IAEA
International Atomic Energy Agency

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

Message-NES tool

NEST tool

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IAEA
INPRO
International Project on
Innovative Nuclear Reactors
and Fuel Cycles

Framework for Nuclear Energy Evolution Scenarios Evaluation Regarding Sustainability

IAEA

➢**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 evaluation is based on a set of scenario-specific Key Indicators in the areas of mass flows, resources, wastes, demands for the front-end and back-end fuel cycle services and economics

➢It allows to consider targeted NES options with enhanced sustainability

➢GAINS has applied the developed framework to the analysis of global NES scenarios and identified several global NES architectures with enhanced NES sustainability

➢GAINS has also shown that enhanced sustainability would be difficult to achieve without broad cooperation between technology holder and technology user countries in the nuclear fuel cycle back-end, as well as the front-end

Analytical framework for nuclear energy evolution scenario evaluation regarding sustainability:

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

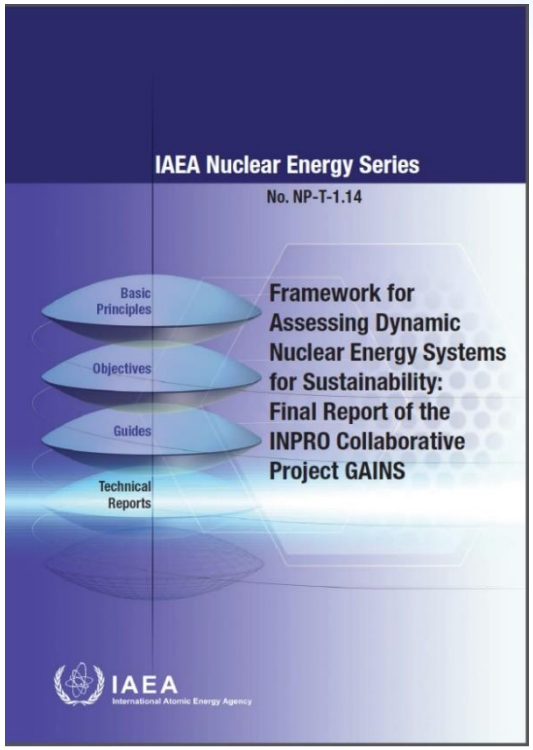
➢**The INPRO collaborative project "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES)** has applied the framework to national NES evolution scenarios with regional cooperation

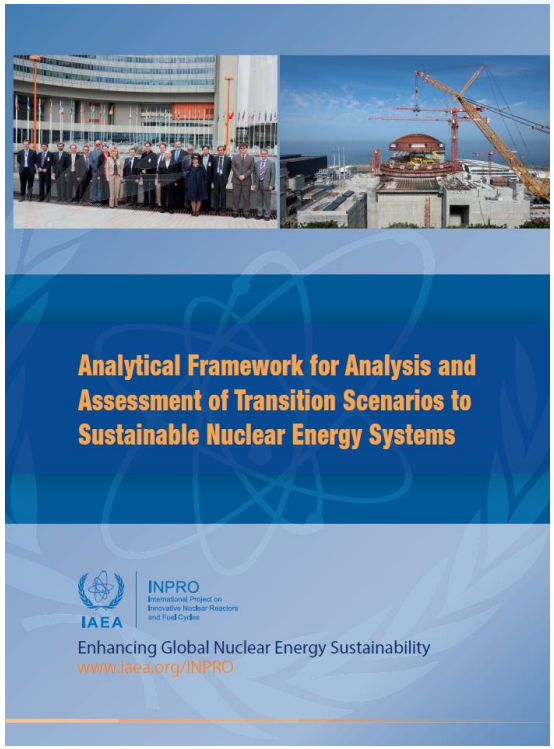
➢SYNERGIES has developed a concept of "Options for enhanced nuclear energy sustainability"

➢Enhanced sustainability may be achieved through improvements in technologies and/or changes in policies, as well as through enhanced cooperation among countries, including the technology holder and technology user countries and internationally recognized bodies responsible for defining sustainable energy policy on a global scale

Analytical framework: elements

- Nuclear demand evaluated for global NES: Two storylines of nuclear energy evolution
- Homogeneous and Heterogeneous World Models
- Four architectures of NES; Fuel cycle schemes
- Metrics (indicators) for scenario analysis
- Reactor/Fuel Data Template
  - Reactor characteristics
  - Isotopic Charge/Discharge
- Tools for NES modelling
- Templates to compare results
- Framework Base Cases
- Framework applications

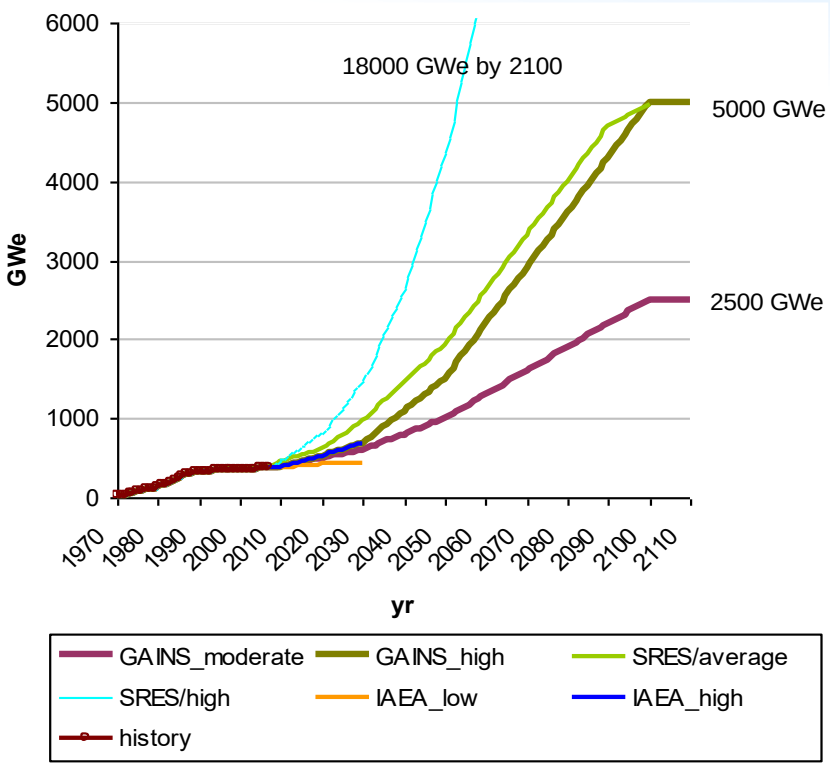




Global nuclear demand

- Comprehensive database (long-term energy demand as one of the key factors in projecting future greenhouse gas emissions and a NE demand as a part of overall energy demand)

- Projections made by competent energy agencies (top down approach) along with the information from Member States compiled by IAEA (bottom up approach)



Two long-term NP *demand scenarios*

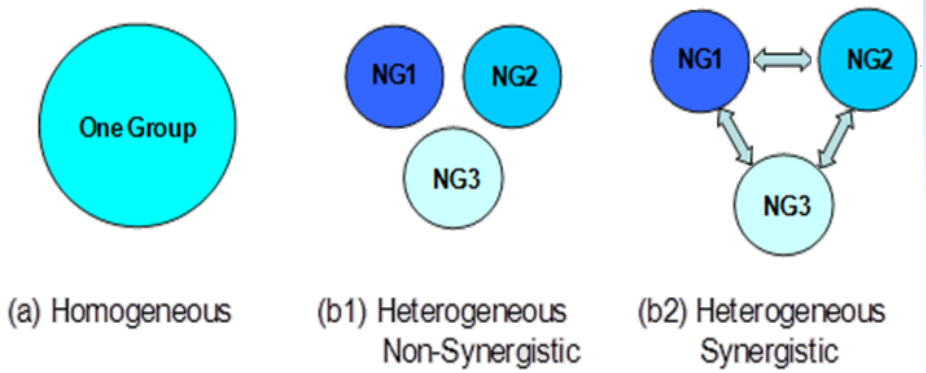
Nuclear demand evaluated for global NES:

- High – 1500 GWe by 2050, 5000 GWe by 2100;

- Moderate -1000 GWe by 2050, 2500 GWe by 2100.

Nuclear demand evaluated for global NES 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**)



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

In the nominal case, 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 to either directly dispose of used fuel, or reprocess used fuel abroad);*
- 20% in NG3 (*General strategy is to use fresh fuel, and send used fuel abroad for either recycle or disposal, or the back-end strategy is undecided).*

Variations of these shares were also applied in GAINS for possible use in sensitivity studies.

NES architectures

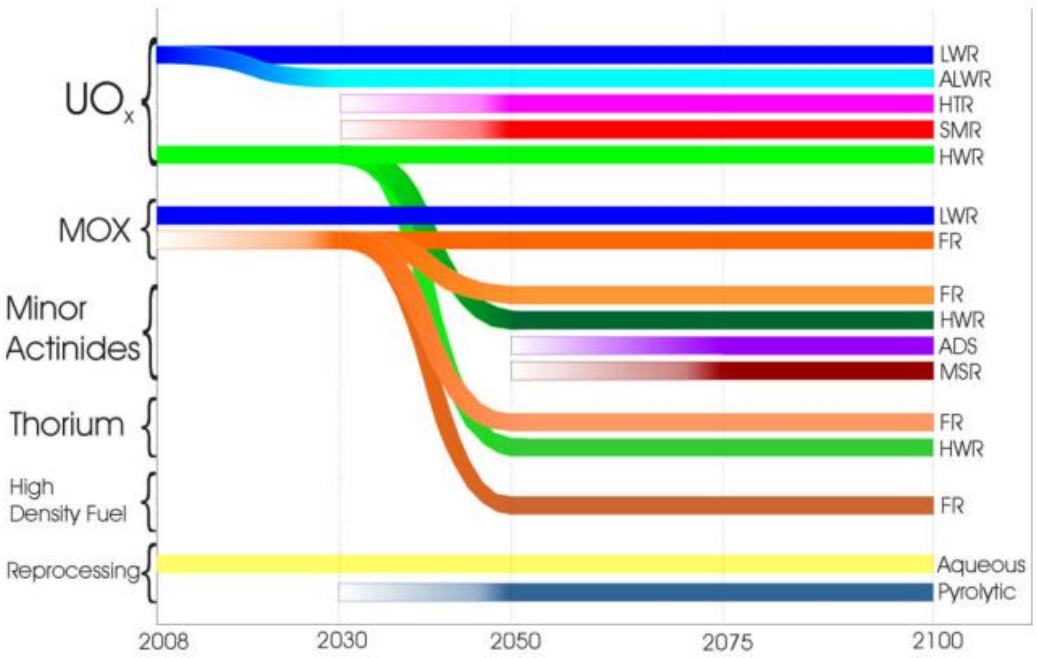
GAINS considered four architectures for NES:

I. Homogeneous "business-as-usual" (BAU) NES based on PWRs (94%) and HWRs (6%) operated in OTFC and CNFC-FR & TR

II. Heterogeneous system: CNFC-FR & TR in NG1, OTFC-TR in NG2; TR with minimal infrastructure in NG3

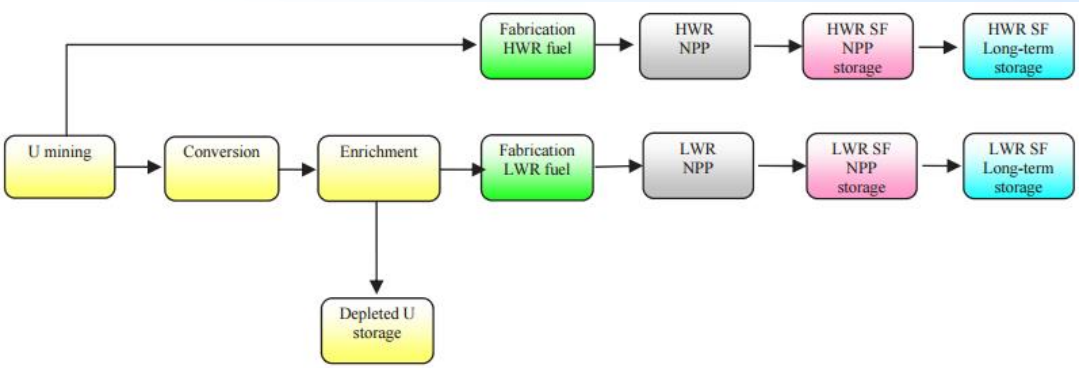
III. Minor actinides (MA) reducing components (Accelerator Driven Systems - ADS or Molten Salt Reactors - MSR)

IV. Thorium fuel cycle with FR and TR

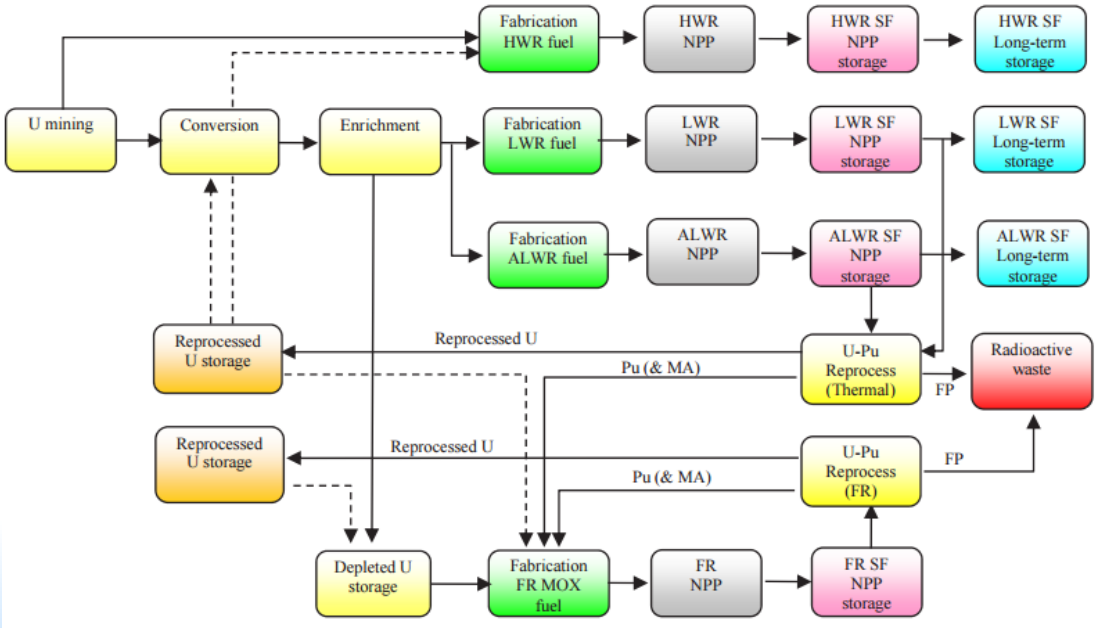


Set of reactor and fuel types and expected timeframes for deployment

Associated nuclear fuel cycle schemes (examples)



Once-through fuel cycle system (BAU scenario)



Combined once-through fuel cycle system with FR closed fuel cycle system

Metrics (Key Indicators and Evaluation Parameters) for scenario analysis

- The idea is that KI would have a distinctive capability for capturing the essence of a given area, and that they would provide a means to establish targets in a specific area to be reached via improving technical or infrastructural characteristics of the NES or through collaboration with other countries.
- Ten KIs were identified by screening ~ 100 indicators of the INPRO methodology
- These KIs represent nuclear power production by reactor types, resources, discharged fuel, radioactive waste, fuel cycle services, costs and investment in a NES

No.	Key indicators and Evaluation Parameters	INPRO assessment areas					
	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	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	

Reactor/fuel data template – reactor characteristics

Reactors considered in GAINS:

- Low, Medium and High burn-up light water reactors (LWRs);
- Heavy water reactors (HWRs);
- Sodium cooled fast reactors with different conversion/breeding ratios;
- Accelerator driven system (ADS) and molten salt reactor (MSR), both for minor actinide (MA) burning;
- ThO_2 and PuO_2 fuelled CANDU (HWR) reactors, and
- ThO_2, ^{233}U and PuO_2 fuelled CANDU reactors.

Added value to IAEA database

- Additional data for IAEA database to simulate material flows from a wide range of reactors and nuclear fuel cycles, in different stage of maturity.

Major specifications of a break-even FR (demonstration type)

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 core inventory	tHM	24.288		
Equilibrium Loading	tHM / y	17.292		

* Equilibrium cycle average

** Half of radial blanket fuel assemblies have 3 refuelling batches; the other half have 4 refuelling batches

Reactor/Fuel data template – Isotopic charge/discharge

Refueling Data	(Attention!! Reload and discharge are as of one refueling in equilibrium cycle.)							
Isotopes	Initial loading (kg)		Reload (kg)		Discharge (kg)		Full core discharge (kg)	
	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)	
U-234					3.863E-03	4.951E-05	7.944E-03	
U-235	6.458E+01	2.659E-01	2.065E+01	2.646E-01	1.932E+01	2.476E-01	6.668E+01	
U-236					1.695E+00	2.173E-02	4.017E+00	
U-238	2.146E+04	8.836E+01	6.862E+03	8.794E+01	6.537E+03	8.377E+01	2.073E+04	
Np-237					1.037E+00	1.329E-02	2.262E+00	
Pu-238	1.381E+01	5.685E-02	4.602E+00	5.898E-02	3.522E-01	4.514E-03	5.661E-01	
Pu-239	1.657E+03	6.822E+00	5.523E+02	7.078E+00	5.767E+02	7.390E+00	1.762E+03	
Pu-240	6.766E+02	2.786E+00	2.255E+02	2.890E+00	2.459E+02	3.151E+00	7.280E+02	
Pu-241	3.010E+02	1.239E+00	1.003E+02	1.286E+00	7.410E+01	9.496E-01	2.463E+02	
Pu-242	1.132E+02	4.662E-01	3.774E+01	4.837E-01	4.006E+01	5.134E-01	1.193E+02	
Am-241					3.926E+00	5.031E-02	8.531E+00	
Am-242m					8.594E-02	1.101E-03	1.455E-01	
Am-243					2.960E+00	3.793E-02	6.071E+00	
Cm-242					2.694E-01	3.452E-03	4.793E-01	
Cm-244					3.094E-01	3.966E-03	4.930E-01	
Cm-245					1.039E-02	1.331E-04	1.425E-02	
Total FP					2.997E+02	3.841E+00	6.166E+02	
Total HM&FP	24288.257	100.000	7803.086	100.000	7803.086	100.000	24288.257	
Total U	21526.758	88.630	6882.586	88.203	6557.715	84.040	20797.868	
Total Pu	2761.499	11.370	920.500	11.797	937.062	12.009	2855.758	
Total MA (Np+Am+Cm)	13.807	0.057	0.000	0.000	8.598	0.110	17.996	

Tools for NES modelling

Codes used for sample scenario studies:

Codes disseminated by the IAEA:

- MESSAGE - Model for Energy Supply System Alternatives and their General Environmental impacts, MESSAGE is IAEA's large-scale dynamic systems-engineering, economic optimization model that is used for development of medium- to long-term energy scenario and policy analysis.
- NFCSS is Nuclear Fuel Cycle Simulation System which estimates nuclear fuel cycle service and material requirements as well as material arising for the each stage of the nuclear fuel cycle.

National codes:

- DANESS (Republic of Korea), DESAE (Belgium, Russia), COSI (France), FAMILY (Japan), TEPS (India), and VISION (USA).

NFCSS

Nuclear Fuel Cycle Simulation System (NFCSS) is a scenario-based simulation system able to estimate long-term nuclear fuel cycle material and service requirements, as well as material arisings.

- The code was redesigned to include new reactor and fuel types and a web based software was developed.

Strategy parameters
- Nuclear power projections
- Reprocessing-recycling strategies
- Reactor mixtures
- Load factors

Fuel Parameters
- Avg. discharge burn-up
- Avg. initial enrichment
- Avg. tails assay

Control Parameters
- Share of MOX fuel in core
- Lead and lag times for different processes
- # of reprocessing cycles

NFCSS

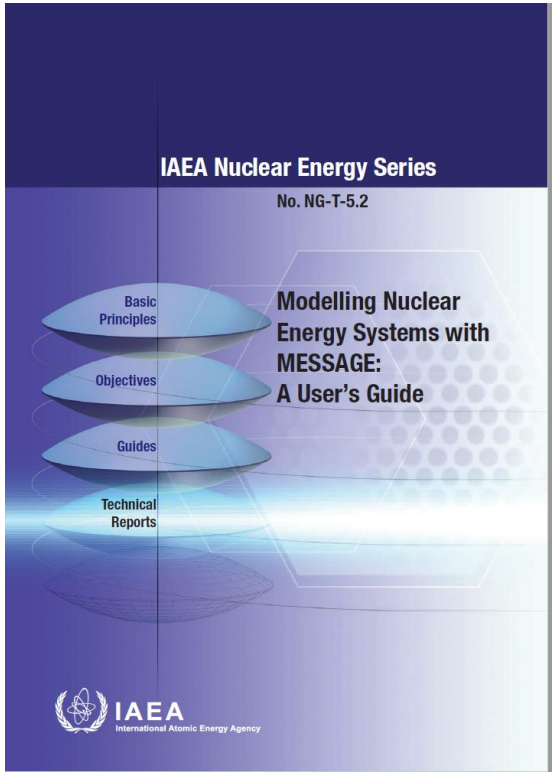
CAIN
Calculation of
Actinide
INventory

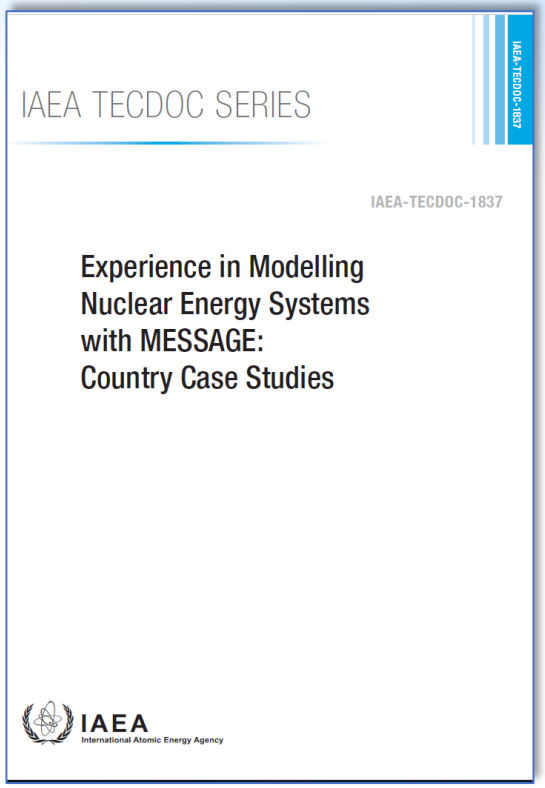
- Natural uranium requirement
- Conversion requirements
- Enrichment requirements
- Fresh fuel requirements
- Spent fuel arisings
- Plutonium accumulation
- Minor Actinide accumulation
- Reprocessing requirements
- MOX fuel fabrication requirements

NFCSS Information Flow

MESSAGE-NES tool (2016)

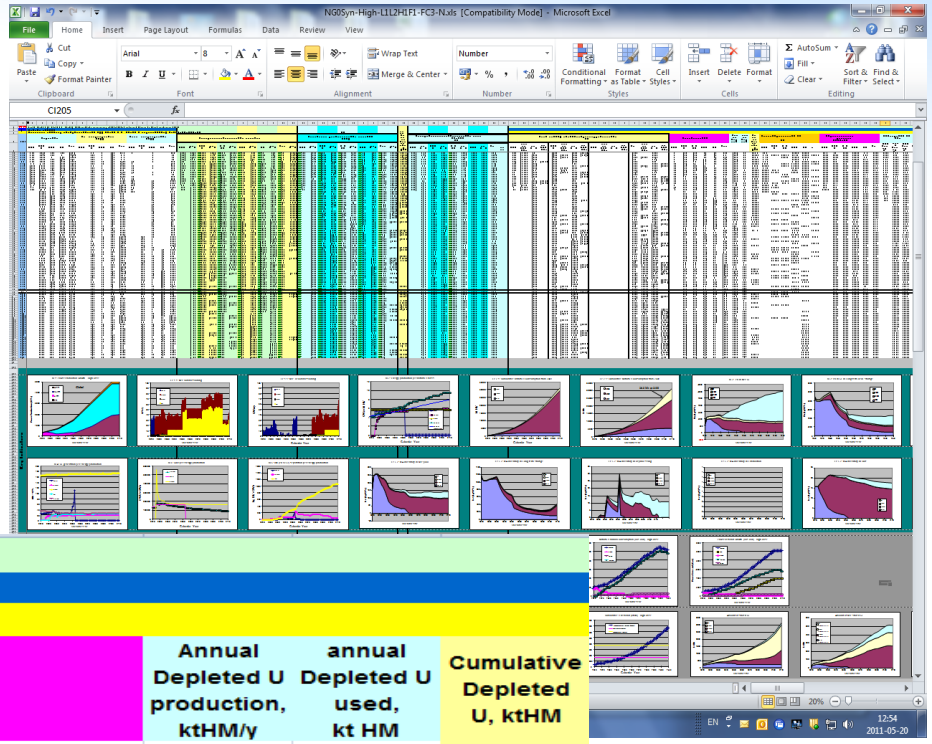
- User's Guide provides a step-by-step guidance to create mathematical models representing nuclear energy systems to the level of detail as necessary
- IAEA-TECDOC-1837 explores the experience gained in modelling national and global nuclear energy systems with MESSAGE-NES and includes feedbacks
- The targeted users for MESSAGE are engineers and economists working at nuclear energy departments, electric utilities, energy ministries and/or R&D institutions, including technical universities, who are interested in using the tool for modelling the entire NES with technical details in order to evaluate options for long term nuclear energy strategies in countries or regions





Template to compare the results

A special template was developed to facilitate joint analysis and cross-checking of the simulation results on material flows (NFCSS as reference).



Global									
1000									
1000									
YEAR	Fuel fabrication, ktHM/y						Annual Depleted U production, ktHM/y	annual Depleted U used, kt HM	Cumulative Depleted U, ktHM
1000	LWR	ALWR	A+LWR	HWR	FR	Total			including 1970-2007
2040	18,3	0,0	18,3	8,7	2,6	29,6	145,1	0,1	5159,7
2041	18,7	0,0	18,7	8,8	2,8	30,3	148,8	0,1	5308,1
2042	18,8	0,0	18,8	9,1	3,1	31,0	150,0	0,1	5458,2
2043	19,4	0,0	19,4	9,5	3,3	32,1	151,9	0,1	5610,3
2044	20,1	0,0	20,1	9,7	3,5	33,2	159,9	0,1	5769,5
2045	20,2	0,0	20,2	9,8	3,7	33,8	161,8	0,1	5931,1
2046	20,1	0,0	20,1	10,0	4,0	34,1	161,3	0,1	6092,3
2047	19,9	0,0	19,9	10,1	4,1	34,2	160,1	0,1	6252,2
2048	19,7	0,0	19,7	10,3	4,4	34,4	158,4	0,1	6410,6
2049	19,5	0,0	19,5	10,6	4,6	34,7	156,3	0,1	6566,9
2050	19,9	0,0	19,9	10,8	4,8	35,6	156,6	0,1	6723,8

GAINS-template to calculate KIs and EPs

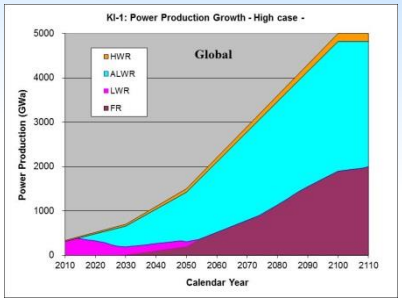
Scenario
- Nuclear power growth
- Reactor data
- Fuel cycle options

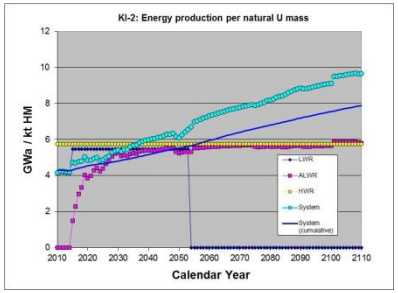
Fuel cycle codes
Mass flow analysis

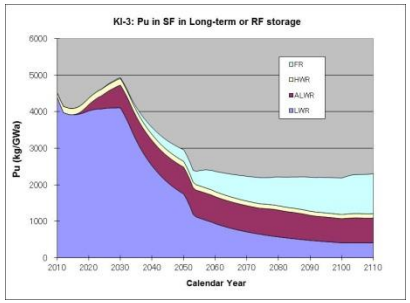
Output

KIs and EPs

GAINS template





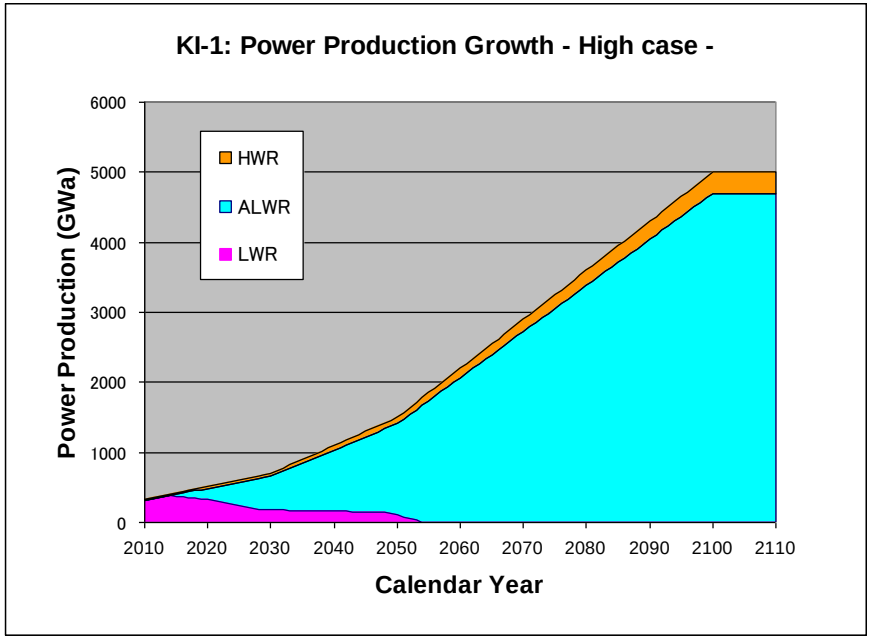


Sample scenario studies

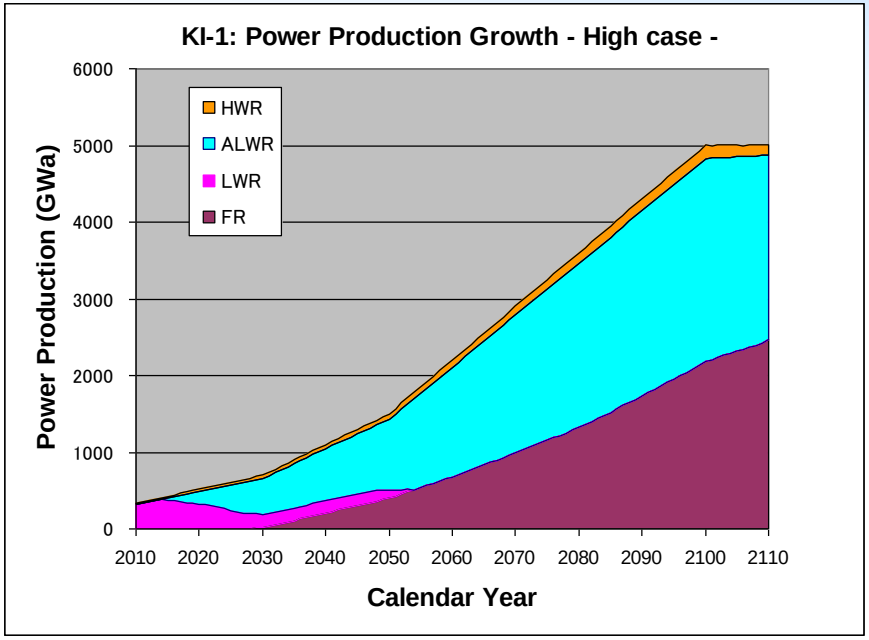
Framework Base Cases

- Homogeneous World
  - Business as Usual scenario
  - Fast Reactor introduction scenario
- Heterogeneous World
  - Non-Synergistic world scenario
  - Synergistic world scenario

KI-1 LWR and FR production comparison



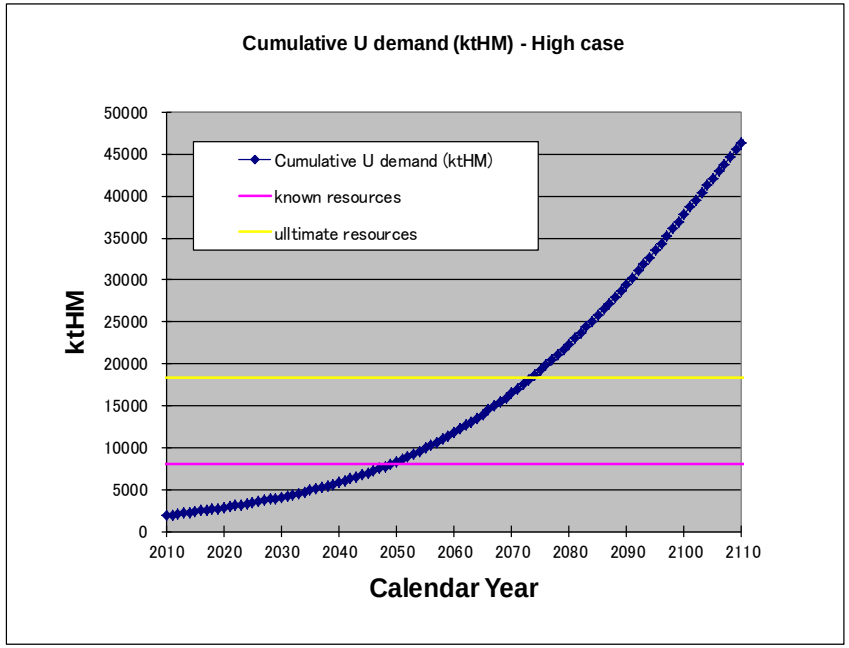
Reactor power share of BAU+
(includes introduction of an advanced PWR replacing conventional PWR technology)



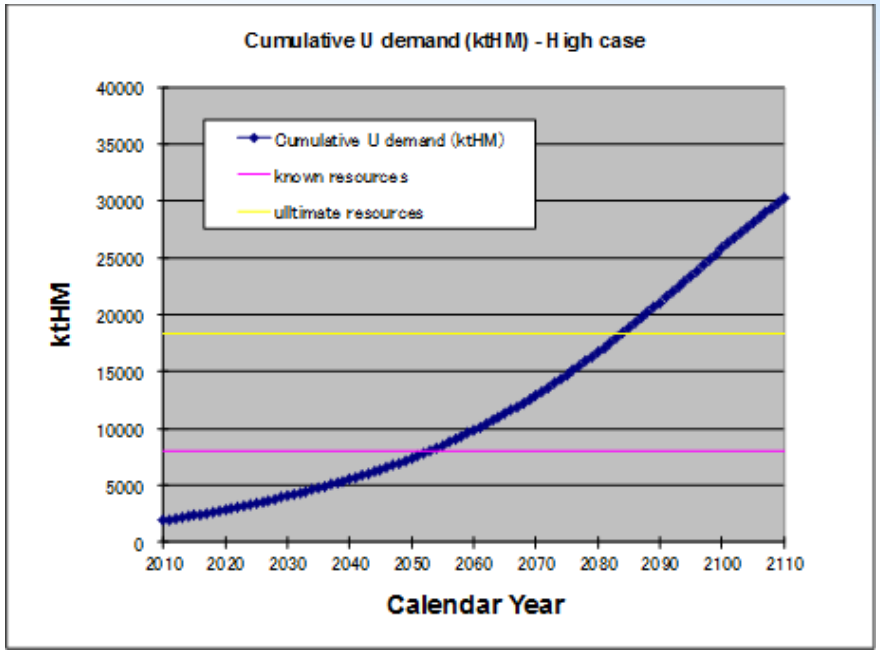
Reactor power share of BAU+FR

ALWRs are introduced in 2015 and gradually replace LWR. The share of HWR is settled as 6% of total nuclear power capacity. By 2100, the share of fast reactors can reach about 44% of the global nuclear energy production. The FR introduction is restrained by zero breeding performance of the considered break-even FR.

EP-2.1 cumulative natural uranium used



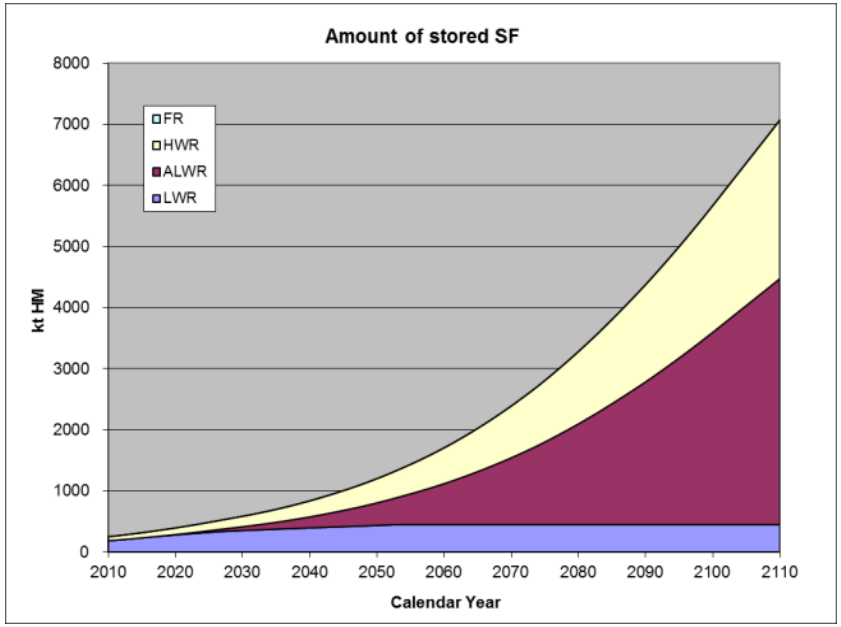
Cumulative natural U demand in BAU+



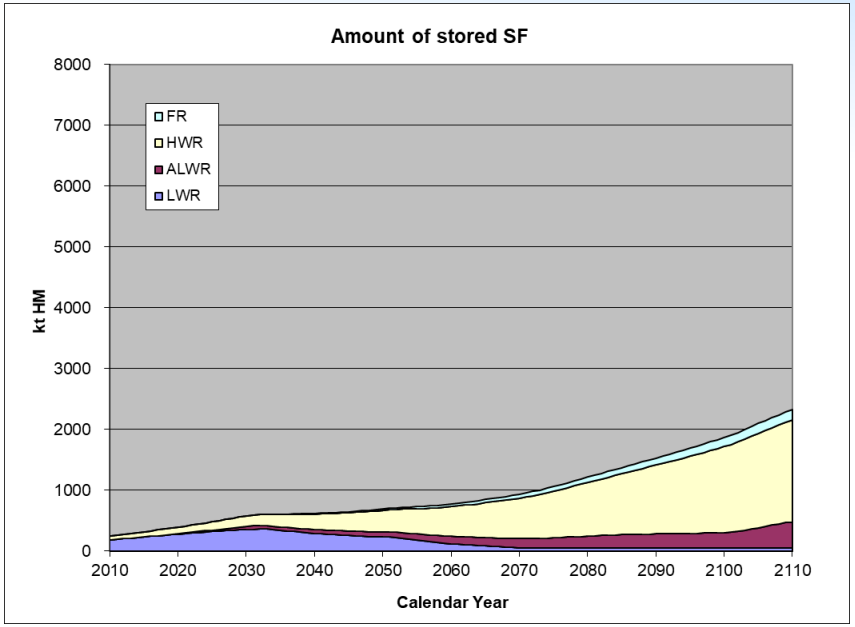
Cumulative natural U demand in BAU+FR

By the end of the century, the total mass of consumed natural uranium would reach 37.8 million tons for BAU+ case. In the BAU+FR case, uranium consumption is by 12 million tons lower in 2100 than in the BAU+ case. The conventional natural uranium resources will be exhausted around 2070 in the BAU+ case and around 2085 in the BAU+FR case.

Cumulative amount of spent fuel



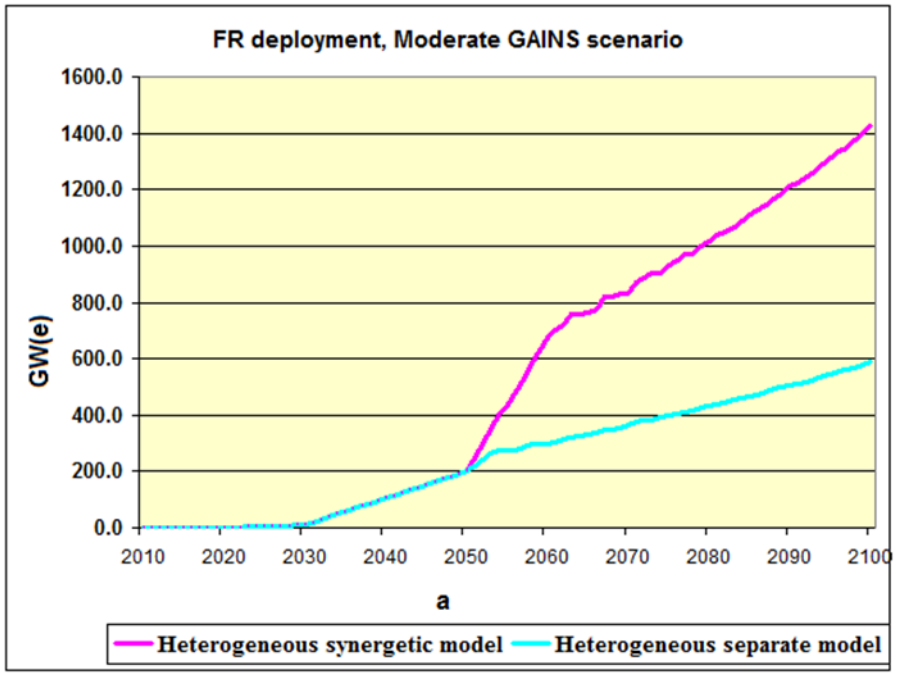
Total amount of SF in BAU+



Total amount of SF in BAU+FR

The total amount of spent fuel accumulated by 2100 in the BAU+ scenario reaches 5.5 million tons. The LWR spent fuel can be significantly reduced by introduction of fast reactors in BAU+FR scenario.

Potential for fast reactor deployment



The figure shows change in fast reactor deployment for the non-synergistic case (no spent fuel exchange between GAINS strategic groups) as compared to the synergistic case.

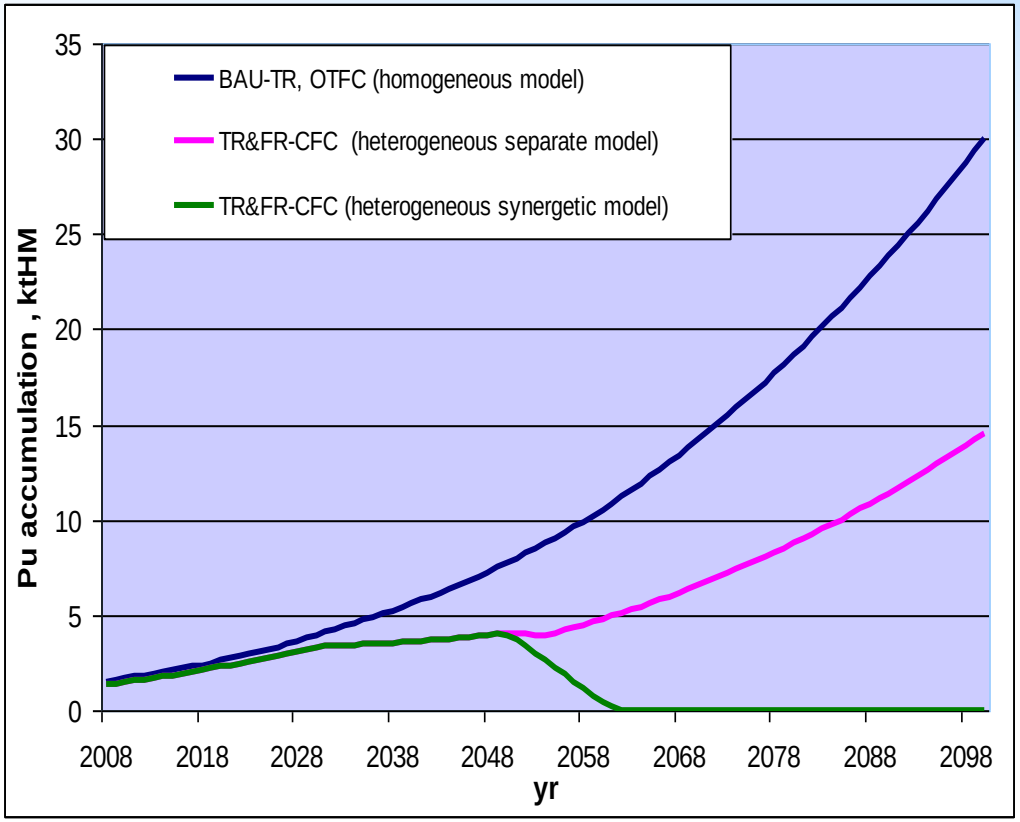
Assuming NG1 has no 'physical' limitation on reprocessing capacity for spent fuel from all country groups, the recovered Pu (and any recovered U) could be used to produce fuel for fast reactors.

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 U resource savings and Pu management options.

Plutonium inventories and plutonium management options

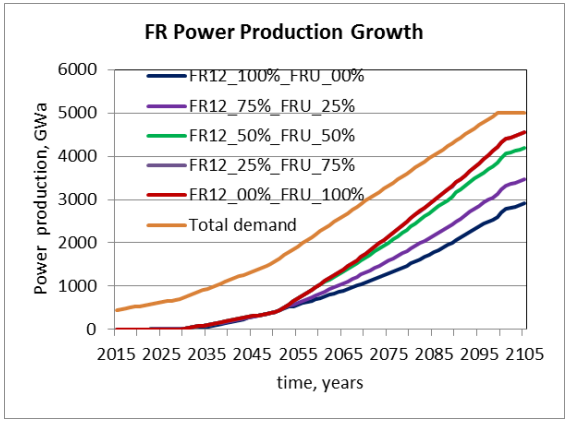
- Once-through global nuclear fuel cycle (BAU) would result in a progressive increase of Pu accumulation (top line in the figure)

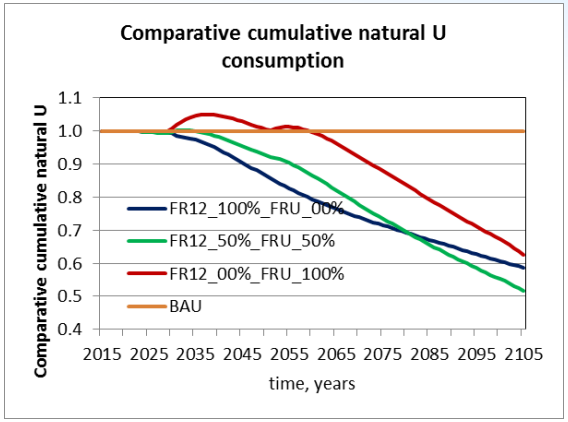
- Pu use by the NES TR&FR (BR=1.16) from the NG1 reduces its accumulation rate, but does not solve the problem globally (pink line in the figure)

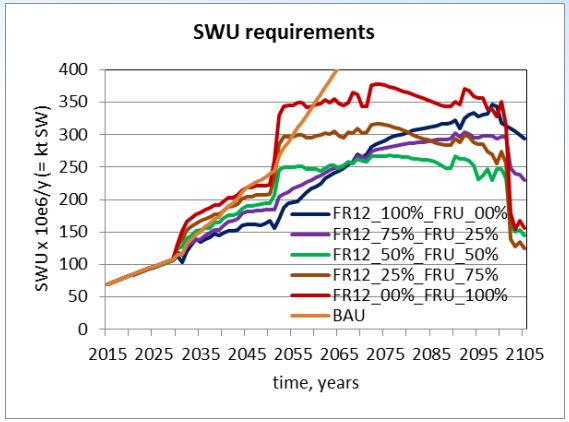


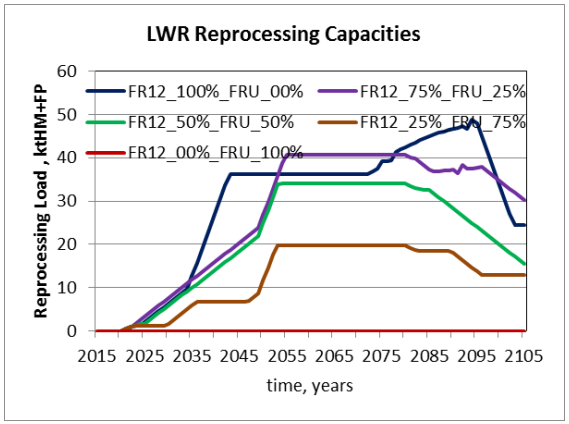
A synergistic global NES CNFC-FR&TR (BR=1.16) gives an opportunity to reduce Pu accumulation to a minimal stock needed for reactors operation (green line in the figure)

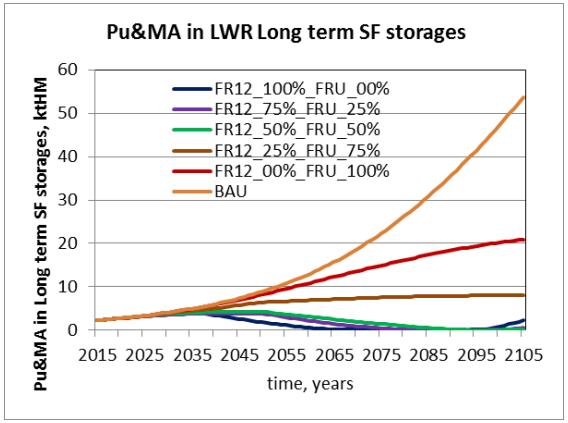
Example of results:
Scenarios with alternative fast reactor deployment approach









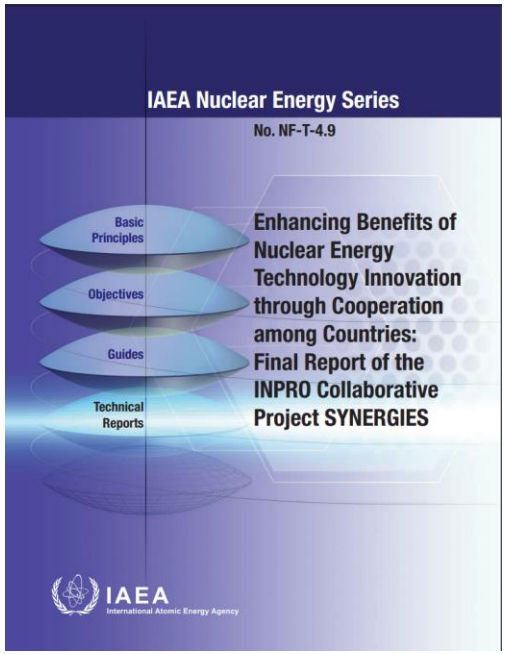


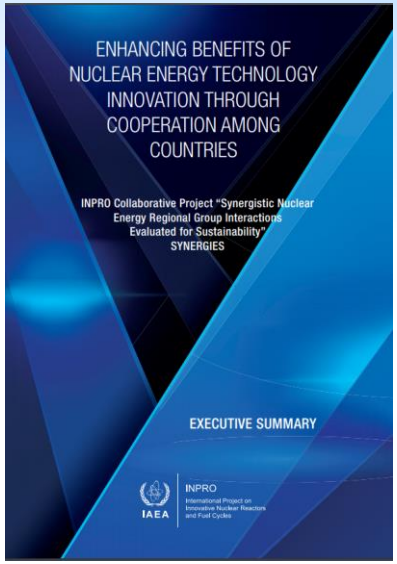
Combined deployment strategy wherein part of FR are started with U-Pu load and part – with enriched U load has a potential to offer attractive compromises in a closed nuclear fuel cycle

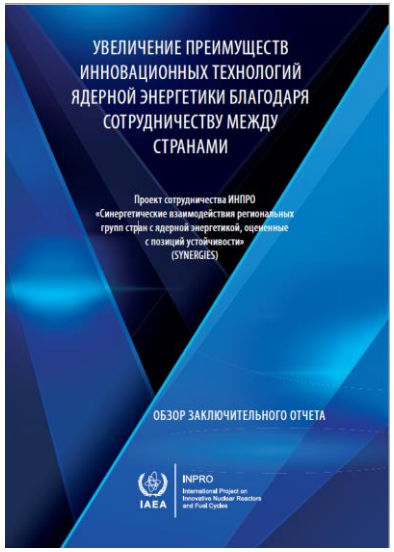
The INPRO collaborative project “Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability” (SYNERGIES)

- SYNERGIES project was established in response to a strong interest expressed by INPRO members to further develop and apply the synergistic approach of GAINS, more on a regional rather than global level, as a method for evaluating the means of technological innovations and cooperation among countries (nuclear trade) for enhancing the sustainability of nuclear energy.

- Its main objective was to identify and evaluate mutually beneficial forms of collaboration, and the driving forces and possible impediments involved in achieving regionally and globally sustainable NES built on a synergistic combination of (i) mature and innovative nuclear energy technologies, and (ii) different forms of collaboration (nuclear trade) among countries.







Major long-term sustainability enhancement issues

In terms of the scope of the SYNERGIES project (focused on the material flow and economic analyses), 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.

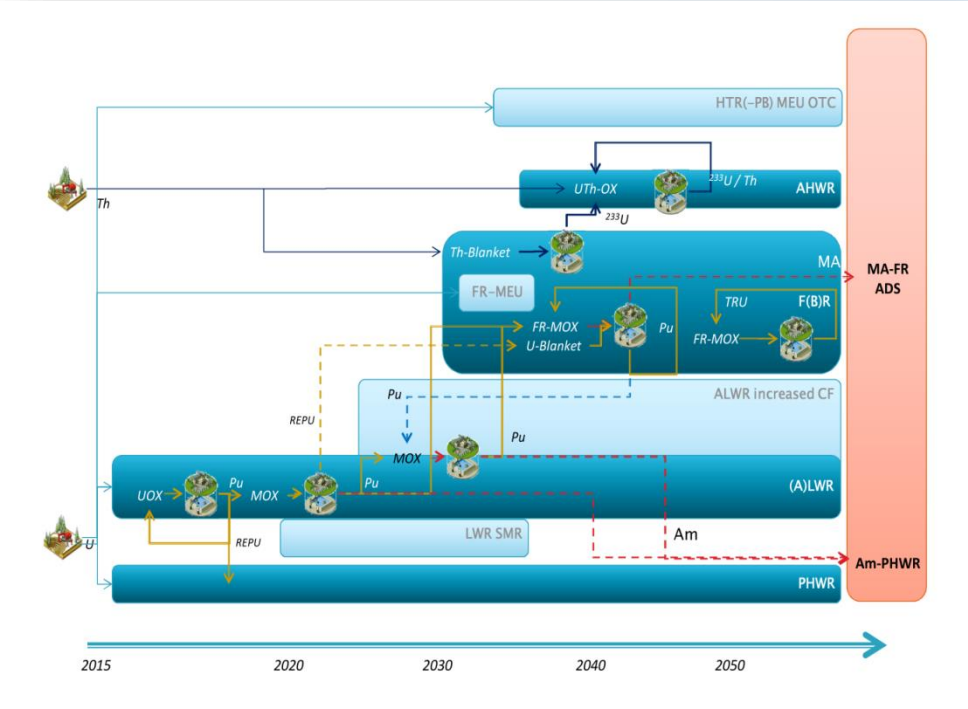
Options for NES sustainability enhancement

- 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

Technological options for NES sustainability enhancement

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 geological disposal of all wastes* (obligatory for all above mentioned options)



Overall view of the considered synergies among the technologies

Case studies performed within the SYNERGIES project

- Case studies performed within the SYNERGIES project indicate growing interest of the IAEA Member States in long term analysis of nuclear energy evolution scenarios and in actions aimed at the implementation of synergies among the various technologies and options for cooperation. This is reflected in the twenty eight case studies performed within the project:
  - 21 explicitly addressed ***synergies in technology***;
  - 20 addressed ***synergistic collaboration in NFC back end with a link to synergies in technology***;
  - 12 touched upon possible ***cooperative solutions on regional/global levels.***

- For the future nuclear energy systems to be globally sustainable, a combination of the various synergistic collaborative solutions may be needed, depending on the pace of nuclear capacity growth.

Major findings of GAINS and SYNERGIES

Nuclear energy sustainability can be enhanced via advanced reactors and nuclear fuel cycles, as well as via collaboration (nuclear trade) among countries. Collaboration could amplify the positive effect of technology innovation in achieving sustainable nuclear energy.

Potential benefits of cooperation among countries:

- Minimizing infrastructure effort for individual countries' NESs;
- Suggesting sound solutions for SNF utilization and disposal;
- Enabling optimum use of available resources;
- Minimizing costs owing to the economy of scale and other factors.

Collaboration among technology holder and technology user countries could secure sustainability enhancement of NESs able to meet the 21st century energy needs

However, collaboration would be possible only when assuring that the related driving forces overcome the impediments

Scope of economics consideration in INPRO

Economics is one of the main areas for evaluation of Nuclear Energy Systems

- INPRO considers economics of nuclear power from several viewpoints:
  - Economic analysis Support for Enhanced Nuclear Energy Sustainability (in Scenario studies for transitions from existing nuclear energy systems to future energy systems).
  - Economic assessment in INPRO methodology (area of Economics and Cost-benefit studies in the area of Infrastructure);

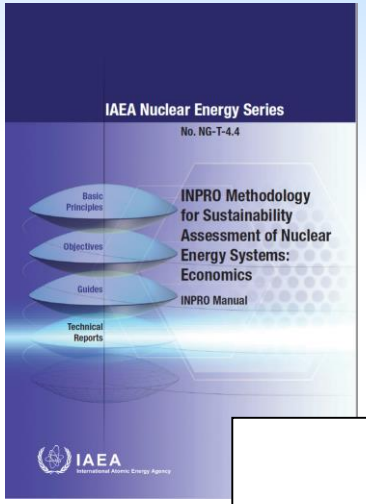
Basic Principle 1 –**Energy and related products and services from nuclear energy systems shall be affordable and available.**

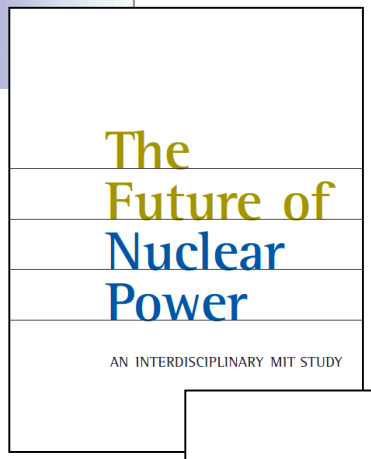
- INPRO manual on Economics covers four issues: Cost competitiveness; Attractiveness and affordability of investments; Risk acceptability; Flexibility of design.

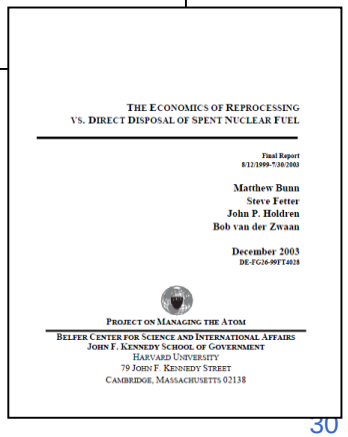
The use of nuclear energy should provide benefits that outweigh the associated costs and risks.

NEST history

- NESA Economics Support Tool (NEST) was developed by INPRO between 2009 and 2012 as an MS Excel application.
- It was designed to perform all calculations necessary to prepare input data for the INPRO assessment in the area of Economics including cost of electricity, internal rate of return, return on investment, net present value and sensitivity studies.
- NEST is a combination of four alternative options based on the IAEA Nuclear Energy Series NG-T-4.4 algorithms and methods published by MIT and Harvard University in 2003. These options can be used for calculations of traditional reactors operating in once-through fuel cycle and partly closed fuel cycle with MOX fuel, innovative reactors operating in closed fuel cycle and alternative power plants (thermal, hydro, wind, etc.).







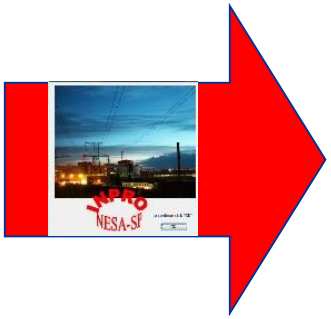
NEST functionality

NEST converts basic technical and economic input parameters into standard functions used in economics (levelized unit energy cost, net present value, internal rate of return etc.).

INPUT

Economic parameters: discount rate, overnight cost, construction schedule, NFC services cost, O&M cost, etc.

Technical parameters: reactor output, capacity factor, lifetime, fuel burnup, etc.



OUTPUT

Energy cost (LUEC), figures of merit (NPV, IRR, ROI)

Levelized Unit Energy Cost (LUEC)

The LUEC represents discounted unit cost have to be charged to recover all discounted costs (amortization, O&M, fuel,) during the assumed operating life time of a plant.

LUEC is equal to:

$$C = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}}$$

CI_t - Capital Investment expenditures at year *t;*
$O\&M_t$ -Operation and Maintenance (O&M) expenditures at year *t;*
F_t = Fuel expenditures at year *t;*
r - discount rate
P_t - Net electrical power of the nuclear system under consideration at year *t*
8760 -Total number of hours in a year
Lf_t = Load factor of plant in year *t*

Financial figures of merit

- Net present value (NPV) – levelized net income (levelized profit produced):

$$NPV(t_0, r) = (PUES - LUEC) \cdot \sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^{t-t_0}}$$

with *PUES* = *constant* reference price per unit of electricity sold to the customer

- Internal rate of return (IRR) – rate of profitability of investment:

$$\begin{cases} r = IRR \\ LUEC(r) - PUES = 0 \end{cases}$$

- Return of investment (ROI) - is the ratio between the net profit and cost of Investment

$$ROI = \frac{PUES - OM - FU}{ONT} \cdot 8760 \cdot Lf$$

ONT is the total overnight cost per unit of installed capacity

Fuel cycle cost components

- LUFC :
  - uranium cost,
  - first load fuel cost ,
  - conversion cost,
  - enrichment cost,
  - fuel fabrication cost,
  - reprocessing cost,
  - HLW/SNF management cost.

$$\frac{\sum_{t=t_{START}}^{t_{END}} \frac{F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUFC$$

Example: the cost of LWR nuclear fuel

FC step	HM	$/kg	US$
Uranium:	7 kg x	50	350
Conversion:	7 kg U x	8	56
Enrichment:	4.8 SWU x	110	530
Fuel fabrication:	1 kg U x	275	275
Total fuel cost per kg HM			1611
SNF management per kg HM		400	400

Harmonization between GIF G4-ECONS and NEST

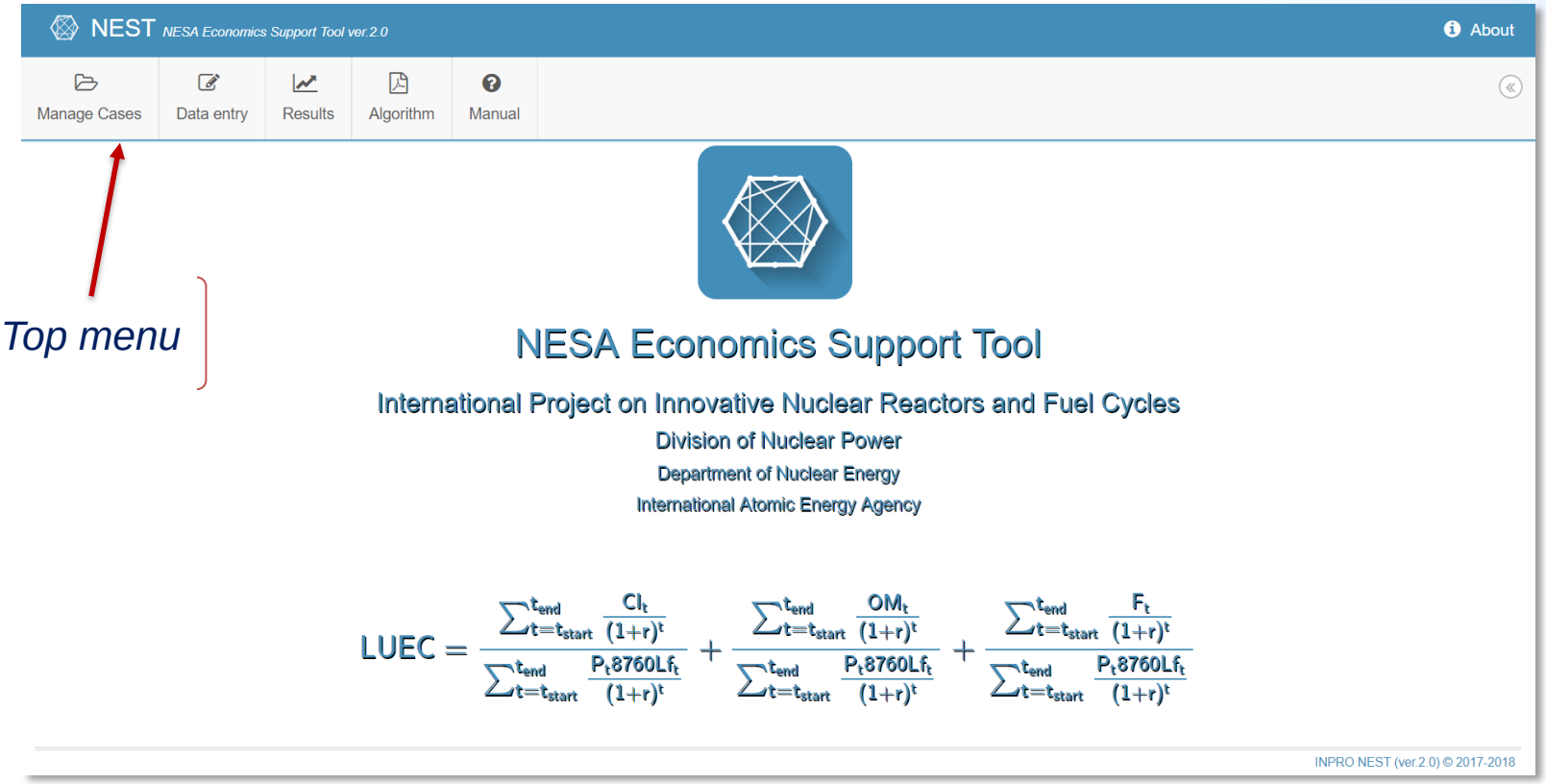
- Collaboration has been established between IAEA INPRO&PESS and the GIF Economic Methodology Working Group (EMWG), which included the performance of benchmarks between the G4-ECONS (the GIF model) and the NEST tools.
- Excellent agreement between the models was found where both codes performed the same types of calculations
- *Moore, M., Korinny, A., Shropshire, D., Sadhankar, R., Benchmarking of Nuclear Economics Tools, Annals of Nuclear Energy, 103, Elsevier, 2017*

NESA ECONOMICS SUPPORT TOOL (NEST) UPDATE

- This activity was started in 2017 with efforts on software and algorithm development.
- The objective is to update the NEST tool and convert it to a modular programming language with a proper graphical user interface (GUI) to facilitate easy use by Member States and maintenance of extensions to the tool..
- The NEST update involves conversion into computer programming language (to make maintenance of the tool more sustainable), updating of algorithms including expansion of options and functions including automated sensitivity analysis and diagram generation, further development of the graphical user interface, etc.

NEST version 3.0

Home page of NEST ver.3.0



Main pages in NEST ver.3.0

Home page displays basic information about software

Manage Cases page provides functionalities for handling cases. There are two parts of this page: Create new NEST case and Demo case containing default set of data

Data entry page is main page for data entry. Page consists of three main entry forms:

a) Main input data entry form

- ***Detailed data entry page***
- ***Grouped data entry page***

b) Capital investment schedule

c) Distribution of backfitting fund

Results page

On this page all output values from calculation will be displayed, together with sensitivity analysis diagram

To see raw data and be able to export results to excel user should click on Results link at the top right corner of Results page

Analysis page

This page provides functionalities to perform advanced sensitivity/uncertainty analysis

Algorithm page downloads basic NEST algorithm

Manual page displays modal window user manual for NEST ver 3.0

NES options included in NEST v.3.0

- Heavy water reactors with once-through fuel cycle (*HWR model**)
- Light water reactors with once-through fuel cycle (*PWR model**)
- Light water reactors using MOX fuel with reprocessing of spent fuel and multi-recycling of plutonium and uranium (*PWRmox model***)
- Break-even fast reactors with a closed fuel cycle (FR model**)
- Fast breeders with a given breeding ratio in a closed fuel cycle (*FBR model***)
- Equilibrium NES with thermal and fast reactors (*NES model****)
- Fossil Power Plant (*FPP model**)

** models for LUFC evaluations based* IAEA Nuclear Energy Series NG T-4.4 algorithms and methods
*** models for LUFC evaluations based on* algorithms and methods published by MIT and Harvard University in 2003.

**** new models for LUFC evaluations based on* algorithms and methods described in NEST tool

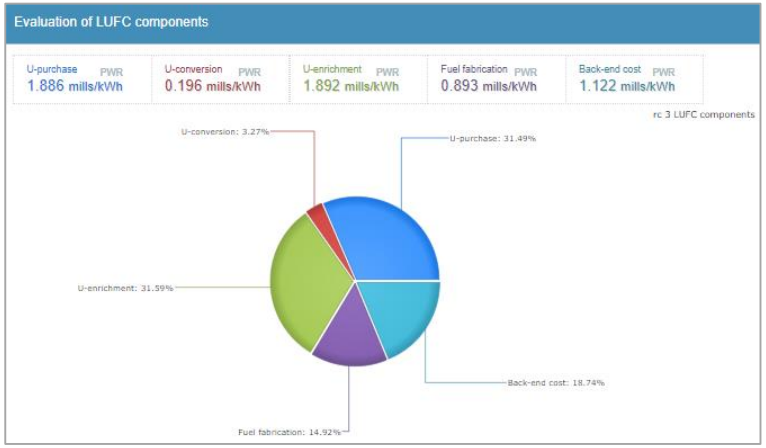
The important feature of NEST v.3.0 is that due to the reconsidered and optimized architecture of this software, new reactor types can be easily incorporated in the tool with minimum efforts.

Areas of the NEST application

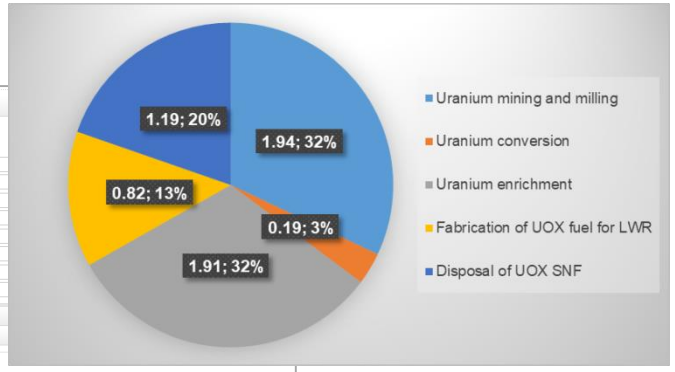
- Performing simple evaluations of LUEC and its components for the reactor types and FPP according to the LUEC calculation models implemented in NEST and technical/economic data specified by users.
- Carrying out a sensitivity/uncertainty analysis for LUEC or its components in regard to technical and economic data including a parameter sensitivity analysis, a tornado diagram, and a multiparametric uncertainty analysis.
- Comparing alternative NES options in view of economic performance (steady-state system or plant level assessment)..
- Selecting the most effective (optimal) technical parameters to minimize LUEC or its components based on the direct search methods for the optimization problem solution.
- Evaluating methodological uncertainties associated with the LUEC evaluation (due to assumptions made for LUEC calculations, especially for LUFC) and comparing these uncertainties with uncertainties due to the cost data and technical parameters.

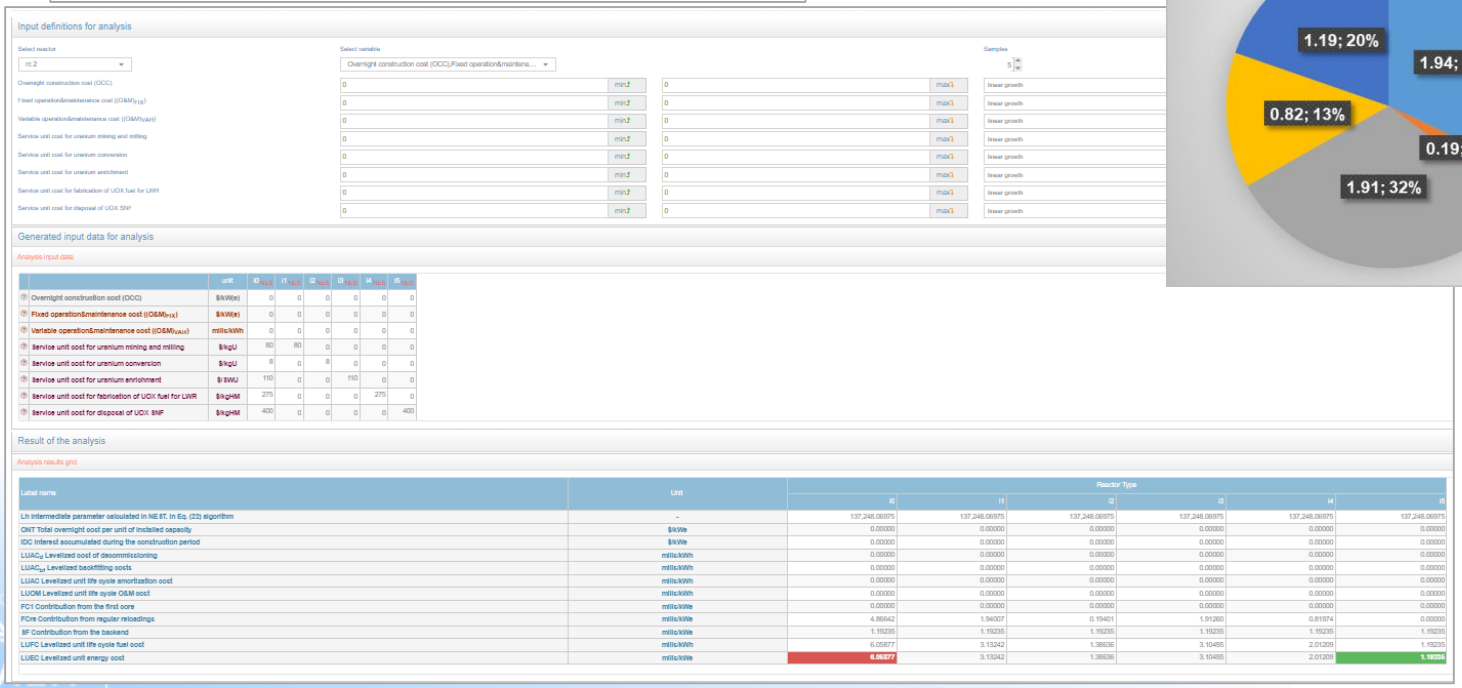
Evaluation of LUFC components - contribution of NFC costs to LUFC (v.3.0)

For PWR and HWR this option is automatized



For other reactor types such evaluation can be performed 'manually' (example - NES)





Input definitions for analysis

Overnight construction cost (OCC)	0	min	0	max	linear growth
Fixed operation&maintenance cost ((O&M)$_{FIX}$)	0	min	0	max	linear growth
Variable operation&maintenance cost ((O&M)$_{VAR}$)	0	min	0	max	linear growth
Service unit cost for uranium mining and milling	0	min	0	max	linear growth
Service unit cost for uranium conversion	0	min	0	max	linear growth
Service unit cost for uranium enrichment	0	min	0	max	linear growth
Service unit cost for fabrication of UOX fuel for LWR	0	min	0	max	linear growth
Service unit cost for disposal of UOX SNF	0	min	0	max	linear growth

Generated input data for analysis

Analysis input data

	unit	i0 Nuclo	i1 Nuclo	i2 Nuclo	i3 Nuclo	i4 Nuclo	i5 Nuclo
Overnight construction cost (OCC)	$/kWe	0	0	0	0	0	0
Fixed operation&maintenance cost ((O&M)$_{FIX}$)	$/kWe	0	0	0	0	0	0
Variable operation&maintenance cost ((O&M)$_{VAR}$)	mills/kWh	0	0	0	0	0	0
Service unit cost for uranium mining and milling	$/kgU	80	80	0	0	0	0
Service unit cost for uranium conversion	$/kgU	8	0	8	0	0	0
Service unit cost for uranium enrichment	$/SWU	110	0	0	110	0	0
Service unit cost for fabrication of UOX fuel for LWR	$/kgHM	275	0	0	0	275	0
Service unit cost for disposal of UOX SNF	$/kgHM	400	0	0	0	0	400

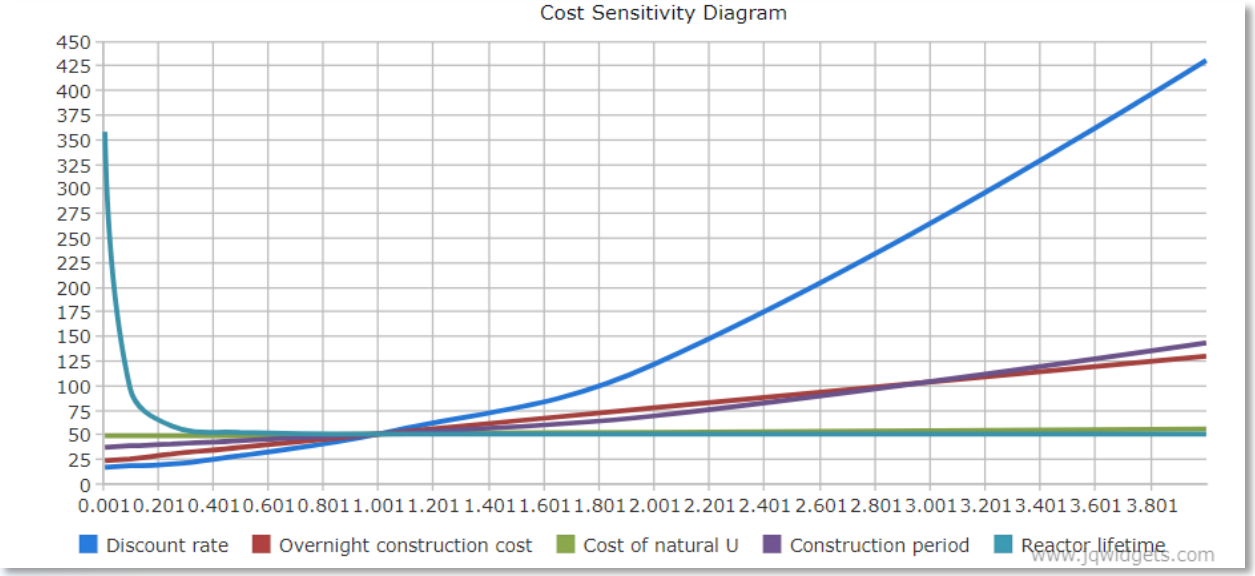
Result of the analysis

Analysis results grid

Label name	Unit	Reactor Type i0	i1	i2	i3	i4	i5
Lh Intermediate parameter calculated in NE 87. In Eq. (22) algorithm	-	137,248.06975	137,248.06975	137,248.06975	137,248.06975	137,248.06975	137,248.06975
ONT Total overnight cost per unit of installed capacity	$/kWe	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
IDC Interest accumulated during the construction period	$/kWe	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LUAC$_d$ Levelized cost of decommissioning	mills/kWh	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LUAC$_{bf}$ Levelized backfilling costs	mills/kWh	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LUAC Levelized unit life cycle amortization cost	mills/kWh	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
LUOM Levelized unit life cycle O&M cost	mills/kWh	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
FC1 Contribution from the first core	mills/kWe	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
FCre Contribution from regular reloadings	mills/kWe	4.86642	1.94007	0.19401	1.91260	0.81974	0.00000
BF Contribution from the backend	mills/kWe	1.19235	1.19235	1.19235	1.19235	1.19235	1.19235
LUFC Levelized unit life cycle fuel cost	mills/kWh	6.05877	3.13242	1.38836	3.10495	2.01209	1.19235
LUEC Levelized unit energy cost	mills/kWe	6.05877	3.13242	1.38836	3.10495	2.01209	1.19235

Cost sensitivity diagram – parameter sensitivity analysis

- A parameter sensitivity analysis determines the results sensitivity to changes in the value of a single model parameter.
- By default, NEST Version 3.0 implements a parametric sensitivity analysis for LUEC.



Parameter sensitivity analysis for LUEC in regard to the discount rate (PWR) (manual inputs, v.3.0)

IAEA

Input definitions for analysis

Select reactor: rc 3

Select variable: Real discount rate (r)

Samples: 19

Real discount rate (r): 0.01 (min) – 0.20 (max) – linear growth

Generated input data for analysis

Analysis input data

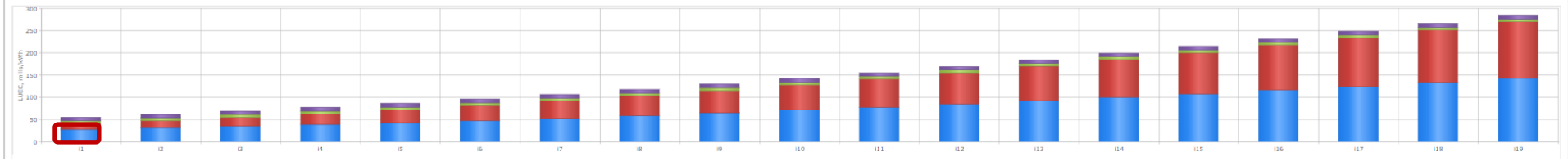
	unit	i0 PWR	i1 PWR	i2 PWR	i3 PWR	i4 PWR	i5 PWR	i6 PWR	i7 PWR	i8 PWR	i9 PWR	i10 PWR	i11 PWR	i12 PWR	i13 PWR	i14 PWR	i15 PWR	i16 PWR	i17 PWR	i18 PWR	i19 PWR
Real discount rate (r)	1/year	0.040	0.010	0.021	0.031	0.042	0.052	0.063	0.073	0.084	0.094	0.105	0.116	0.126	0.137	0.147	0.158	0.168	0.179	0.189	0.200

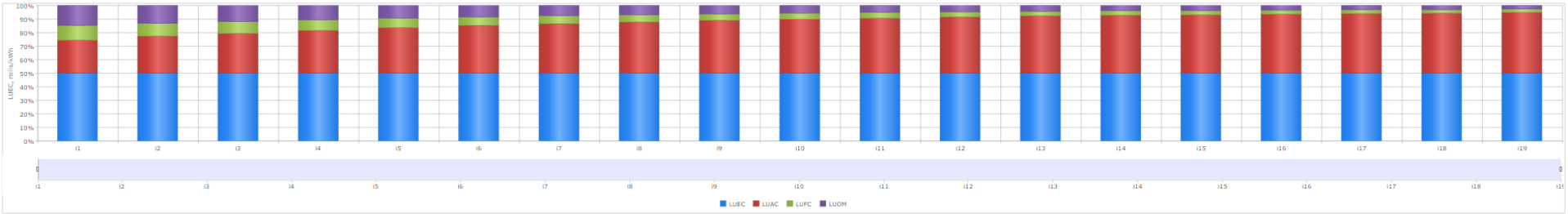
Result of the analysis

Analysis results grid

Label name	Unit	Reactor Type																			
		i0	i1	i2	i3	i4	i5	i6	i7	i8	i9	i10	i11	i12	i13	i14	i15	i16	i17	i18	i19
Lh intermediate parameter calculated in NEST. In Eq. (22) algorithm	-	137,248.07	225,398.54	186,747.09	157,080.13	133,963.85	115,764.81	101,243.88	89,515.21	79,929.27	72,005.19	65,383.68	59,793.75	55,029.08	50,931.12	47,376.93	44,270.29	41,535.23	39,111.25	36,949.75	35,011.39
ONT Total overnight cost per unit of installed capacity	$/kWe	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00
IDC Interest accumulated during the construction period	$/kWe	249.79	60.60	125.89	192.56	260.64	330.13	401.06	473.47	547.36	622.76	699.70	778.19	858.26	939.93	1,023.23	1,108.18	1,194.81	1,283.13	1,373.17	1,464.96
$LUAC_d$ Levelized cost of decommissioning	mills/kWh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$LUAC_{bf}$ Levelized backfitting costs	mills/kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LUAC Levelized unit life cycle amortization cost	mills/kWh	23.68	13.58	16.74	20.33	24.34	28.77	33.59	38.80	44.38	50.31	56.58	63.19	70.11	77.36	84.92	92.80	100.99	109.51	118.35	127.53
LUOM Levelized unit life cycle O&M cost	mills/kWh	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13	8.13
FC1 Contribution from the first core	mills/kWe	0.53	0.34	0.40	0.47	0.54	0.62	0.70	0.78	0.86	0.94	1.03	1.11	1.19	1.27	1.34	1.42	1.50	1.57	1.64	1.71
FCre Contribution from regular reloadings	mills/kWe	4.34	4.52	4.45	4.39	4.33	4.27	4.21	4.15	4.10	4.04	3.99	3.94	3.89	3.84	3.79	3.74	3.70	3.65	3.61	3.56
SF Contribution from the backend	mills/kWe	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
LUFC Levelized unit life cycle fuel cost	mills/kWh	5.99	5.98	5.97	5.98	5.99	6.01	6.03	6.05	6.08	6.11	6.14	6.17	6.20	6.23	6.26	6.29	6.31	6.34	6.37	6.40
LUEC Levelized unit energy cost	mills/kWe	37.80	27.69	30.85	34.44	38.47	42.91	47.76	52.99	58.59	64.55	70.85	77.49	84.44	91.72	99.31	107.22	115.44	123.99	132.86	142.06

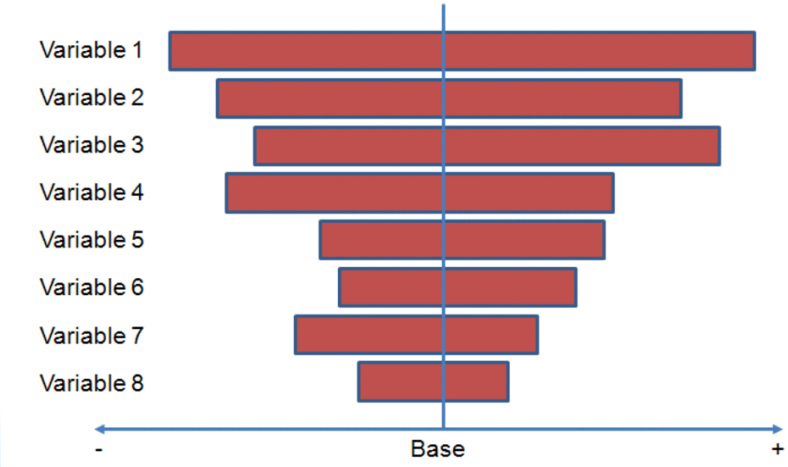
Analysis results chart





Tornado graphs

- Tornado graphs are used in deterministic sensitivity analyses to compare the relative importance of variables.
- For each variable/uncertainty considered, it is required to estimate the low, base, and high outcomes.
- Sensitive variables are modeled as uncertain values while all other variables are held at baseline (stable) values.
- This makes it possible to test the sensitivity associated with one uncertain variable.



Tornado graph for PWR LUEC (v.3.0)

Preparation of initial data for the tornado graph

Input definitions for analysis

Select reactor	Select variable					Samples
rc 1	Overnight construction cost (OCC),Fixed operation&maintena...					16
Overnight construction cost (OCC)	3000	min	5000	max	linear growth	
Fixed operation&maintenance cost ($(O\&M)_{FIX}$)	40	min	60	max	linear growth	
Variable operation&maintenance cost ($(O\&M)_{VAR}$)	0.5	min	1.5	max	linear growth	
Natural U purchase cost (SC_1)	50	min	150	max	linear growth	
U conversion cost (SC_2)	5	min	15	max	linear growth	
U enrichment cost (SC_3)	80	min	150	max	linear growth	
Nuclear fuel fabrication cost (SC_4)	200	min	350	max	linear growth	
Nuclear fuel backend cost ($(\$/kg\ HM)_{SF}$)	300	min	500	max	linear growth	

Incorporation of data for the tornado graph

Generated input data for analysis

Analysis input data

Input has been changed.

	unit	i0 PWR	i1 PWR	i2 PWR	i3 PWR	i4 PWR	i5 PWR	i6 PWR	i7 PWR	i8 PWR	i9 PWR	i10 PWR	i11 PWR	i12 PWR	i13 PWR	i14 PWR	i15 PWR	i16 PWR
Overnight construction cost (OCC)	$/kW(e)	4,000.000	3,000.000	5,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000	4,000.000
Fixed operation&maintenance cost ($(O\&M)_{FIX}$)	$/kW(e)	49.000	49.000	49.000	40.000	60.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000	49.000
Variable operation&maintenance cost ($(O\&M)_{VAR}$)	mills/kWh	0.900	0.900	0.900	0.900	0.900	0.500	1.500	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900
Nuclear fuel backend cost ($(\$/kg\ HM)_{SF}$)	$/kg	400.000	400.000	400.000	400.000	400.000	400.000	400.000	300.000	500.000	400.000	400.000	400.000	400.000	400.000	400.000	400.000	400.000
Natural U purchase cost (SC_1)	$/kg-Unat	80.000	80.000	80.000	80.000	80.000	80.000	80.000	80.000	80.000	50.000	150.000	80.000	80.000	80.000	80.000	80.000	80.000
U conversion cost (SC_2)	$/kgHM	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	5.000	15.000	8.000	8.000	8.000	8.000
U enrichment cost (SC_3)	$/SWU	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	110.000	80.000	150.000	110.000	110.000
Nuclear fuel fabrication cost (SC_4)	$/kgHM	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	275.000	200.000	300.000

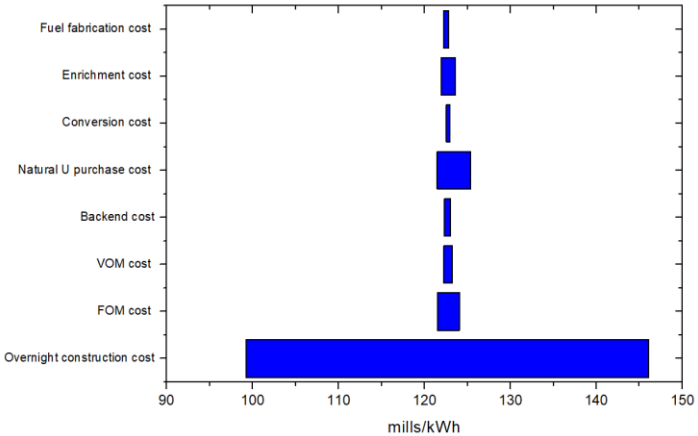
Resulting table

Resulting graph

Result of the analysis

Analysis results grid

Label name	Unit	i0	i1	i2	i3	i4	i5	i6	i7
Lh intermediate parameter calculated in NEST. In Eq. (22) algo...	-	65,699.91	65,699.91	65,699.91	65,699.91	65,699.91	65,699.91	65,699.91	65,699.91
ONT Total overnight cost per unit of installed capacity	$/kWe	4,362.00	3,362.00	5,362.00	4,362.00	4,362.00	4,362.00	4,362.00	4,362.00
IDC Interest accumulated during the construction period	$/kWe	2,347.87	1,809.62	2,886.13	2,347.87	2,347.87	2,347.87	2,347.87	2,347.87
$LUAC_d$ Levelized cost of decommissioning	mills/kWh	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
$LUAC_{bf}$ Levelized backfitting costs	mills/kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LUAC Levelized unit life cycle amortization cost	mills/kWh	106.70	83.28	130.11	106.70	106.70	106.70	106.70	106.70
LUOM Levelized unit life cycle O&M cost	mills/kWh	7.12	7.12	7.12	5.97	8.51	6.72	7.72	7.12
FC1 Contribution from the first core	mills/kWe	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
FCre Contribution from regular reloadings	mills/kWe	5.53	5.53	5.53	5.53	5.53	5.53	5.53	5.53
SF Contribution from the backend	mills/kWe	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.01
LUFC Levelized unit life cycle fuel cost	mills/kWh	8.84	8.84	8.84	8.84	8.84	8.84	8.84	8.51
LUEC Levelized unit energy cost	mills/kWe	122.66	99.24	146.07	121.51	124.05	122.26	123.26	122.32

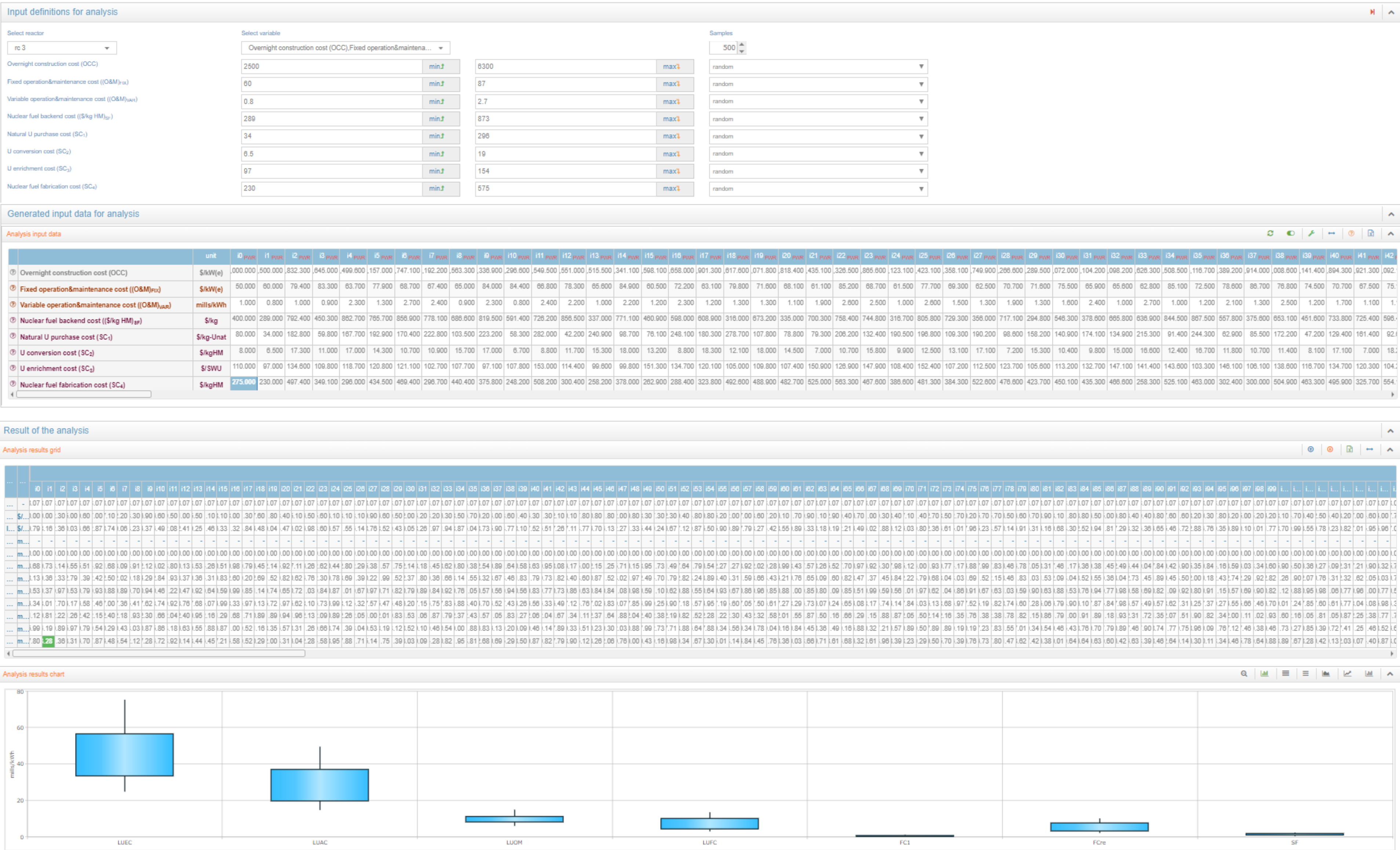


Monte-Carlo based multi-parametric uncertainty analysis

- One of the most popular approaches to analyze uncertainties is the use of statistical methods, which involve setting uncertainties as random variables with the known distribution law (Monte Carlo methods).
- It is necessary to define a set of input parameters that affect the resulting functional uncertainty, form sets of initial input data by randomly selecting input parameters, calculate the functionals of interest, statistically process the calculation results, and estimate statistical characteristics of the distributed resulting functionals.
- It is reasonable to reflect the LUEC and its components spreads by means of box-and-whisker plots, which are most commonly used in statistical analysis, demonstrate the distribution of data into quartiles, highlighting the mean and outliers. The boxes may have lines extending vertically called “whiskers”. These lines specify variability outside the upper and lower quartiles, and any point outside these lines or whiskers is considered an outlier.

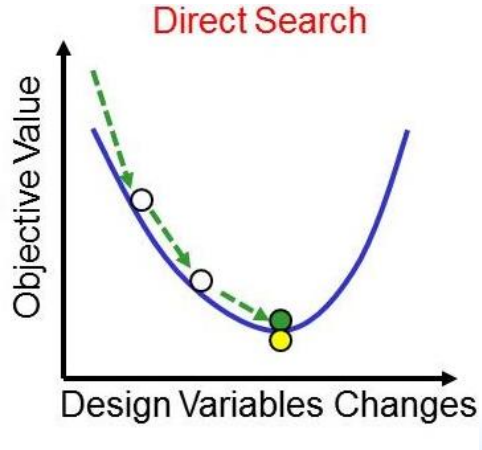
Spreads in LUAC, LUOM, LUFC and LUEC for PWR (v.3.0)

IAEA



Selecting technical parameters minimizing LUEC or its components

- Selection of the most effective (optimal) technical parameters to minimize LUEC can be performed using NEST as follows.
- First, experts should select a specific technical parameter and define a set of values for this parameter for which LUEC calculations will be performed by NEST (for example, uranium enrichment tails assays).
- Second, after performing the calculations, experts should analyze the results and select a parameter value providing a minimum value of LUEC (it is a sort of a simple direct search method; if experts want to obtain a more precise solution, they should consider more sample values for the parameter to be optimized).



IAEA
International Atomic Energy Agency

Thank you!

IAEA
International Atomic Energy Agency

Back up viewgraphs

Collaborative enhancements

- 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 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:
  - *bilateral agreement - this is an umbrella trade and co-operation agreement signed as a treaty between two trading partners describing the legal structure and obligations of the two parties – these could be quite complex and include also third parties to the agreement;*
  - *multiple bilateral agreements – several bilateral agreements depending on the needs of national industry for imports and exports of materials, equipment, services and intellectual property – multiplicity is commonly viewed as a tool to emulate certain competitive market conditions in nuclear trade;*
  - *multilateral agreements - a more rare agreement for co-operation on peaceful nuclear energy that is an umbrella trade and co-operation agreement, signed as a treaty between a larger set of trading partners (could be a region), that creates a broader common understanding of nuclear trade and co-operation within the block of partner countries (e.g. EURATOM) – these are much more complex to achieve also in terms of the time required.*
- 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
- Projecting long-term perspectives of national nuclear power programme could facilitate timely planning and implementation of the provisions necessary for competitive nuclear trade

Collaboration among countries towards enhanced nuclear energy sustainability

How a solid basis for cooperation could be established?

- **Bringing together decision-makers and senior technical experts** from MS institutions, non-governmental organizations (NGO), nuclear industry, utilities, academia and R&D institutions involved in nuclear energy programs planning or implementation, long term strategic planning and international cooperation to exchange their perspectives on all the cooperation aspects and issues;
- **Understanding** the nuclear technology developer countries and user countries **standpoints** regarding the driving forces and the impediments for such cooperation;
- **Identifying viable collaboration options**, based on “win-win“ approach, to reach the national NESs sustainability in regional and global context;

Motivation factors/drivers for collaboration

- ***Energy policy considerations:*** national policy should consider both energy security and the potential to become a regional provider of energy, once the national needs are fulfilled.
- ***Economics and market developments :*** Benefits related to costs and useful applications of nuclear technology have to be taken into account. Large energy markets would lead to increasing the potential of countries for benefits and reduction of financial burdens due to collaborative and sharing efforts.
- ***Sharing of facilities and resources :*** The following should be considered: R&D collaborations, sharing expertise on licensing, regulations, environmental assessment, exchange of specialized human resources, infrastructure sharing, training etc. A strongly motivation could be given by sharing of common goals, similar challenges, common interests, mutual long-time benefits, scientific interest.
- ***Security of supply and waste management considerations :*** Both assurance of nuclear fuel supply (in direct connection to assurance of NPPs operation) and used fuel management (including the longer term interim used fuel storage and also the reprocessing and recycling of the SNF) need to be considered. To guarantee the security of supply, the averaged preferences of technology holder, technology user and newcomer countries indicate as reasonable a number of 3 suppliers.

Impediments to collaboration

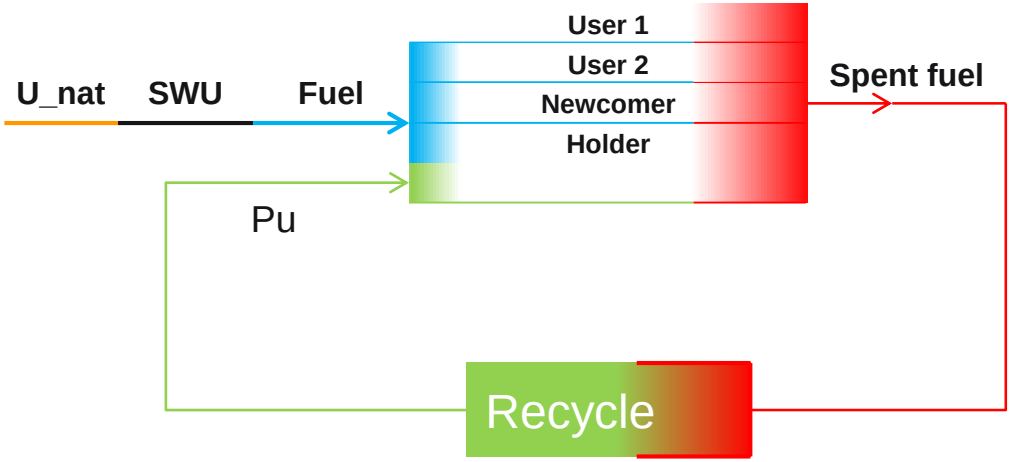
- ***National regulations*** *still have essentially a national focus and sometimes prohibit synergistic collaborations with other countries*; *National laws often prohibit accepting third parties' ultimate waste for storage and final disposal*;
- ***High investment costs and long term commitment:*** *the long term nature of nuclear energy projects and high capital investment is an impediment for cooperation among countries as it requires the long term commitment in a changing socio-political and economic environment.*
- ***Political environment:*** *nuclear technologies can be considered as competitive advantage in the region and could impede establishing of cooperation among countries, mainly based on the tendency of dominance as regional provider of energy. At the same time, unavailability of similar technologies can impede cooperation among countries as the integration with regional infrastructure might be costly for some countries.*
- ***Public concerns*** *Radiation' is the common factor for the concerns associated with nuclear energy. Decreasing of the public acceptance for nuclear energy development especially after Fukushima accident (neighbouring countries apprehension) could be taken into account as an impediment in the cooperation among countries. Other concerns are proliferation risk related to non-civil use of nuclear materials, and ultimate waste management challenges spanning centuries. The public concerns are transposed in the level of public acceptance and more often have influenced the political considerations/political willingness of Governments towards nuclear energy development. The public concerns diminishing will consequently lead to positive reactions and a better public acceptance for nuclear energy .*

Steady regional collaboration

Some case studies in SYNERGIES addressed the issues related to sustainability enhancement of several national NESs within steady regional collaboration

- The study on 'EU27 scenarios' with the extended use of regional fuel cycle centre consisting of the La Hague and MELOX facilities demonstrated proven options for synergistic collaboration between 9 European Union countries, such as commercial LWR spent fuel reprocessing and MOX-fuel supply for a single recycle in LWRs. The study presents the main drivers for such services such as preservation of natural resources through a 10% to 15% reduction in natural uranium consumption, minimization of generated waste and deep geological disposal requirements and some others

- The study of experts from Armenia, Belarus, Russian Federation and Ukraine also analyzed the issues of regional collaboration

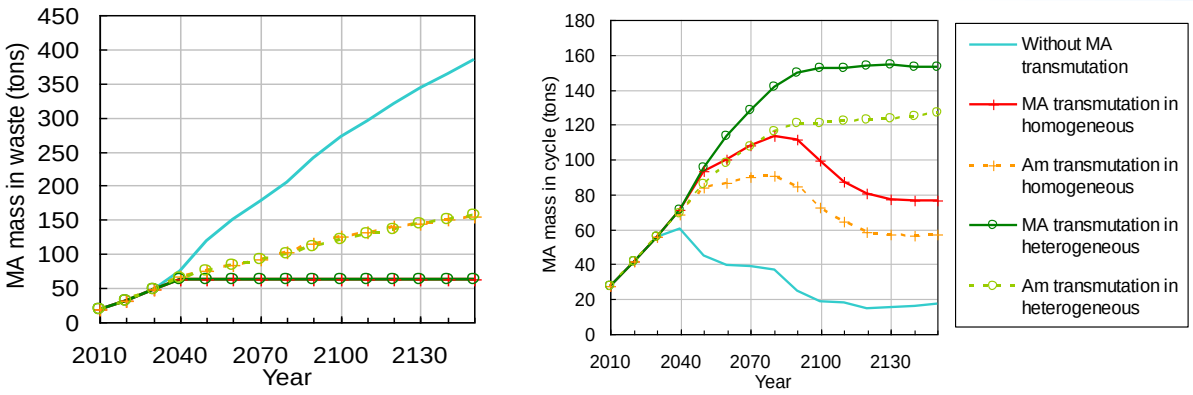


Scheme of the regional collaboration for SNF utilization

Radioactive waste transmutation

- The objective of the French study on radioactive waste transmutation options was to obtain an assessment of industrial perspectives on partitioning and transmutation of long lived radioactive elements

- It was shown that the transmutation of MA significantly reduces their inventory in the geological repository; however, the MA inventory in the reactors and plants increases



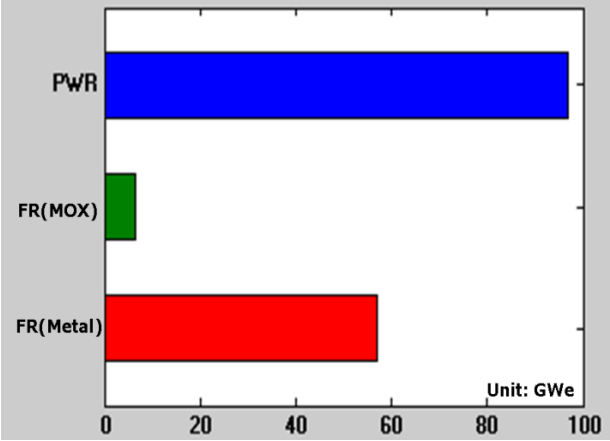
Reduction of MA in the waste and increases inventory of MA in the fuel cycle under transmutation of MA

- Only the transmutation of all MA enables stabilization of their inventory over time

- The economic studies conducted show that the cost increase related to the transmutation process could vary between 5 to 9% in SFR and 26 % in the case of ADS

Plutonium multi-recycling

- Four scenarios of plutonium multi-recycling in China examined the potential of indigenously developed SFRs to meet high national nuclear energy demand targets in the short and medium term
  - It was shown that meeting the challenging national targets requires conducting intensive RD&D and implementing the metal fuelled SFR with a breeding ratio of above 1.4, as well as advanced reprocessing technologies
- Long term scenario study for NFC in Japan investigated possible role of SFRs and closed NFC in three national scenarios representing a reduction of the role of nuclear energy in the national energy mix, as a follow-up of the energy policy change after the Fukushima Daiichi nuclear power station accident in 2011
  - It was concluded that advantages of reprocessing strategy compared to direct disposal strategy and partial reprocessing strategy are observed in all considered scenarios



China: Nuclear power scale for each type of NPP in 2050 (scenario IV)

National R&D programmes and international cooperation

- The case studies from Argentina, Indonesia, Romania, and Ukraine addressed a model of nuclear power development and deployment in which execution of domestic nuclear R&D programmes is combined with participation in international R&D programmes and use of the opportunities provided by external markets
- These countries use and intend to use in the future nuclear power plants of foreign designs. Along with the commonalities, case studies of these countries have demonstrated some specific features of the collaboration model implementation

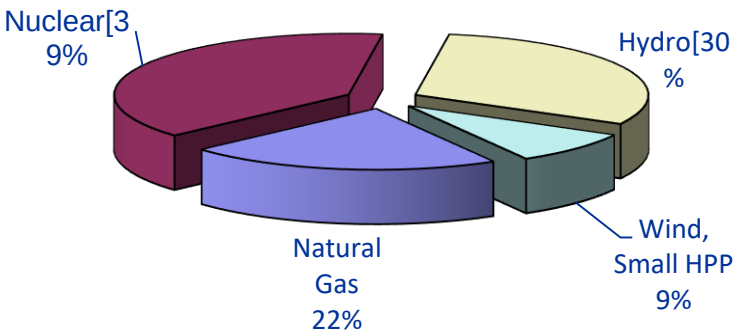
Cernavoda NPP in Romania: unit 1 & 2 (~700 MW) PHWR CANDU6 type

- For example, Argentina develops capabilities as a nuclear technology holder. The plans are to become a supplier of small reactors of the Argentine design

Minimization of R&D and nuclear fuel cycle infrastructure

Case study from Armenia presented an approach to minimize R&D and investments in NFC infrastructure deployment by means of cooperation with regional or interregional nuclear technology holders

- The Armenian NPP with the WWER reactor units (PWR type) has demonstrated successful operation and generation of competitive electricity with a minimal once-through NFC infrastructure
- Different scenarios for further development of national nuclear power taking into account cooperative opportunities are presented and analyzed
- Two of the issues addressed in the study are aimed at a long-term prospect:
  - evaluation of different options for management of spent nuclear fuel in order to solve the problem of its progressive accumulation, and
  - expediency of introduction of small reactors into national NES.



Share of nuclear power in electricity production in Armenia

Conclusion

- The LUEC model is commonly used for general economic comparison of different types of power plants.
- The INPRO assessment in the area of economics is supported by the Nuclear Economics Support Tool (NEST).
- NEST is a powerful software tool than can be applied by both experienced and non-experienced experts interested in the nuclear power economic assessments.
- NEST comprises several models and options to calculate parameters necessary for the INPRO economic assessment.
- NEST converts basic technical and economic input parameters into standard functions used in economics (levelized unit energy cost, net present value, internal rate of return, etc.).
- NEST provides a preliminarily assessment of economic performance of different reactor technologies in the absence of infrastructural and resource factors taken in account.