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International Atomic Energy Agency

Options to Enhance Nuclear Energy Sustainability through Synergies in Technology and Collaboration among Countries.

Major findings of the INPRO collaborative project SYNERGIES

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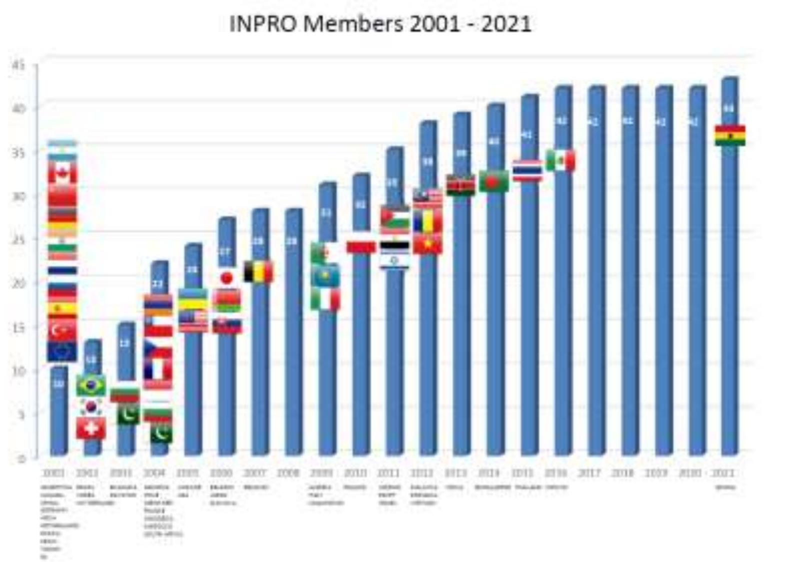
Task leader "Global scenarios"
NENP/ INPRO

INPRO
International Project on Innovative Nuclear Reactors and Fuel Cycles
IAEA

Introduction:



- The International Project for Innovative Nuclear Reactors and Fuel Cycles (INPRO) supports Member States in their long-term planning for development of *sustainable nuclear energy systems*.
- INPRO's main activities focus on four themes: Global scenarios, Innovations, Sustainability assessment and strategies, and Dialogue and outreach. INPRO activities take place through close cooperation of the IAEA's Member States – INPRO members *(43 member countries and international organizations, Ghana has joined as 43rd member in 2021).*

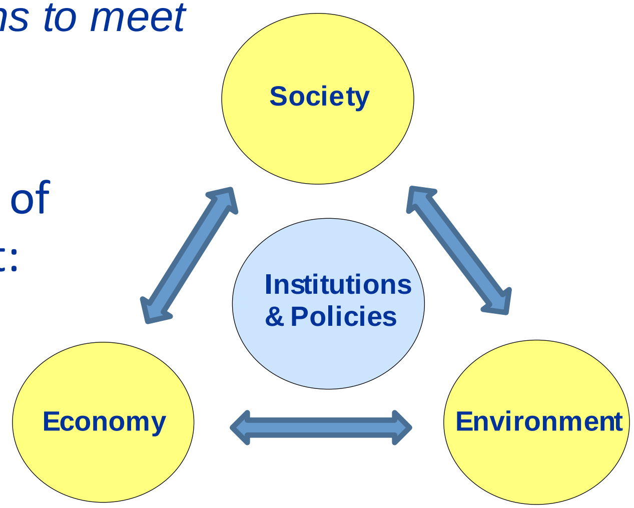
Sustainability of a nuclear energy system

Definition of sustainable development according to the report of the Brundtland Commission (“Our Common Future”, Oxford University Press, Oxford (1987)

"Sustainable Development is the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs,"

Three dimensions/pillars of sustainable development:

- Social
- Economical
- Environmental



More recent developments:

2012 the Rio+20 conference on sustainable development

2015 High level Political Forum on sustainable development

Universal, integrated and transformative 2030 Agenda for Sustainable Development, along with a set of 17 Sustainable Development Goals (SDGs) and 169 associated targets

2016 Climate Change Conference (Conference of the Parties -COP22)

…

Nuclear Energy potential: Affordable and clean energy (SDG 7) and Climate change mitigation (SDG 13)

INPRO methodology for NES sustainability Assessment

Basic Principles: goal for development of a sustainable NES

User Requirements: what should be done by designer, operator, industry and/or State to meet the goal defined in the Basic Principle

Criteria:
Assessor's metric to check whether a User Requirement is being met

Concept and assessment tool for (basic) NES sustainability:

- Is what we have or what we target sustainable?
- What are the gaps?

- Developed by qualified experts – representatives of the IAEA Member States – INPRO Members
- Provides a basis for all other INPRO projects/ activities
- Consistent with the UN concept of sustainable development,
- 7 Basic Principles, 30 User requirements and more than one hundred criteria in the assessment areas of Economics, Safety, Infrastructure, Environment, Proliferation Resistance and Waste Management, each consisting of an indicator and an acceptance limit
- INPRO methodology is primarily a tool to identify gaps in sustainability of a particular NES (facilitating finding a pathway to eliminate them)
- INPRO Methodology defines the basic concept of NES sustainability and includes provisions for further sustainability enhancements (introduces the notion of *Key Indicators (KIs)* by which substantial enhancements of sustainability in particular assessment areas could be evaluated and quantified)

INPRO area “Global scenarios”

The objective of the INPRO Area “Global scenarios” is to develop global and regional nuclear energy scenarios, using developed scientific-technical analysis tools that lead to a global vision of sustainable nuclear energy development in the current century and beyond

INPRO area “Global scenarios” vs. INPRO area “Sustainability assessment and strategies”

Global scenarios
(analysis and comparative evaluation)

Sustainability assessment and strategies
(NES assessment for sustainability)

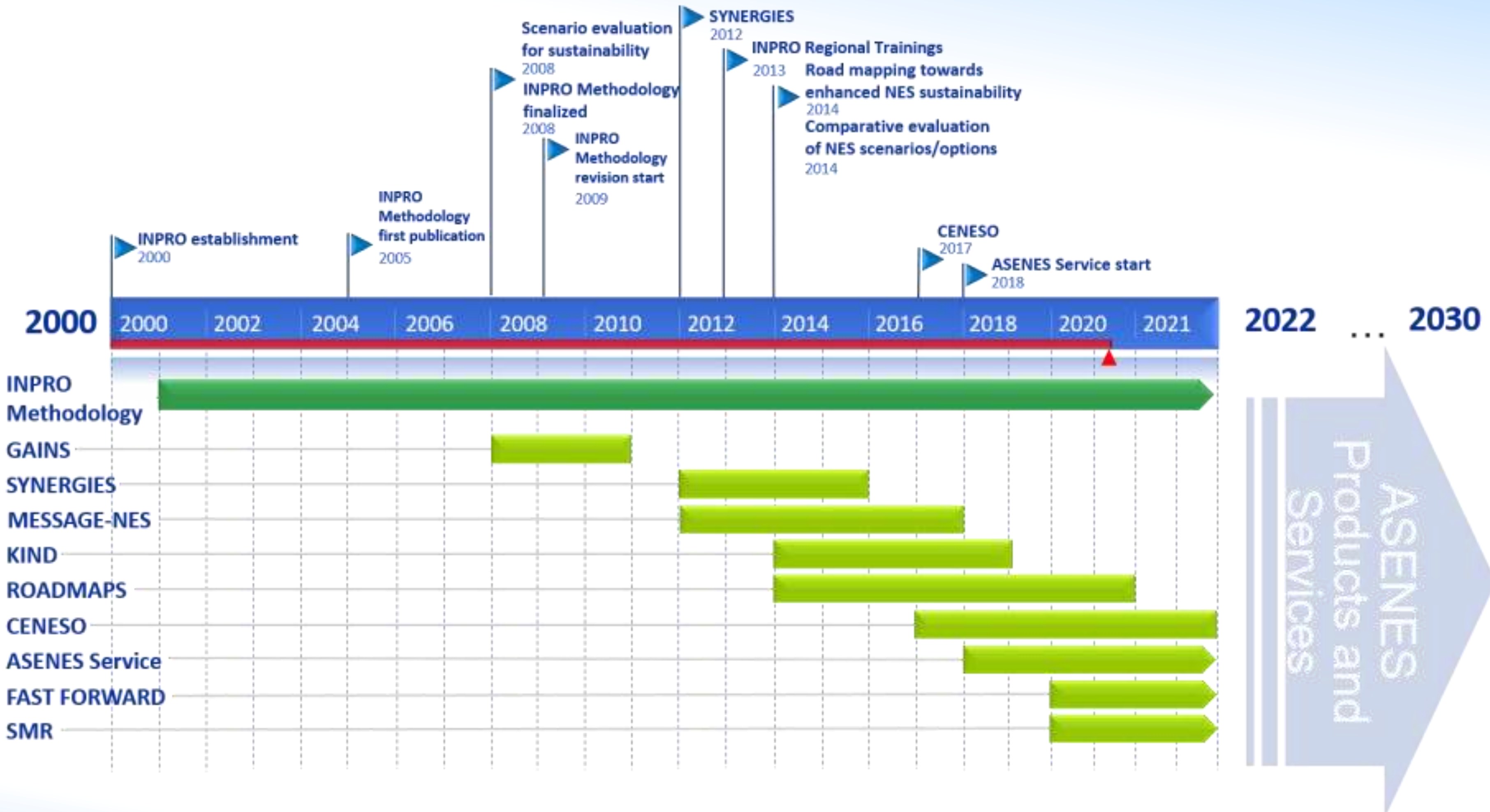
- Modelling of nuclear energy evolution Scenarios
- Economic evaluation of alternatives
- Comparative evaluation of NESs or Scenarios
- Road mapping for enhanced nuclear energy sustainability

- Economics,
- Safety,
- Infrastructure,
- Environment,
- Proliferation Resistance
- Waste Management

ASENES support package:
MESSAGE-NES; NEST; KIND-ET
ROADMAPS-ET

NESA support package: NEST

INPRO area “Global scenarios”



INPRO collaborative projects GAINS and SYNERGIES

- Responding to Member States need, The NPRO collaborative project "Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle" (GAINS) has developed an analytical framework for nuclear energy evolution scenario evaluation regarding sustainability

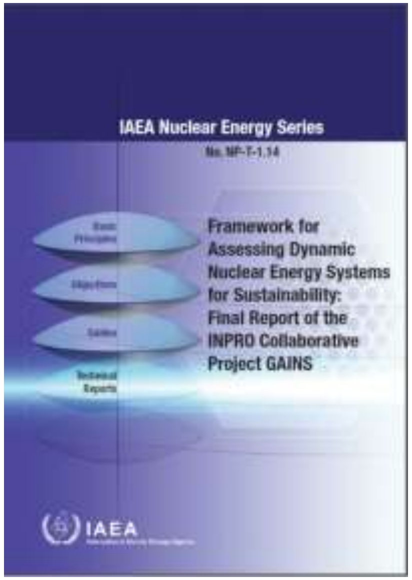
- The INPRO collaborative project "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES) has applied the framework to national NES evolution scenarios with regional cooperation

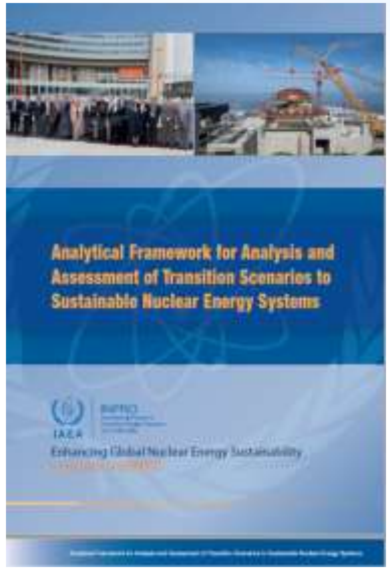
Analytical framework for nuclear energy evolution scenario evaluation regarding sustainability:

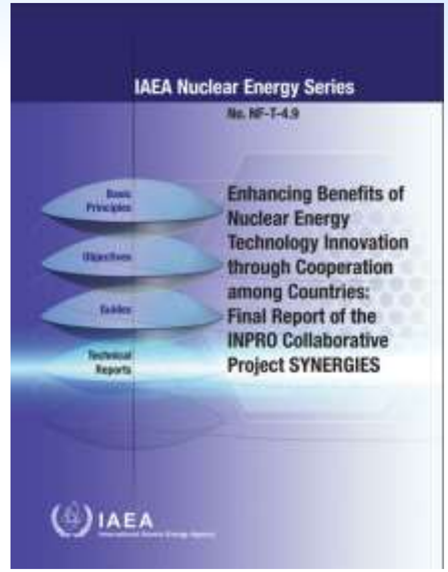
- **How we get from what we have today to our targeted sustainable future?**

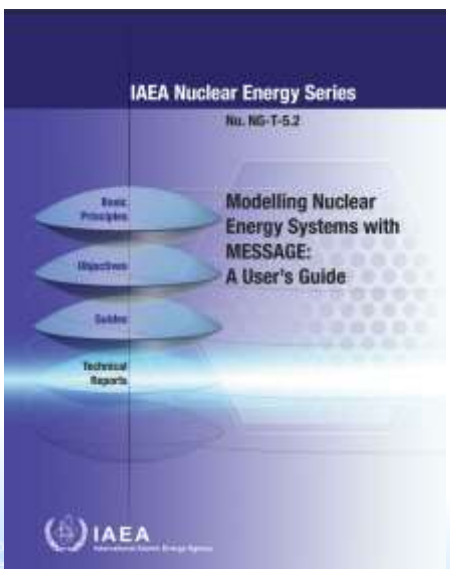
These projects have also shown enhanced sustainability may be achieved through improvements in technologies and/or changes in policies, as well as through enhanced cooperation (nuclear trade) among countries, including the technology holder and technology user countries and internationally recognized bodies responsible for defining sustainable energy policy on a global scale

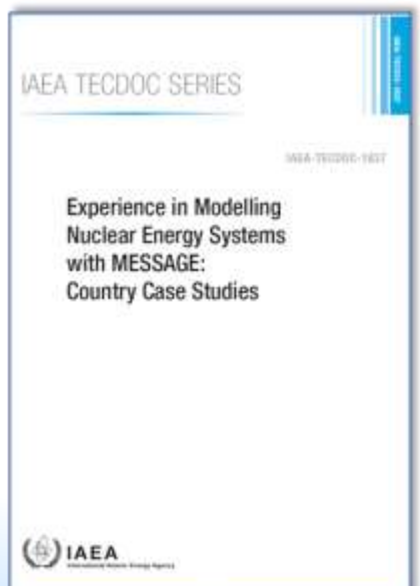
GAINS and SYNERGIES collaborative projects: outputs







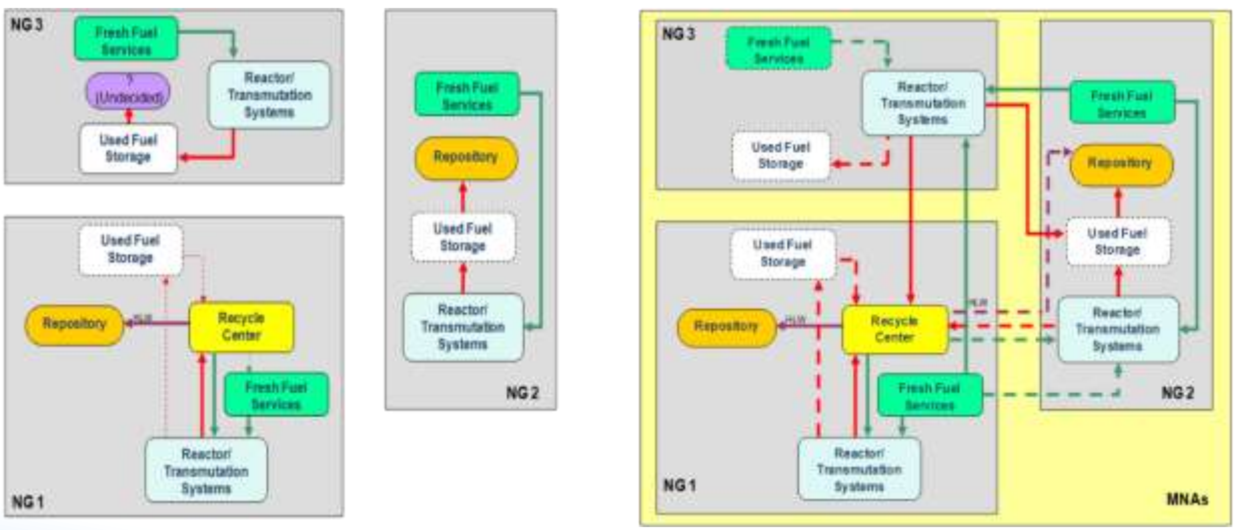




Framework for assessing dynamic nuclear energy systems for sustainability: elements

The most significant elements of this framework are:

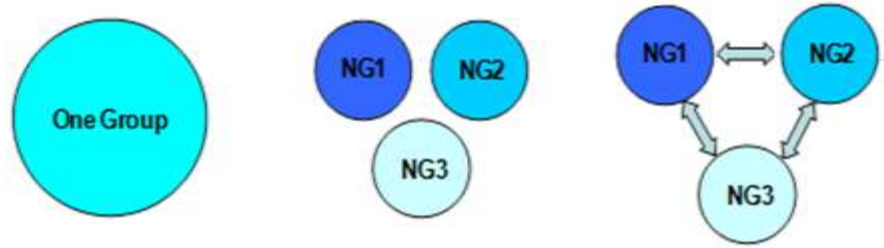
- Homogeneous and heterogeneous world models comprising groups of non-personified non-geographical countries with different policies regarding the nuclear fuel cycle back-end.
- Metrics and tools for assessing material flows and key performance indicators associated with NES deployment scenarios;
- The internationally verified tools and database with characteristics of existing and advanced nuclear reactors and relevant NFCs needed for a detailed material flow analysis



Homogeneous and heterogeneous world models

- Homogeneous world model involves full cooperation between different parts of the world and uniform technology implementation (**synergistic world**)

- Heterogeneous world model involves either no cooperation (**non-synergistic case**) or different degrees of cooperation among the country groups implementing different reactor technologies and fuel cycle strategies (**synergistic case**)



(a) Homogeneous (b1) Heterogeneous Non-Synergistic (b2) Heterogeneous Synergistic

In GAINS, the shares of nuclear energy generation in groups related to the total nuclear energy generation by 2100 were:

- 40% in NG1 (*general strategy is to recycle used fuel*);

- 40% in NG2 (*general strategy is either to directly dispose used fuel or to reprocess used fuel abroad);*

- 20% in NG3 (*general strategy is to use imported fresh fuel and send used fuel abroad for either disposal or recycle, or the back-end strategy is undecided).*

Variations of these shares were applied in GAINS to analyze sensitivities.

Nuclear energy strategy groups (NGs)	GW(e)/year						
	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

Metrics for scenario analysis

- Key Indicator (KI) should have a distinctive capability for capturing the essence of a given area
- KIs should provide means to establish targets in specific areas to be reached via improving technical or infrastructural characteristics of the NES, or through nuclear trade with other countries.

Selection of KIs for scenario analysis

- Ten KIs were identified by screening of ~ 100 indicators of the INPRO methodology
- These KIs represent nuclear power production by reactor types, fissile material resources, discharged fuel, radioactive waste, requirements for fuel cycle services, costs and investment in a global NES

No.	Key indicators and Evaluation Parameters	INPRO assessment areas: 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	

How synergies were defined in GAINS and SYNERGIES projects

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- Synergies within the context of nuclear energy are those actions that a country or a group of countries may undertake to facilitate (i.e., enable, accelerate, optimize) the deployment of the NESs with enhanced sustainability

- All synergies are systematized in two groups:
  - The first one includes synergies that are of essentially 'technical' nature that can be considered, at least, in principle, within one large enough national NES;
  - The second one comprises the cases where a combination of nuclear energy systems across countries may bring benefits that each of the countries alone wouldn't be able to achieve.

- Enhanced sustainability may be achieved via:
  - Technological options for NES sustainability enhancement
  - Collaborative enhancements

SYNERGIES: major long-term sustainability enhancement issues

In terms of the scope of the GAINS and SYNERGIES projects (focused on the material flow and economic analysis), the major long-term sustainability enhancement issues addressed were as follows:

a) Progressive accumulation of spent nuclear fuel that creates a burden for future generations;

b) Non-effective use of natural fissile resources that in the future might create problems related to fissile resource non-availability;

c) Presence of direct use materials (plutonium) in spent nuclear fuel, first in irradiated form, and, in several hundreds of years, already in a form that might be rated as unirradiated and that might create long lasting (hundreds of thousands of years) proliferation resistance and security concerns in the case of direct disposal of spent nuclear fuel in non-nuclear-weapon States;

d) Huge investments required to develop and deploy innovative technologies for nuclear power, making such innovative options unaffordable for many current and potential users of nuclear technology;

e) Risks related to global spread of sensitive technologies of uranium enrichment and spent fuel reprocessing, addressing the consequences of which would be a huge burden for future generations.

It is well recognized that not all the countries using or planning to use nuclear energy can address indigenously all the sustainability issues listed above. Even if technically possible for some of such countries, it would not be economic to solve all the sustainability issues in isolation. The majority of countries would thus have or opt to rely on imported 'off the shelf' nuclear energy technologies and supply of nuclear fuel and other services and would increasingly demand regional or/and international cooperation among countries.

TECHNOLOGICAL OPTIONS FOR NES SUSTAINABILITY ENHANCEMENT

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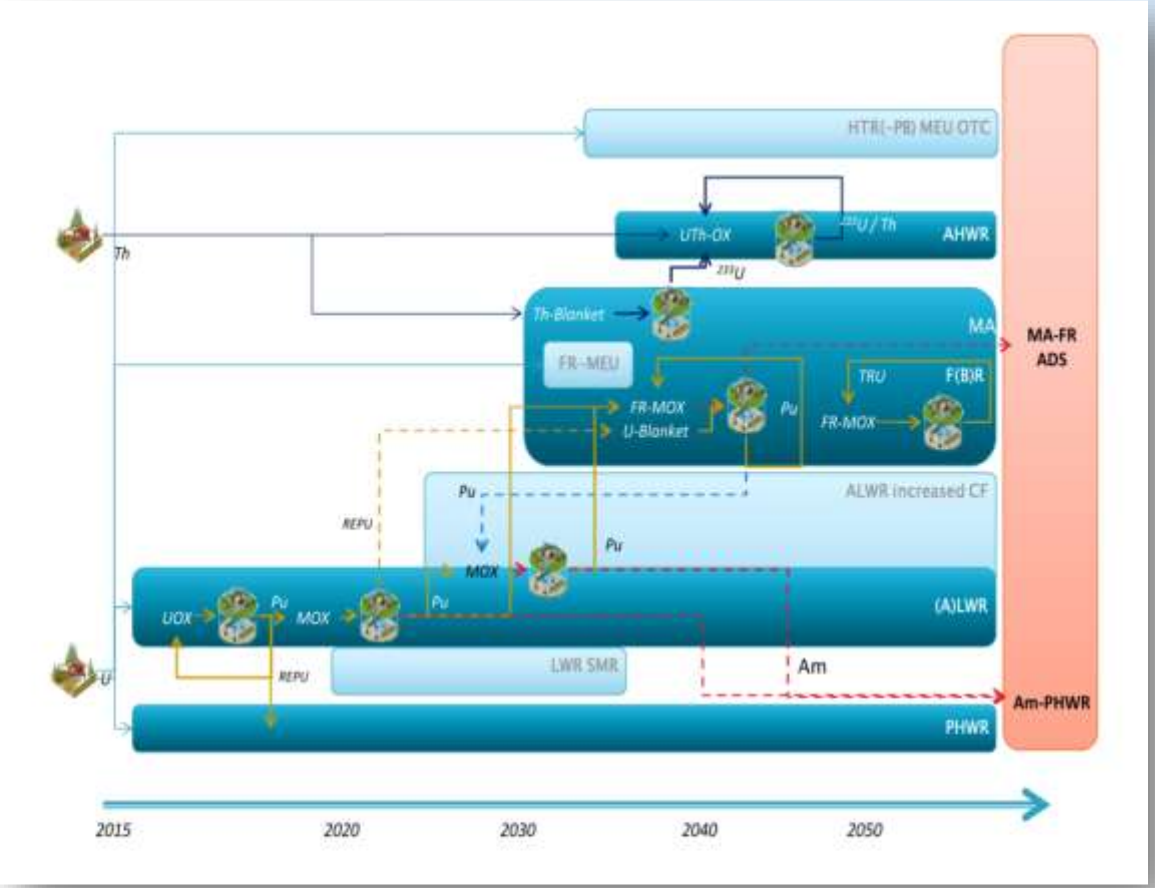
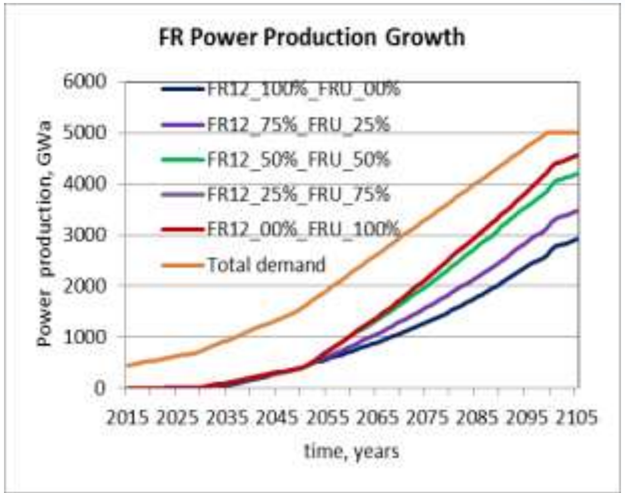
Enhancing sustainability via technology innovations (in reactors and nuclear fuel cycles):

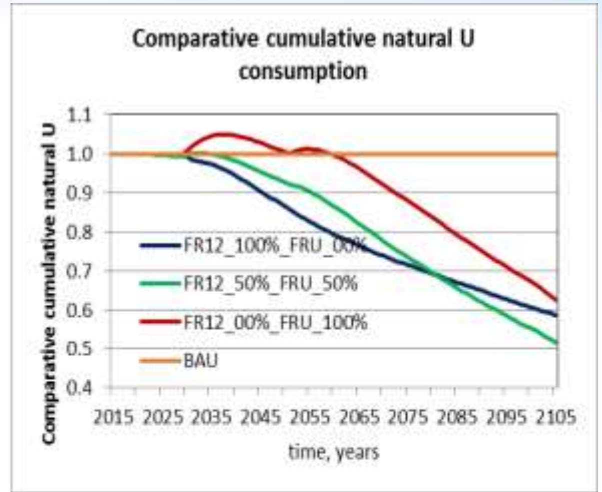
- *Once-through NFC*
- *Recycle of SNF with only physical processing*
- *Limited recycling of SNF*
- *Complete recycle of SNF*
- *Minor actinide or minor actinide and fission product transmutation*
- *Final disposal of all wastes*

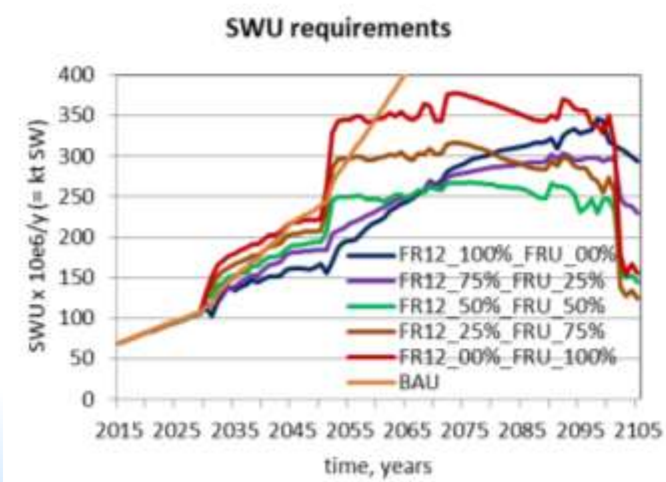


Overall view of the considered synergies among the technologies

TECHNOLOGICAL OPTIONS FOR NES SUSTAINABILITY ENHANCEMENT







Studies of alternative strategies for fast reactor deployment:

- *FR12 – fast reactor with BR=1.16 started from U-Pu fuel obtained from reprocessed SNF of thermal reactors*
- *FRU- fast reactor with BR=1.05 started from enriched uranium with subsequent recycling of its own spent fuel.*
- *BAU – once-through fuel cycle with LWR and HWR*

COLLABORATIVE ENHANCEMENTS

- The benefits of innovations in technology could be amplified through collaboration among technology holder and technology user countries

- Nuclear trade is more complex compared to that involving conventional goods. Before any contract in nuclear trade is put in place, agreements between countries need to be concluded, which may be:

- *A bilateral agreement*
- *Multiple bilateral agreements*
- *A multilateral agreement*

- Preparing and signing agreements on nuclear trade may require changing national laws and carrying out lengthy negotiations with targeted partners - it can take considerable time

- Activities in the INPRO area "Innovation" carry out a more detailed studies of drivers and barriers regarding cooperation, in particular in the back end of the fuel cycle

COLLABORATIVE ENHANCEMENTS

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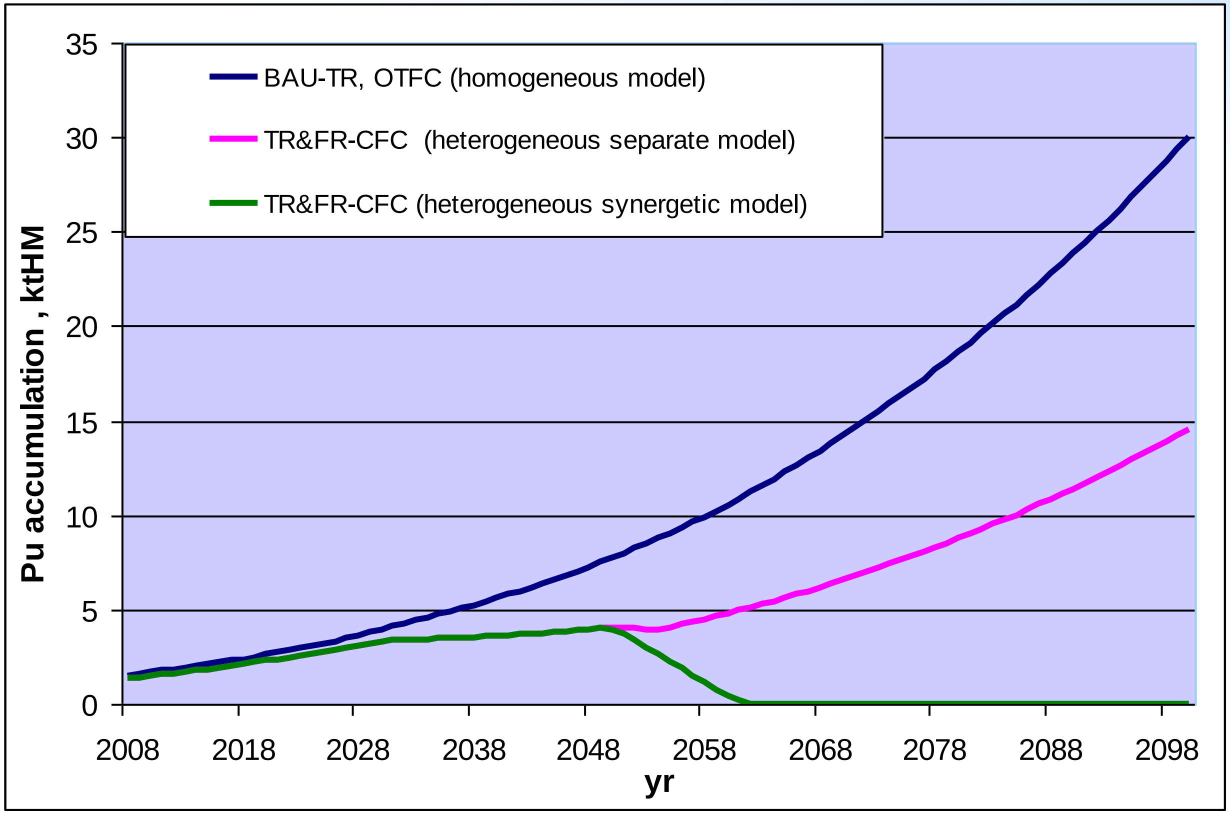


Excess plutonium inventory in the nuclear energy system (surplus to the minimal plutonium stock needed for system operation) for GAINS 2500 GW(e) scenario *(BAU-TR is business as usual with thermal reactors, OTFC is once through fuel cycle, TR&FR CFC is closed nuclear fuel cycle with thermal and fast reactors).*

Major findings (1)

- Major conclusion of the INPRO Task "Global scenarios" is that the real world developments take place and will take place in line with the heterogeneous synergistic model. Therefore, all major studies of this task are being performed in this model.

- The benefits of innovations in technology could be amplified (brought to those technology users who are not able or willing to deploy innovative facilities domestically) through collaboration (nuclear trade) among technology holder and technology user countries, in particular as related to nuclear fuel cycle services in both, the front and the back end of the nuclear fuel cycle.

- Another major conclusion of INPRO Task 1 is that collaboration (nuclear trade) among technology holder and technology user countries is equally as important for enhancing nuclear energy sustainability as innovations in nuclear energy technology themselves.

- The basic concept of synergistic collaboration with respect to sustainability is to have the whole achieve more than the parts. In a heterogeneous synergistic world sustainability of nuclear energy makes sense at a global scale rather than on a national or even regional scale.

Major findings (2)

- Economic competitiveness of nuclear energy has been identified as the primary driver for cooperation (nuclear trade) among countries. On the other hand, the technology developer countries, who are running large and costly research, design and demonstration (RD&D) programmes on innovative nuclear reactors and fuel cycles, look at strategic and business growth in anticipated national and world markets.

- The synergistic collaboration between technology developers and users could help exploit the economic benefits associated with the economy of scale of fuel cycle facilities and the economy of accelerated learning. Should such economies work, it could be a 'win-win' strategy for both.

- To make the synergistic collaboration possible, the driver for such a collaboration shall outweigh the impediments, such as for example non-available or insufficiently elaborated institutional procedures to govern spent nuclear fuel/ HLW transactions and price formation mechanisms for such transactions.

- Near and medium-term actions are needed to continue to ensure and improve the longer-term sustainability of global nuclear energy. Near and medium-term actions for technology development are focused on developing and demonstrating enabling technologies for the sustainability improvement options.

Major findings (3)

- Looking forward to managing growing SNF inventories in the near to medium term, geological repositories need to be opened for SNF disposal or reprocessing capacities need to be expanded and geological repositories opened for disposal of HLW. Either option will allow for reductions in SNF inventories while providing a waste solution missing from today's NES.

- Synergistic collaborative development would and could be beneficial, though the drivers towards such development should primarily be induced by the current nuclear technology leaders.

- Synergistic collaborations among technology holders and technology users in fuel cycle back ends are likely to start from services being provided by fuel cycle service vendors to the technology users under individual contracts governed by bilateral agreements between countries.

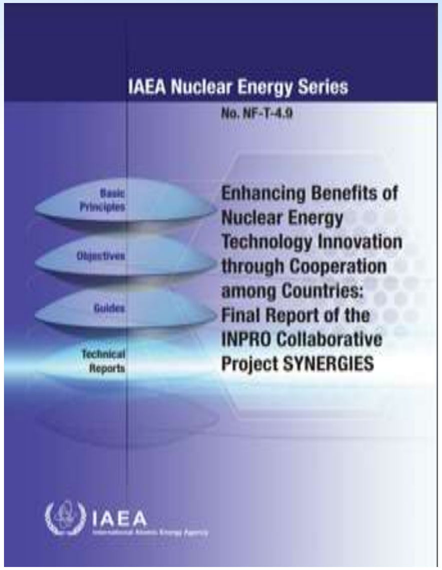
- However, representatives of the newcomer countries see an international solution for fuel cycle back end as preferable in the medium and long term, to exclude any monopolistic or cartel arrangement approaches.

Thank you!

SYNERGIES: SCOPE

Of the 28 case studies accomplished in SYNERGIES:

- 21 explicitly addressed synergies in technology;
- 20 – synergistic collaboration in fuel cycle back end with a link to synergies in technology;
- six studies touched upon possible cooperative solutions on a regional level;
- another 6 – upon possible regional and global solutions;
- and yet another study – upon possible global solutions.



SYNERGIES: MEETINGS OF RELEVANCE

Technical meetings

Vienna, Austria: 4-8 June 2012

Vienna, Austria: 30 July-3 August 2012 (under TC project INT/2/07)

Vienna, Austria: 3-7 June 2013

Yogyakarta, Indonesia: 21 October -1 November 2013

Vienna, Austria: 18-22 November 2013

Vienna, Austria: 20-23 October

Consultants' meetings

Vienna, Austria: 10-14 October 2011

Moscow, Russia: 6-10 February 2012

Vienna, Austria: 12-16 November 2012

Kiev, Ukraine: 16-17 May 2013

Yerevan, Armenia: 4-6 November 2013

Consultants' meetings (cont.)

Vienna, Austria: 19-22 May 2014

Vienna, Austria: 30 March – 2 April 2015

INPRO Steering Committee meetings:

Vienna, Austria 2-4 November 2011

Vienna, Austria 11-13 July 2012

Vienna, Austria 22-24 May 2013

Vienna, Austria 18 -20 November 2013

Vienna, Austria: 22-24 June 2014

Vienna, Austria: 11-13 June 2015

Vienna, Austria: 11-13 November

SYNERGIES: REVIEW SCOPE

(85 experts from 30 Member States and IAEA)

Argentina	2
Armenia	2
Bangladesh	2
Belarus	1
Belgium	1
Bulgaria	1
Canada	2
China	6
Croatia	1
Egypt	1
France	5
Germany	1
Ghana	1
IAEA	17 (INPRO, PESS, SG, NSNS)
India	2
Indonesia	3
Italy	2
Japan	3
Malaysia	3
Mexico	1
Morocco	1
Netherlands	1
Romania	1
Russia	9
Spain	3
Switzerland	1
Thailand	2
UK	3
Ukraine	4
USA	1
Viet Nam	2

Collaborative projects/ activities and publications of INPRO in the area "Global scenarios" (1 of 2)

#	Activity/CP	Implemented in	Deliverables	MSs/Participants	Impact
1	"Global architecture of innovative nuclear energy systems with fast reactors and a closed nuclear fuel cycle" (GAINS)	2008-2011 Completed	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) Brochure	13 MSs, European Commission 1 observer 40 contributors	55 global case studies/scenarios
2	"Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES)	2012-2016 Completed	INTERNATIONAL ATOMIC ENERGY AGENCY, Enhancing Benefits of Nuclear Energy Technology Innovation through Cooperation among Countries, Final Report of the INPRO Collaborative Project on Synergistic nuclear energy regional group interactions evaluated for sustainability (SYNERGIES), IAEA Nuclear Energy Series NP-T-4, (2016). Brochure	23 MSs 91 contributors	13 national case studies 13 global/ regional case studies
3	"Modelling Nuclear Energy Systems with MESSAGE" (MESSAGE-NES)	2012-2018 Completed	(1)INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling Nuclear Energy Systems with MESSAGE: A Users' Guide, IAEA Nuclear Energy Series No. NG-T-5.2, IAEA, Vienna (2016). (2)INTERNATIONAL ATOMIC ENERGY AGENCY, Experience on Modelling Nuclear Energy Systems with MESSAGE: Country Case Studies, IAEA-TECDOC-1837, IAEA, Vienna (2018).	6 MSs 28 contributors	5 national case studies 6 global/regional case studies
4	"Key Indicators for Innovative Nuclear Energy Systems" (KIND)	2014-2019 Completed	INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Multi-criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND, IAEA Nuclear Energy Series No. NG-T-3.20, Vienna (2019) Brochure	16 MSs 53 contributors	5 national case studies 2 global/regional case studies

Collaborative projects/ activities and publications of INPRO in the area "Global scenarios" (2 of 2)

#	Activity/CP	Implemented in	Deliverables	MSs/Participants	Impact
5	"Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems" (ROADMAPS)	2014- till present On-going	INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Roadmaps to Enhance Nuclear Energy Sustainability: Final Report of the INPRO Collaborative Project ROADMAPS, IAEA Nuclear Energy Series No. NG-T-3.22, IAEA, Vienna (content approved by IAEA PC).	17 MSs 56 contributors	5 national case studies 4 global/regional case studies
6	"Comparative evaluation of nuclear energy system options" (CENESO)	2017 - till present On-going	IAEA TECDOC (in preparation)	16 MSs 48 contributors	11 national case studies 3 global/regional case studies
7	"Scenario Analysis and Decision Support for Planning Enhanced Nuclear Energy Sustainability: An INPRO Service to Member States"		INTERNATIONAL ATOMIC ENERGY AGENCY, Scenario Analysis and Decision Support for Planning Enhanced Nuclear Energy Sustainability: An INPRO Service to Member States, IAEA Nuclear Energy Series No. NG-T-3.21, IAEA, Vienna (content approved by IAEA PC).	20 MSs 34 contributors	Materials and tools for training. Trainings in Mexico and Russia held in 2019. Trainings in Thailand and Russia are planned to be held in 2021.
8	"Analysis of scenarios involving initially small numbers of innovative nuclear energy installations to support multi-recycling of fuel in a nuclear energy system" (STEP FORWARD)	2021- Start up	IAEA TECDOC (TBD)		
9	"Sustainable deployment scenarios for small modular reactors" (SMR)	2020- Start up	IAEA TECDOC (TBD)		

INPRO integrated service to Member States

IAEA

Analysis Support for Enhanced Nuclear Energy Sustainability

ASENES

Scenario modelling and analysis	Economic analysis and evaluation of Nuclear Energy System (NES)	Comparative evaluation of NESs and scenario options	Road mapping towards enhanced NE sustainability
MESSAGE-NES	NEST	KIND-ET	ROADMAPS-ET

Nuclear Energy System Assessment

NESA

Assessment areas of Economics, Safety, Infrastructure, Environment, Proliferation Resistance and Waste Management

NESA support package