Analytical Framework for Analysis and Assessment of Transition Scenarios to Sustainable Nuclear Energy Systems

IAEA

INPRO
International Project on Innovative Nuclear Reactors and Fuel Cycles

Enhancing Global Nuclear Energy Sustainability

www.iaea.org/INPRO

Table of Contents

SUMMARY

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in 2000 to help ensure that nuclear energy is available to contribute to meeting global energy needs of the 21st century in a sustainable manner. INPRO activities on global and regional nuclear energy scenarios provide countries embarking on a new nuclear power programme ('newcomers') and countries with a mature nuclear power programme with a better understanding of the options available to achieve sustainable nuclear energy.

The INPRO Collaborative Project on Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS), conducted in 2008 – 2011, developed an international analytical framework for assessing transition scenarios to future sustainable nuclear energy systems and applied it in sample analyses.

This brochure presents major elements of the analytical framework and selected results of its application including:

- A common methodological approach, including basic principles, assumptions, and boundary conditions;
- Scenarios for long term nuclear power evolution based on IAEA Member States' high and low estimates for nuclear power demand until 2050, and trend forecasts to 2100 based on projections of international energy organizations;
- A heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle;
- Metrics and tools to assess the sustainability of scenarios for a dynamic nuclear energy system, including a set of key indicators and evaluation parameters;
- An international database of best-estimate characte ristics of existing and future innovative nuclear reactors and associated nuclear fuel cycles for material flow analysis, which expands upon other IAEA databases and takes into account different preferences of Member States;
- Findings from analyses of scenarios of a transition from present nuclear reactors and fuel cycles to future nuclear energy system architectures with innovative technological solutions.

The framework is a part of the integrated services provided by the IAEA to Member States considering the initial development or expansion of their nuclear energy programmes.

1. Introduction

One of the main objectives of INPRO is to help to ensure that nuclear energy is available to contribute to meeting the energy needs of the 21st century in a sustainable manner. A methodology for assessing capabilities of innovative nuclear energy systems to meet national sustainability requirements was developed in the first phase of INPRO [1, 2]. A significant task of the current, second phase of the Project is to find ways for an optimal introduction of innovative nuclear energy technologies into national energy systems, taking into account the regional and global trends of nuclear energy system development, the attractiveness of multilateral solutions for spent nuclear fuel (SNF) management and non-proliferation from an economic perspective, and the fact that nuclear energy is a global undertaking in terms of safety, nuclear material resources, and non-proliferation.

When performing a study on transition scenarios, it is essential to quantify the key aspects characterizing development and deployment of nuclear energy system components over particular periods of time, including estimations of technical parameters, economic performance, infrastructural and institutional arrangements. While many States and international organizations have performed relevant studies, it is increasingly recognized that more efforts are needed to harmonize national decisions on technical, institutional and political issues which are raised by the transition to a nuclear energy system with enhanced sustainability features. One of four INPRO major activities is to perform scenario studies to understand key issues in a transition to future nuclear energy systems. Several IAEA Member States have expressed interest in joint modelling of global trends toward a sustainable nuclear power supply, taking into account the potential of technical innovations and multilateral cooperation.

Responding to this request, the INPRO Collaborative Project GAINS was established in 2008. The project defined “architecture” as a system with different types of reactors and corresponding fuel cycle installations, as well as interactions between their components to serve a common goal. The objective of the GAINS project was to develop a standard framework for assessing future nuclear energy systems taking into account sustainable development, and to validate the simulation results through sample analyses. Sixteen participants from different regions of the world – Belgium, Canada, China, Czech Republic, France, India, Italy, Japan, the Republic of Korea, the Russian Federation, Slovakia, Spain, Ukraine, the USA, the European Commission (EC), plus Argentina as an observer – carried out coordinated investigations and contributed to the GAINS final report [3]. This broad membership, as well as the cooperation of the thermal and fast reactor ‘communities’, collaboration with similar international initiatives, and the IAEA’s auspices and expertise are considered strengths of the project.

This brochure summarizes the results of and provides examples from the GAINS Collaborative Project.

FIG.1. 5th Meeting of the INPRO Collaborative Project GAINS, 27 May 2010.

2. Member States' Needs in Developing Transition Scenarios towards Sustainable Nuclear Energy Systems

Existing nuclear energy systems, which are almost entirely based on thermal reactors operating in an open fuel cycle, will continue to be the main contributor to nuclear energy production for at least several more decades. However, results of multiple national and international studies show that the criteria for developing sustainable nuclear energy cannot be achieved without major innovations in reactor and nuclear fuel cycle technologies. New reactors, nuclear fuels and fuel cycle technologies are under development and demonstration worldwide. Expectations for their large-scale introduction into operational nuclear energy systems differ (Fig. 2).

Innovative reactors expected to have a major impact on the future nuclear energy system architecture include advanced light water reactors (ALWR), advanced heavy water reactors (AHWR), high temperature reactors (HTR), fast reactors (FR), and potentially, accelerator driven systems (ADS) and/or molten salt reactors (MSR). Small and medium-sized reactors (SMR) were initially considered in the GAINS project, but were not evaluated as they are not distinctly different from their technology type (LWR, FR, etc.). Combining the different reactor types and associated fuel chains creates a multiplicity of nuclear energy system arrangements aimed at solving specific goals, such as production of various energy products, better use of natural resources, and minimization of radioactive waste.

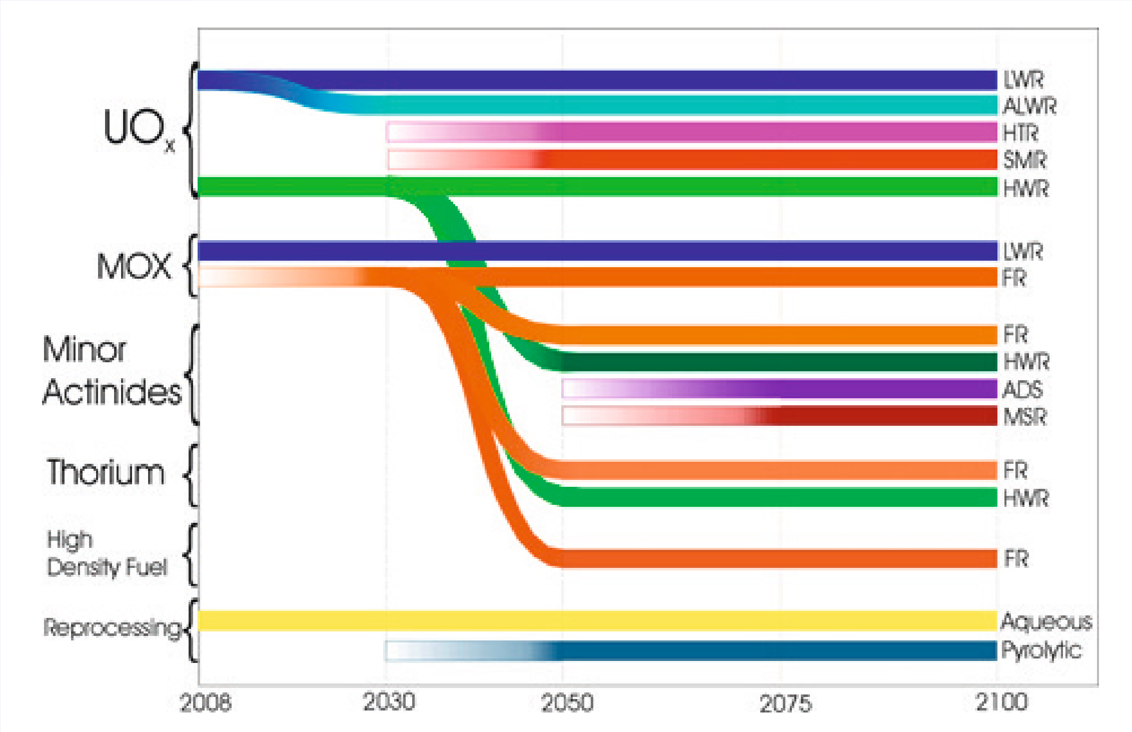

FIG. 2. Set of reactor and fuel types with deployment time frames.

Analytical groups and decision makers involved in developing a national nuclear power strategy typically select from the set of available technologies within a given period of time and adjust it to local needs, taking into account national capabilities and preferences as well as potential reactor sales and fuel cycle services provided by regional or global markets. It is becoming increasingly clear that national strategies will have to be harmonized with regional and global nuclear power architectures to make a national nuclear energy system more effective.

An established market exists at the front end of the fuel cycle, and there are also promising examples of cooperation at the back end. Simulations of the transition to sustainable nuclear energy systems at national, regional, and global levels have become an essential part of the scientific work that supports the decision making process on national nuclear power programmes.

The GAINS project provides IAEA Member States with a framework (hereafter called the GAINS framework) to help explore transition scenarios to a future global nuclear energy system that would combine the synergy of nuclear technologies together with innovative institutional approaches to foster collaboration among countries to amplify the benefits of the innovation.

3. Definition of the GAINS Framework

The GAINS framework is based on CP participants' experiences in implementing similar studies at national and international levels. The framework can be used for developing national nuclear energy strategies, exploring opportunities for cooperation and partnerships on the nuclear fuel cycle, and highlighting how global trends may affect national developments (and vice versa). Individual countries can make use of this framework to evaluate particular approaches in a global or regional context based on national and regional data.

The GAINS framework includes:

- A common methodological approach with the basic principles, assumptions and boundary conditions;
- Scenarios for nuclear power evolution and a future transition to innovative nuclear energy systems with thermal and fast reactors;
- Use of IAEA models and tools for material flow simulation to support evaluation along with national instruments;
- International data on reactors and associated fuel cycles as needed for material flow analysis and comparative economic evaluations;
- Agreed metrics for scenario analyses and assessment;
- Templates for analysis of simulation results;
- Sample scenario studies, including a set of basic cases which could be used for comparison and reference purposes.

4. A Common Methodological Approach

Basic principles and assumptions, uniform boundary conditions, and a common methodological platform are prerequisites for the development of a comprehensive framework for the analysis and assessment of transition scenarios.

The underlying assumption of the GAINS project is that growing human needs in the 21st century will require large scale deployment of nuclear power together with other energy sources. The international community has recognized the risks associated with growing energy use, such as increasing levels of pollution, accelerated resource depletion, accumulation of waste, and other threats. Responding to these concerns, the United Nations has defined requirements for sustainable energy supply as part of the general concept of sustainable development [4, 5]. These requirements make it possible to assess whether prospective energy sources will meet the increasing demands of society and generate energy in a safe, environmentally-responsible, and affordable manner.

In cooperation with IAEA Member States, INPRO has defined the requirements for a sustainable nuclear energy system consistent with the UN concept for sustainable development [4, 5]. These requirements are also consistent with the high-level goals and requirements for a Generation IV nuclear energy system developed independently by the Generation IV International Forum (GIF) [6]. INPRO has also developed the methodology and manuals to assess how these achieve these requirements are achieved [7–9].

INPRO methodology is a holistic approach to assess the sustainability of innovative nuclear systems across seven areas: economics, infrastructure, waste management, proliferation resistance, physical protection, environment, and safety of nuclear installations. For each of these areas a hierarchical set of Basic Principles, User Requirements, and Criteria forms the basis for a sustainability assessment. Through a bottom-up approach, the fulfilment of a Criterion is confirmed by an Indicator complying with the Acceptance Limit(s); the fulfilment of a User Requirement is confirmed by the fulfilment of the corresponding Criterion (Criteria); and the fulfilment of a Basic Principle is achieved by meeting the related User Requirement(s). 14 Basic Principles, 52 User Requirements and 125 Criteria with Indicators and Acceptance Limits must be satisfied to confirm that a nuclear energy system is sustainable [9].

INPRO methodology and manuals provided a useful resource for the participants of the GAINS project. However, INPRO methodology was designed as a tool for assessing the capabilities of a national nuclear energy system to meet requirements of sustainability, whereas the GAINS framework is aimed at comparing options and possible scenarios at the national, regional, and global levels. Accordingly, the GAINS framework relates to INPRO methodology primarily through the concept of ‘key indicators’ (KIs) introduced in INPRO methodology reports [8, 9].

A nuclear energy system sustainability assessment must also take into account specific local conditions. Because the scope of indicators relevant to the GAINS objectives is limited to those aspects of a nuclear energy system that have a broader and more general context, KIs for GAINS have been defined for selected INPRO assessment areas that reflect the focus areas of the GAINS project. These KIs provide a distinctive capability for capturing the essence of a given area and provide a means to establish targets to be reached by improving technical or infrastructural characteristics of a nuclear energy system.

The GAINS framework measures the transition from an existing to a future sustainable nuclear energy system by the degree to which the selected targets (e.g. minimized waste, minimized amounts of direct use materials in storage, or minimized natural resource depletion) are approached in particular evolution scenarios. KIs are compared to determine the more promising options for achieving the selected targets. Possible benefits and issues between the different options are also analysed.

GAINS project participants sought to reduce the number of KIs to a minimum to facilitate implementation of a scenario-based approach. However, evaluation parameters (EP) were introduced as sub-indicators to further clarify the indicators, and in some cases, to obtain quantitative values. These parameters add an additional depth to the estimation of the nuclear energy system sustainability.

In addition to an expectation of large-scale deployment of nuclear energy in the future, the GAINS project is characterized by several general assumptions. In particular, project participants recognize the critical role of R&D in the sustainable deployment of nuclear power, and that there is wide variation in the development and deployment of nuclear technologies worldwide. It is assumed that this imbalance and the extent of multilateral cooperation (addressed in many IAEA publications, e.g. [10]) will continue to be important factors in the future evolution of the global nuclear energy system as a whole.

5. Scenarios for Nuclear Power Evolution

Nuclear power is an integral part of the energy sector. Similar to other energy options, deployment of nuclear power depends on demand for primary energy and electricity, environmental constraints, and progress in technological development, among other things. According to recent long term projections, the range of expected nuclear energy demand varies considerably because of the uncertainty in future conditions and the driving forces that define the need for energy [3].

Different assumptions of demographic, social, economic, technological, and environmental developments result in divergent trends of nuclear power deployment, from exponential growth to full phase-out. To help define an area of concern and allow for specific conclusions regarding nuclear architecture, GAINS participants developed the framework according to high- and moderate-growth scenarios.

In addition to surveying nuclear power projections based on macroeconomic studies, including the Special Report on Emission Scenarios (SRES) of the International Panel for Climate Change (IPCC) [11], the GAINS project also examined national medium and long term nuclear strategies and programmes, in close cooperation with the IAEA Planning and Economic Studies Section (PESS) [12]. This helped narrow the scope of uncertainty in selecting two long term nuclear energy demand scenarios based on high and low estimations of nuclear power deployment until 2100 (Fig. 2).

These scenarios can serve as reference points in analyses of the global nuclear energy system. The following was noted:

- The high nuclear energy demand scenario is an averaged expectations of the IPCC SRES – in this scenario, global annual nuclear electricity production reaches approximately 1500 GWa by 2050, and 5000 GWa by 2100;
- The moderate nuclear energy demand scenario assumes approximately 1000 GWa by 2050, and 2500 GWa by the end of the century.

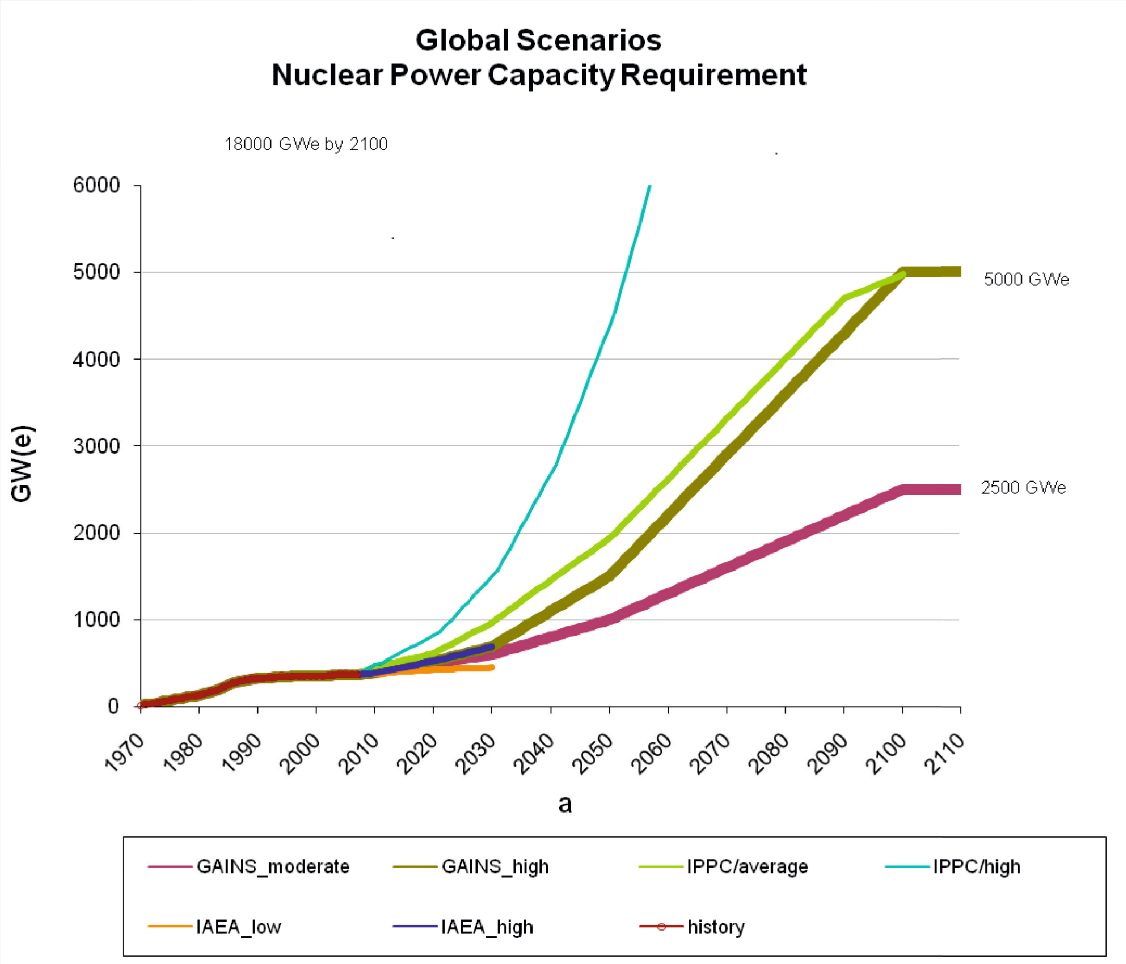

FIG. 2. GAINS scenarios for modelling nuclear power generation (GWa values show actual electric power produced annually, not installed capacity).

The growth curves have three distinct growth periods. Each is modelled by linear growth to reach the specific level of the production by the end of the period:

- 2009–2030: 600 GWa for the moderate case and 700 GWa for the high case;
- 2031–2050: 1000 GWa for the moderate case and 1500 GWa for the high case;
- 2051–2100: 2500 GWa for the moderate case and 5000 GWa for the high case.

When analyzing thermal power annual production profiles (e.g. to study possible production of non-electrical nuclear energy products such as heat, potable water, hydrogen, etc.), these scenarios can be used to construct a set of companion profiles of thermal power production demand (GWa(th)) by applying an assumed thermal-to-electric efficiency conversion value.

6. Models and Simulation Tools

Most studies on the future of nuclear energy are based on a homogeneous global model, which suggests a world rapidly converging toward global solutions for economic, social, and environmental challenges. This model emphasizes the opportunities facilitating creation of the regional and global nuclear architecture, such as unification of reactor fleets and associated technologies, infrastructure sharing, multinational fuel cycle centres, and innovative approaches to financing and licensing, among other things. However, it does not take into account the barriers to cooperation between different parts of the world, or national preferences and capabilities.

To complement this model, the GAINS project developed a heterogeneous model based on grouping countries with similar fuel cycle strategies. This model can facilitate a more realistic analysis of transition scenarios toward a global architecture of innovative nuclear energy systems. It can also illustrate the global benefits that would result from some countries introducing innovative nuclear technologies, which would limit the exposure of the majority of countries to the financial risks and other burdens associated with the development and deployment of these technologies.

The heterogeneous world model developed by GAINS organizes countries into groups according to their strategies of SNF management (see Fig. 3):

Group NG1 countries pursue a general strategy to recycle spent nuclear fuel and plan to build, operate, and manage spent fuel recycling facilities and permanent geologic disposal facilities for highly radioactive waste;

Group NG2 countries follow a strategy either to directly dispose SNF or send it abroad for reprocessing. These countries plan to build, operate, and manage permanent geologic disposal facilities for highly radioactive waste (either as spent fuel or reprocessing waste) but may work synergistically with countries from another group to recycle fuel;

Group NG3 countries have a general strategy for the front end of the fuel cycle – to acquire fresh fuel from abroad and send spent fuel abroad for either recycling or disposal – but have not developed plans to build, operate, or manage spent fuel recycling facilities or permanent geologic disposal facilities for highly radioactive waste.

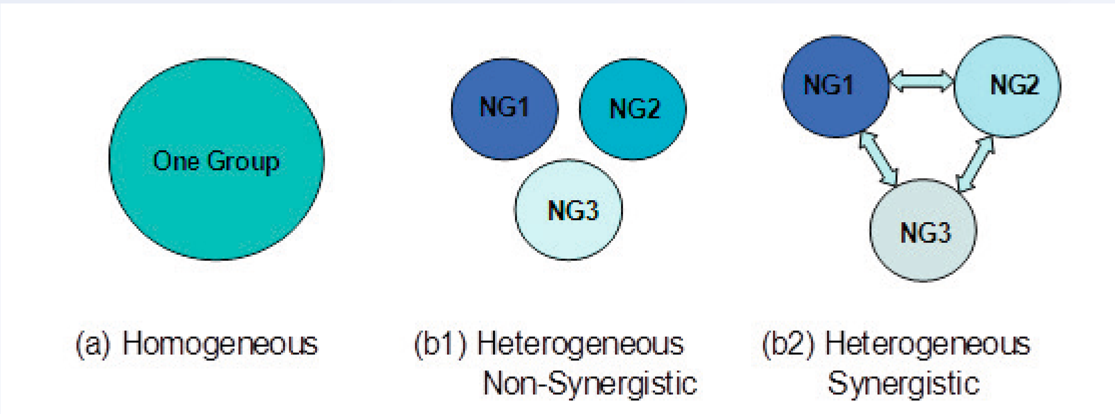

FIG. 3. Heterogeneous models for future global nuclear fuel cycles.

The heterogeneous model may involve some degree of cooperation between groups (synergistic case) as shown in Figure 3, or it may not involve any cooperation (non-synergistic case). Figure 4 illustrates the flow of nuclear fuel cycle operations for each group in a non-synergistic and a synergistic heterogeneous world model. Solid lines indicate required functions and actions, while dotted lines indicate additional options.

(a) (b)

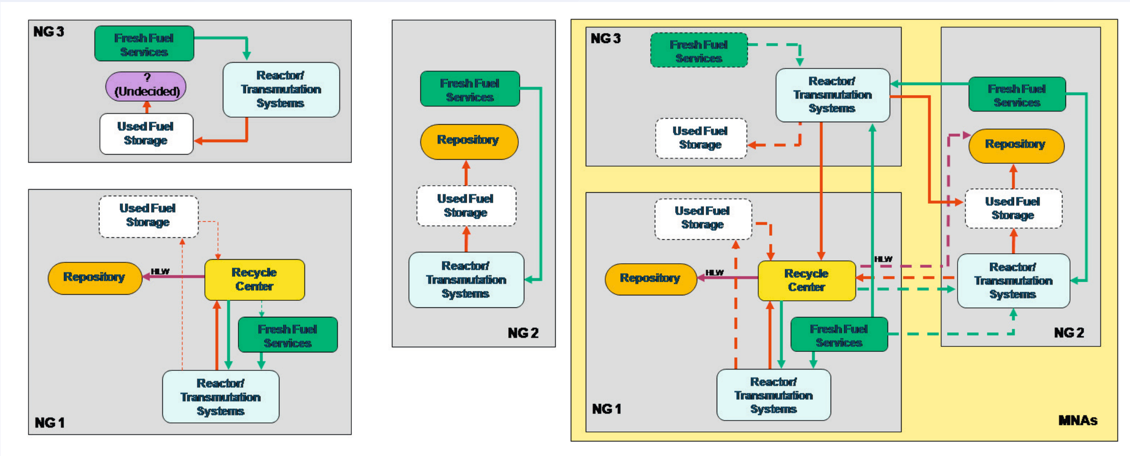

FIG. 4. Heterogeneous model: non-synergistic (a) and synergistic (b).

The GAINS project conducted analyses of national energy strategies and competent energy agencies' surveys on short, medium and long term projections of global nuclear power deployment. On the basis of this analysis, estimated nominal scenarios of future annual nuclear electricity production were developed for each GAINS group (TABLE 1).

TABLE 1. NOMINAL SCENARIO OF ANNUAL NUCLEAR ELECTRICITY PRODUCTION FOR GAINS HETEROGENEOUS MODEL GROUPS

GAINS groups	GWa						
	2008	2030 Moderate	2030 High	2050 Moderate	2050 High	2100 Moderate	2100 High
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

The heterogeneous model allows for indicators to be calculated for each group of countries (NG1, NG2, NG3), whereas a homogeneous model could only provide indicators for the world as a whole. (Due to uncertainty in the medium and long term forecasts, the group and world total scenarios should be considered as reference points. Variations of the country group shares were considered in the SYNERGIES project [16], a follow-up to GAINS, for possible use in sensitivity studies to complement the GAINS framework.)

Additionally, the IAEA and some Member States have developed analytical methods and computer codes for modelling scenarios which allow calculation of a wide range of indicators. Three codes – MESSAGE, NFCSS and DESAE – are distributed by the IAEA and are available to all interested Member States.

MESSAGE (Model for Energy Supply System Alternatives and their General Environmental impacts) is a large-scale dynamic model for development of medium to long term energy scenarios and policy analysis [13]. MESSAGE allows for different energy technologies (including nuclear) with their specific features to be modelled for the purpose of optimizing of a specific objective (e.g. least cost, lowest environmental impact, maximum self-sufficiency) under a set of constraints.

NFCSS (Nuclear Fuel Cycle Simulation System) [14] is a code which estimates the requirements for nuclear fuel cycle services and nuclear materials during each phase of a transition scenario. NFCSS was developed mainly to evaluate nuclear fuel cycle services and materials requirements for existing thermal nuclear reactor types and fast reactors of some types.

DESAE (Dynamics of Energy Systems – Atomic Energy) [15] is an interactive material flow analysis code for quantitative assessment of nuclear fuel cycle requirements, material balances, and economic parameters for a given combination of nuclear reactors during a specific time period.

GAINS participants also reviewed and took into consideration several of the modelling codes developed by Member States, including DANESS and VISION (USA), COSI (France), FAMILY (Japan), and TEPS (India).

7. Architectures for Nuclear Energy Systems and Data on Nuclear Reactors and Associated Fuel Cycles

In developing the GAINS framework, participants defined several nuclear energy system architectures and evaluated the effect implementation of innovative technologies and cooperation among countries belonging to different groups would have on KIs. Potential architectures include:

- A homogeneous ‘business-as-usual’ (BAU) scenario based on pressurized water reactors (PWRs) (94% of power generation) and heavy water reactors (HWRs) (6% of power generation) operating in a once-through fuel cycle, or a ‘BAU+’ variation involving Advanced PWRs;

- A homogeneous scenario for a closed fuel cycle based on thermal and fast reactors;

- A hybrid heterogeneous scenario comprised of a once-through fuel cycle strategy in NG2, a closed fuel cycle strategy in NG1, and use of thermal reactors in a once-through mode in NG3; (this scenario includes both synergistic and non-synergistic cases – in the synergistic case, NG3 receives fresh fuel from NG2 and NG1 and returns the associated SNF to those groups (see Fig. 5));

- Other innovative architectures in the homogeneous model, including fast-spectrum reactors or thermal-spectrum HWRs using thorium fuel to reduce natural uranium requirements, and those featuring reduction of minor actinides (MA) using accelerator driven systems (ADS) or molten salt reactors (MSR).

The GAINS architecture includes the entire range of reactor technologies – from the most common systems currently operating, to the systems planned for near to medium term deployment, to the most innovative systems which are in early stages of research and development (Fig. 5). Table 2 gives an example of the averaged parameters for a break-even fast reactor (the reactor with breeding ratio BR~ 1.0).

To build a simulation model for these architectures and assess related KIs, it is necessary to acquire data on material flows and economics for each reactor design and related nuclear fuel cycle technology. The GAINS framework incorporates and extends data from existing IAEA databases of modelling scenarios and also takes into account the different perspectives of countries which participated in the project.

For nuclear reactor systems, global mass flow analysis requires data on fuel burn-up performance and refuelling for each reactor concept. For nuclear fuel cycle systems, the basic flow diagrams of typical systems and some important conditions which affect mass flow analysis results are needed.

FIG. 5. Variation in technical maturity for reactor designs in the GAINS database

The basic fuel material flows for the examined architectures are defined together with key analysis conditions, e.g. uranium enrichment tails assay is assumed to be 0.2% and spent fuel from HWRs is assumed to be temporarily stored. The framework also assumes that there are no limitations to acquiring and operating fuel cycle infrastructure related to mining, conversion, enrichment, fuel fabrication, long term storage for spent fuel, interim storage for separated nuclear materials (e.g. plutonium, minor actinides (MA), fission products), reprocessing and geological disposal capacities.

TABLE 2. EXAMPLE OF REACTOR DATA (BREAK-EVEN FAST REACTOR)

Reactor net electric output	MW	870		
Reactor thermal output	MW	2100		
Thermal efficiency	%	41.43		
Average load factor	%	85		
Operation cycle length	EFPD	140		
		Core	Axial blanket	Radial blanket
Power share of each region*	%	94.5	3.0	2.5
No. of refuelling batches**		3	3	3.5
Fuel residence time**	EFPD	420	420	490
Specific power density*	MW/t	157.00	11.465	8.532
Average discharged burnup*	MWd/t	65939	4815	4181
Thermal power of each region*	MW	1984.5	63.0	52.5
Heavy metal weight share				
Intial core and full core discharge	%	52.0	22.6	25.4
Equilibrium refueling	%	54.0	23.5	22.5
Average burnup of whole core*	MWd/t	37677		
Average residence time of whole core*	EFPD	435.771		
Average power density of whole core*	MW/t	86.462		
Initial fuel inventory	tHM	24.288		
Equilibrium Loading	tHM / y	17.292		

Figure 6 provides an example of the flow chart for a combined once-through fuel cycle and fast reactor closed fuel cycle system. As shown in the figure, the once-through fuel cycle system consists of facilities for uranium mining, conversion, enrichment, depleted uranium storage, fuel fabrication, nuclear power production, spent fuel storage at the nuclear power plant, and long term spent fuel storage. In the case of HWRs, the steps of conversion, enrichment and depleted uranium storage do not exist because HWRs operate on natural uranium fuel.

The GAINS framework incorporates certain assumptions regarding the rate that fast reactors would be introduced into a system initially consisting of LWRs and HWRs. These assumptions impose a constraint on the power production by fast reactors in the years between 2030 and 2050 by specifying a maximum deployment rate depending on the overall nuclear energy growth scenario, resulting in a total electricity production rate of 10 GWa from fast reactors in 2030 and a total of 400 GWa in 2050 for the high scenario case. After 2050, the deployment rate of fast reactors is maximized and limited only by the amount of plutonium available and the overall nuclear growth rate.

The combined system shown in Fig. 6 includes a reprocessing facility for the recycle of plutonium, MA and uranium, and a radioactive waste management facility for the fast reactor cycle. The reprocessed uranium from LWRs or ALWRs can be used as the feed for re-enrichment or in fuel for FRs and HWRs.

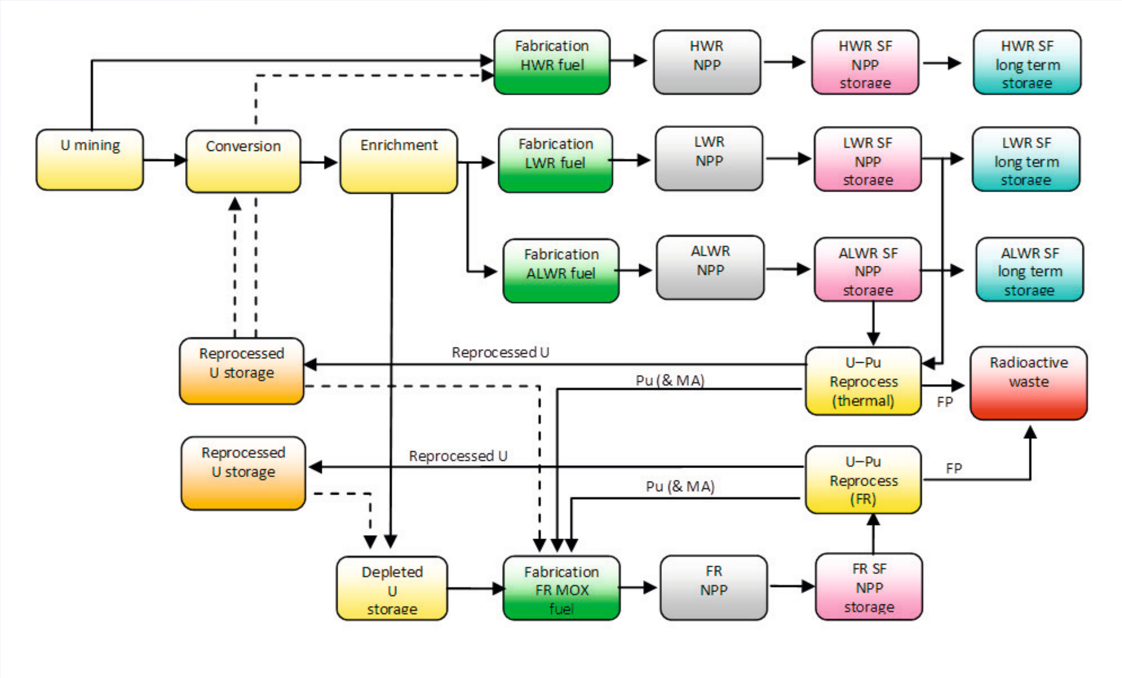

FIG. 6. Flow chart for a combined once-through cycle and fast reactor closed fuel cycle system

8. Metrics for Scenario Analysis and Assessment

As described in Chapter 4, the GAINS framework employs the concept of 'key indicators' (KIs) and 'associated evaluation parameters' (EPs) to enable a comparative analysis and sustainability assessment of dynamic nuclear energy systems. The framework provides ten KIs with associated EPs (Table 3).

The set of KIs and EPs provided in Table 3 is based on more than one-hundred indicators comprising all assessment areas of the INPRO methodology. These KIs/EPs depict nuclear power production of a global nuclear energy system according to reactor type, resources, discharged fuel, radioactive waste, fuel cycle services, costs, and investments. Although developed for global architectures, the set of GAINS KIs and EPs can also be adapted for a more localized application of the framework.

Database values may not be readily available for calculating some of the KIs or EPs. For a more complete application of the framework, economic data and probabilistic risk assessment data for advanced systems should be collected, as technologies mature with time and data become available.

TABLE 3. GAINS KEY INDICATORS AND EVALUATION PARAMETERS

No.	Key indicators and Evaluation Parameters Color coding indicative of relative uncertainty level in estimating specific quantitative values for future NES (can vary based on a particular scenario): Low / Medium-low / Medium-high / High	INPRO assessment areas: Resource Sustainability	Waste Management and Environmental Stressors	Safety	Proliferation Resistance and Physical Protection	Economics	Infrastructure
Power Production							
KI-1	Nuclear power production capacity by reactor type						X
EP-1.1	(a) Commissioning and (b) decommissioning rates		X				X
Nuclear Material Resources							
KI-2	Average net energy produced per unit mass of natural uranium	X	X				
EP-2.1	Cumulative demand of natural nuclear material, i.e. (a) natural uranium and (b) thorium	X	X				
KI-3	Direct use material inventories per unit energy generated (Cumulative absolute quantities can be shown as EP-3.1)	X			X		X
Discharged Fuel[3]							
KI-4	Discharged fuel inventories per unit energy generated (Cumulative absolute quantities can be shown as EP-4.1)		X				X
Radioactive Waste and Minor Actinides							
KI-5	Radioactive waste inventories per unit energy generated[4] (Cumulative absolute quantities can be shown as EP-5.3)		X				X
EP-5.1	(a) radiotoxicity and (b) decay heat of waste, including discharged fuel destined for disposal		X				X
EP-5.2	Minor actinide inventories per unit energy generated		X				X
Fuel Cycle Services							
KI-6	(a) Uranium enrichment and (b) fuel reprocessing capacity, both normalized per unit of nuclear power production capacity				X		X
KI-7	Annual quantities of fuel and waste material transported between groups		X		X		X
EP-7.1	Category of nuclear material transported between groups				X		
System Safety							
KI-8	Annual collective risk per unit energy generation			X			
Costs and Investment							
KI-9	Levellized unit of electricity cost (LUEC)					X	
EP-9.1	Overnight cost for Nth-of-a-kind reactor unit: (a) total and (b) specific (per unit capacity)					X	
KI-10	Estimated R&D investment in Nth-of-a-kind deployment					X	X
EP-10.1	Additional functions or benefits[5]					X	

9. Templates for Analysis of Modelling Results

GAINS participants developed special templates for visualization of the mass flows and fuel cycle service requirements to facilitate analysis of KIs and EPs of nuclear energy systems under consideration. Transition scenarios were generally defined in general by the type and timing of nuclear energy system deployment, and more specifically by the complete set of assumptions used in their calculation or code case. A naming convention helped to identify and distinguish between analytical cases. The assumptions, input data and results obtained by each GAINS participant were documented in the annexes of the final report of the project [3]. The templates contain:

- Fuel composition data for each reactor system in the scenario studies;
- Descriptions of scenario cases and their denotation;
- A set of analysis conditions related to the fuel cycles;
- Growth rate tables for base cases; and,
- Results of calculation of the KIs provided in table and graph formats.

As an example, Table 4 demonstrates a fragment of fresh and discharged fuel data of a break-even fast reactor.

The development of the templates for a global nuclear energy system scenario evaluation indicates essential progress in harmonizing analytical tools of the Member States, which can be used to support decision making related to long term nuclear energy strategy and energy planning.

TABLE 4. SELECTED FUEL-RELATED DATA FROM THE TEMPLATE.

Isotopes	Initial loading (kg)		Reload (kg)		Discharge (kg)		Full core discharge at retirement (kg)	
	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)	(%)
U-234					3.863E-03	4.951E-05	7.944E-03	3.271E-05
U-235	6.458E+01	2.659E-01	2.065E+01	2.646E-01	1.932E+01	2.476E-01	6.668E+01	2.745E-01
U-236					1.695E+00	2.173E-02	4.017E+00	1.654E-02
U-238	2.146E+04	8.836E+01	6.862E+03	8.794E+01	6.537E+03	8.377E+01	2.073E+04	8.534E+01
Np-237					1.037E+00	1.329E-02	2.262E+00	9.312E-03
Pu-238	1.381E+01	5.685E-02	4.602E+00	5.898E-02	3.522E-01	4.514E-03	5.661E-01	2.331E-03
Pu-239	1.657E+03	6.822E+00	5.523E+02	7.078E+00	5.767E+02	7.390E+00	1.762E+03	7.253E+00
Pu-240	6.766E+02	2.786E+00	2.255E+02	2.890E+00	2.459E+02	3.151E+00	7.280E+02	2.997E+00
Pu-241	3.010E+02	1.239E+00	1.003E+02	1.286E+00	7.410E+01	9.496E-01	2.463E+02	1.014E+00
Pu-242	1.132E+02	4.662E-01	3.774E+01	4.837E-01	4.006E+01	5.134E-01	1.193E+02	4.913E-01
Am-241					3.926E+00	5.031E-02	8.531E+00	3.512E-02
Am-242m					8.594E-02	1.101E-03	1.455E-01	5.990E-04
Am-243					2.960E+00	3.793E-02	6.071E+00	2.500E-02
Cm-242					2.694E-01	3.452E-03	4.793E-01	1.973E-03
Cm-244					3.094E-01	3.966E-03	4.930E-01	2.030E-03
Cm-245					1.039E-02	1.331E-04	1.425E-02	5.868E-05
Total FPs					2.997E+02	3.841E+00	6.166E+02	2.539E+00
Total HM & FPs	24288.257	100.000	7803.086	100.000	7803.086	100.000	24288.257	100.000
Total U	21526.758	88.630	6882.586	88.203	6557.715	84.040	20797.868	85.629
Total Pu	2761.499	11.370	920.500	11.797	937.062	12.009	2855.758	11.758
Total MAs (Np + Am + Cm)	13.807	0.057	0.000	0.000	8.598	0.110	17.996	0.074

When exploring results of cross-check assessments and comparing the results of different codes using the standard template, both national tools and tools being disseminated by the IAEA provided consistent results for the calculation of indicators related to fresh and discharged fuel flows and waste flows. The accuracy of the calculation allows for reliable conclusions to be drawn on trends in the consumption of uranium, and the accumulation of discharged fuel, fissile material and main components of radioactive waste for the selected scenarios.

At the same time, a comparison of the calculation tools used in routine analysis with more mature and capable tools provided by certain Member States identified several options for further development of the IAEA tools. Additional cross-check comparisons for multi-group (heterogeneous) synergistic scenarios are recommended.

The GAINS project also recommends future studies to compare calculation tools in economics. The INPRO CP 'SYNERGIES' (Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability) [16] has already amended the GAINS analytical framework to include an on-line updateable library of best estimate economic data for reactors and fuel cycle technologies [17]. The library includes data for reactors and nuclear fuel cycle steps which are sufficient to calculate the levelized cost of unit electricity for comparative economic analysis of the various nuclear energy system options. Data are presented in table and graphic format, and in each case appear as a range with minimum, maximum and recommended values. Economies of scale curves for fuel enrichment and reprocessing facilities are also included.

10. Sample Scenario Studies

A key objective of the GAINS project was to produce a joint analysis of the obtained simulation results and to evaluate the sustainability potential of different configurations of a global nuclear energy system. Many of the challenges related to sustainable development of a global nuclear energy system are directly linked to the architecture of the system. GAINS case studies seek to address some of these challenges by providing a sample assessment of KIs and EPs by project participants.

This brochure summarizes a few of the findings of the study related to the role of the nuclear energy system architecture in addressing concerns, such as the assurance of nuclear material resources, fissile material and high-level radioactive waste inventories, and investment barriers to the commercial introduction of innovative nuclear energy system, among other things.

The following nuclear energy systems were selected from the GAINS architectures to illustrate possible applications of the framework:

- The business-as-usual scenario based on LWR and HWR (BAU);
- BAU option with a break-even fast reactor (BR~ 1) based on a uranium-plutonium closed nuclear fuel cycle with reprocessing of the thermal reactors' spent fuel for its recycle in fast reactors (BAU&FR).

10.1. Power production

Indicator number one (KI-1) in the list of GAINS key indicators (Table 3) – nuclear power production capacity by reactor type – shows expected nuclear energy demand growth and the share of each reactor technology in the nuclear energy mix. Figure 7 shows the calculated growth curves of power production for each reactor type in the BAU and BAU&FR high case scenarios.

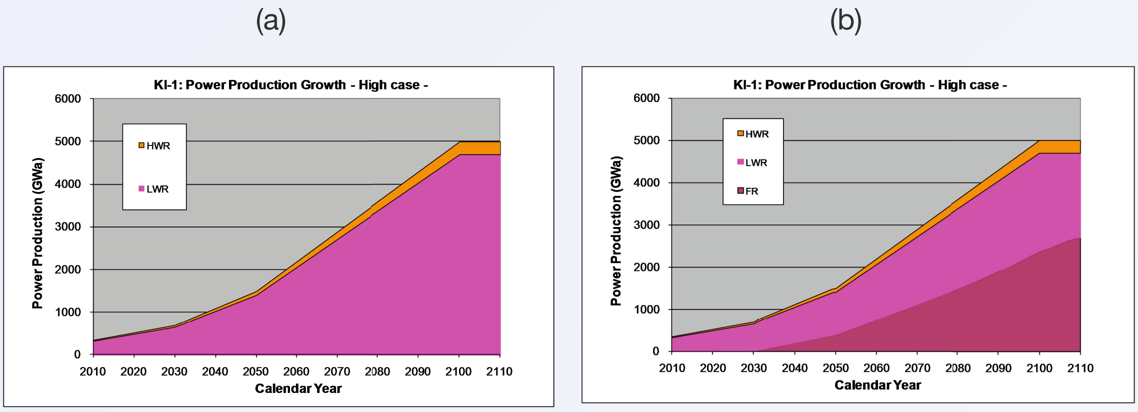

FIG. 7. Power production growth for BAU (a) and BAU&FR systems (b).

As Fig. 7 shows, the structure of the selected reactor types evolves from 100% of thermal reactors in the BAU system to about 50% of fast reactors in the BAU&FR system by 2100. A further increase of the fast reactor share is restricted by the limited breeding performance of the break-even fast reactor. Other KIs and EPs selected from Table 3 illustrate expected impacts caused by changes in the nuclear energy system structure.

10.2. Nuclear material resources

Cumulative demand of natural uranium (evaluation parameter EP-2.1) is an important dimension of NE sustainability which indicates the coherent effect of technical and institutional innovations. The cumulative natural uranium requirements for both considered options are presented in Figure 8.

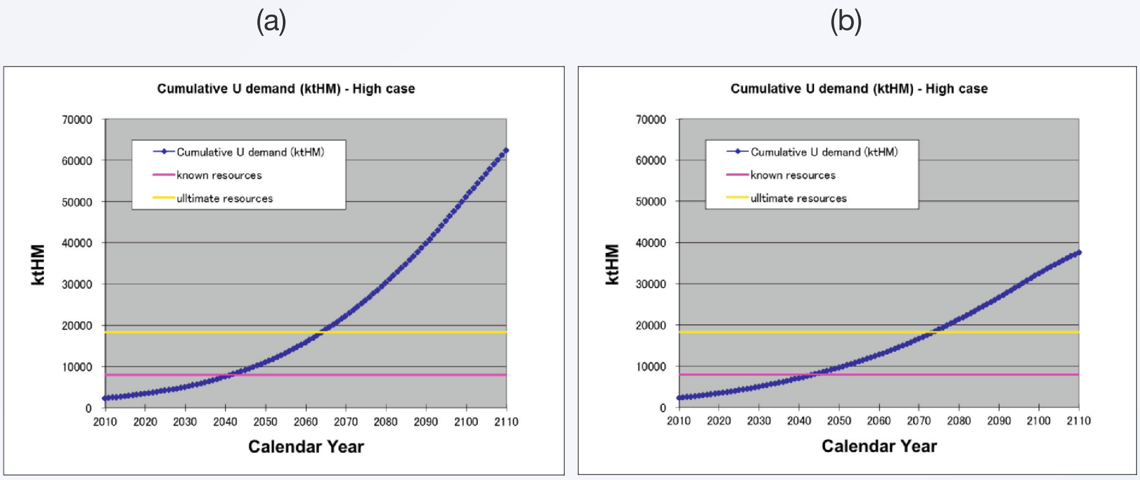

FIG. 8. Cumulative natural uranium demand in BAU (a) and BAU&FR (b) systems for the high GAINS scenario.

For the high scenario of the global nuclear power generation (5000 GWa by the end of the century), Figure 8(a) predicts the total mass of the consumed natural uranium for the BAU case to be about 50 million tonnes. The consumption would exceed 16–18 million tonnes of conventional natural uranium at the available economical price (as estimated in the publication on *Uranium 2009: Resources, Production and Demand* [18]; newer versions of this publication have been published since the completion of the GAINS project, and they could be used to update this estimate in further studies employing the analytical framework), exhausting conventional uranium resources by 2062. More recent editions of this book could be used in further applications of the GAINS analytical framework.

In the BAU&FR case (Figure 8(b)), uranium consumption is 18 million tonnes lower in 2100 compared to the BAU case. Nevertheless, conventional uranium resources would still be exhausted around 2072. Consideration of fast reactors with slightly higher breeding ratio (BR~1.2) does not significantly alter this projection. Thus, modeling of the BAU&FR system does not exclude a possible shortage of the estimated uranium resource after the third quarter of the century unless more advanced fuel cycles are adopted.

Some GAINS participants supported this assessment, while others contended that vast uranium resources are currently available (if one takes into account non-conventional resources) and even more may become available in the future, which may steer the growth of nuclear power closer to the moderate scenario than to the high one. Some technical innovations under consideration could significantly affect uranium demand, such as further increasing the breeding ratio of fast reactors or introducing the thorium fuel cycle. Multilateral cooperation could also contribute to uranium savings. In this regard, modelling has shown that the synergistic BAU&FR case – in which group NG1 employs fast reactors with a breeding ratio in the range 1–1.2, pursues a policy to recycle spent fuel, and intensively cooperates with other strategic groups on spent fuel flows (Fig. 4) – is consistent with a moderate demand scenario requiring 16 million tonnes of conventional uranium.

10.3. Discharged fuel

The management of SNF from nuclear power reactors is an important concern related to the use of nuclear energy. GAINS studies have shown that synergistic variants of a global nuclear energy system architecture may lead to efficient long term spent fuel management strategies. These strategies can facilitate SNF management for a specific group of countries or globally.

The BAU case is characterized by sustained growth of the installed capacity of thermal reactors with proportional accumulation of SNF (EP 4.1). The total amount of spent fuel accumulated by 2100 in the BAU scenario reaches 6 million tonnes (see Fig. 9(a)). The amount of LWR spent fuel can be significantly reduced (down to ~1.8 million tonnes) by introduction of FRs in a closed fuel cycle, with their first fuel loads made from the reprocessed LWR spent fuel (see Fig. 9(b)).

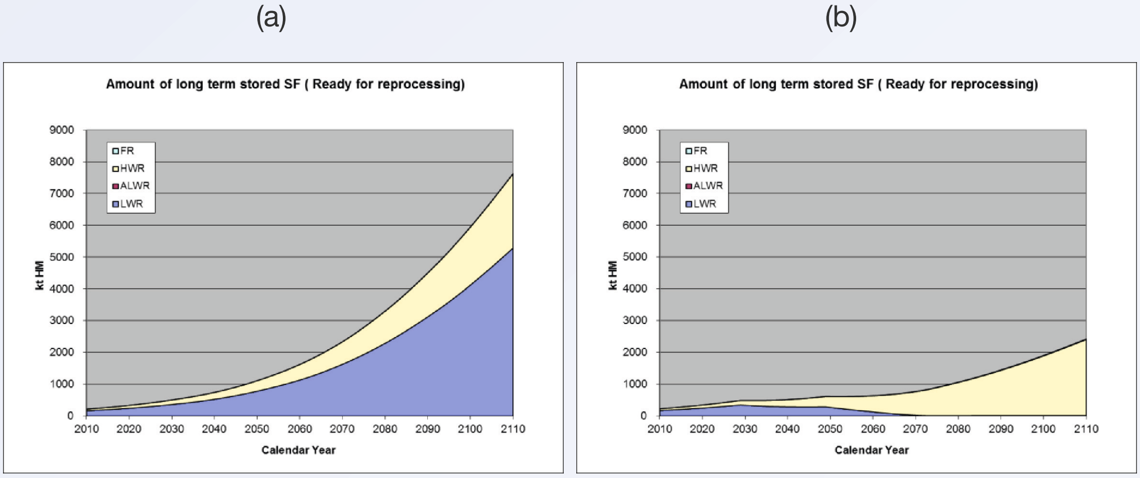

FIG. 9. Cumulative amounts of spent fuel in BAU(a) and BAU&FR (b) systems for the high GAINS scenario.

While Fig. 9 demonstrates the impact of technical innovations that could be achieved by introduction of innovative closed fuel cycle technologies, the GAINS framework can also be useful for a better understanding of the role of multilateral approaches in addressing the problem of spent fuel management.

As it was assumed in the study, the GAINS nuclear group NG3 pursues a strategy to limit infrastructure investments by building only reactors and obtaining fuel cycle services from NG1 (recycling group) and NG2 (once-through fuel cycle group). In this case, any highly radioactive waste generated by reprocessing of NG3 spent fuel for use in reactors in NG1 is kept in NG1. As analyzed in the GAINS study and illustrated in related figures, the global impacts on most of the key indicators and performance parameters of NG1 and NG2, including those related to discharged fuel, are very small.

At the same time, benefits are significant for all groups. NG3 benefits by not having to develop, site, and construct nuclear fuel cycle facilities including those related to the disposition of highly radiotoxic spent fuel. NG1 and NG2 must slightly augment their fuel cycle infrastructure to support this strategy. In return, NG1 gains a source of additional used LWR fuel to support its strategy of transitioning to fast reactors. Benefits to NG2 are also common to other groups, including supporting the global growth of nuclear power for economic development and reduced greenhouse gas emissions while seeking to reduce proliferation risks.

Potentially, the synergistic approach might provide more scaled options for decreasing discharged fuel inventories. Assuming NG1 has no ‘physical’ limitation on reprocessing capacity for spent fuel from all groups, the recovered plutonium (and any recovered uranium) could be used to produce fuel for fast and thermal reactors. Figure 10 illustrates the potential increase in fast reactor deployment for the non-synergistic case (no spent fuel exchange between GAINS strategic groups) as compared to the synergistic case presented in Figures 3 and 4.

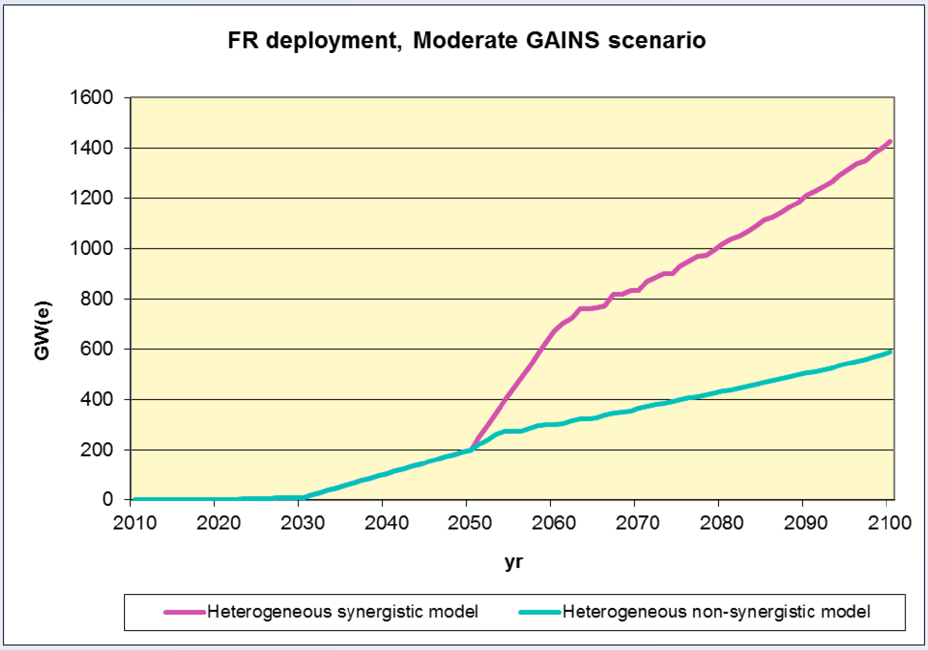

FIG. 10. Potential for fast reactor deployment.

The global fleet of fast reactors could be doubled in the synergistic case compared to the non-synergistic case, which would reduce accumulation of the discharged LWR spent fuel. This can also be of interest with respect to uranium resource savings and plutonium management options.

10.4. Plutonium inventories and plutonium management options

National strategy on spent fuel management depends to a large degree on national approaches towards the plutonium accumulated in SNF. A gradual transition from managed storage of used fuel in the BAU option to plutonium use in the BAU&FR system increases the number of possible synergistic approaches. Simulation of plutonium management options in the GAINS scenarios indicated high sensitivity of related key indicators to innovations in nuclear technologies and to innovations in the global nuclear architecture.

Figure 11 shows that in the synergistic case, the plutonium inventory in storage could be kept at a minimum in the second half of the century through intensive introduction of MOX fuelled fast reactors in NG1 and the relevant arrangement of fresh and used thermal reactor fuel flows between the three groups of countries.

As plutonium is a long-lived hazardous radiotoxic element which can be used for nuclear weapons production, managing the plutonium inventory is very important, both in terms of waste management and proliferation risk.

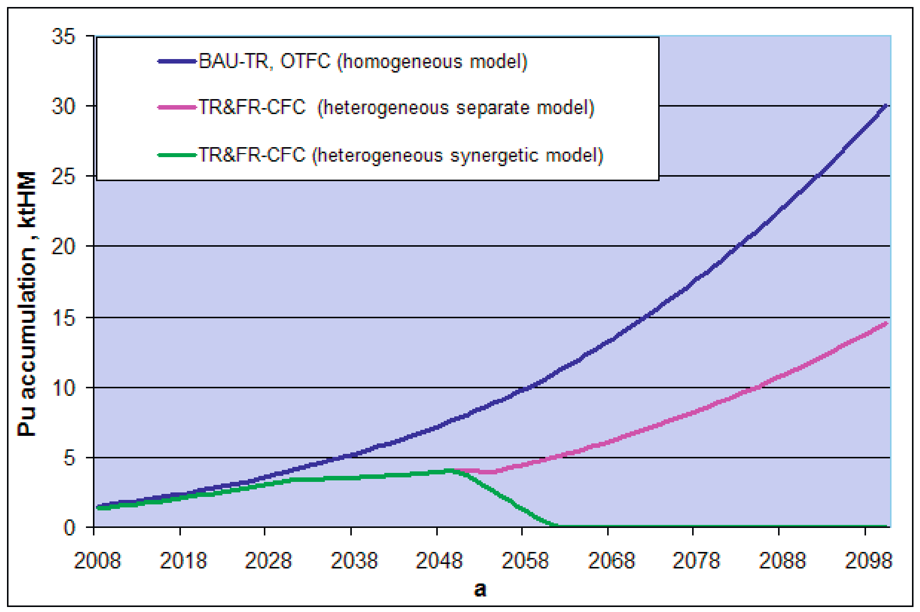

FIG. 11. Plutonium in short-term cooled SNF for the moderate GAINS scenario.

10.5. Economic drivers and challenges

Economics is an important assessment area in the INPRO methodology [1]. However, due to the high degree of uncertainty in costs for a wide range of nuclear energy technologies, GAINS participants did not use KIs related to economics (such as electricity cost or investments) and addressed only R&D investments in fast reactor technology.

The economic studies in GAINS were undertaken using the IAEA's energy model MESSAGE [10]. The R&D costs for the development and deployment of an innovative nuclear energy system (KI-10 in TABLE 3) were examined in cooperation with PESS by using sodium FR technology as an example. It was assumed in the study that the R&D costs for developing the innovative nuclear energy system (reactor and associated fuel cycle) ranged between $10 billion and $40 billion. It was also assumed that the new capacity would be commissioned at the rate of 1 GW(e)/a. The investment cost was assumed to be 2000 $/kW(e), and the construction time of the power units was 5 years. The annual return of the construction investment was calculated with 5% interest. It was also assumed that the funds provided for the implementation of R&D had to be included into the electricity cost generated by the system and returned with zero interest.

Figure 12 shows the impact of the market size (i.e. the new electricity generation capacity based on the innovative nuclear energy system) on the pay-back period for the R&D costs. The figure indicates that the R&D costs are justified only if the new capacity is 30 GW(e) or more. These costs can be recovered within 20 years for investments of $10 billion, and within 40 years for investments of $40 billion. However, if the market size is only around 10 GW(e), the R&D expenditures of about $40 billion are not justified since they will not be recovered for more than a century.

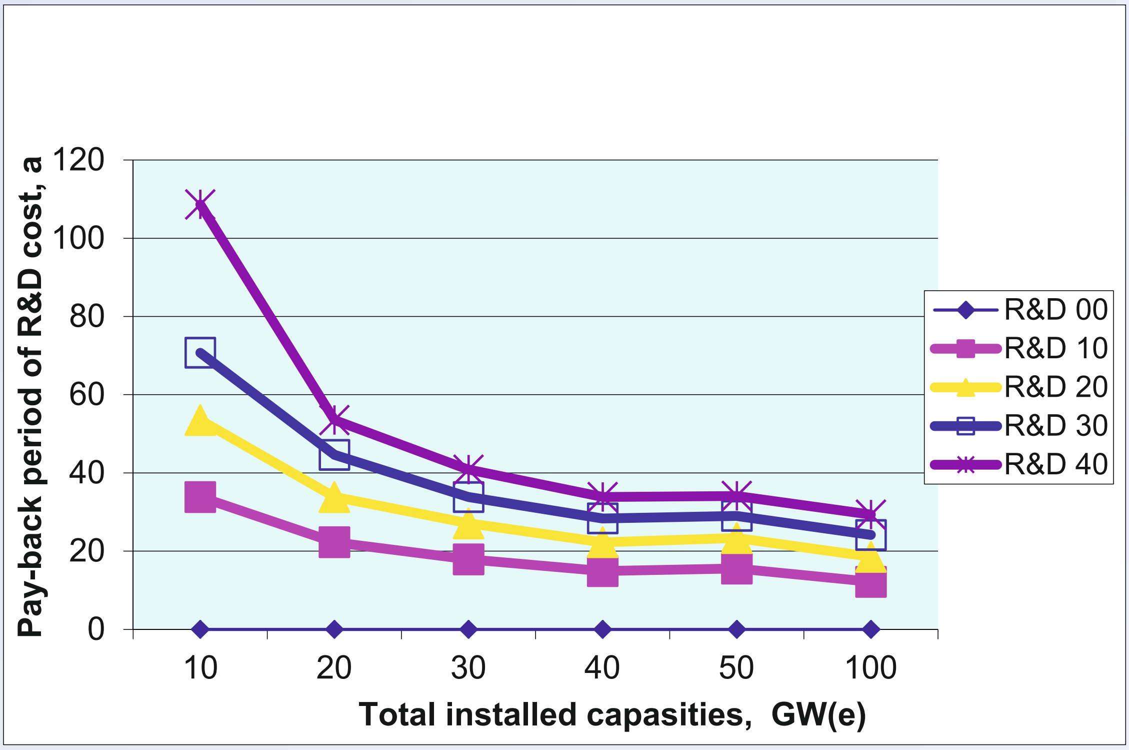

FIG. 12. Pay-back period for R&D cost for the innovative nuclear energy system for different installed capacities.

This example illustrates that for small programmes of innovative nuclear energy system deployment, the expected economic benefits do not compensate the amount of investment necessary for development, demonstration and deployment. Only countries with large nuclear energy programmes (30 GW(e) or more) can bear the burden of such a degree of technology development and deployment.

Thus, the evaluation of KI-9 reveals economic challenges in justifying transition at the national level from BAU to BAU&FR and, generally, to a radically innovative nuclear energy system. A synergistic approach could facilitate benefits from the global sustainable nuclear energy system for countries with small nuclear energy programmes without an excessive investment in national infrastructure, provided that market prices for services are acceptable.

11. Conclusion

The analytical framework for analysis and assessment of transition scenarios to sustainable nuclear energy systems was developed in the IAEA's INPRO collaborative project GAINS.

The framework includes a heterogeneous world model to consider specific fuel cycle development strategies that different countries may pursue. This model is capable of realistically simulating global nuclear energy development and allows countries to identify and assess areas of potential cooperation. This cooperation could amplify the positive effects of technology innovation in achieving sustainable nuclear energy.

The analytical model and framework can also explain and clarify challenges which may need to be overcome in order to realize the associated benefits.

Sample analysis of the selected nuclear energy system scenarios using the GAINS framework has shown quantitatively that a synergistic nuclear energy system architecture based on technological and institutional innovations could provide the potential for a mutually beneficial ('win-win') collaboration between technology holders and users, facilitating nuclear energy production, resource preservation, waste and direct use material inventory reductions, and improving economics.

Although these are the first examples of a successful use of the framework in evaluating the synergistic approach in the back end of the nuclear fuel cycle, it is understood that scaled implementation of the approach is a lengthy path with many obstacles to reaching industrial, public and political consensus. However, to provide timely global answers to global challenges, the application of the framework to examining the synergistic architecture at the back end of the nuclear fuel cycle should be continued and expanded. Further scenario studies on the synergistic architectures and identification of practical steps in this direction would support IAEA Member States' efforts to enhance sustainability of regional and global NES.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual, IAEA-TECDOC-1575, Vol. 1, IAEA, Vienna (2008).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, web page of INPRO Section: http://www.iaea.org/INPRO.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability, Final Report of the INPRO Collaborative Project on Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed Nuclear Fuel Cycle (GAINS), IAEA Nuclear Energy Series NP-T-1.14, (2013).

[4] UNITED NATIONS, World Energy Assessment, Energy and the Challenge of Sustainability, United Nations Publication, Sales No.OO.III.B.5, New York (2000).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, INTERNATIONAL ENERGY AGENCY, EUROSTAT, EUROPEAN ENVIRONMENT AGENCY, Energy Indicators for Sustainable Development: Guidelines and Methodologies, STI/PUB/1222, IAEA, Vienna (2005).

[6] A Technology Roadmap for Generation IV Energy Systems. US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum. GIF-002-00, December 2002.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the evaluation of innovative nuclear reactors and fuel cycles. IAEA-TECDOC-1362, Vienna (2003).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for the assessment of innovative nuclear reactors and fuel cycles. IAEA-TECDOC-1434, Vienna (2004).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems. INPRO Manual. IAEA-TECDOC-1575, Vienna (2008):
http://www-pub.iaea.org/MTCD/Publications/PDF/TE_1575_web.pdf

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Multilateral Approaches to the Nuclear Fuel Cycle, Expert Group Report to the Director General of the IAEA, Vienna (2005).

[11] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Special Report on Emissions Scenarios, A Special Report of Working Group III, Cambridge University Press, Cambridge (2000).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, IAEA, Vienna (2013).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Capacity Building: PESS Energy Models. http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.html

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Simulation System (VISTA), IAEA-TECDOC-1535, IAEA, Vienna (2007).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles, Report of Phase 1A of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1362, IAEA, Vienna (2003).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, http://www.iaea.org/INPRO/CPs/SYNERGIES/index.html

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, http://www.iaea.org/INPRO/CPs/SYNERGIES/rev4_4_2_Economic_assessment_method_data.pdf

[18] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT / NUCLEAR ENERGY AGENCY and INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2009: Resources, Production and Demand, OECD/NEA, Paris (2010).

ABBREVIATIONS

a	year
ADS	accelerator driven system/s
ALWR	advanced light water reactor/s
BAU [system]	business as usual system comprising light water and heavy water reactors and once-through nuclear fuel cycle
BAU+ [system]	BAU system with advanced light water reactors
BAU&FR [system]	BAU system with inclusion of fast reactors operating in a closed nuclear fuel cycle
BR	breeding ratio
CP	collaborative project (INPRO)
DESAE [code]	dynamics of energy systems –– atomic energy
EP	evaluation parameter (INPRO)
FR	fast reactor
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (CP of INPRO)
GWa [GWyear]	Electrical energy produced over one year
GW(the)a [GWyear]	Thermal energy produced over one year
HTR	high temperature reactor
HWR	heavy water reactor
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KI	key indicator/s (INPRO)
LWR	light water reactor
MA	minor actinide/s
MESSAGE [code]	model for energy supply systems
MOX	fuel mixed oxide uranium-plutonium fuel
MSR	molten salt reactor
NES	nuclear energy system/s
NFC	nuclear fuel cycle
NFCSS [code]	nuclear fuel cycle simulation system
NG	nuclear strategy group (GAINS framework)
PWR	pressurized water reactor
R&D	research and development
SNF	spent nuclear fuel
UOX	uranium oxide

Contact information

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)
Division of Nuclear Power, Department of Nuclear Energy
International Atomic Energy Agency
Vienna International Centre, 1400 Vienna, Austria

Telephone: +43 1 2600 0
Email: inpro@iaea.org

Web site: www.iaea.org/INPRO

Printed by the IAEA in Austria
June 2014

14-20931