EPJ Nuclear Sci. Technol. **1**, 1 (2015)

DOI: 10.1051/epjn/e2015-50031-2

EPJ Nuclear Sciences & Technologies

Available online at:
http://www.epj-n.org

REGULAR ARTICLE OPEN ACCESS

Heterogeneous world model and collaborative scenarios of transition to globally sustainable nuclear energy systems

Vladimir Kuznetsov* and Galina Fesenko

International Atomic Energy Agency, Vienna International Centre, PO Box 100, 1400 Vienna, Austria

Received: 11 May 2015 / Received in final form: 2 July 2015 / Accepted: 20 July 2015
Published online: 27 November 2015

Abstract. The International Atomic Energy Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is to help ensure that nuclear energy is available to contribute to meeting global energy needs of the 21st century in a sustainable manner. The INPRO task titled "Global scenarios" is to develop global and regional nuclear energy scenarios that lead to a global vision of sustainable nuclear energy in the 21st century. Results of multiple studies show that the criteria for developing sustainable nuclear energy cannot be met without innovations in reactor and nuclear fuel cycle technologies. Combining different reactor types and associated fuel chains creates a multiplicity of nuclear energy system arrangements potentially contributing to global sustainability of nuclear energy. In this, cooperation among countries having different policy regarding fuel cycle back end would be essential to bring sustainability benefits from innovations in technology to all interested users. INPRO has developed heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle in regional and global scenarios of nuclear energy evolution and applied in a number of studies performed by participants of the project. This paper will highlight the model and major conclusions obtained in the studies.

1 Introduction

The International Atomic Energy Agency's (IAEA's) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has the objective of helping to ensure that nuclear energy is available to contribute to meeting global energy needs of the 21st century in a sustainable manner. The INPRO task titled "Global scenarios" has the objective to develop, based on scientific and technical analysis, global and regional nuclear energy scenarios that lead to a global vision of sustainable nuclear energy in the 21st century [1–5].

Existing nuclear energy systems, which are almost entirely based on thermal reactors operating in a once-through 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. Combining different reactor types and associated fuel chains creates a multiplicity of nuclear energy system arrangements potentially contributing to global sustainability of nuclear energy. In this, cooperation among countries having different policy regarding fuel cycle back end would be essential to bring sustainability benefits from innovations in technology to all interested users. It is becoming increasingly clear that national strategies will have to be harmonized with regional and global nuclear power architectures to make national nuclear energy systems more sustainable.

INPRO is a part of the integrated services of the IAEA provided to Member States considering initial development or expansion of nuclear energy programmes. To provide such countries with better understanding of the options available to achieve sustainable nuclear energy, INPRO has developed an internationally verified analytical framework for assessing transition scenarios to future sustainable nuclear energy systems (hereafter, the framework) and applied in a number of studies performed by participants of the project.

The economic studies carried out by INPRO have shown that investments in Research, Design & Demonstration (RD&D) for innovative technologies, such as fast reactors and a closed nuclear fuel cycle, are huge and provide reasonable pay-back times only in the case of a foreseen large scale deployment of such technologies. Not all of the countries interested in nuclear energy could and would afford such

*e-mail: V.Kuznetsov@iaea.org

investments. Then, benefits associated with innovative technologies can be amplified, and may also be brought to many interested users through mutually beneficial cooperation among countries in fuel cycle back end.

Reflecting upon this finding, the INPRO collaborative project on Global Architecture of Innovative Nuclear Energy Systems based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) has developed heterogeneous global model to capture countries' different policies regarding the back end of the nuclear fuel cycle and to analyze cooperation options available thereof. The heterogeneous model may involve certain degrees of cooperation between groups of non-personified, non-geographical countries (synergistic case) or it may involve no cooperation (non-synergistic case). The heterogeneous world model is included in the framework to consider specific fuel cycle development strategies that different countries may pursue and examine a potential for mutually beneficial cooperation.

Synergies among the various existing and innovative nuclear energy technologies and options to amplify them through collaboration among countries in fuel cycle back end are being further examined in the INPRO collaborative project on Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability (SYNERGIES). This project is still ongoing; it is to be finalized in 2015.

2 INPRO collaborative project on global architecture of innovative nuclear energy systems with thermal and fast reactors and a closed nuclear fuel cycle (GAINS)

The INPRO collaborative project, GAINS addressed technical and highlighted some institutional issues to develop a global architecture for sustainable nuclear energy in the 21st century, and it also outlined plausible transitions to such architecture.

Sixteen participants from different regions of the world – Belgium, Canada, China, Czech Republic, France, India, Italy, Japan, Republic of Korea, Russian Federation, Slovakia, Spain, Ukraine, USA, European Commission (EC), plus Argentina as an observer, carried out coordinated investigations and contributed to the GAINS final report [1].

GAINS has developed an international analytical framework for assessing transition scenarios to future sustainable nuclear energy systems and conducted sample analyses, including [1]:

- A common methodological approach, including basic principles, assumptions, and boundary conditions.
- Storylines for nuclear power evolution and long-term nuclear energy demand scenarios based on IAEA Member States' high and low estimates for nuclear power demand until 2050, and expected trends until 2100 based on forecasts of international energy organizations.
- A heterogeneous world model comprised of groups of non-personified countries with different policies regarding the nuclear fuel cycle back end.

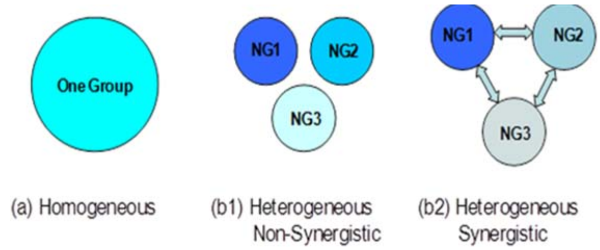

Fig. 1. Possible world models for fuel cycle analysis.

- Metrics and tools for the sustainability assessment of scenarios for a dynamic nuclear energy system, including a set of key indicators and evaluation parameters.
- An international database with best-estimate characteristics of existing and advanced nuclear reactors and associated nuclear fuel cycles required for material flow and economic analysis; this database extends other IAEA databases and takes into account preferences of different countries.

All previous studies of global nuclear energy scenarios, even those done region-wise [2], used the so-called homogeneous world model, wherein all countries in the world or a region were assumed to pursue the same policy regarding nuclear reactors and nuclear fuel cycle and use the same facilities at a given time. Different from that, GAINS has introduced a model of the heterogeneous world comprising different nuclear strategy groups of countries non-personified, non-geographical (NG) based on the spent nuclear fuel management strategy being pursued for the back end of the nuclear fuel cycle (Fig. 1).

For the purpose of GAINS analysis, three country groups (NGs) were defined as follows: NG1 recycles spent nuclear fuel and pursues a fast reactor programme; NG2 directly disposes of spent fuel or sends it for reprocessing to NG1; and NG3 sends spent nuclear fuel to NG1 or NG2. The methodology applied in the analysis does not assign individual countries to groups, but allocates a fraction of future global nuclear energy generation to each group as a function of time to explore "what if" scenarios. For the GAINS studies the NG1:NG2:NG3 ratio was fixed at 40:40:20 allowing further sensitivity analysis to variations of the NG fractions. In this, two alternative scenarios of nuclear power growth were considered in GAINS ending at 2500 GW(e) and 5000 GW(e) by the century end.

The GAINS metrics is presented in Table 1. It reflects sustainability areas related to power production, nuclear material resources, discharged fuel, radioactive waste and minor actinides, fuel cycle services, system safety and costs, and investment.

Innovative reactors expected to have a major impact on the future nuclear energy system architecture include advanced light water reactors (ALWRs), advanced heavy water reactors (AHWRs), high temperature reactors (HTRs), fast reactors (FRs), and potentially, accelerator driven systems (ADSs) and/or molten salt reactors (MSRs). Combining the different reactor types and associated fuel chains creates a multiplicity of nuclear energy system arrangements aimed at solving specific goals,

Table 1. GAINS key indicators and evaluation parameters [1].

No.	Key indicators and Evaluation Parameters	Resource Sustainability	Waste Management and Environmental Stressors	Safety	Proliferation Resistance and Physical Protection	Economics	Infrastructure
	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						
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	

such as production of various energy products, better use of natural resources, and minimization of radioactive waste.

Four types of nuclear energy system (NES) architecture were defined and then analyzed in GAINS to evaluate the effect of implementation of innovative technologies and their influence on the considered key indicators (KIs):

– Homogeneous "business-as-usual" (BAU) scenario based on pressurized water reactors (PWRs) (94% of power generation) and heavy water reactors (HWRs) (6%) operated in a once-through fuel cycle in which the world was modelled as a single NG. A variant of this scenario included the introduction of an advanced PWR replacing conventional PWR technology (named the "BAU+" scenario).
– Homogeneous (single group) scenario for a closed cycle using thermal and fast reactors to be compared with the above mentioned scenarios. Some of these fuel-recycle scenarios included HWRs (6%) operated in a once-through mode.
– A hybrid heterogeneous-architecture scenario comprising 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. Both synergistic and non-synergistic cases were analyzed for this scenario. In the synergistic case, NG3 receives fresh fuel from NG2 and

NG1 and returns the associated spent nuclear fuel to those groups.
- Other innovative NES scenarios in the homogeneous world model, including: (a) operation of fast-spectrum reactors or thermal-spectrum HWRs using thorium fuel cycle for the reduction of natural uranium consumption; (b) reduction of minor actinides (MAs) using accelerator driven systems (ADSs) or molten salt reactors (MSRs), and other innovative NES scenarios.

The 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, see Table 1) are approached in particular evolution scenarios. The KIs are compared to determine the more promising options for achieving the selected targets. Possible benefits and issues of different options could also be analyzed.

The framework developed in GAINS is based on the 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 or partnerships with other countries in nuclear fuel cycle back end, also highlighting how global trends may affect national developments. Individual countries can make use of this framework with their own national and regional data to evaluate particular approaches in a global or regional context.

3 INPRO collaborative project on synergistic nuclear energy regional group interactions evaluated for sustainability (SYNERGIES)

The ongoing collaborative project SYNERGIES [5] was started in 2012 with Algeria, Armenia, Belarus, Belgium, Bulgaria, Canada, China, Egypt, France, India, Indonesia, Israel, Italy, Japan, Republic of Korea, Malaysia, OECD-NEA, Pakistan, Poland, Romania, Russian Federation, Spain, Ukraine, USA and Vietnam as participants or observers.

The SYNERGIES project applies and amends the analytical framework developed in GAINS to examine more specifically the various forms of regional collaboration among nuclear energy suppliers and users. In particular, a database of best estimate cost data for each step of the nuclear fuel cycle and each component of the levelized unit electricity cost for nuclear reactors has been compiled and is being maintained with the project [6].

Synergies among the various existing and innovative nuclear energy technologies and options to amplify them through collaboration among countries in fuel cycle back end are being examined in SYNERGIES through case studies performed by the project participants. The project focuses on short- and medium-term collaborative actions that can help developing pathways to long-term NES sustainability.

To meet its objectives, the SYNERGIES project investigates sustainability indicators of a dynamic NES, including a variety of technologies and infrastructure-related factors, as well as the collaborative scenarios and architectures of interest to participants, involving, inter alia, fuel cycle infrastructure development with shared facilities.

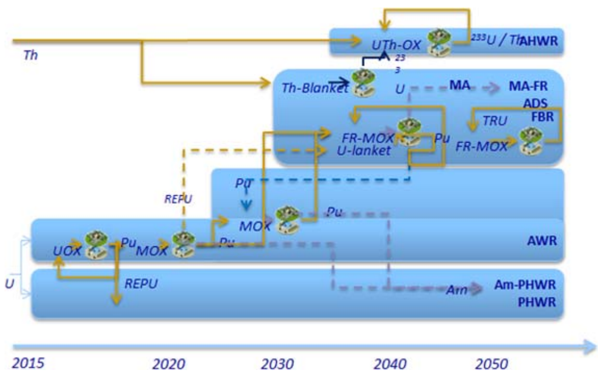

Fig. 2. Scenario families in the SYNERGIES project.

Within SYNERGIES the focus is on regional studies of collaboration among countries in line with the agreed upon overall picture of the global nuclear energy system evolution in the 21st century. Summaries of 27 case studies performed by the participants are grouped in families of scenarios as follows, see Figure 2:

- Business-as-usual scenarios and scenarios with mono-recycling of U/Pu in thermal-spectrum reactors.
- Scenarios with the introduction of a number of fast reactors to support multi-recycling of Pu in light water reactors (LWRs) and fast reactors.
- Fast reactor centered scenarios — scenarios with reprocessing of thermal reactors' fuel to enable noticeable growth rate of fast reactor capacity.
- Scenarios of transition to Th/^{233}U fuel cycle and scenarios with U/Pu/Th fuel cycles.

The SYNERGIES project explores the various issues related to synergies in technology and synergistic collaborations among countries, including selection of reactor and fuel cycle options, uncertainties in the scale of nuclear energy demand growth, possible modes of collaboration among countries, the sensitivity studies of possible impacts to the market shares of countries with different nuclear fuel cycle policy and to the scale of collaboration among countries, etc.

4 Major findings and conclusions of the GAINS and SYNERGIES collaborative projects

Major findings and conclusions of the GAINS and SYNERGIES collaborative projects are as follows [1,5,7]:

- The dynamics of world's nuclear power capacity expansion indicates that in all cases low projections are more likely to meet the reality compared to the high ones.
- The sensitivity studies to the shares of country groups with different policy regarding nuclear fuel cycle back end (NG) taking into account possible synergistic

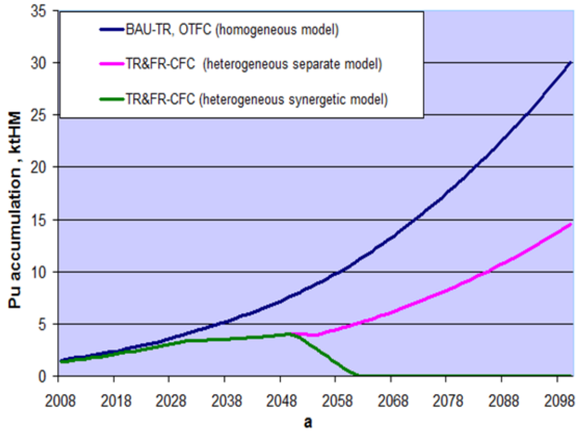

Fig. 3. Plutonium in short-term cooled spent nuclear fuel for the moderate GAINS scenario [1].

collaborations among countries indicate that LWRs will retain their position as the larger part of the overall reactor park all throughout the 21st century.

- In the present century, global nuclear energy is likely to follow a heterogeneous world model, within which most of the countries will continue to use thermal reactors in a once-through nuclear fuel cycle.
- Cooperation among countries could amplify the positive effects of technology innovation in achieving sustainable nuclear energy.
- The global fleet of fast reactors could be doubled in the synergistic case compared to the non-synergistic case; this 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, see Figure 3.
- Natural uranium savings up to 20–40% could be achieved in heterogeneous world with synergistic collaboration among countries (NG1 countries could deploy more fast and less thermal reactors at the expense of U–Pu extracted from spent nuclear fuel of the NG3 or NG3 + NG2 countries), see Figure 4.
- The NG1 (recycling group) power demand as well as reprocessing capacity is critical for the fast reactor introduction rate and for the capability of NG1 to reprocess all spent fuel from other NGs (once-through fuel cycle groups), see Figure 5.
- Sharing of the reprocessing facilities contributes to a reduction of the cumulative expenditures for spent nuclear fuel reprocessing; however, adequate evaluation of the resulting benefits for future generation requires an analysis performed in terms of cash flows without a discount rate, see Figure 6.
- Simulations of a 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. To support this activity from an international perspective, the IAEA's INPRO Section provides online training sessions and workshops on nuclear energy sustainability and INPRO's activities for students at all levels, as well as faculty and research

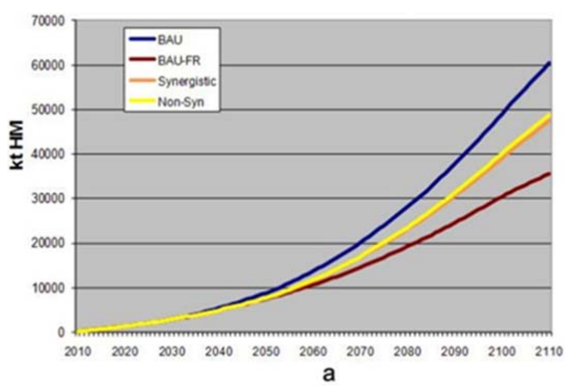

Fig. 4. Cumulative natural uranium consumption versus time in different GAINS scenarios.

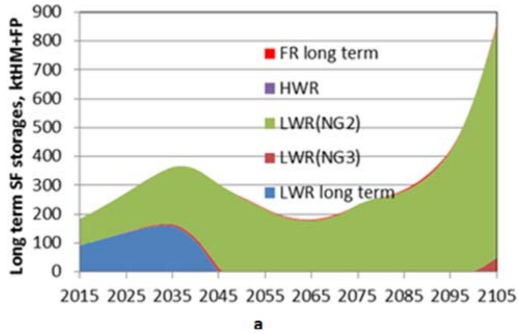

Fig. 5. Long-term spent fuel storage requirements versus time for NG1 group of countries in one of the scenarios considered in the SYNERGIES project (green colour corresponds to spent nuclear fuel imported from NG2 countries and not reprocessed because of the insufficient reprocessing capacity in NG1).

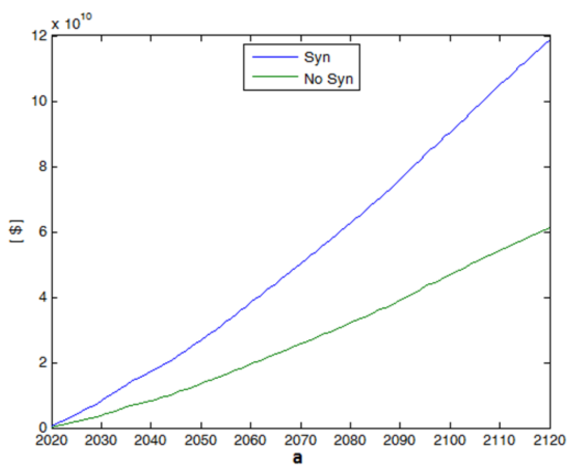

Fig. 6. Cumulative reprocessing expenditures versus time for synergistic and non-synergistic cases in one of the scenarios of the SYNERGIES project (NG1 and NG2 synergies were explored in that study).

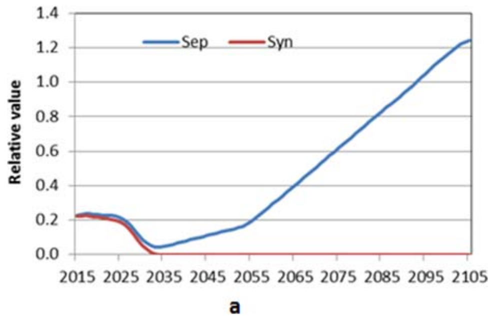

Fig. 7. Long-term spent fuel storage volume requirements versus time for synergistic (Syn) and non-synergistic (Sep) cases in one of the scenarios of the SYNERGIES project (NG1 and NG2 synergies were explored in that study).

staff of nuclear universities and research centres in interested Member States [7]. A web-based conferencing service facilitates lecturing from the IAEA to audiences in different Member States.

- Countries that do not pursue fast reactor programmes could benefit from the synergistic approach as it results in reduced requirements to long-term spent nuclear fuel storage and ultimate disposal of waste, see Figure 7. However, there are a number of important legal and institutional impediments for cooperation among countries in nuclear fuel cycle back end [8], those will be addressed in more detail in the future INPRO activity titled "Cooperative approaches to the back end of nuclear fuel cycle: drivers and legal, institutional and financial impediments".
- Achieving synergistic NFC backend architectures requires industrial, public and political consensus. For timely global answers to global challenges, building of the architecture has to be started straight away.
- Scenarios with the introduction of a limited number of fast reactors to support multi-recycling of plutonium in LWRs and in fast reactors could be a flexible and risk-balanced option under uncertainties in the scale of demand for nuclear energy and before fast reactors are proven to be reliable and competitive source of energy with a potential of broad deployment, see Figure 8; upon recommendations from participants of the SYNERGIES project such scenarios will be examined in more detail in future INPRO projects.

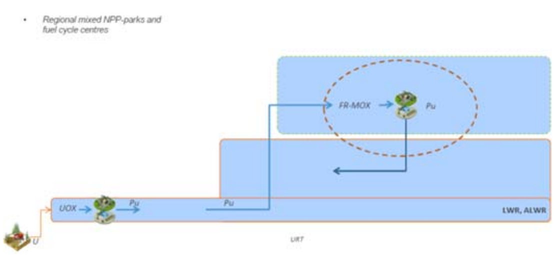

Fig. 8. Scenarios with LWRs and a limited number of fast reactors for Pu multi-recycling.

5 Conclusions

This paper summarizes the major findings and conclusions of the INPRO collaborative projects, GAINS and SYNERGIES, that performed studies related to the role of global and regional architectures of nuclear energy systems in making a transition to future sustainable nuclear energy, in terms of the assurance of sufficient nuclear material resources, minimized inventories of spent nuclear fuel and high-level radioactive waste and overcoming of the investment barriers to commercial introduction of innovative nuclear technologies.

The completed GAINS project provided IAEA Member States with the analytical framework to help explore transition scenarios to future globally sustainable nuclear energy systems that would combine the synergy of nuclear technologies with innovative institutional approaches to foster collaboration among countries to amplify the benefits of the innovation. The ongoing SYNERGIES project applies and amends this framework to explore the various issues related to synergies in technology and synergistic collaborations among countries.

The outputs of the INPRO collaborative projects on GAINS and SYNERGIES clearly indicate that the criteria for developing sustainable nuclear energy cannot be achieved without major innovations in reactor and nuclear fuel cycle technologies. Cooperation among countries could then amplify the positive effects of technology innovation in achieving sustainable nuclear energy for all interested users. Collaborative solutions in nuclear fuel cycle and, specifically, in the fuel cycle back end are a key for moving toward global sustainability of nuclear energy systems from the near (2012–2030) through the medium (2030–2050) toward the long (2050–2100) term.

Both projects indicate that, to pursue sustainability goals efficiently, national strategies would need to be harmonized with regional and global nuclear energy architectures.

The authors would like to express their gratitude to all participants of the GAINS [1] and SYNERGIES [5] collaborative projects for their contribution to the development and application of the framework for the analysis and assessment of dynamic nuclear energy systems for sustainability.

References

1. 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)
2. International Atomic Energy Agency, *Nuclear energy development in the 21st century: global scenarios and regional trends*, (IAEA Nuclear Energy Series No. NP-T-1.8, Vienna, 2010): http://www-pub.iaea.org/MTCD/publications/PDF/Pub1476_web.pdf
3. International Atomic Energy Agency, *The role of thorium to supplement fuel cycles of future nuclear energy systems*, (IAEA Nuclear Energy Series, NF-T-2.4, IAEA, Vienna, 2011)

4. International Atomic Energy Agency, *Joint study: assessment of nuclear energy systems based on a closed nuclear fuel cycle with fast reactors (CNFC-FR)*, IAEA-TECDOC-1639 (IAEA, Vienna, 2009): http://www-pub.iaea.org/MTCD/Publications/PDF/te_1639_web.pdf
5. International Atomic Energy Agency, *Web page of the SYNERGIES collaborative project*: http://www.iaea.org/INPRO/CPs/SYNERGIES/index.html
6. Economic input data for SYNERGIES, *Web page of the SYNERGIES collaborative project*: http://www.iaea.org/INPRO/CPs/SYNERGIES/rev4_4_2_Economic_assessment_method_data.pdf
7. INPRO provides training on nuclear energy sustainability, *INPRO web-page*: https://www.iaea.org/INPRO/News/2015-05-22-inpro.html
8. Drivers and Impediments for Regional Cooperation on the Way to Sustainable Nuclear Energy Systems, *Materials of the 4th INPRO Dialogue Forum, 30 July-3 August 2012*, (IAEA, Vienna): http://www.iaea.org/INPRO/4th_Dialogue_Forum/index.html

Cite this article as: Vladimir Kuznetsov and Galina Fesenko, Heterogeneous world model and collaborative scenarios of transition to globally sustainable nuclear energy systems, EPJ Nuclear Sci. Technol. **1**, 1 (2015)