the fuel fabrication capabilities and corresponding surpluses are presented separately. The present annual demand for LWR and HWR fuel fabrication services is about 7000 and 3000 t HM per year, respectively. The overall worldwide LWR and HWR fuel fabrication capacities are approximately 13 500 and 4000 t HM per year, respectively. According to evaluations, global fuel fabrication capacities are currently about 1.6 times greater than the demand for this service and more than sufficient to cover projected demand for both first cores and reloads until 2040: global cumulative nuclear fuel demand is about 11 000 t HM, and overall capacities are about 17 500 t HM. It is expected that, for the considered demand projections, the fuel fabrication requirements will increase twice up to 2050. Considering the supply–demand balance for an individual nuclear fuel type, it could be noted that the surplus becomes negative for MOX LWR nuclear fuel in 2020–2025 and for UOX LWR nuclear fuel in 2040–2045 for the NES deployment scenario considered.

To simplify evaluations in the base case calculations, only annual nuclear fuel reloads are considered. In fact, the demand for fuel fabrication services increases as new installed reactor capacities requiring a full first core load are put into operation, leading to a short term demand peak for fuel fabrication services (for a typical LWR, the first core load equals approximately three annual reloads, leading to a factor of 1.4 increase in the demand for fuel fabrication services within a 5 year aggregation assumption). These fuel fabrication peaks also lead to corresponding peaks in uranium conversion and enrichment demands and, if necessary, may be taken into consideration within a more detailed roadmap.

Fuel fabrication requirements	2015	2020	2025	2030	2035	2040	2045	2050
Fuel fabrication requirements for AGR	294	294	210	38				
Fuel fabrication requirements for GCR	225	113						
Fuel fabrication requirements for LWGR	550	520	370	170	50			
Fuel fabrication requirements for HWR	3320	3526	3735	4288	4427	4842	5118	5533
Fuel fabrication requirements for VVER	864	969	1083	1159	1170	1224	1248	1292
Fuel fabrication requirements for BWR	1197	1330	1425	1596	1642	2151	2948	3414
Fuel fabrication requirements for BWR-MOX	231	456	618	722	760	817	893	931
Fuel fabrication requirements for PWR	4085	4142	5045	6498	7323	8611	9418	9725
Fuel fabrication requirements for PWR-MOX	231	456	618	722	760	817	893	931
Total, tHM	10996	11806	13104	15193	16132	18461	20518	21826
Supply								
Primary supply, tHM	20802	20902	19852	19852	19552	19052	18552	18552
UOX LWR fuel fabrication	13832	13832	13832	13832	13832	13832	13832	13832
MOX LWR fuel fabrication	250	350	400	400	400	400	400	400
HWR fuel fabrication	4320	4320	4320	4320	4320	4320	4320	4320
Other	2400	2400	1300	1300	1000	500		
Total supply, tHM	20802	20902	19852	19852	19552	19052	18552	18552
Surplus (supply - demand)								
Surplus for UOX LWR fuel fabrication	7379	6783	5455	3616	2683	757	-972	-1840
Surplus for MOX LWR fuel fabrication	96	46	-12	-81	-107	-145	-195	-221
Surplus for HWR fuel fabrication	1000	3070	3117	3566	3667	4025	4225	4602
Surplus for Other	1331	1474	720	1092	950	500		

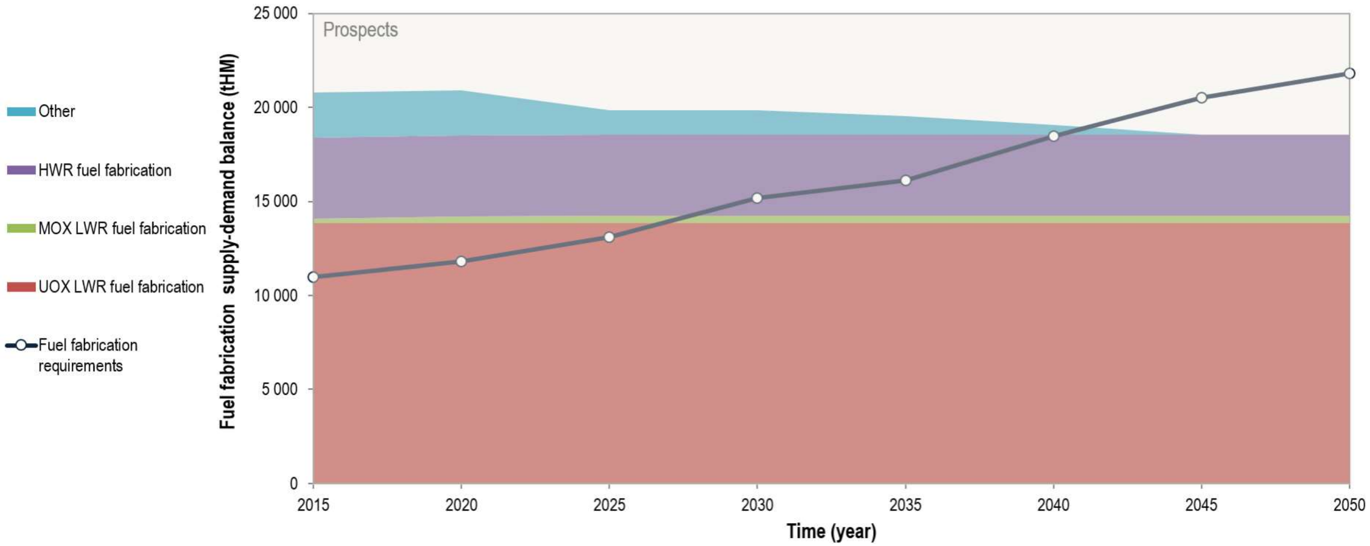


FIG. IX.31. Supply–demand balance for fuel fabrication. Legend: AGR — advanced GCR.

IX.4.2.5. Spent nuclear fuel storage

The nuclear fuel cycle back end, which is considered to be the most challenging part of the nuclear fuel cycle from different viewpoints, includes a variety of spent nuclear fuel storage facilities, spent nuclear fuel reprocessing plants and spent nuclear fuel or HLW potential repositories for final disposal. The main nuclear fuel cycle back end objective is safe and reliable spent nuclear fuel management providing, if required, extraction and reuse of secondary fissile materials. Nevertheless, at the moment, a practice of plutonium mono-recycling in thermal reactors (PWR and BWR) in the MOX fuel form is realized; however, this does not provide significant reductions in natural uranium consumption, enrichment requirements and needs for spent nuclear fuel final disposal, which will remain unresolved in the coming decades. The international market of nuclear fuel cycle back end services is significantly constrained by legal (international conventions, national legislation etc.) and objective (long term programmes, lack of proven technical solutions, social aspects etc.) reasons.

As is known, unloaded spent nuclear fuel from nuclear reactors is firstly stored in at-reactor pools and, after appropriate cooling, may be safely packaged and transported to away-from-reactor dry and wet interim (decentralized or centralized) storage facilities or sent to reprocessing plants, where plutonium and uranium are extracted for further reuse and HLW is vitrified into borosilicate glass and sealed into containers to be finally disposed.

According to the data reported in IAEA publications, global annual spent nuclear fuel production today is about 10 500 t HM per year, with approximately 8500 t HM being sent to spent nuclear fuel storage and about 2 000 t HM to reprocessing plants [IX.3]. Based on IAEA projections, it was assessed that the cumulative amount generated in the world by 2015 may surpass 390 000 t HM, of which about 277 000 t HM will be in spent nuclear fuel storage in at-reactor pools and away-from-reactor wet and dry storage facilities. It is expected that the fraction of spent nuclear fuel being stored relative to the fraction to be reprocessed will tend to increase owing to the fact that in many countries the lack of final repositories and the postponement of the corresponding decisions will lead to extended storage periods of uncertain duration. As a consequence, the lifetime of existing spent nuclear fuel storage facilities will have to be prolonged and new long term spent nuclear fuel storage facilities will have to be built (especially dry away-from-reactor spent nuclear fuel storage facilities).

Figure IX.31 demonstrates the supply–demand balance for spent nuclear fuel services (the cumulative amount of spent nuclear fuel produced within the given time frames). Owing to the lack of information regarding spent nuclear fuel production by each reactor type in the past, corresponding values have been assessed. For the considered scenario of global nuclear reactor fleet deployment, a steadily growing demand for spent nuclear fuel storage facilities will continue and the existing and planned spent nuclear fuel storage capacities will be sufficient to 2030–2035 (Fig. IX.31). It is impossible to stabilize spent nuclear fuel accumulation if the current tendencies of spent nuclear fuel reprocessing continue (about 30% of all spent nuclear fuel arisings will be annually reprocessed) even in the event of decreasing spent nuclear fuel amount per unit of energy produced owing to the increased fuel burnup and LWR commissioning: the expected growth of the nuclear reactor fleet governs the steadily increasing spent nuclear fuel amount.

A possible practical solution to the problem at the national level is temporary spent nuclear fuel storage in countries with available unused capacities for intermediate spent nuclear fuel storage. In the future, an increase of spent nuclear fuel storage capacities is needed especially within international cooperation; for instance, a regional repository project may provide more flexibility in terms of the most effective utilization of capacities.

SNF storage requirements	2015	2020	2025	2030	2035	2040	2045	2050
SNF storage requirements for AGR	11800	13270	14740	15790	15979	15979	15979	15979
SNF storage requirements for GCR	52600	53725	54288	54288	54288	54288	54288	54288
SNF storage requirements for LWGR	24000	26750	29350	31200	32050	32300	32300	32300
SNF storage requirements for HWR	85500	102100	119731	138406	159847	181981	206189	231781
SNF storage requirements for VVER	22100	26418	31263	36678	42473	48323	54441	60680
SNF storage requirements for BWR	58500	64485	71135	78260	86240	94452	105207	119948
SNF storage requirements for BWR-MOX		1155	3435	6526	10136	13936	18021	22486
SNF storage requirements for PWR	134000	154425	175135	200360	232850	269465	312522	359610
SNF storage requirements for PWR-MOX		1153	3433	6525	10135	13935	18020	22485
Total, tHM	388500	443481	502509	568031	643997	724659	816965	919555
				Supply				
Primary supply, tHM	479800	507819	550756	606582	643648	707767	770535	815545
At-reactor-pools	163692	180299	210297	250639	270812	314955	355034	375992
Wet away-from-reactor storage	75000	75000	75000	75000	75000	75000	75000	75000
Dry away-from-reactor storage	160000	160000	160000	160000	160000	160000	160000	160000
SNF reprocessing	81108	92520	105458	120943	137836	157812	180501	204553
Geological disposal repository								
Total supply, tHM	479800	507819	550756	606582	643648	707767	770535	815545
				Surplus (supply - demand)				
Surplus, tHM	91300	64338	48246	38551	-349	-16892	-46430	-104010

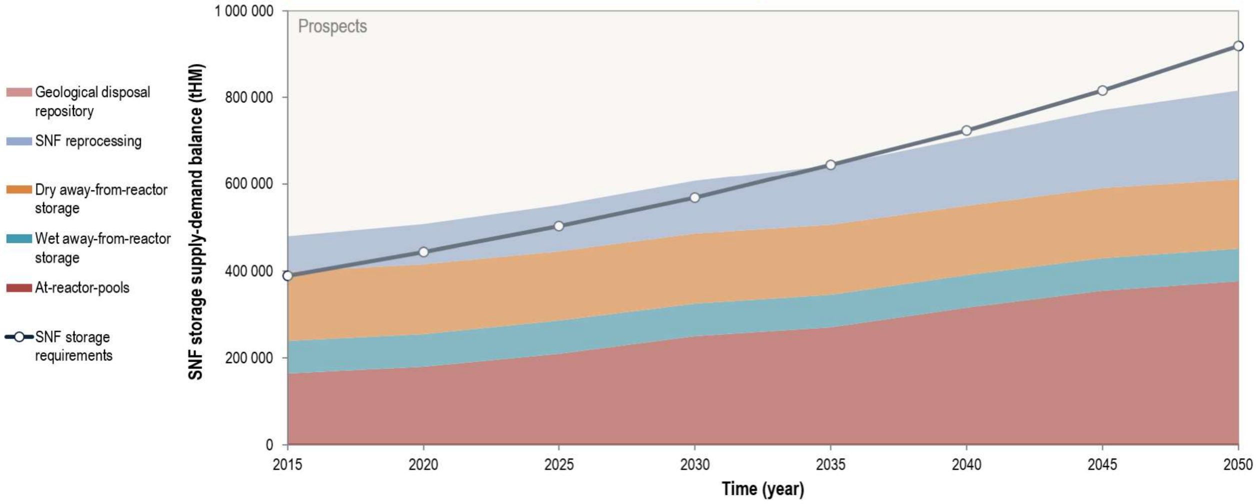


FIG. IX.32. Supply–demand balance for spent nuclear fuel services. Legend: AGR — advanced GCR; SNF — spent nuclear fuel.

IX.4.2.6. Spent nuclear fuel reprocessing and plutonium stocks

The current global capacities of commercial spent nuclear fuel reprocessing plants are about 5300 t HM per year, including the Rokkasho reprocessing plant (Japan), which is expected to start operation in the coming years. During the past 50 years, about 80 000 t HM of spent nuclear fuel have been reprocessed. Currently, spent nuclear fuel reprocessing plants are not used at full capacity, but important efforts have been made in regard to further development of aqueous (wet) and pyrochemical (dry) radiochemical reprocessing processes. According to the WNA report [IX.6], in 2015, the use of enriched reprocessed uranium was expected to save 820 Mt U and the use of plutonium in MOX 900 t U.

Figures IX.32 and IX.33 demonstrate the supply–demand balance for spent nuclear fuel reprocessing services and the supply–demand balance for plutonium in terms of cumulative plutonium stocks. From about 2000 t HM of spent nuclear fuel allocated for reprocessing at the reprocessing plants annually, about 20 tonnes of plutonium are extracted. According to the International Panel on Fissile Materials, 267 tonnes of civilian reactor grade plutonium will have been extracted from spent nuclear fuel by 2015 (in 2015, about 2100 tonnes of plutonium were expected to remain in spent nuclear fuel, available for reprocessing) [IX.16]. Currently, the overall irradiated and unirradiated plutonium stocks are growing at an average rate of approximately 50 tonnes per year and most of the separated plutonium (approximately 14 tonnes) is used almost immediately in MOX fuel. The global MOX fuel production capacity is currently around 200 t HM per year.

The separated reactor grade plutonium accumulation will continue if the present day level of reprocessed spent nuclear fuel to produced MOX fuel ratio is preserved. Plutonium proliferation concerns may be partly mitigated in the event of the implementation of multilateral approaches: the organization of regional spent nuclear fuel reprocessing centres, the realization of mechanisms of fuel leasing or some other approaches.

In conclusion, it could be noted that the expected global growth of nuclear power capacities, changes in their structure and in nuclear fuel supply parameters will need a corresponding increase in all nuclear fuel cycle capacities from uranium production to spent nuclear fuel storage, requiring appropriate investments over the coming years.

SNF reprocessing requirements	2015	2020	2025	2030	2035	2040	2045	2050
SNF reprocessing requirements for AGR	98	98	70	13				
SNF reprocessing requirements for GCR	75	38						
SNF reprocessing requirements for LWGR								
SNF reprocessing requirements for HWR								
SNF reprocessing requirements for VVER	288	323	361	386	390	408	416	431
SNF reprocessing requirements for BWR	399	443	475	532	547	717	983	1138
SNF reprocessing requirements for BWR-MOX								
SNF reprocessing requirements for PWR	1362	1381	1682	2166	2441	2870	3139	3242
SNF reprocessing requirements for PWR-MOX								
Total, tHM	2222	2283	2588	3097	3379	3995	4538	4810
				Supply				
Primary supply, tHM	4630	5030	5330	5330	5730	5730	5730	5730
UP2, UP3/France	1700	1700	1700	1700	1700	1700	1700	1700
THORP, B205/UK	2100	2100	2100	2100	2100	2100	2100	2100
RT1-RT2/Russia	400	400	400	400	800	800	800	800
Tokaimura, Rokkasho/Japan	100	500	800	800	800	800	800	800
PREFRE, KARP/India	330	330	330	330	330	330	330	330
Total supply, tHM	4630	5030	5330	5330	5730	5730	5730	5730
				Surplus (supply - demand)				
Surplus, tHM	**2408**	**2748**	**2742**	**2233**	**2351**	**1735**	**1192**	**920**

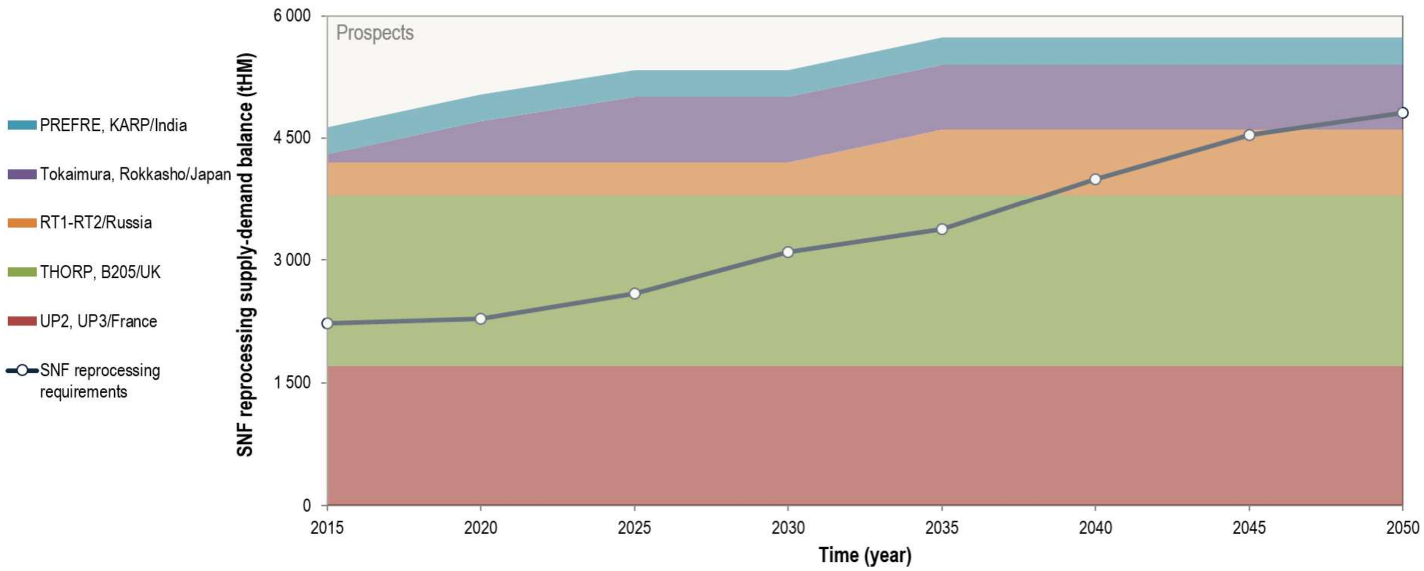


FIG. IX.33. Supply–demand balance for spent nuclear fuel reprocessing. Legend: SNF — spent nuclear fuel; AGR — advanced GCR.

IX.4.3. Discussion and results

The steadily approaching capacity limits of nuclear fuel cycle front end and back end commercial facilities in the coming decades as well as concerns about the insufficiency of new installations in response to the expected demand for nuclear fuel cycle products and services caused by projected nuclear power growth are challenges of prime importance. In order to address these concerns, it would be necessary to thoroughly combine both the different technological and collaborative options (from improving nuclear reactors and fuel characteristics to implementing a variety of promising bilateral and multilateral approaches to nuclear fuel cycle such as fuel leasing, international uranium enrichment centres and regional spent nuclear fuel management centres). Only in terms of gradually improving the technological performance and effective implementation of collaboration strategies, will it be possible to coordinate nuclear power development at the national, regional and global levels and create synergies between such crucial factors as reliable spent nuclear fuel management, the prevention of nuclear proliferation and assurance of fuel supply for the long term perspective that help enhance overall NES sustainability.

The elaborated roadmap of the global evolutionary NES with its trial application has demonstrated that this roadmap may meet different needs and be used for diverse purposes related to an examination of the impacts of various technological, institutional and structural means of maintaining and enhancing NES sustainability at the global level as well as the evaluation of their performance. This roadmap may also be simply updated to assess various technological factors affecting the nuclear fuel cycle products and services markets, including enrichment levels, cycle lengths and fuel burnups. This study has demonstrated that a combined use of an energy planning tool, open access databases, informational and statistical sources on nuclear power and the nuclear fuel cycle, as well as the ROADMAPS-ET, provide a self-sufficient toolkit to produce and present global nuclear energy roadmaps.

Due to the limited scope of the study, the results of this trial analysis obviously cannot be seen as a foundation for making substantial management conclusions. At the same time, these results are sufficient to demonstrate the basic aspects related to the ROADMAPS-ET application to a global nuclear fuel cycle infrastructure examination outlining general deployment trends and providing a basis for specific recommendations. The elaborated global roadmap gives an opportunity to organize a unified analysis, structure the results of studies associated with an examination of evolutionary NES deployment strategies and demonstrate the merits and demerits of the considered options.

The ROADMAPS-ET based analysis could also form the basis for decision making and help adopt a definite position on the most promising NES deployment strategy. To this end, it is necessary to involve different stakeholders and expert groups in the roadmap elaboration process. Particular attention needs to be paid to the consideration of issues related to database formation and to specification of assumptions because there is no single resource containing all necessary and verified actual information regarding nuclear fuel cycle facilities and their status in general. Such information presented in different sources (open access databases, company reports and presentations, industry press etc.) may be contradictory and therefore it needs to be carefully examined, verified and confirmed. With the support of subject matter expertise, it would be possible to elaborate the representative roadmaps to be used within different applied studies for identifying and providing a rationale for the most promising directions to maintain and enhance the global evolution of NES sustainability by different technological, institutional and structural means.

Cumulative Pu requirements	2015	2020	2025	2030	2035	2040	2045	2050
Cumulative Pu requirements for AGR								
Cumulative Pu requirements for GCR								
Cumulative Pu requirements for LWGR								
Cumulative Pu requirements for HWR								
Cumulative Pu requirements for VVER								
Cumulative Pu requirements for BWR								
Cumulative Pu requirements for BWR-MOX	29	86	163	253	348	451	562	679
Cumulative Pu requirements for PWR								
Cumulative Pu requirements for PWR-MOX	29	86	163	253	348	450	562	678
Total, t	58	172	326	507	697	901	1124	1357
				Supply				
Primary supply, t	376	490	620	774	943	1143	1370	1611
Civilian plutonium stocks	265	265	265	265	265	265	265	265
Reprocessed plutonium (new arisings)	111	225	355	509	678	878	1105	1346
Total supply, t	376	490	620	774	943	1143	1370	1611
				Surplus (supply - demand)				
Surplus, t	318	318	293	268	247	242	246	254

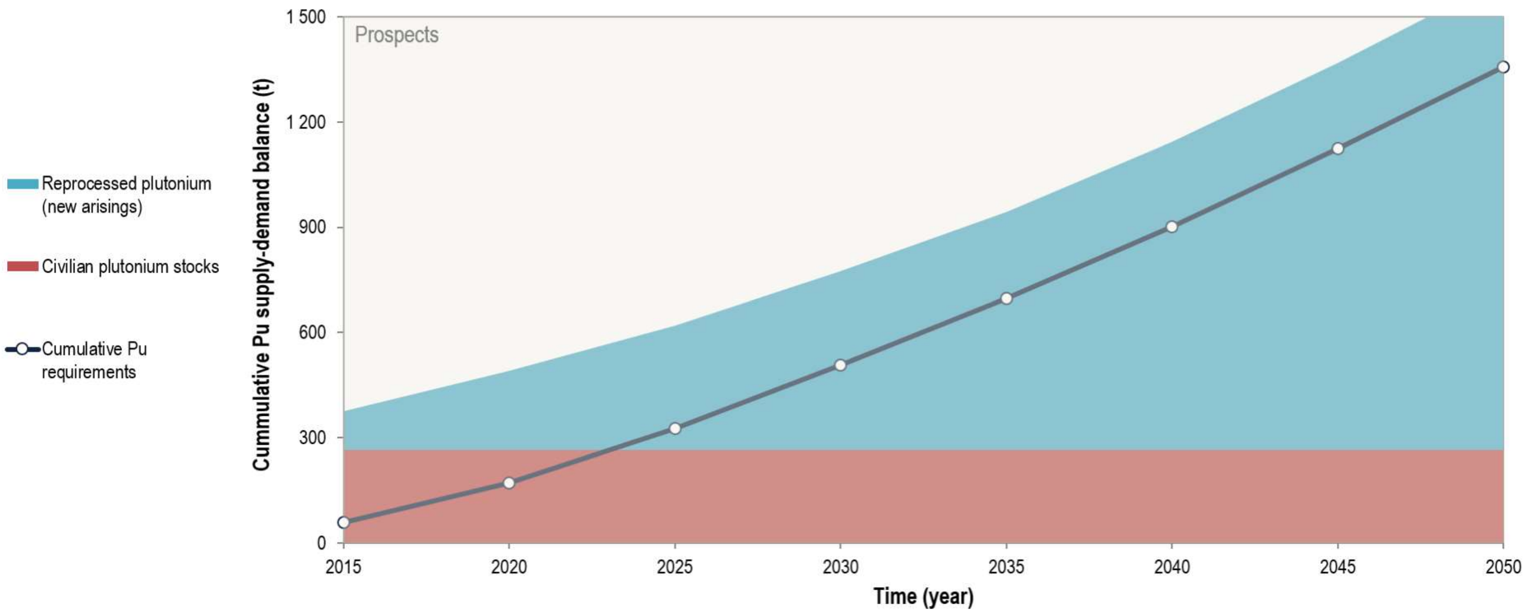


FIG. IX.34. Supply–demand balance for cumulative plutonium stocks. Legend: AGR — advanced GCR.

IX.5. CROSS-CUTTING ANALYSIS OF DRIVERS AND IMPEDIMENTS FOR COLLABORATION AMONG COUNTRIES

The fourth INPRO Dialogue Forum on Drivers and Impediments for Regional Cooperation on the Way to Sustainable Nuclear Energy Systems discussed issues related to sustainable nuclear energy development and deployment, bringing together technology holders, technology users and newcomers to exchange views on the benefits and issues associated with regional cooperation in building sustainable NESs and, specifically, to understand the standpoints of the newcomer, user and supplier countries regarding the driving forces for and the impediments to such a cooperation.

All participants filled in a questionnaire with six sections addressing a variety of issues (e.g. U resources in the form of yellowcake, enrichment, NPP, reprocessing, HLW management, long term spent fuel storage, final disposal of waste, advanced nuclear fuel cycles) related to a transition to sustainable NESs, in the short term (2012–2030), medium term (2030–2050) and long term (2050–2100). To analyse the responses, the participants were sorted into one of the following nuclear fuel cycle policy groups: group NG1 starts with LWRs and transitions to a closed nuclear fuel cycle with FRs; group NG2 maintains a once-through nuclear fuel cycle with LWRs and HWRs; and group NG3 starts with no reactors, deploys LWRs and minimal nuclear fuel cycle infrastructure. This section provides a cross-cutting analysis of participants’ responses by country group.

The cooperation among countries is seen by all participants as a condition for making a transition to future NESs with enhanced sustainability:

- Cooperation on NPPs has the highest priority in the short term for all countries, and is also rated ‘very important’ in the medium and long terms, as can be seen in Fig. IX.34.
- Cooperation on the final disposal of waste is the second short term priority, offering the newcomers a good chance to initiate future sustainable NESs from the outset of their national nuclear power programme. In the medium and long terms, cooperation on final disposal of waste becomes the top priority for technology holder and user countries. The newcomers also rate it important, but in their case the long term spent fuel storage remains the best option and highest priority for cooperation in the long term.

Regarding the approach for the final disposal of radioactive waste, both technological and infrastructure aspects were suggested for rating. The absence of proven commercial solutions for the final disposal of waste was reflected by the majority of respondents who voted for long term, controlled storage of spent nuclear fuel pending availability of (proven) disposal technologies. As seen from Fig. IX.35:

- A national solution is the preferred solution at all points in time in the view of the respondents from both technology holder and user countries (NG1+NG2); meanwhile, the newcomers (NG3) definitely prefer international and regional solutions to national ones at all points in time, with a cautious preference also for the solution of fully or partially outsourcing to the fuel supplier in the short term.
- Regarding the technological solution for the final disposal of radioactive waste, controlled spent fuel storage over a long period has the highest rating on all terms for both technology holder and user countries and also newcomers; however, for NG3 countries the final disposal of fission products only is also evenly preferred for the medium and long term, probably based on the possibility to deal with fission products only after the spent fuel has been reprocessed and recycled in a supplier country or in a regional or international centre.

The participants were asked to prioritize several prespecified issues regarding their current or potential future importance in the national context with respect to a nuclear energy programme. All the issues were considered to be substantially important (the issues were rated over 3, 1 being not important and 5 very important), the NG3 countries considering more issues as highly important compared with the NG1 and NG2 countries considered together. As seen from Fig. IX.36:

— Security of supply was rated with the highest importance by the newcomers, closely followed by energy independence, political considerations and political willingness, financial resources and human resources. For NG1 and NG2 countries, financial resources are considered the most important issue, with human resources being rated as the second most important, closely followed by public health and environmental issues, political considerations and political willingness and public perception and acceptance.
— Land requirements were rated with the lowest importance by both technology holder and user countries and newcomer countries. The newcomer countries rated the industrial base also with low importance, and did not consider financial resources and human resources with the highest importance, probably based on the expectation of future support from the NPP provider.

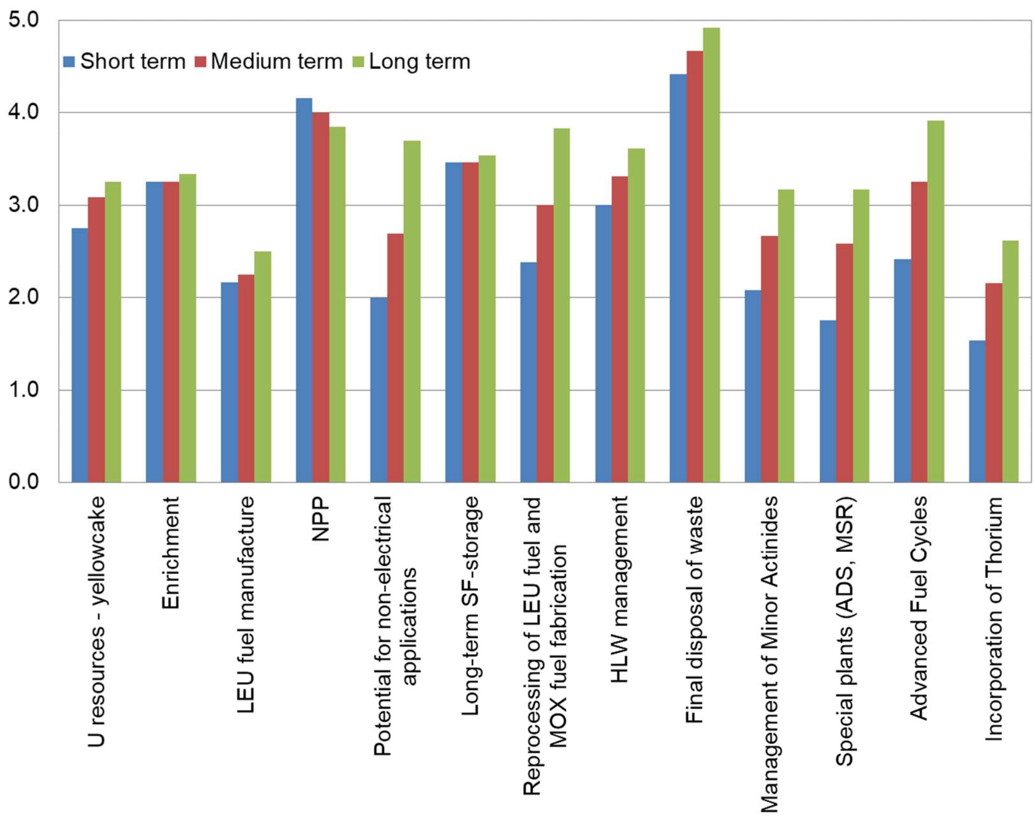


FIG. IX.35. (a). Summary of responses of NG1+NG2 countries to the DF4 questionnaire, Section 1 'Importance of Collaboration with Other Countries' (1 — lowest priority, 5 — highest priority). Legend: LEU — low enriched uranium; SF —spent fuel; ADS — accelerator driven system; MSR — molten salt reactor.

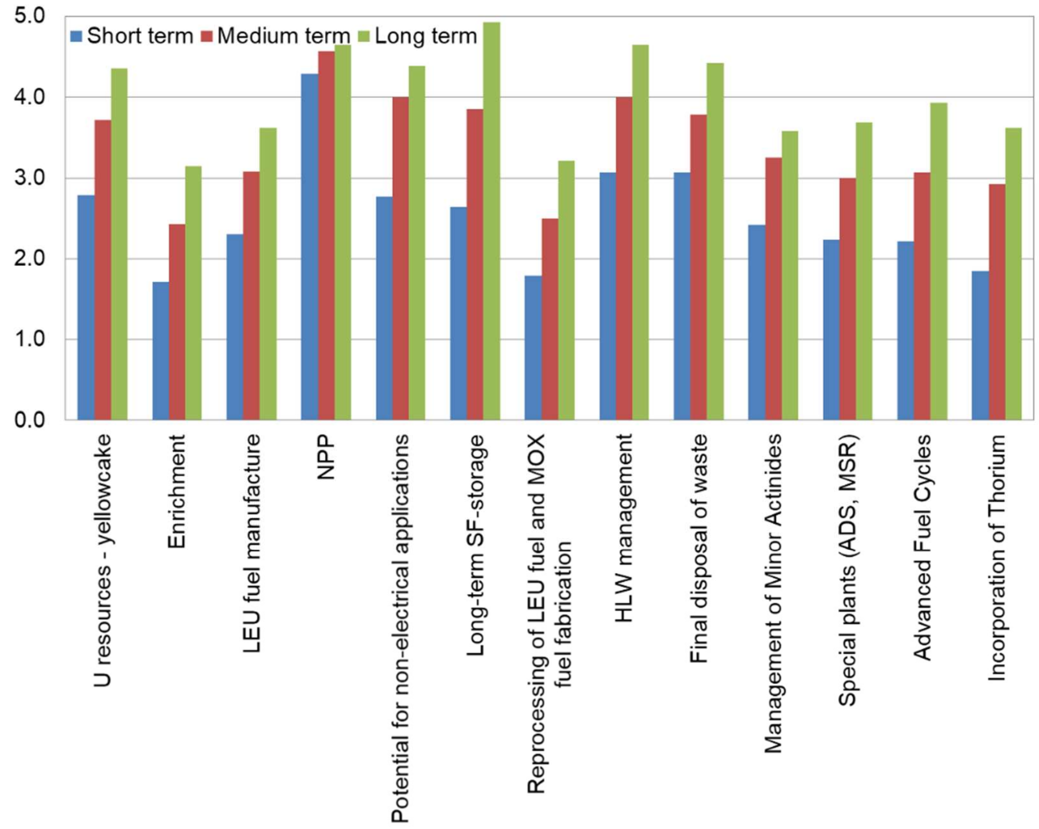


FIG. IX.35 (b). Summary of responses of NG3 countries to the DF4 questionnaire, Section 1 Importance of Collaboration with Other Countries (1 — lowest priority, 5 — highest priority). Legend: LEU — low enriched uranium; SF —spent fuel; ADS — accelerator driven system; MSR — molten salt reactor.

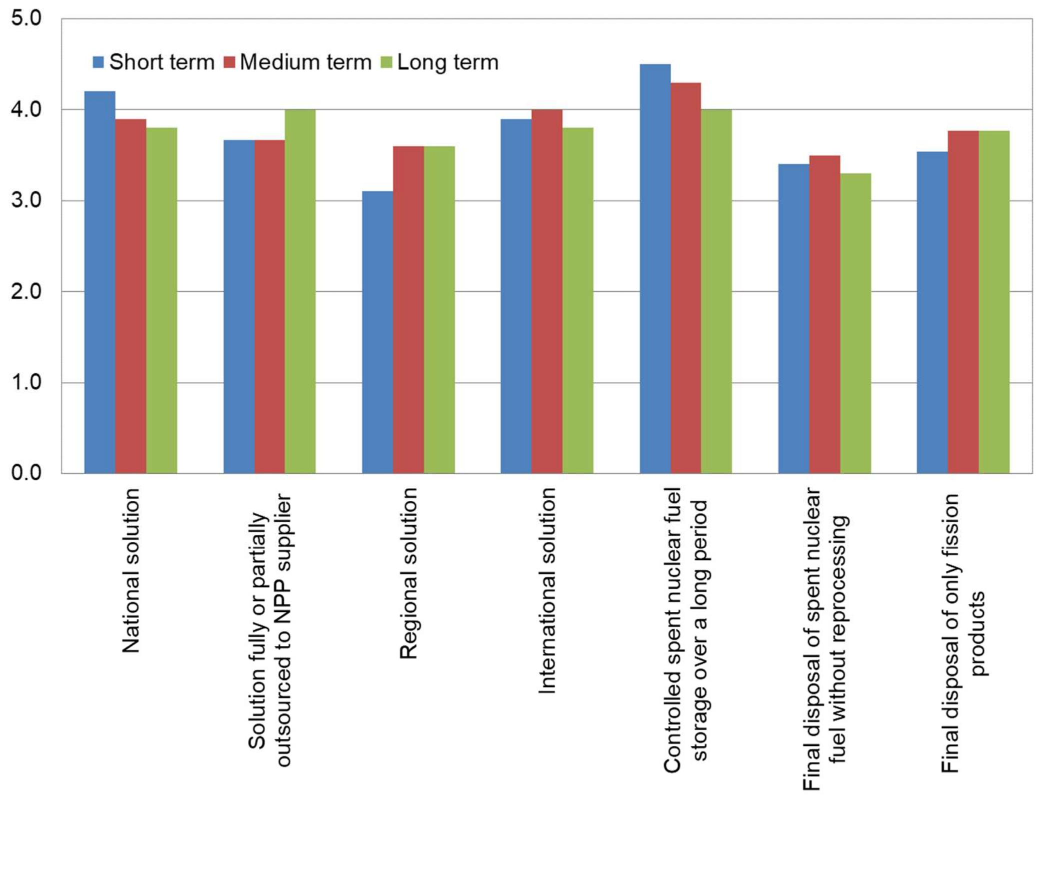


FIG. IX.35 (c). Summary of responses of NG1+NG2 countries to the DF4 questionnaire, Section 3 Final Disposal of Radioactive Waste (1 — least preferred, 5 — most preferred).

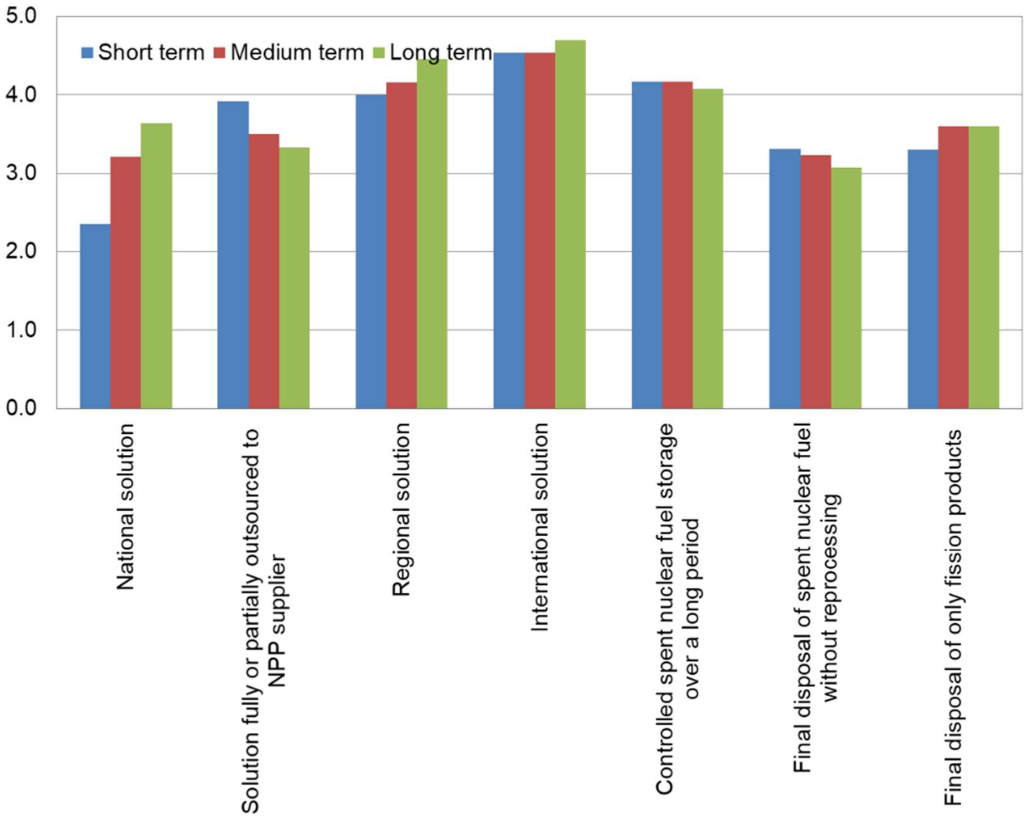


FIG. IX.35 (d). Summary of responses of NG3 countries to the DF4 questionnaire, Section 3 Final Disposal of Radioactive Waste (1 — least preferred, 5 — most preferred).

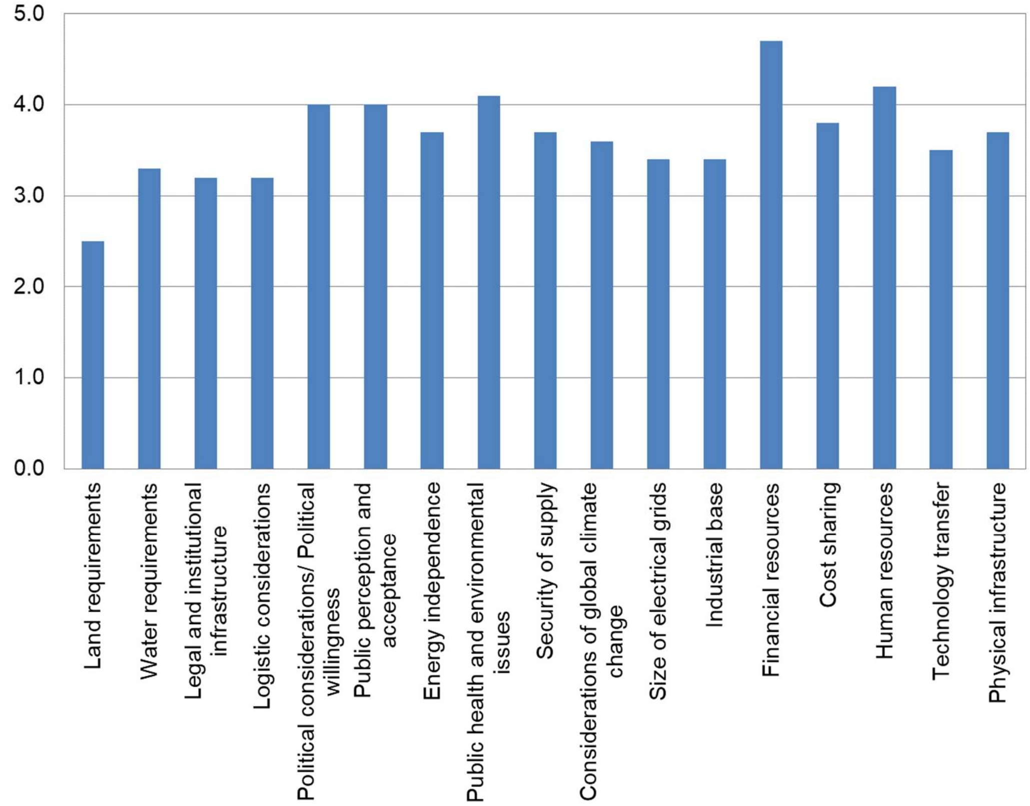
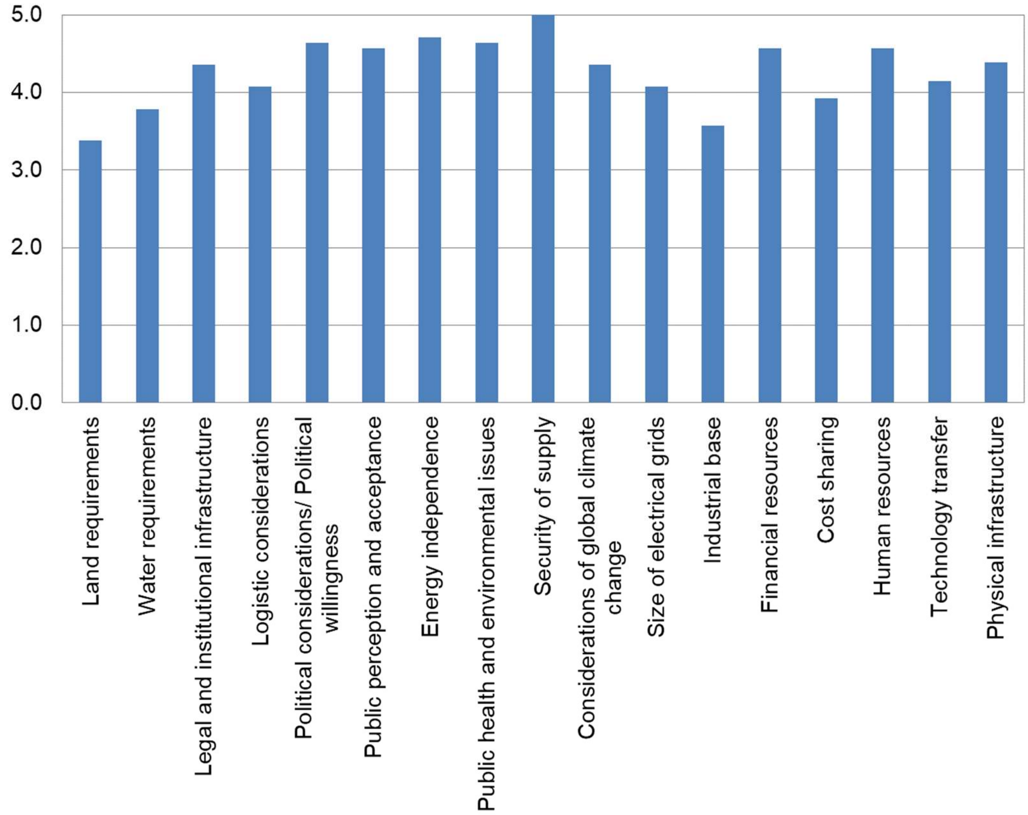


FIG. IX.36(a). Summary of responses of NG1+NG2 countries to the DF4 questionnaire, Section 5 Issues Important [When] Considering a National Nuclear Energy Project (1 — not important, 5 — very important).



IX.36(b). Summary of responses of NG3 countries to the DF4 questionnaire, Section 5 Issues Important [When] Considering a National Nuclear Energy Project (1 — not important, 5 very important).

The participants were asked to provide answers to three questions:

(a) Do national laws exist prohibiting or restricting the return of spent nuclear fuel to suppliers from other countries?

(b) Do national laws exist prohibiting or restricting the transboundary transport of spent nuclear fuel?

(c) Assuming a service or a particular product for a nuclear energy project, how many suppliers would be preferred to guarantee the security of supply?

The responses showed that in about 20% of the countries represented at the fourth INPRO Dialogue Forum there were national laws that either prohibit or restrict the return of spent nuclear fuel to suppliers from other countries or prohibit or restrict the transboundary transport of spent nuclear fuel.

- In 30% of the technology holder and user countries and in 10% of the newcomer countries, national laws exist prohibiting or restricting the return of spent nuclear fuel to suppliers from other countries.
- In 10% of the technology holder and user countries and 30% of the newcomer countries national laws exist prohibiting or restricting the transboundary transport of spent nuclear fuel.
- Regarding the number of suppliers that would guarantee the security of supply, the respondents preferred, on average, between two and four suppliers (technology holder and user countries) and two to three suppliers (newcomer countries).

REFERENCES TO ANNEX IX

[IX.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[IX.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems, IAEA Nuclear Energy Series No. NF-T-2.4, IAEA, Vienna (2012).

[IX.3] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2016: Resources, Production and Demand, OECD Publishing, Paris (2016).

[IX.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling Nuclear Energy Systems with MESSAGE: A User's Guide, IAEA Nuclear Energy Series No. NG-T-5.2, IAEA, Vienna (2016).

[IX.5] Nuclear Fuel Cycle Simulation System: Improvements and Applications, IAEA TECDOC Series No. 1864, IAEA, Vienna (2019).

[IX.6] WORLD NUCLEAR ASSOCIATION, The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2015–2035, WNA, (2015).

[IX.7] INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends in Spent Fuel Reprocessing, IAEA-TECDOC-1467, IAEA, Vienna (2005).

[IX.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Spent Fuel Reprocessing Options, IAEA-TECDOC-1587, IAEA, Vienna (2008).
[IX.9] OECD NATIONAL ENVIRONMENT AGENCY, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, OECD Publishing, Paris (2006).
[IX.10] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Fuel Cycle Profiles, 2nd edn, Technical Reports Series No. 425, IAEA, Vienna (2005).
[IX.11] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No. 1, IAEA, Vienna (2017).
[IX.12] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology Review 2016, IAEA, Vienna (2016).
[IX.13] WORLD NUCLEAR ASSOCIATION, Conversion and Deconversion (2019), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/conversion-and-deconversion.aspx
[IX.14] WORLD NUCLEAR ASSOCIATION, Uranium Enrichment (2020), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx
[IX.15] WORLD NUCLEAR ASSOCIATION, Nuclear Fuel and its Fabrication (2020), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx
[IX.16] INTERNATIONAL PANEL ON FISSILE MATERIALS, http://fissilematerials.org/