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Scenario Analysis and Decision Support for Development of Nuclear Energy Systems with Enhanced Sustainability:

Modelling and comparison of Nuclear Energy Systems (NES)

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

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International Project on Innovative Nuclear Reactors and Fuel Cycles

Content

- Introduction in International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)
- Scenario Analysis and Decision Support Tools for Enhancing Nuclear Energy Sustainability
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Introduction:

- The IAEA implements elaborate programmes for supporting its Member States for conducting national energy studies to identify the potential role for various energy technologies, including nuclear power, in meeting their future energy needs. One of such programmes is offered under the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).
- INPRO was established in 2000 with the objective to help ensure that nuclear energy remains available to contribute to meeting global energy needs during the 21st century and beyond. It 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 in close cooperation with the IAEA's Member States (42 member countries and international organizations).
- Using scientific-technical analysis tools, INPRO develops global and regional nuclear energy scenarios to investigate how collaborations among different States and organizations can facilitate the transition to globally sustainable nuclear energy systems. INPRO supports collaborative projects including studies on waste potentially generated by innovative reactors and fuel cycles; and how increased Member State cooperation in the back-end of the nuclear fuel cycle could produce broader benefits for nuclear energy sustainability in the future.

IAEA/INPRO Area “Global Scenarios”

In the area of “Global scenarios” INPRO has been conducting scenario modelling for evolution nuclear energy systems to understand major issues for sustainability of NES. Several collaborative projects have been implemented with active participation of Member States.

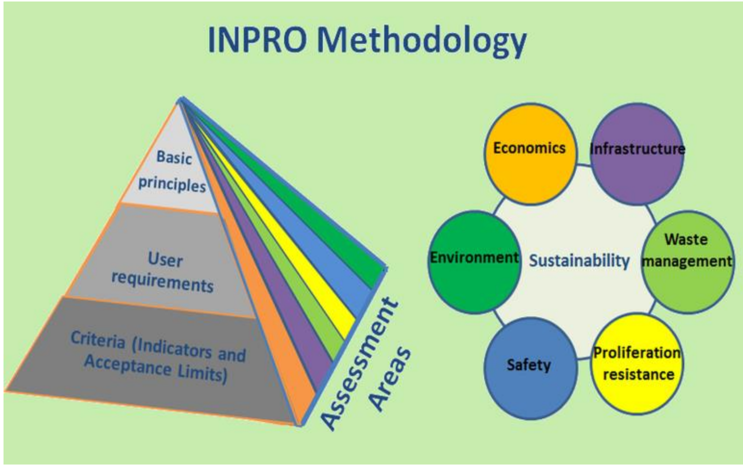
- Global Architecture of Innovative Nuclear Energy Systems **(GAINS)** developed framework to model NESs including trade relationships and applied it at global level
- Synergetic Nuclear Energy Regional Group Interactions Evaluated for Sustainability **(SYNERGIES)** amended and applied this framework to national/regional case studies
- Key Indicators for Innovative Nuclear Energy System Development **(KIND)** developed an approach for comparative evaluation of nuclear energy system options based on multi-criteria decision analysis
- Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems”**(ROADMAPS)** has developed a structured approach for mapping the course toward globally sustainable NESs to be achieved through technology innovations and international cooperation. Specific standardized template was developed and implemented in a software tool. ROADMAPS integrated the outputs of SYNERGIES, GAINS and several other studies on global nuclear energy scenarios

In all of the above-mentioned activities valuable experience has been accumulated and software tools have been developed and validated to support modelling, analysis and evaluation. Sharing this experience with INPRO members and providing them with training on application of the relevant software tools will be organized into a new INPRO service to Member States.

INPRO Methodology for NES sustainability Assessment

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

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



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

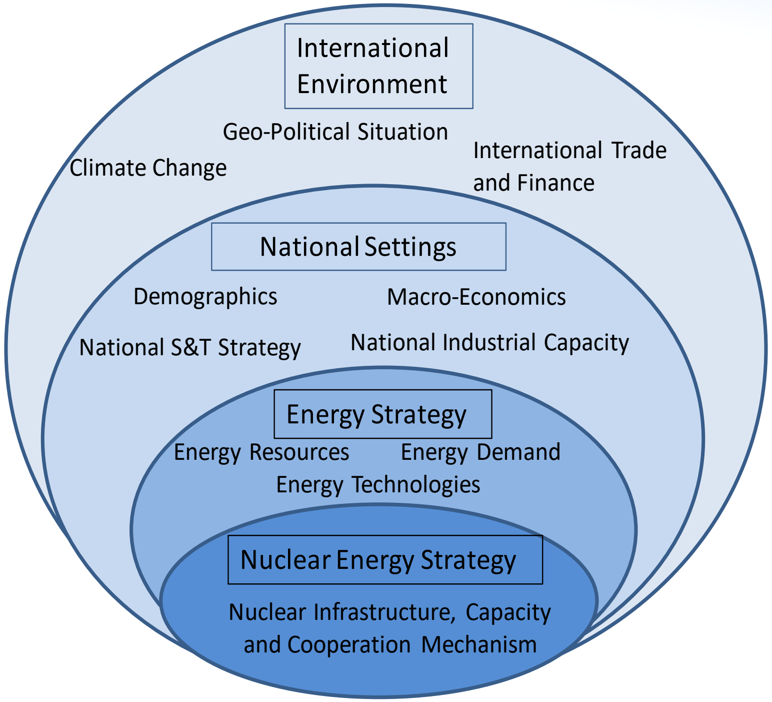
Criteria:
Assessor's tool to check whether a User Requirement is being met by a considered NES

- Consistent with the UN concept of sustainable development,
- The sustainability of a NES is understood as a capability of the system to comply with the requirements developed by the representatives of the IAEA Member States
- 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
- NES that meets all of the criteria is deemed to be sustainable
- 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

Developing Scenarios

For evaluating alternative strategies for development of nuclear energy, the use of scenario analysis can be very valuable. It can provide a systematic framework for combining a large number of factors that may drive the future development.

- Since every system interacts with its surroundings, scenarios should be developed by taking into account the evolution of surroundings systems
- Nuclear energy system is a part of the overall energy system of a country. The potential role of nuclear energy has to be evaluated by considering all the options for delivering required energy services to the society and economy in a safe, clean and affordable manner
- National decision on nuclear energy should, therefore, be evaluated in the context of a bigger picture for the development of a country which is firmly tied with the international environment



Linkage of Nuclear energy system with its surroundings

Scenario Analysis for Enhancing Nuclear Energy Sustainability

– FRAMEWORK FOR NES SCENARIO MODELLING
  - GAINS
  - SYNERGIES

– APPROACH FOR COMPARATIVE EVALUATION OF NES/SCENARIOS
  - KIND

Framework for Nuclear Energy Evolution Scenarios Evaluation Regarding Sustainability

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- **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 may 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?**
- **First application of the Key Indicator approach allowing to compare NES evolution scenarios**

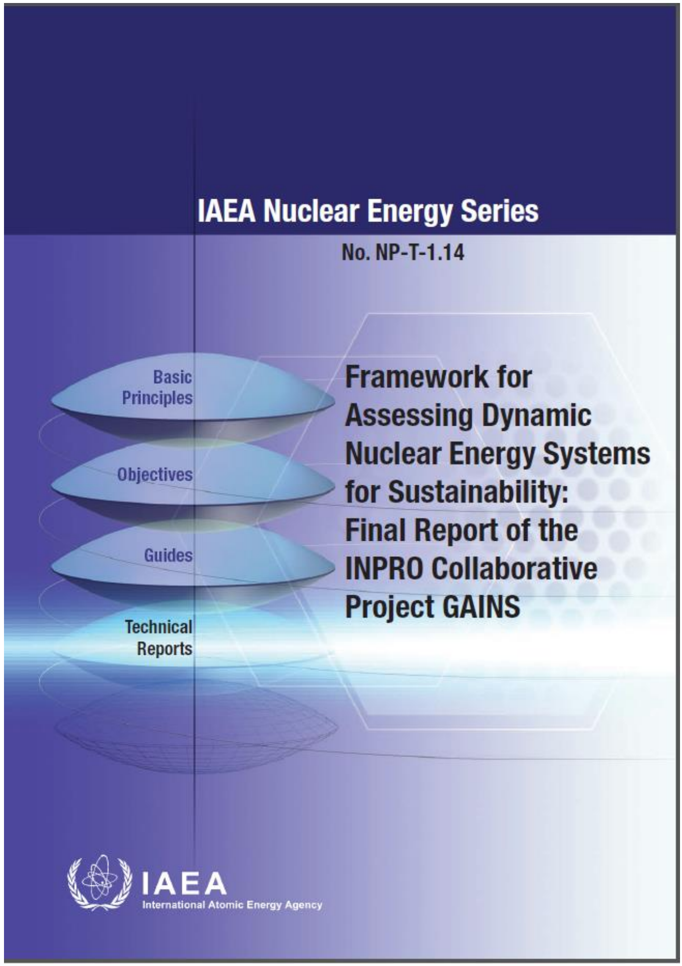
- **The INPRO collaborative project "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES)** has applied the framework to national NES evolution scenarios with regional cooperation
- SYNERGIES has developed a concept of "Options for enhanced nuclear energy sustainability"
- 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

Framework for NES Scenario Modelling and Evaluation

- The INPRO collaborative project “Global Architecture of Innovative Nuclear Energy Systems” (GAINS) was launched in response to a strong interest expressed by several Member States in developing and understanding future trends of nuclear energy development at the global level and the potential role of technical innovations and multilateral cooperation for deployment of a sustainable nuclear energy system
- GAINS developed a framework for modelling and analysis of transition scenarios to future sustainable nuclear energy systems and applied it in sample analyses
- The GAINS framework is based on the participants’ experiences in implementing similar studies at national and international levels. The framework can be used for developing national nuclear energy strategies, exploring opportunities for cooperation and partnerships on the nuclear fuel cycle, and highlighting how global trends may affect national developments (and vice versa). Individual countries can make use of this framework to evaluate particular approaches in a global or regional context based on national and regional data.

GAINS framework elements

- Nuclear demand assessed for global NES
- Homogeneous and Heterogeneous World Model
- Architectures of NES
- Fuel cycle schemes
- Metrics (indicators) for scenario analysis
- Reactor/Fuel Data Template
  - Reactor characteristics
  - Isotopic Charge/Discharge
- Assumptions
- Tools for NES modelling
- Framework applications



Nuclear demand assessed for global NES Homogeneous and Heterogeneous World Model

- 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

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

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

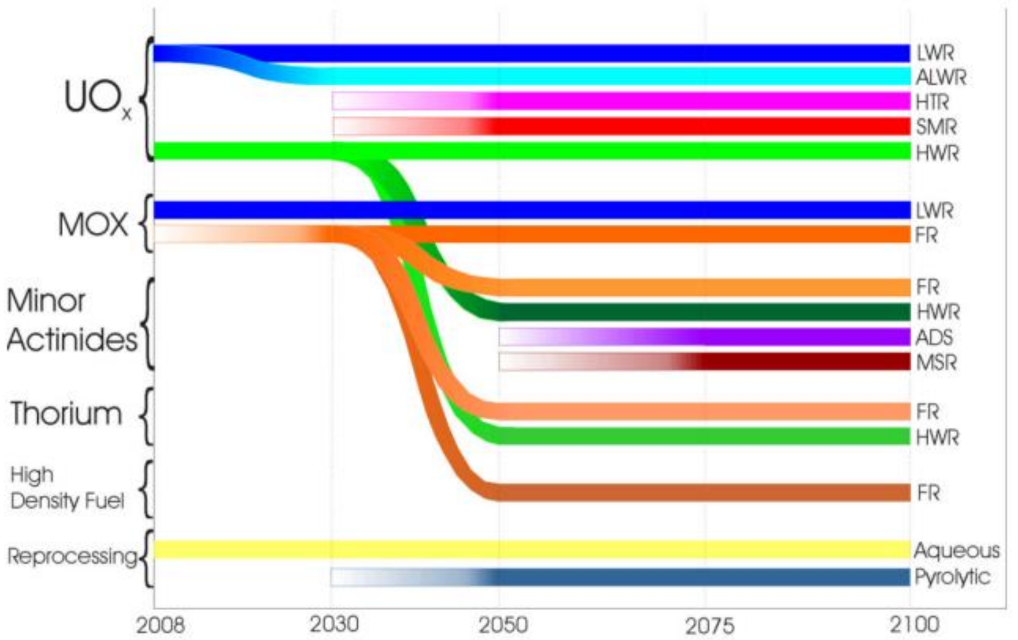
- 40% in NG1 (*General strategy is to recycle used fuel*);
- 40% in NG2 (*General strategy is to either directly dispose of used fuel, or reprocess used fuel abroad);*
- 20% in NG3 (*General strategy is to use fresh fuel, and send used fuel abroad for either recycle or disposal, or the back-end strategy is undecided).*

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

NES architectures

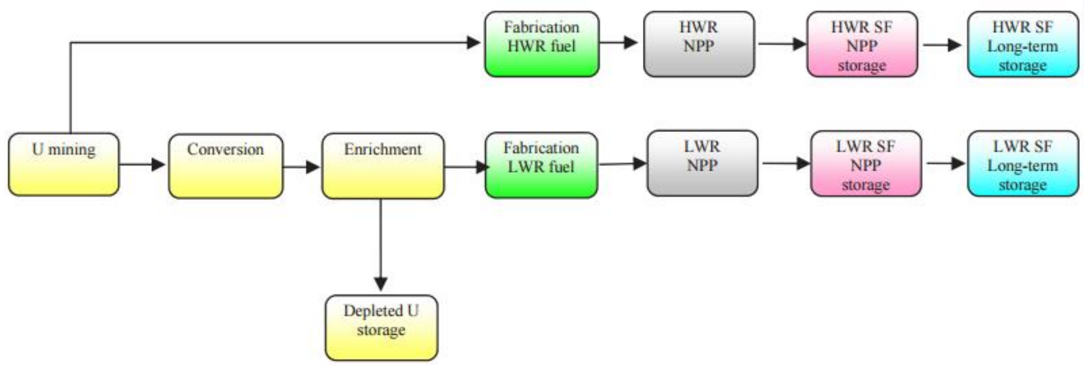
GAINS considered four architectures for NES:

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 FC with FR and TR

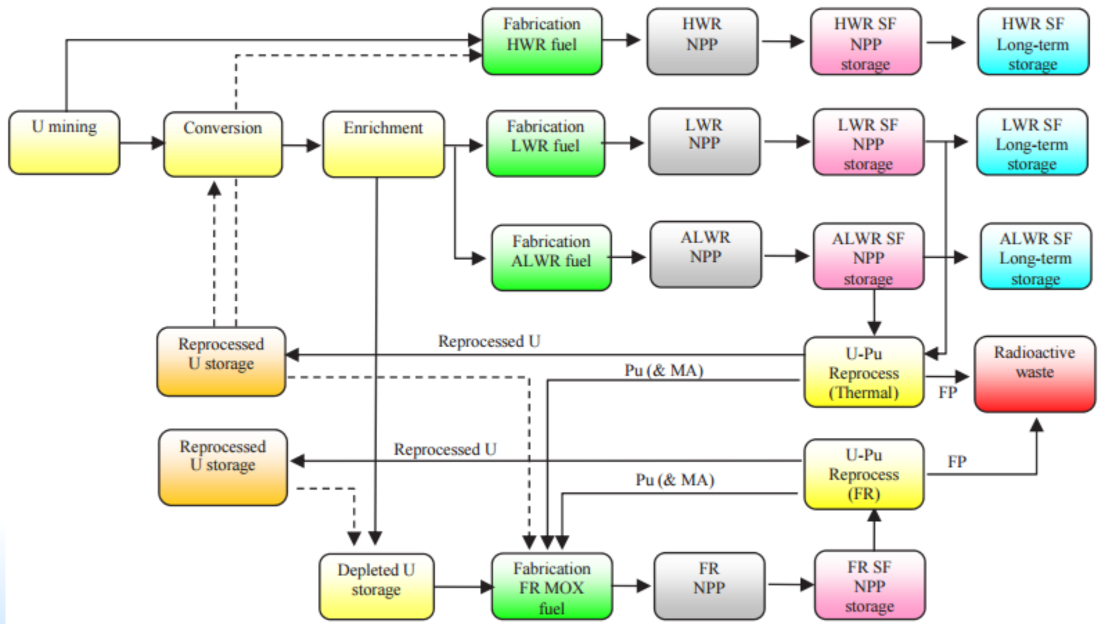


Set of reactor and fuel types and expected timeframes for deployment

Associated NFC 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

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The idea is that a 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.

Selection of *'Key Indicators (KI)'*

-Ten KIs were identified by screening ~ 100 indicators of the INPRO methodology

-These KIs present nuclear power production by reactor types, resources, discharged fuel, radioactive waste, fuel cycle services, costs and investment in a global 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

KI-1 LWR and FR production comparison

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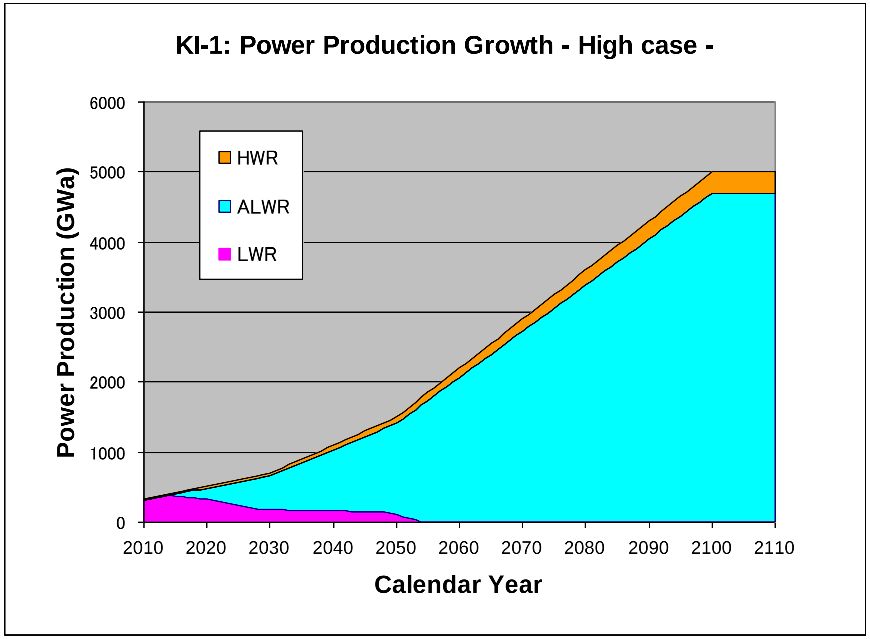
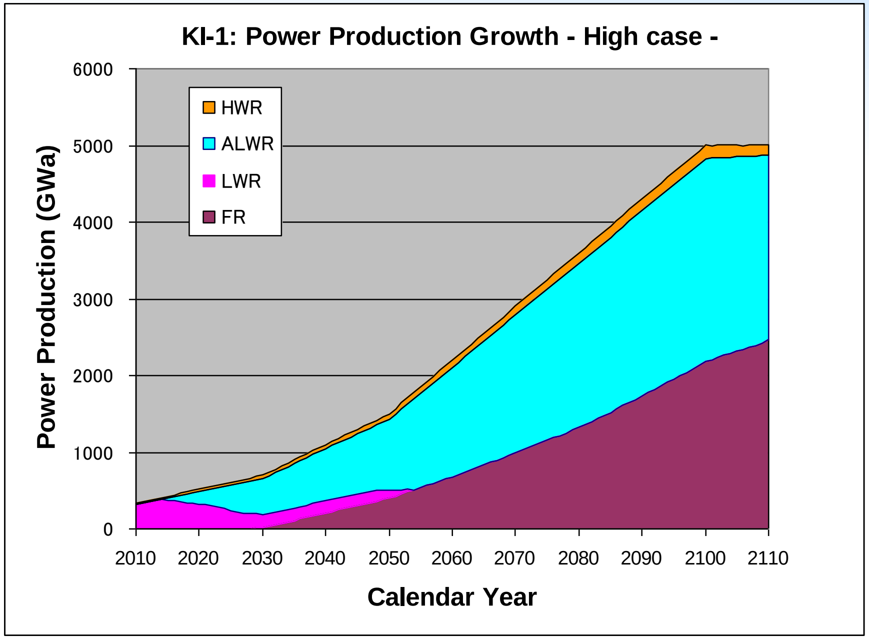


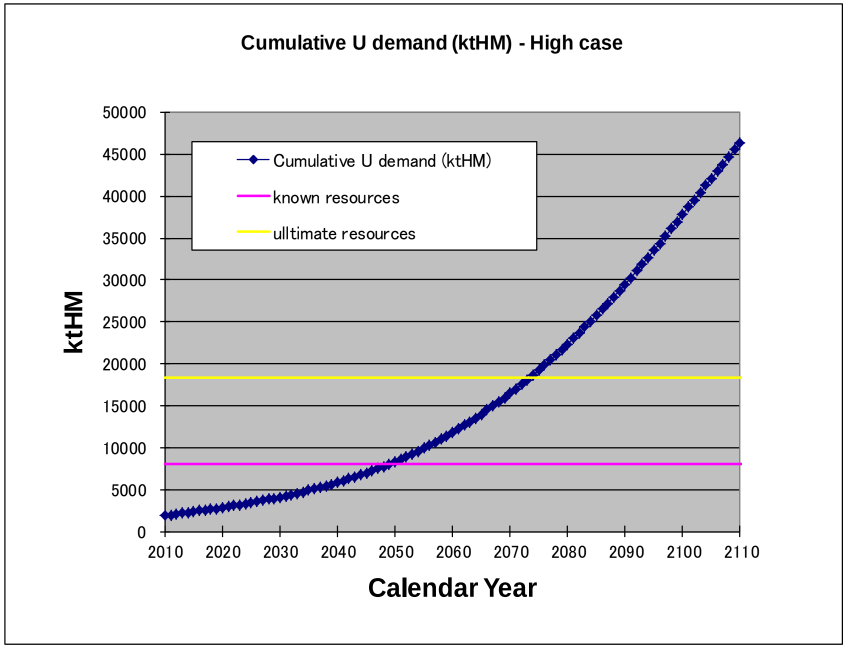
Reactor power share of BAU+
(includes introduction of an advanced PWR replacing conventional PWR technology)



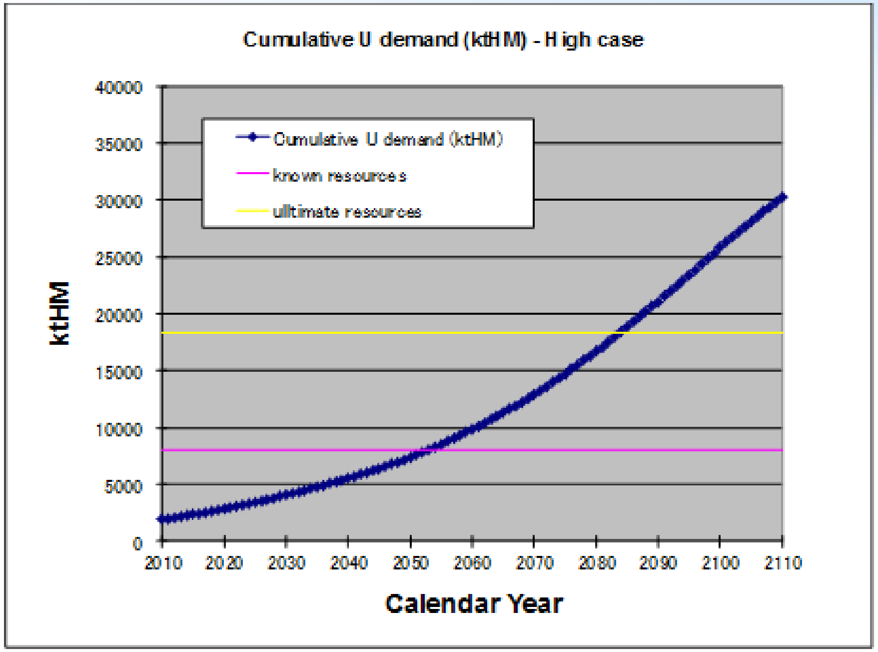
Reactor power share of BAU+FR

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



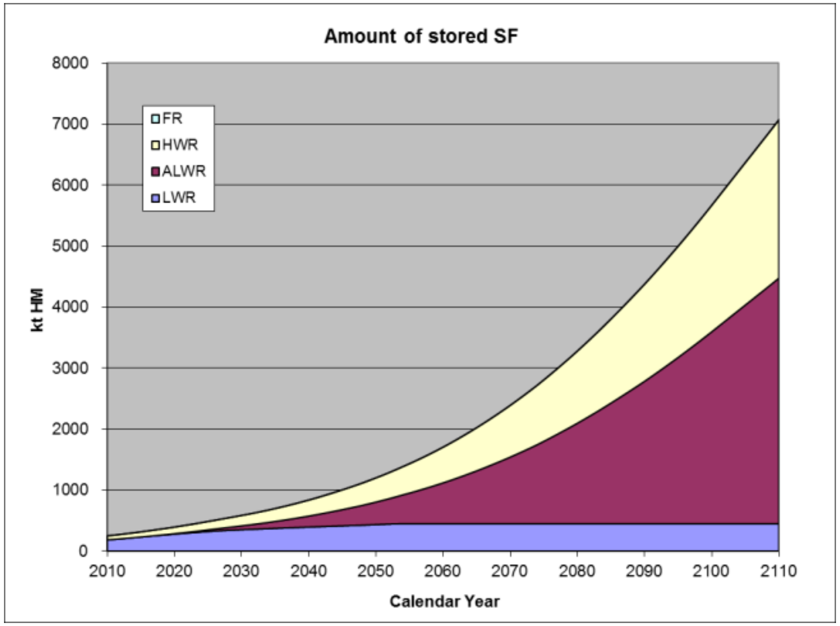
Cumulative natural U demand in BAU+



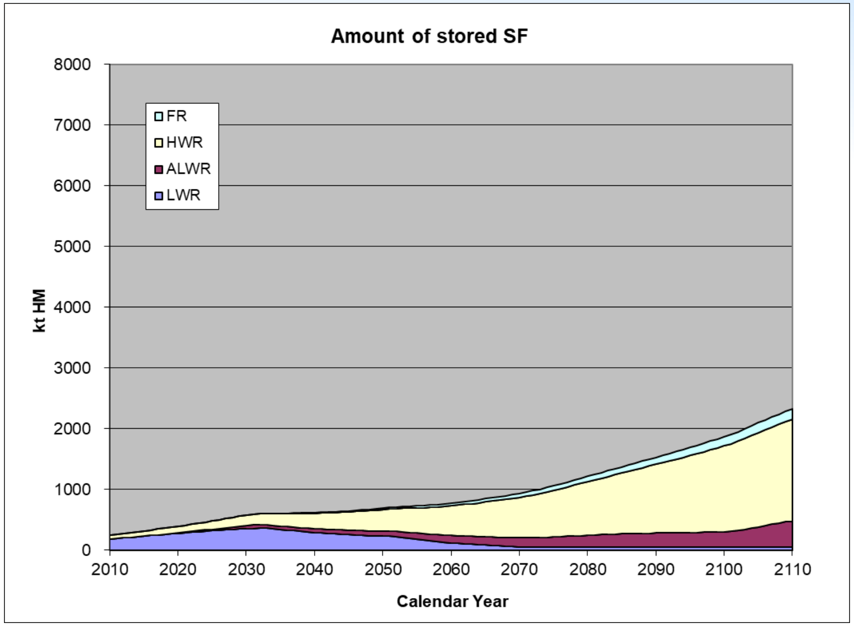
Cumulative natural U demand in BAU+FR

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



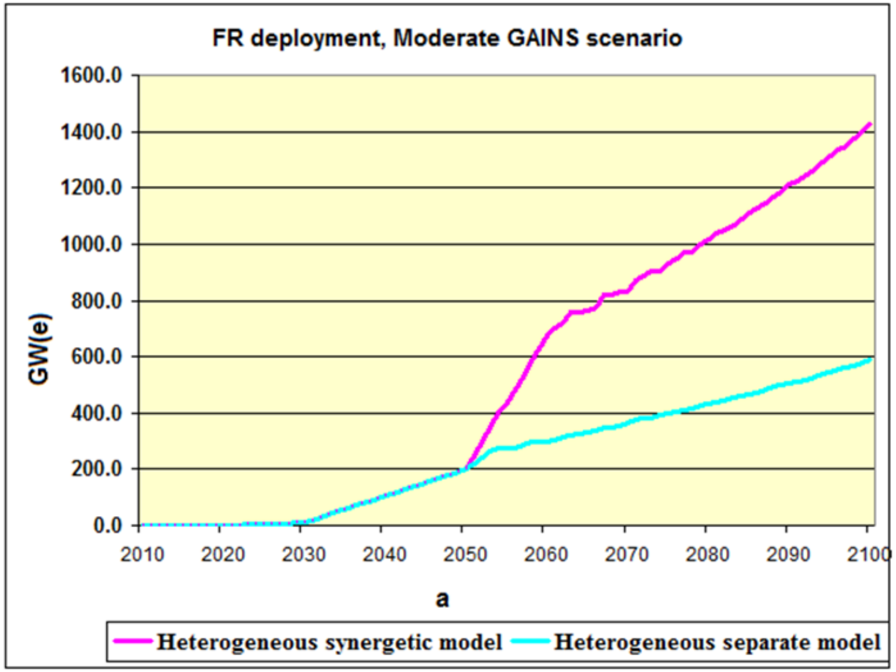
Total amount of SF in BAU+



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.

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.

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.

Plutonium inventories and plutonium management options

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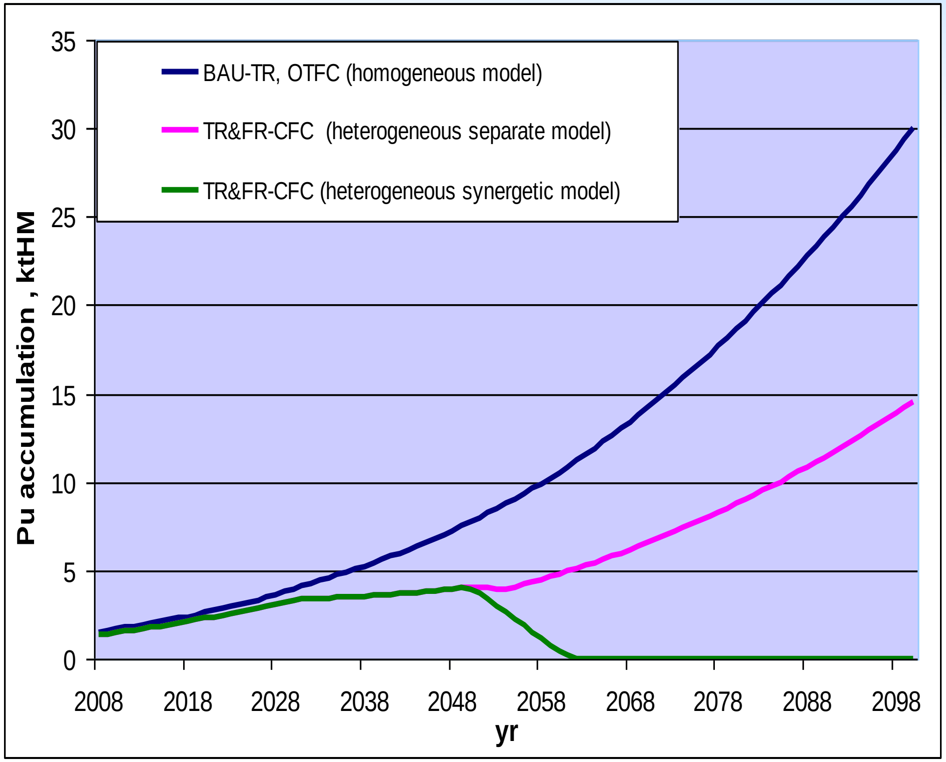
- **Once-through global nuclear fuel cycle** (BAU) would result in a **progressive increase of Pu accumulation** (top line in the figure)

- **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)

Output

- The IAEA/INPRO GAINS project has provided a foundational framework for analysis of global NES architecture which can be applied, customized and enhanced to support national and international collaborative evaluations of NES technologies and scenarios
- The diversity in approaches and perspectives offered by Member States participating in the project proved to be valuable in constructing a framework which is flexible and can be used to analyze a wide range of possible global nuclear energy futures
- Application of the GAINS framework allows:
  - Developing national nuclear energy strategies
  - Exploring cooperation/partnerships with other countries in nuclear fuel cycle
  - Exploring regional options/solutions for nuclear fuel cycle
  - Highlighting global trends and how they may affect national developments

Collaborative project SYNERGIES

- The collaborative project 'Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability' (SYNERGIES) has examined ability of the synergistic approach to enhance efficiency and competitiveness of the nuclear energy production
- SYNERGIES CP involved experts from Algeria, Argentina, Armenia, Belgium, Bulgaria, Canada, China, France, India, Indonesia, Israel, Italy, Japan, Republic of Korea, Malaysia, OECD-NEA, Pakistan, Romania, Poland, Russian Federation, Spain, UK, Ukraine, USA and Viet Nam contributing as participants or observers.
- The analysis performed in the project provides both newcomers and mature nuclear countries with better understanding of the drivers and impediments for the various forms of partnership, such as support by technology holders of the users' national R&D and deployment programmes, regional collaboration in nuclear fuel cycle or, for example, joint development and elaboration of methods and tools for collaborative scenario evaluation, etc.

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

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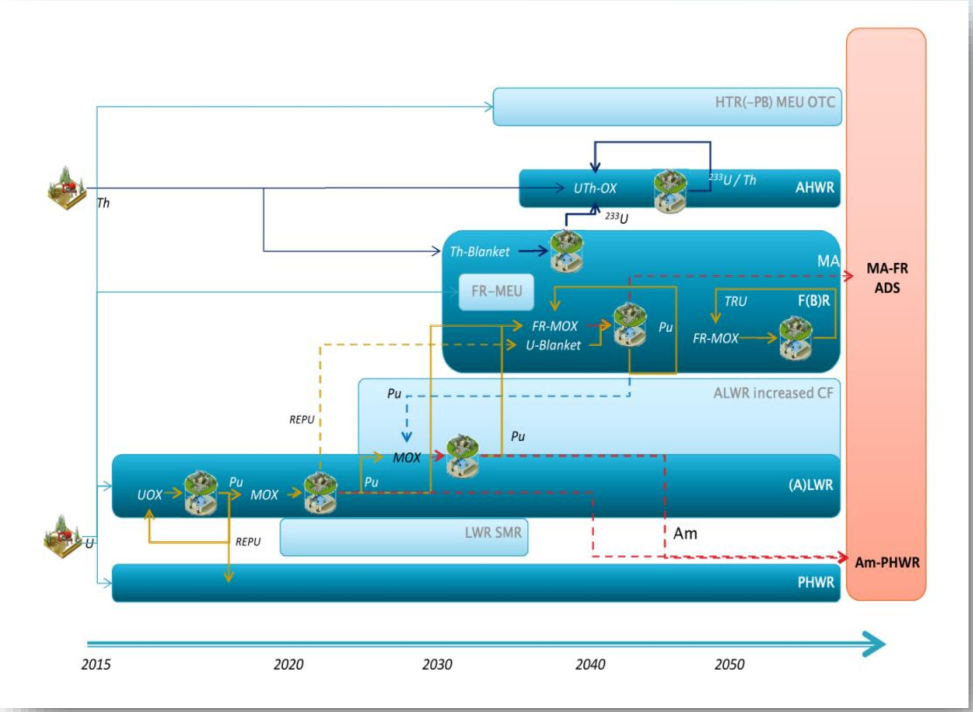
Enhancing sustainability via technology innovations (in reactors and nuclear fuel cycles):

- *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 geological disposal of all wastes*



Overall view of the considered synergies among the technologies

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

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- ***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 .*

Case studies performed within the SYNERGIES project

- The 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.***

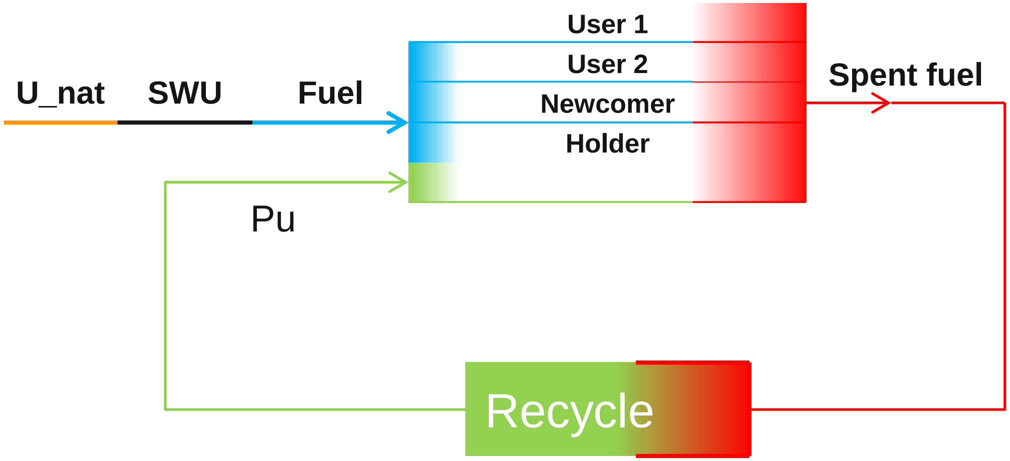
- For the future nuclear energy systems to be globally sustainable, a combination of the various synergistic collaborative solutions may be needed, depending on the pace of nuclear capacity growth.

Steady regional collaboration

Following case studies of the SYNERGIES final report 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

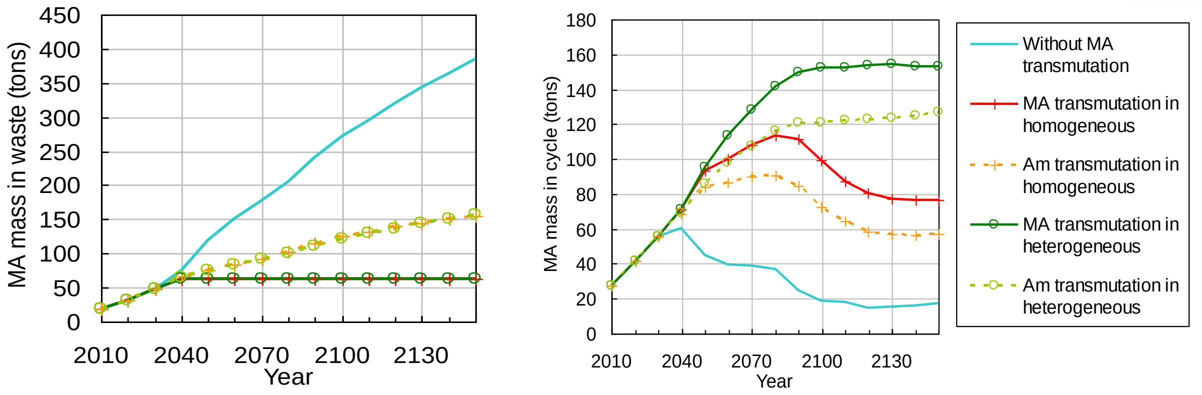
- The study of experts from Armenia, Belarus, Russian Federation and Ukraine also analysed the issues of regional collaboration



Scheme of the regional collaboration on SNF utilization

French case study

- 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

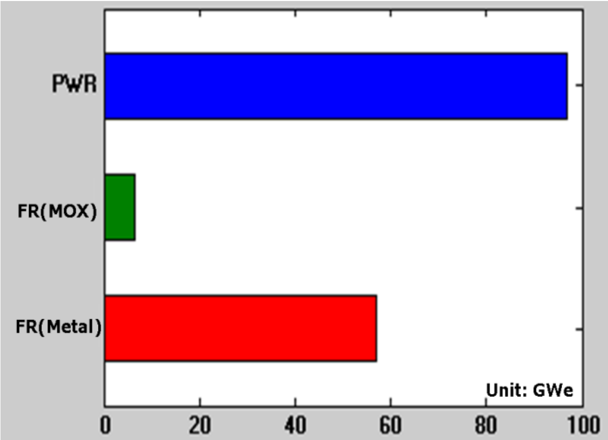


Reduction of MA in the waste and increases inventory of MA in the fuel cycle under transmutation of MA

- 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

China and Japan case studies

- 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 nuclear power station accident in 2011
  - It was concluded that advantages of the reprocessing strategy compared to the direct disposal strategy and the partial reprocessing are observed in all considered scenarios



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 the group have demonstrated some specific features of the collaboration model implementation

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

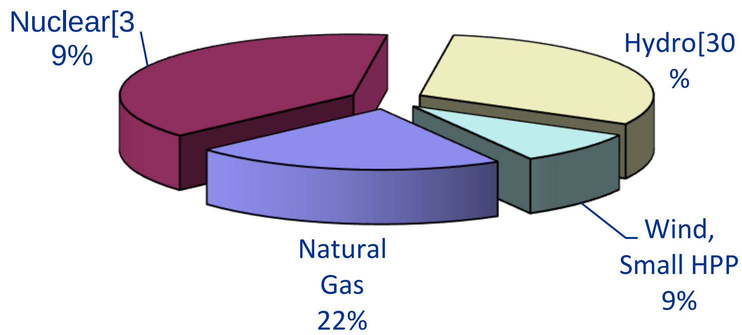
- Argentina develops capabilities as a nuclear technology holder. The plans are to become a supplier of small reactors of the Argentine design

Minimization of R&D and nuclear fuel cycle infrastructure

IAEA

The case study from Armenia presented an approach on minimization of 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 of the 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 the cooperative opportunities are presented and analysed in the Armenian case study
- 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 the national NES.



Share of nuclear power in electricity production in Armenia

GAINS and SYNERGIES project have found that:

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;

However, such a collaborative effort would be possible only when assuring that the related driving forces overcome the impediments

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

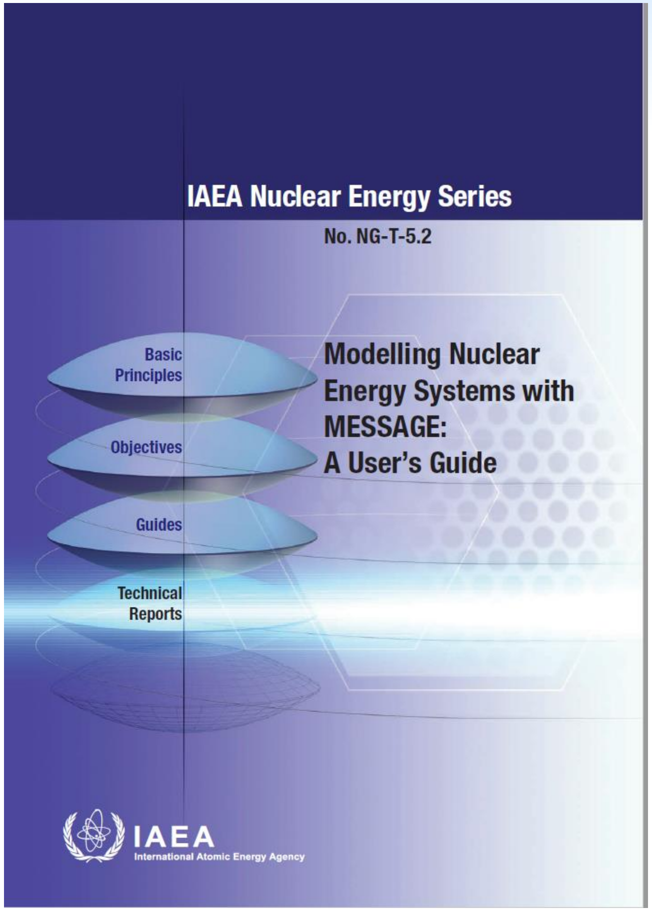
Conclusion

- Synergies of the widely used LWR reactors with the reactors of other types (HWR, SFR, ADS) can provide essential improvement of sustainability indicators in the areas of radioactive waste management, rational use of fissile materials (plutonium, reprocessed uranium) and proliferation resistance. However, harmonization with some other indicators of the entire system, first of all, with the economic ones, is required.
- Collaborative synergies in the form of bilateral or multilateral 'win-win' cooperation could help spreading the benefits of innovative nuclear technologies developed in technology holder countries to all counties of the world. This could enable improvements in economics, severe accident risk reduction, sound solutions for final waste disposal and more transparent implementation of the nonproliferation regime.
- Some technical, economic and political impediments in realization of the potential of synergistic approaches were identified. Better understanding of the impediments and finding the pathways to overcome them is crucially important to define and implement joint actions of the IAEA Member States to enhance viability and sustainability of the global nuclear energy system.

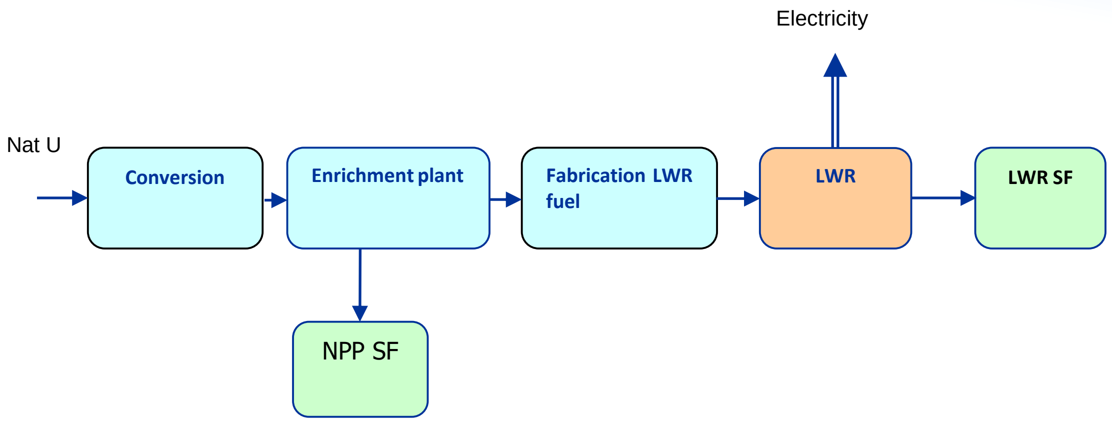
Users' Guide for Modelling Nuclear Energy Systems with MESSAGE, IAEA Nuclear Energy Series No. NG-T-5.2 (2016)

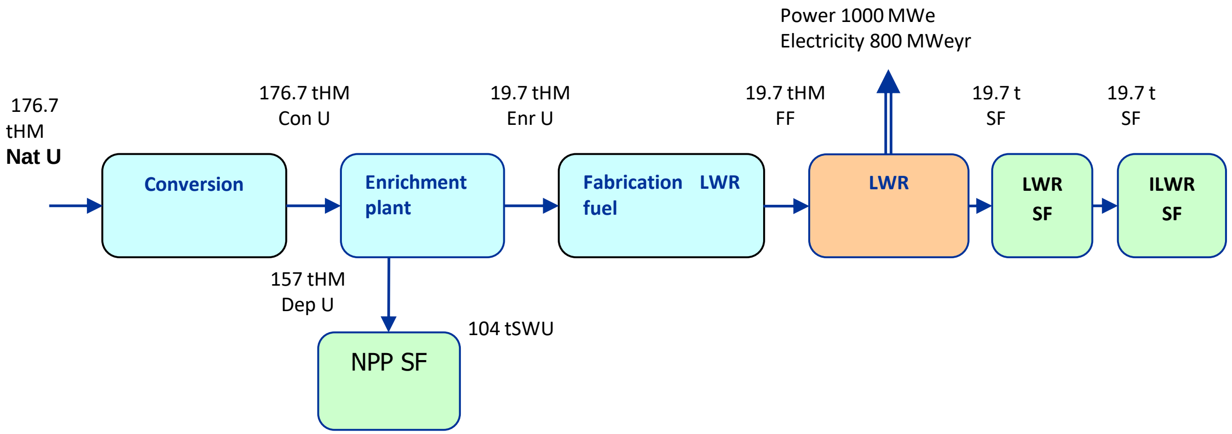
Users Guide provides a step-by-step guidance to create mathematical models representing nuclear energy systems to the level of detail as necessary

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



Exercise on NES modelling (part I) Example for LWR





LWR Reactor data and Mass flow calculation

IAEA

Item	Symbol	unit	LWR
Nuclear Capacity	NC	GW	1
Thermal efficiency	Eff	wt%	0.33
Load factor	Lf	wt%	0.8
Discharge burnup	Bu	GWd/tHM	45
Residence time	Tr	EFPD	1168
Enrichment of fresh fuel	Enr	wt%	0.04
Tail assay	Ta	wt%	0.003

Exemple of calculation for LWR

Annual output	unit	Equation	Result
Fresh fuel	tHM	$FF = \frac{365 * NC * Lf}{Eff * Bu}$	19.7
First fuel loading	tHM	$FuelInCore = \frac{FF * Tr}{365 * Lf}$	78.7
Natural U	tHM	$NatU = \frac{FF * (Enr - Ta)}{(0.007114 - Ta)}$ where 0.007114 is the content of ^{235}U in NatU	176.7
Conversion	tHM	$Cn = NatU$	176.7
SWU	tSWU	$SWU = M_p * V_p + M_t * V_t - M_f * V_f$ where $V_x = (2e_x - 1)\ln\frac{e_x}{(1-e_x)}$	104
Depleted U	tHM	$DepU = \frac{FF * (Enr - 0.007114)}{(0.007114 - Ta)}$	157
SF Discharged	tHM+tFP	$SFD = FF$	19.7

$$SWU = FF * (V(Enr) + V(Ta)\frac{Enr - 0.007114}{0.007114 - Ta} - V(0.007114)\frac{Enr - Ta}{0.007114 - Ta})$$

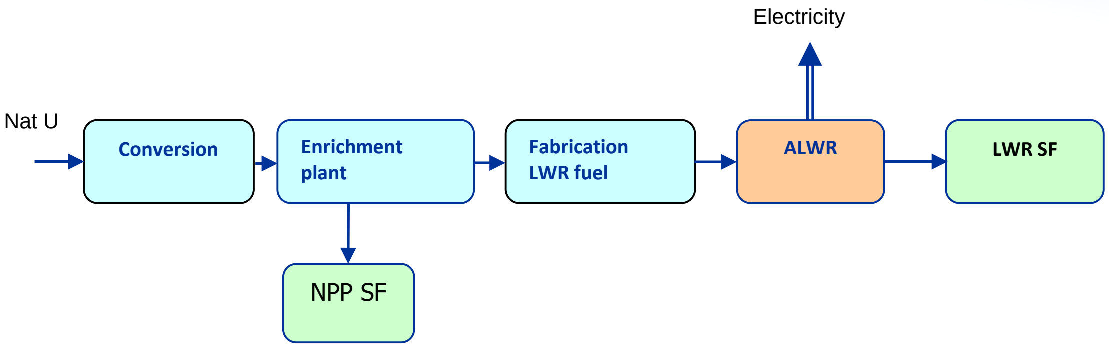
Remarks about mass units

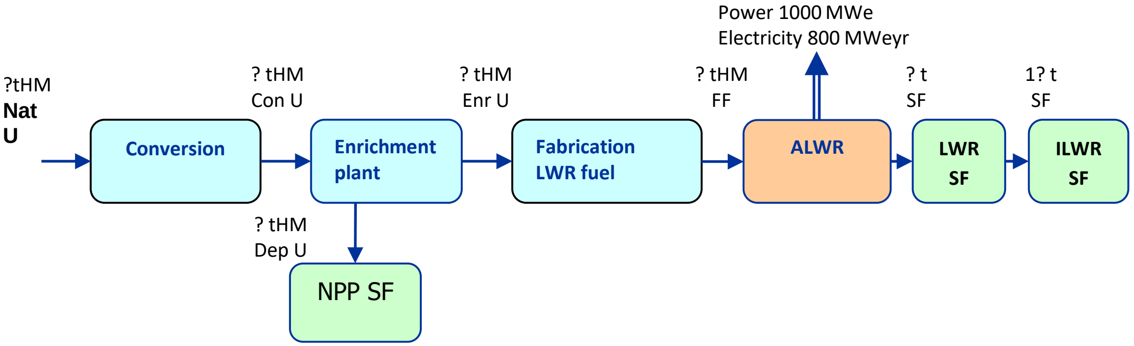
Specify what do you mean by "nuclear fuel":

a) fuel assemblies	kton
b) fuel tablets	ktonUO_2
c) metal uranium (U238+U235)	ktonHM

nuclear fuel weight is calculated in ktonHM

Exercise on NES modelling Example for ALWR





ALWR Reactor data and Mass flow calculation

IAEA

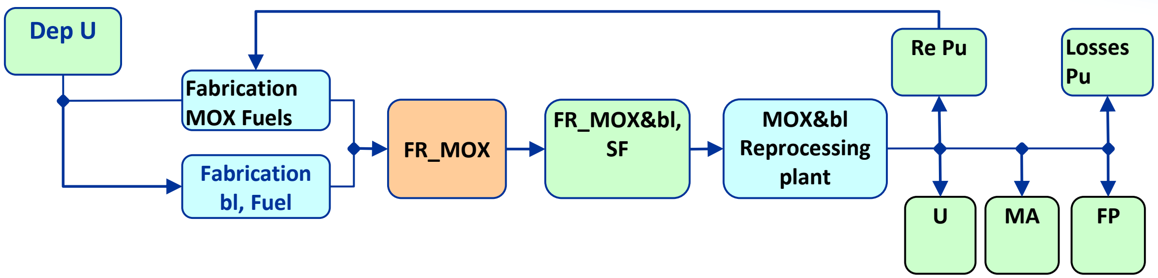
Item	Symbol	unit	LWR
Nuclear Capacity	NC	GW	1.5
Thermal efficiency	Eff	wt%	0.34
Load factor	Lf	wt%	0.8
Discharge burnup	Bu	GWd/tHM	60
Residence time	Tr	EFPD	1760
Enrichment of fresh fuel	Enr	wt%	0.0495
Tail assay	Ta	wt%	0.002

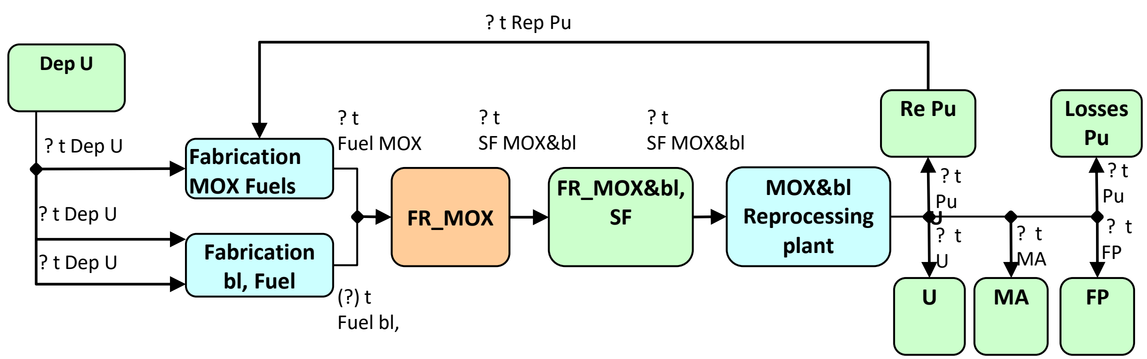
Exemple of calculation for LWR

Annual output	unit	Equation	Result
Fresh fuel	tHM	$FF = \frac{365 * NC * Lf}{Eff * Bu}$	
First fuel loading	tHM	$FuelInCore = \frac{FF * Tr}{365 * Lf}$	
Natural U	tHM	$NatU = \frac{FF * (Enr - Ta)}{(0.007114 - Ta)}$ where 0.007114 is the content of ^{235}U in NatU	
Conversion	tHM	$Cn = NatU$	
SWU	tSWU	$SWU = M_p * V_p + M_t * V_t - M_f * V_f$ where $V_x = (2e_x - 1)\ln\frac{e_x}{(1-e_x)}$	
Depleted U	tHM	$DepU = \frac{FF * (Enr - 0.007114)}{(0.007114 - Ta)}$	
SF Discharged	tHM+tFP	$SFD = FF$	

$$SWU = FF * (V(Enr) + V(Ta)\frac{Enr - 0.007114}{0.007114 - Ta} - V(0.007114)\frac{Enr - Ta}{0.007114 - Ta})$$

Task on NES modelling Example for FR





FR Reactor data

Item	Symbol	Unit	FR_MOX		
Nuclear capacity	NC	MW(e)	870		
Thermal efficiency (electricity)	Eff	%/100	0.4143		
Load factor	Lf	%/100	0.85		
			Core	Axial blanket	Radial blanket
Fuel residence time	Tr	EFPD	420	420	490
Discharged burnup	Bu	MW·d/t	65.9	4.8	4.2
First loading	FuLoad	t HM	12.6	5.5	6.2
Plutonium content	TotPuFF	%/100	0.218	DepU	DepU

Item	Symbol	Unit	FR fuel
Reprocessing losses	RepLos	%	0.755

Item	Symbol	Unit	Value
Uranium total	TotUSF	%/100	0.8404
Plutonium total	TotPuSF	%/100	0.1189
Minor actinides	TotMASF	%/100	0.0023
Fission products	TotFPSF	%/100	0.0384
Heavy metal	TotHMSF	%/100	0.9616

Analytical mass flow calculations for FR

Annual output parameters		Unit	Equation	Analytical result
Fresh Fuel MOX	FF MOX	tHM	$FF_i = \frac{365 \times Lf \times FuLoad_i}{Tr_i}$ where i = {Core, Rad, Ax};	
Fresh Fuel Ax, blanket	FF Ax	tHM		
Fresh Fuel Rad, blanket	FF Rad	tHM		
SF Discharge	SFS	tHM+tFP	$SFD = FFcore + FFAx + FFRad$	
Reprocessed Pu used	RepPuUsed	tHM	$RepPu = SFR \times TotPuSF \times (1 - RepLos)$	
SF Reprocessing	SFR	tHM+tFP	SFR=SFD	
Reprocessed Pu	RepPu	tHM	$RepPu = SFR \times TotPuSF \times (1 - RepLos)$	
Pu Losses	LosPu	tHM	$LosPu = SFR \times TotPuSF \times RepLos$	
MA	RepMA	tHM	$RepMA = SFR \times TotMASF$	
FP	RepFP	t	$RepFP = SFR \times TotFPSF$	

Scenario Analysis for Enhancing Nuclear Energy Sustainability

IAEA

- FRAMEWORK FOR NES SCENARIO MODELLING
  - GAINS
  - SYNERGIES
- APPROACH FOR COMPARATIVE EVALUATION OF NES/SCENARIOS
  - KIND

Approach for Comparative Evaluation of Nuclear Energy System/ Scenario Options

➢The INPRO collaborative project "Key indicators for innovative nuclear energy systems" (KIND) has developed an approach for comparative evaluation of NES/ scenario options

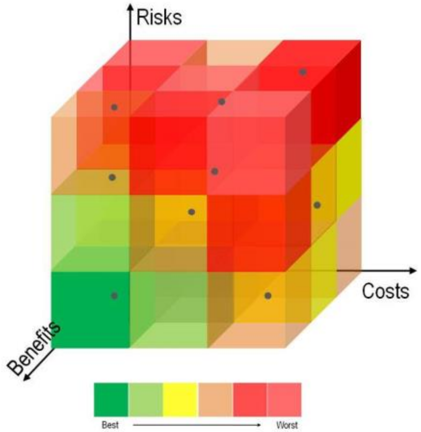
➢The approach is based on the application of a set of selected key indicators, reflecting upon certain subject areas of the INPRO methodology, and a selected verified judgment aggregation/ uncertainty analysis method (of the Multi-Criteria Decision Analysis – MCDA)

➢Case studies on trial application of the KIND approach have shown its high potential for the solution of various decision-making support problems, such as comparative evaluations of the evolutionary and innovative NES, nuclear energy evolution scenarios and even nuclear vs. non-nuclear energy system options, etc.

➢The developed approach is recommended for establishing a productive dialogue between energy-option proponents and decision makers regarding sustainable nuclear energy options

Approach for comparative evaluation of nuclear energy system/ scenario options:

- **Compare different NES/scenario options based on selected set of key indicators and verified judgment aggregation/ uncertainty analysis method**
- **Establish productive dialogue with decision makers**



MCDA implementation for comparative evaluation of NES/scenarios

The problem of alternatives evaluation may be defined as ranking or ordering of the alternatives from best to worst one.

	KI 1	KI 2	…	KI n
Alternative 1			…	
Alternative 2			…	
…	…	…	…	…
Alternative m			…	

Alternatives are evaluated based on defined set of Key Indicators (KI). Some alternative's indicator can show better or worse performance in comparison with another alternatives.
How to select the best alternative? - *Multiple Criteria Decision Making (MCDM) techniques.*

Overview of relevant MCDM techniques

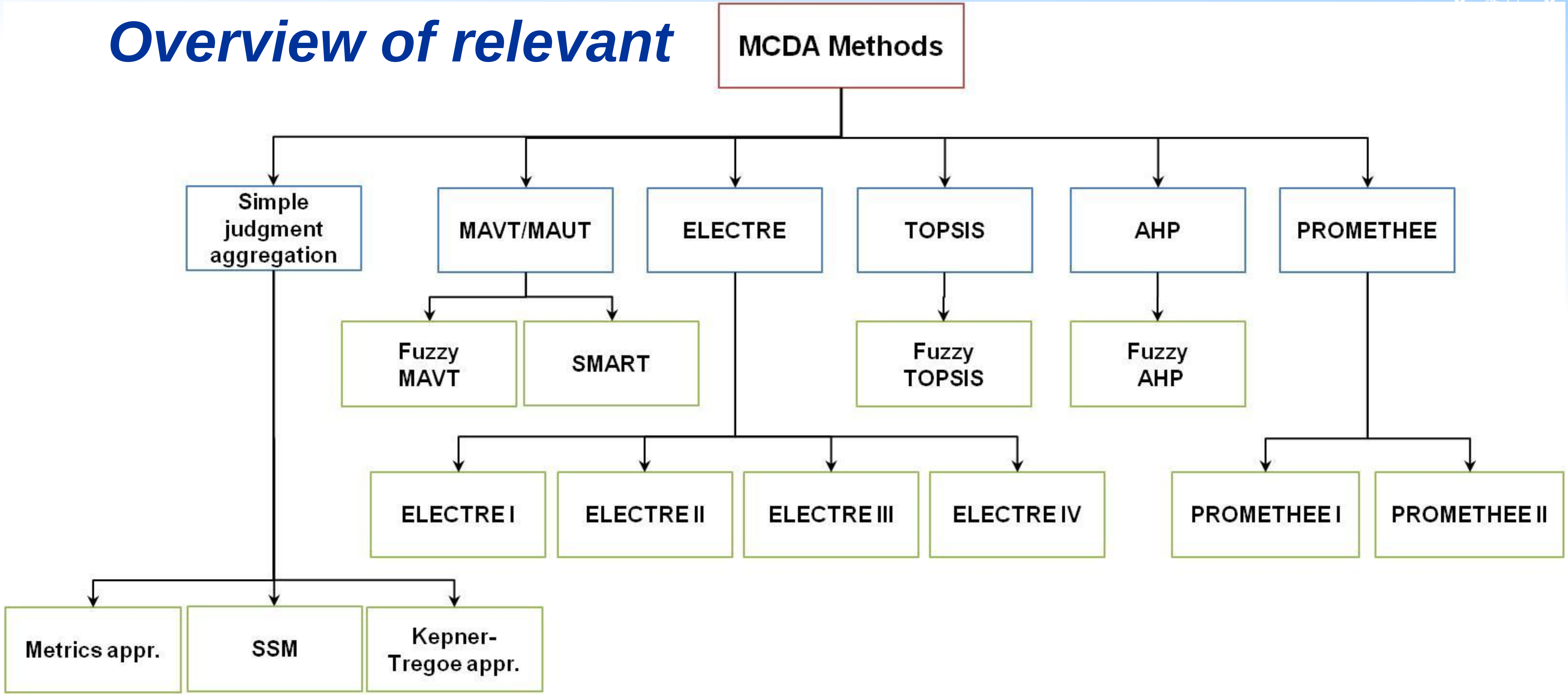
- *Multiple Criteria Decision Making (MCDM)* techniques are a tool aimed at supporting decision makers who are faced with making numerous and **conflicting evaluations**, MCDM techniques intend to **highlight conflicts** and **find compromises** in the decision making process. *Multi-Criteria Decision Analysis (MCDA)* and *Multi-Objective Decision Making (MODM)* are the main components of MCDM.

✓ The MCDA problems consist of a finite number of alternatives, explicitly known in the beginning of the solution process. Each alternative is represented by its performance in multiple criteria. The objective is to find the best alternative for a decision maker, or find a set of good alternatives.

✓ In the MODM problems, the alternatives are not explicitly known. An alternative (solution) can be found by solving a mathematical model. The number of alternatives is either infinite or not countable (when some variables are continuous) or typically very large, if countable, (when all variables are discrete).

✓ **MCDA approach was found to be the most appropriate for the objective and studies if the KIND collaborative project.**

Overview of relevant



The MCDA methods may be categorized into the following groups: value-based, outranking, reference-based, and other methods.
Value-based methods (for instance, MAVT, MAUT, AHP) are based on an evaluation of a single overall score for each alternative.
Outranking methods (PROMETEE) imply forming an ordered relation of a given set of alternatives.
Reference-based methods (for instance, TOPSIS etc.) determine the similarity of alternatives to an ideal and anti-ideal alternative.
The use of MAVT based on simplified additive weighted aggregation is recommended for the needs of the KIND project because in KIND a universal tool is needed to be able to compare mature to mature or less mature nuclear technologies or even nuclear to non-nuclear technologies. MAVT has found wide application for different kinds of problems in the nuclear and non-nuclear engineering fields. A wide experience of applying this method summarized in different publications and the available extensive set of recommendations and software tools implementing the method are the main incentives and arguments for the selection of this method.

Approach for comparative evaluation of NES developed in the KIND project

- At the start of the comparative evaluation process, interaction among decision makers, experts and other main stakeholders is very important
- The next step, formulation of alternatives, is meant to identify the technology options and the factors or driving forces that influence the system evolution
- The selection of key indicators should be based on their measurability and the availability of data and analytical tools for their computation
- The next stage is computation of the selected key indicators for each of the alternative scenarios and application of a suitable methodology for calculating the overall rank of each scenario by aggregation of the key indicators using experts' judgement and decision makers' preferences

Problem Formulation (decision makers, experts and other stakeholders)

The comparative evaluation approach developed in the KIND project follows a systematic process spread over several sequential steps with feedbacks at different stages

Formulation of Alternative NES/Scenarios

Identification and evaluation of Key Indicators

Determination of overall Ranking of Alternative NES/Scenarios

Uncertainty and sensitivity analysis

Comparative Evaluation and Interpretation of Results

Features and specifications of the multi-attribute value/utility theory (1)

Performance table

	KI 1	KI 2	…	KI n
Alternative 1			…	
Alternative 2			…	
…	…	…	…	…
Alternative m				

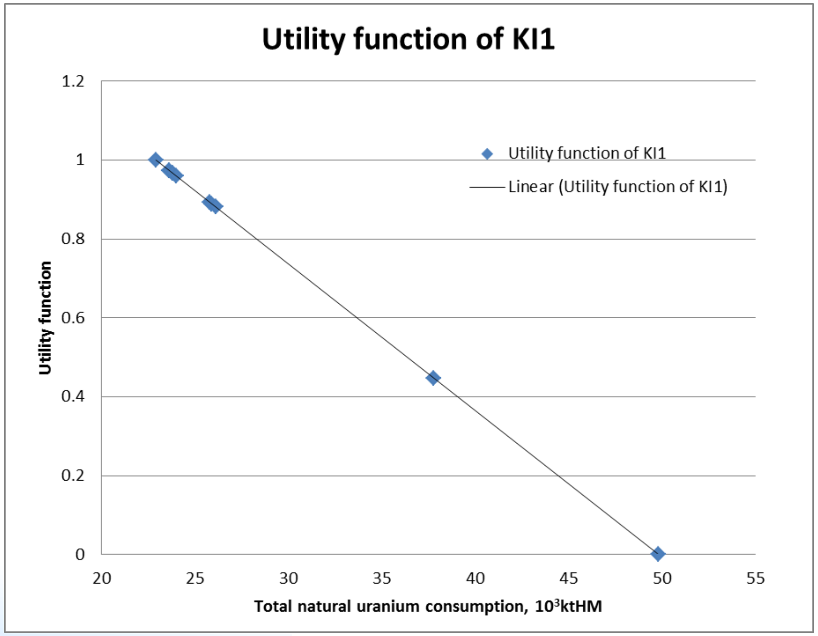
xi ranges as worst ≤ xi ≤ best

Value/ utility function ranges from worst to best

from 0 to 1 0≤ ui(xi) ≤1

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \Rightarrow \begin{pmatrix} u_{11} & \cdots & u_{1n} \\ \cdots & \cdots & \cdots \\ u_{m1} & \cdots & u_{mn} \end{pmatrix}$$

u: Single-attribute utility/value function



Features and specifications of the multi-attribute value/utility theory (2)

Performance table

	KI 1	KI 2	…	KI n
Alternative 1			…	
Alternative 2			…	
…	…	…	…	…
Alternative m				

xi ranges from worst to best

worst ≤ xi ≤ best

Value/ utility function ranges from 0 to 1 0≤ ui(xi) ≤1

u: Single-attribute utility/value function

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \rightarrow \begin{pmatrix} u_{11} & \cdots & u_{1n} \\ \cdots & \cdots & \cdots \\ u_{m1} & \cdots & u_{mn} \end{pmatrix} \xrightarrow{w=\{w_1, w_2, \ldots w_n\}} U = \begin{pmatrix} U_1 \\ \cdots \\ U_m \end{pmatrix} \xrightarrow{\text{ranking}}$$

Alternative 1	
Alternative 2	
…	…
Alternative m	

U :Multi-attribute utility/value function – General indicator

R={R1,R2…Rm}

The Multi-Attribute Value/Utility Theory (MAVT/MAUT)

w={w$_1$, w$_2$,…w$_n$}

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \Rightarrow \begin{pmatrix} u_{11} & \cdots & u_{1n} \\ \cdots & \cdots & \cdots \\ u_{m1} & \cdots & u_{mn} \end{pmatrix} \Rightarrow U = \begin{pmatrix} U_1 \\ \cdots \\ U_m \end{pmatrix} \Rightarrow \text{ranking}$$

	U_2
Alternative 1	U_1
Alternative 2	
…	…
Alternative m	

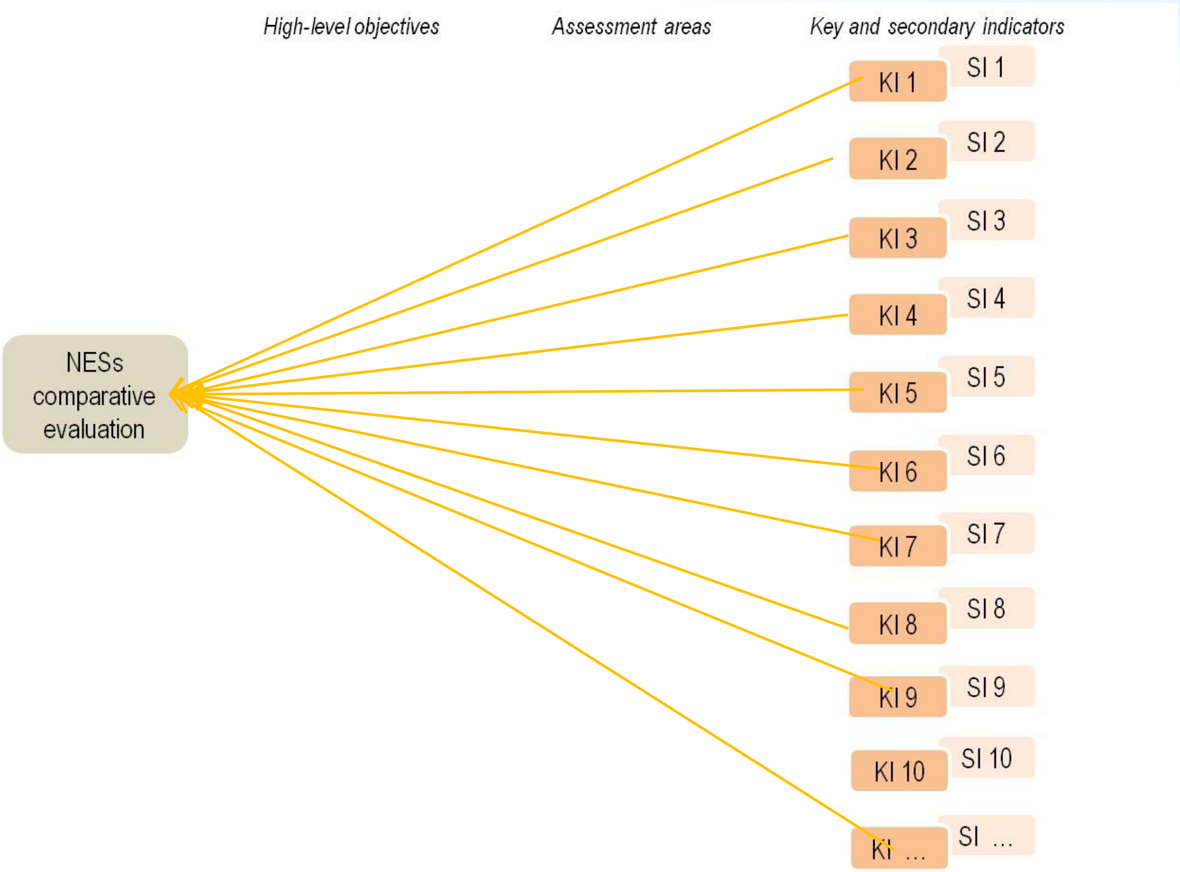
R={R1,R2…Rm}

U :Multi-attribute utility/value function – General indicator

- *Weights wi, Σwi=1*
- *General* simple additive *value/utility function*

$$U_1 = \Sigma w_i \times u_{1i}$$

Aggregation of indicators and objectives tree (1)



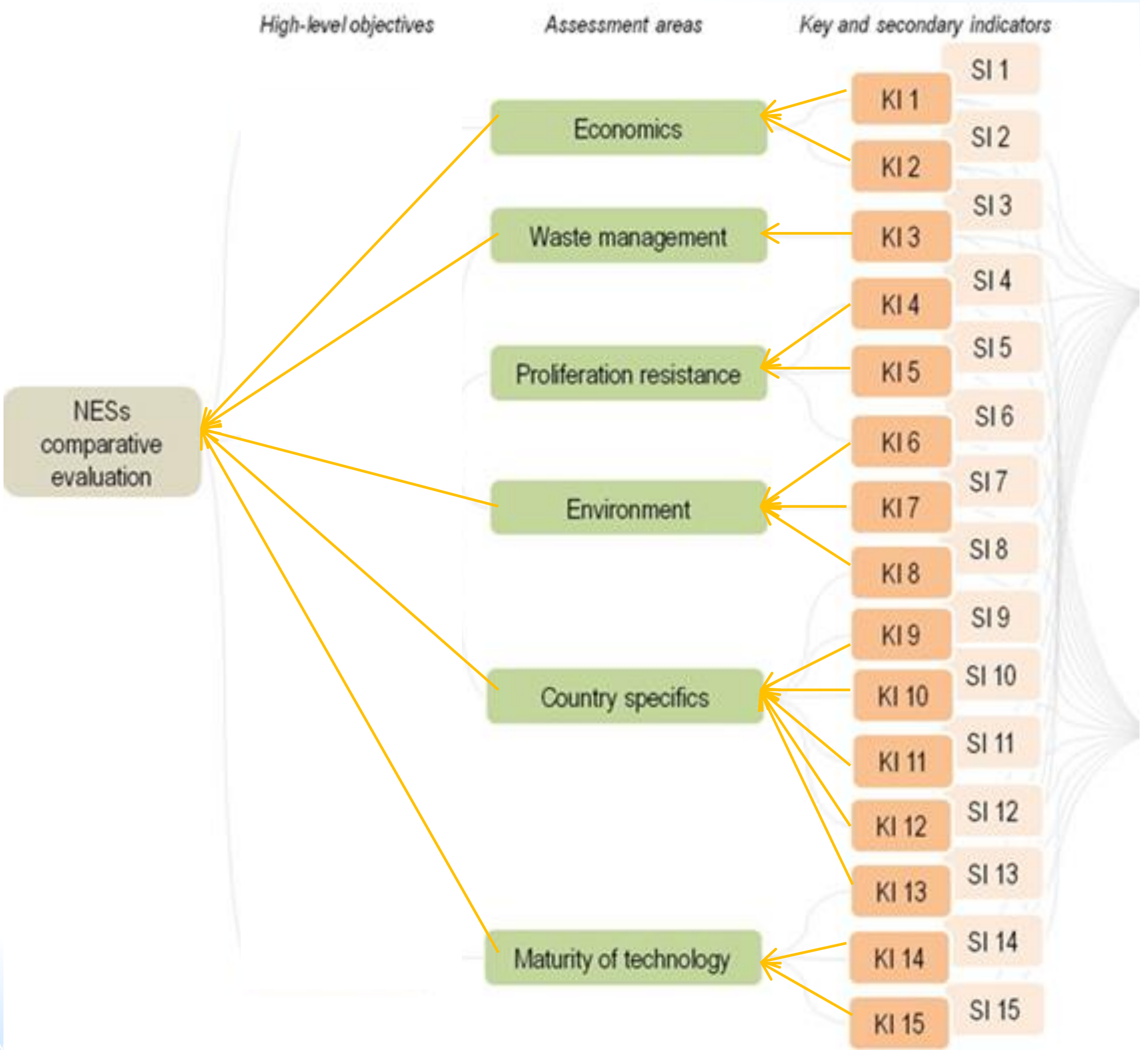
1 -level objectives tree;

2-level objectives tree;

3-level objectives tree;

The objectives tree defines procedures of indicator aggregation and weighting factors evaluation and the ranking results interpretation. Such structuring makes it possible to simplify preparation of the indicator weights and provides a clear explanation of the ranking results.

Aggregation of indicators and objective tree (2)

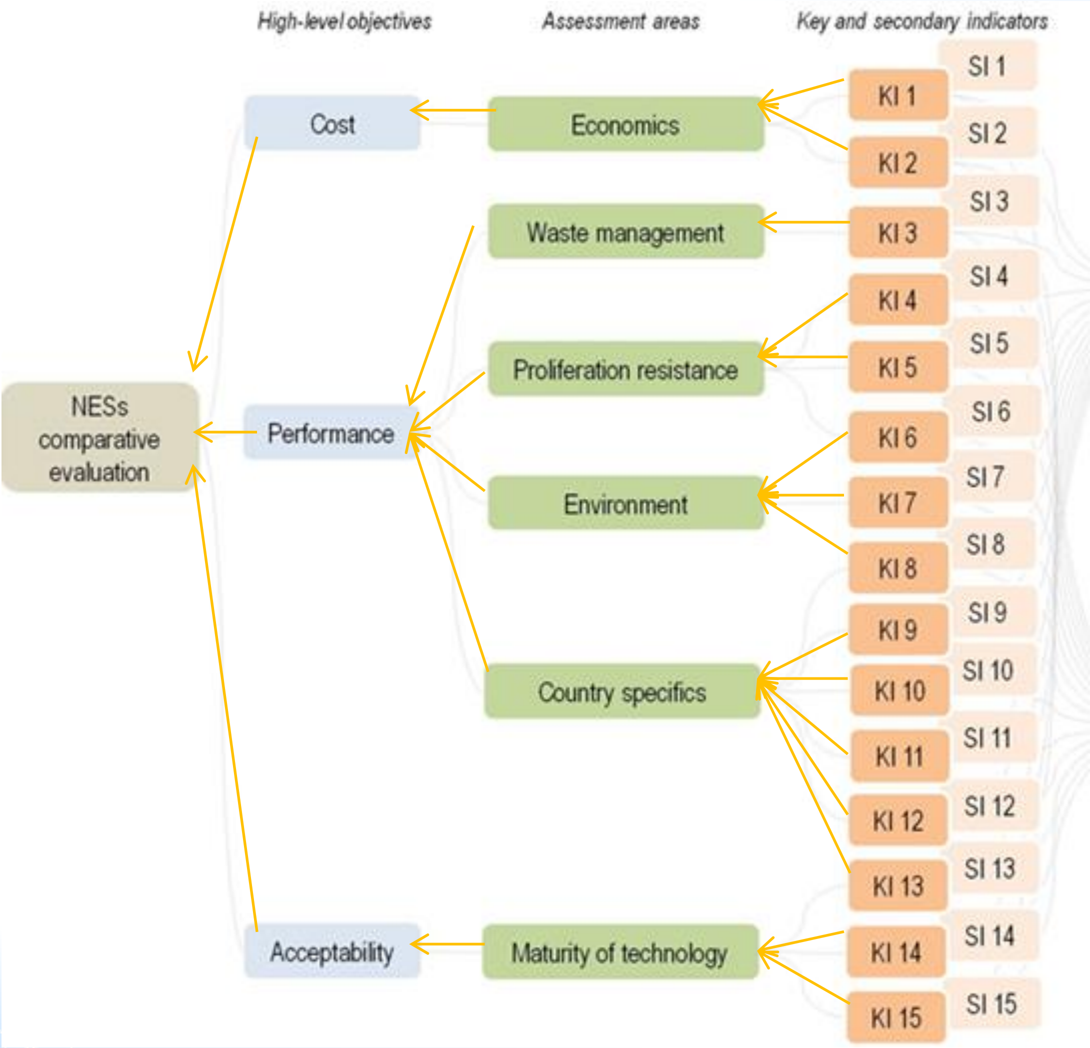


1 -level objectives tree;

2-level objectives tree;

3-level objectives tree;

Aggregation of indicators and objective tree (3)



1 -level objectives tree;

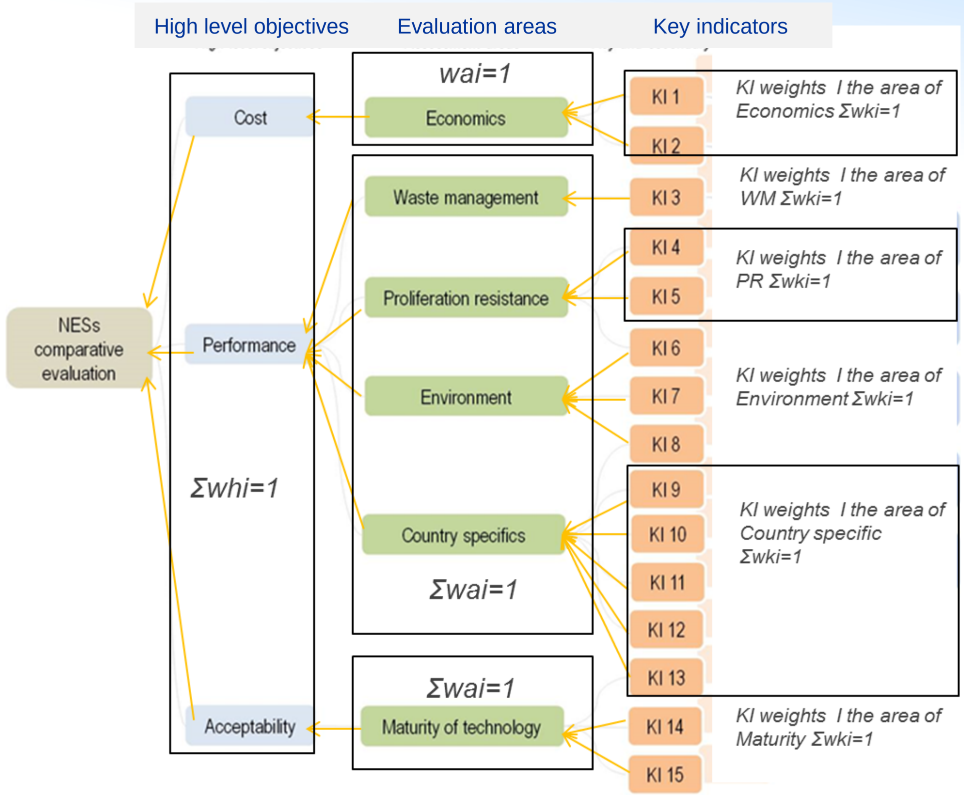
2-level objectives tree;

3-level objectives tree;

Weighting factor

- In order to use the MCDA methods it is necessary to specify weights which reflect experts' preferences related to the KIs' importance/significance
- The representation of preferences among different criteria (weights identification) is the most sensitive issue in the formal application of MCDA methods
- Weighting of indicators or areas should be the responsibility of each Member State or other user and could be used to reflect the anticipated scale of national nuclear power deployment in a country as well as other considerations

OBJECTIVES TREE, HIERARCHICAL WEIGHTING



High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators titles	Indicators weights	Final weighting factors
Cost	w_c	Economics	w_e	E,1	$w_{e,1}$	$W_{E,1}$
				E,2	$w_{e,2}$	$W_{E,2}$
Performance	w_p	Waste management	w_{wm}	WM,1	$w_{wm,1}$	$W_{WM,1}$
				WM,2	$w_{wm,2}$	$W_{WM,2}$
				WM,3	$w_{wm,3}$	$W_{WM,3}$
		Proliferation resistance	w_{pr}	PR,1	$w_{pr,1}$	$W_{PR,1}$
				PR,2	$w_{pr,2}$	$W_{PR,2}$
				PR,3	$w_{pr,3}$	$W_{PR,3}$
				PR,4	$w_{pr,4}$	$W_{PR,4}$
		Environment	w_{env}	ENV,1	$w_{e,1}$	$W_{ENV,1}$
		Country specific	w_s	S,1	$w_{s,1}$	$W_{S,1}$
				S,2	$w_{s,2}$	$W_{S,2}$
				S,3	$w_{s,3}$	$W_{S,3}$
				S,4	$w_{s,4}$	$W_{S,4}$
				S,5	$w_{s,5}$	$W_{S,5}$
Acceptability	w_a	Maturity of technology	w_m	M,1	$w_{m,1}$	$W_{M,1}$
				M,2	$w_{m,2}$	$W_{M,2}$
				M,3	$w_{m,3}$	$W_{M,3}$
				M,4	$w_{m,4}$	$W_{M,4}$

- weights for the high-level objectives :

$w_c+w_p+w_a=1$;

- weights for each of the evaluation areas :

$w_e=1,\ w_{wm}+w_{pr}+w_{env}+w_s=1,\ w_m=1;$

- weights on the level of key indicators:

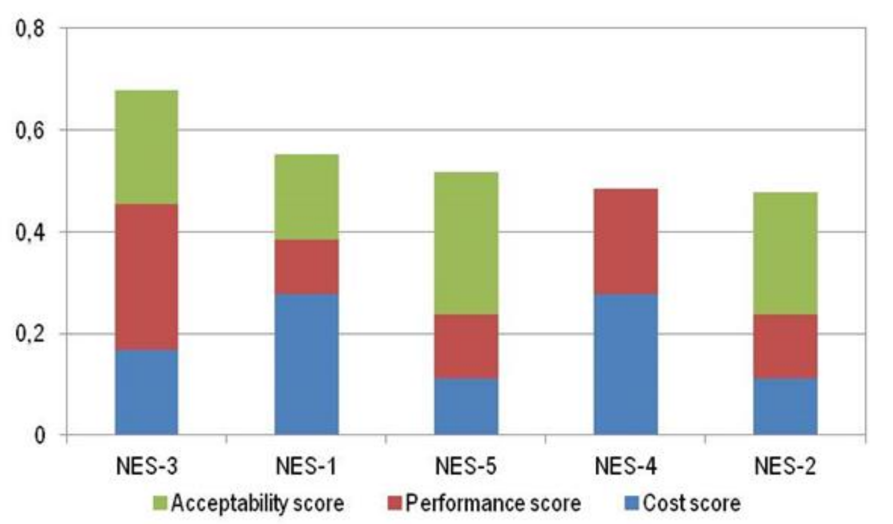
$w_{e,1}+w_{e,2}=1,\ w_{wm,1}+w_{wm,2}+w_{wm,3}=1,\ w_{pr,1}+w_{pr,2}+w_{pr,3}+w_{pr,4}=1,\ w_{e,1}=1,\ w_{s,1}+w_{s,2}+w_{s,3}+w_{s,4}+w_{s,5}=1,$
$w_{m,1}+w_{m,2}+w_{m,3}+w_{m,4}=1,$

$$W_{KEY\ INDICATOR}=w_{high\text{-}level\ objective}\cdot w_{assessment\ area}\ w_{key\ indicator}$$

Numerical example

High-level objective titles	High-level objective weights	Area titles	Area weights	Indicators abbr.	Indicator weights	Final indicator weights
Cost	0.333	*Economics*	1	*E.1*	0.5	0.167
				E.2	0.5	0.167
Performance	0.333	*Waste management*	0.25	*WM.1*	1	0.083
		Proliferation resistance	0.25	*PR.1*	0.333	0.028
				PR.2	0.333	0.028
				PR.3	0.333	0.028
		Environment	0.25	*ENV.1*	1	0.083
		Country specific	0.25	*S.1*	0.2	0.017
				S.2	0.2	0.017
				S.3	0.2	0.017
				S.4	0.2	0.017
				S.5	0.2	0.017
Acceptability	0.333	*Maturity of technology*	1	*M.1*	0.333	0.111
				M.2	0.333	0.111
				M.3	0.333	0.111

Results presentation



	Cost score	Performance score	Acceptability score	Total score
NES-1	0.278	0.106	0.167	0.55
NES-2	0.111	0.126	0.241	0.478
NES-3	0.167	0.288	0,222	0,677
NES-4	0.278	0.206	0	0.483
NES-5	0.111	0.127	0.278	0.516

Sensitivity and uncertainty analysis: general comments (1)

IAEA

- The approach to comparative evaluation of NES/scenarios developed within the KIND project pays special attention to uncertainties through sensitivity and parametric analyses. Uncertainty and sensitivity analysis is an inevitable step providing better grounds for judgment; it enables decision-makers to estimate the stability and robustness of the produced results.

- Sensitivity analysis: The purpose of sensitivity analysis is to examine the change in model output values (ranking result) owing to modest changes in the model input values (indicators, weights, value function).

- Uncertainty analysis: Uncertainty analysis is aimed at involving multiple uncertainty sources into comparative evaluations to provide overall ranking results with uncertainty.

Sensitivity and uncertainty analysis: general comments (2)

IAEA

- (1) Identify uncertainty source:
  - indicator values (objective)
  - weights (subjective)
  - specific parameters used in MCDA tool (the shape of single-attribute value/utility functions in MAVT/MAUT)

- (2) Make an informed estimation of uncertainty:

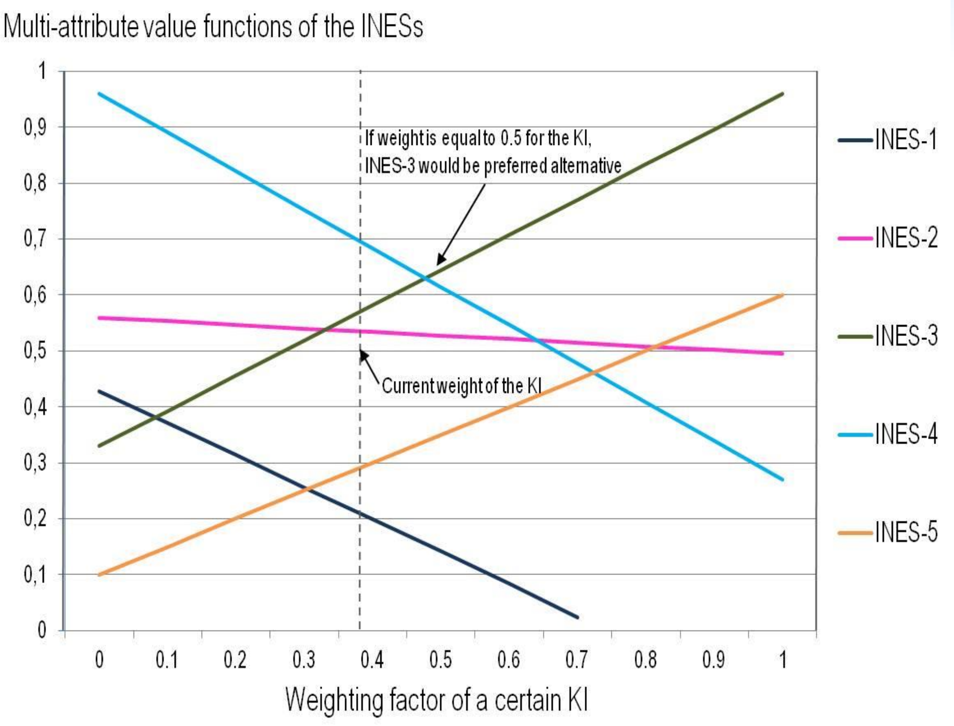
  -- deterministic/probabilistic nature of inputs, range, confidence intervals with a certain probability

- (3) Evaluation of uncertainty in the results
  - sensitivity analysis;
  - uncertainty analysis

Weights' sensitivity

Linear weight approach

In the framework of the 'linear weight' approach, the expert can choose an indicator for a weight sensitivity analysis and analyze how the ranking alternatives will change with a weighting factor changing from 0 to 1 (other weights are automatically changed proportionally holding the weight sum equal to unity).



The figure shows the total scores for each alternative as a function of the corresponding weighting factor value and the base case value of a weighting factor.

Based on this information, the ranks of alternatives may be identified for different weighting factor values as well as the weighting factor areas may be obtained providing the same ranking result.

Linear weight approach

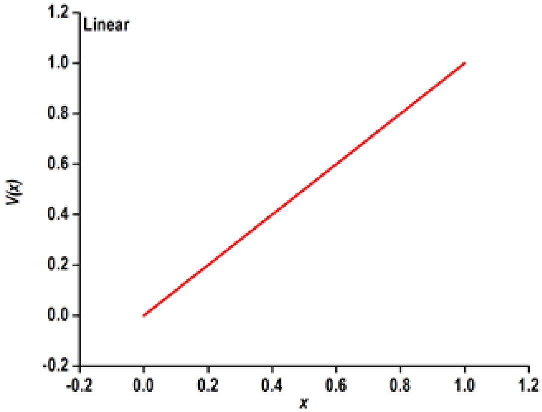
Advanced MCDA tools

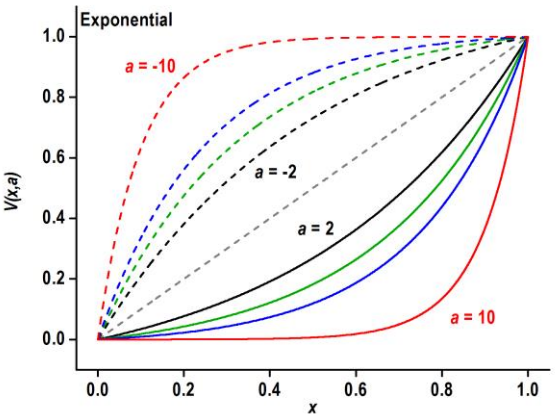
Fuzzy MCDA methods

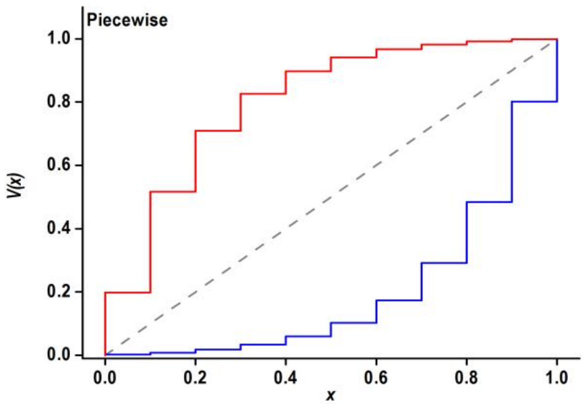
ASPID method

Utility/Value function sensitivity

- *Impact of single-attribute value function forms* on the final results (ranks of alternatives)







Direct approach

Statistical approach

Uncertainty of Key Indicator/ Secondary Indicator values

- Direct approach is used for a qualitative (often visual) analysis: an expert modifies the performance indicator values and directly observes changes in the alternative ranking results and the values of multi-attributive value functions. Based on this procedure, a posteriori experience is created which makes it possible to develop an understanding of ranking results sensitivity to performance indicator values.
-
- Advanced MCDA tools: Multiple Attribute Utility Theory (MAUT) extends the MAVT by using probabilities and expectations to deal with uncertainties. An indicator value uncertainty is represented in the MAUT by a random variable with a given probability density function. The overall utility function for each alternative can be consequently considered as a random variable. Ranking of alternatives within the MAUT is based on a comparison of the expected utilities: one alternative exceeds another one if the mathematical expectation of a utility function for this alternative is larger than that of the corresponding expectation of the utility function for the other ones.

Comparison with other MCDA tools Ranking of nuclear energy systems (1 – best, 5 - worst)

Nuclear energy systems/Alternatives	Ranking of nuclear energy systems		
	MCDA method 1	……	MCDA method k
1	3		3
2	1		1
3	2		2
4	4		5
5	5		4

Hypothetical NES comparison

This case study demonstrates a procedure to perform a comparative evaluation of NESs and interpret the results

I. Comparative evaluation of 5 hypothetical NESs – testing the KIND approach and demonstrating the relevant comparative evaluation procedure

Assumptions: 3-level objectives tree, 15 KI and 15 SI, linear decreasing value functions

II. Comparative evaluation of 2 hypothetical NESs – demonstration of the specifics using different scoring scales and domains of a single-attribute value function

Assumptions: 3-level objectives tree, 19 KI, linear increasing value functions

Five NESs: performance table

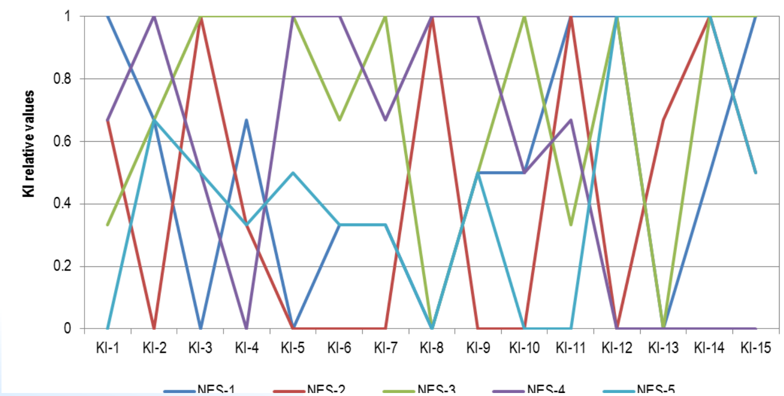
An indicator value with **score 1 is the best value**; an indicator value with **score 5 is the worst one**

Performance tables were formed randomly

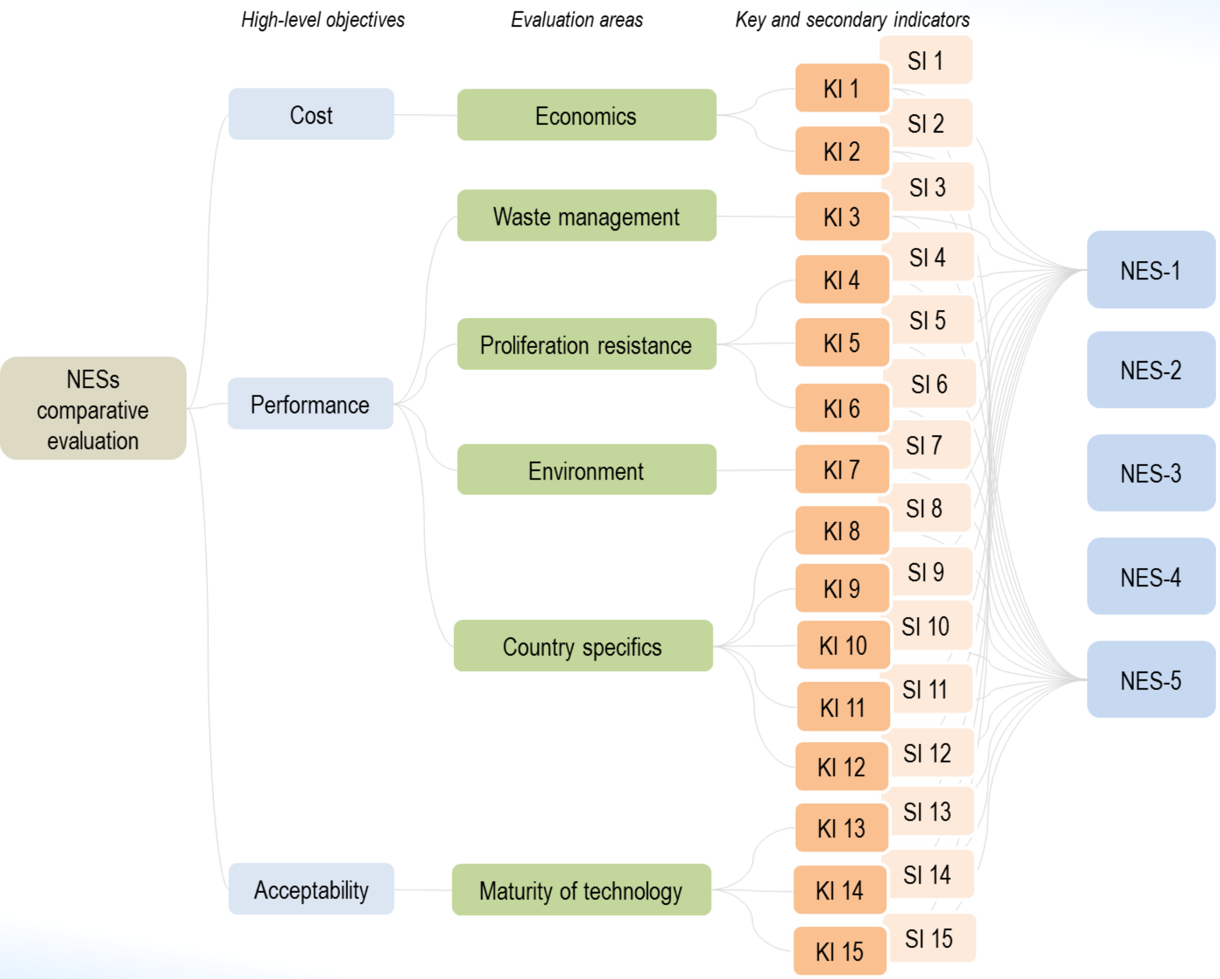
Model parameters were selected in line with the recommendations of the KIND project:

- 15 KIs are used
- The target is to minimize all KIs
- Linear decreasing functions defined on local domains were used as single-attribute value functions for the base case

KIs	#	NES-1	NES-2	NES-3	NES-4	NES-5
E.1	1	1	2	3	2	4
E.2	2	2	4	2	1	2
WM.1	3	5	1	1	3	3
PR.1	4	2	3	1	4	3
PR.2	5	5	5	3	3	4
PR.3	6	4	5	3	2	4
ENV.1	7	3	4	1	2	3
S.1	8	4	3	4	3	4
S.2	9	3	4	3	2	3
S.3	10	3	4	2	3	4
S.4	11	2	2	4	3	5
S.5	12	2	4	2	4	2
M.1	13	4	2	4	4	1
M.2	14	4	3	3	5	3
M.3	15	3	4	3	5	4



Five NESs: objectives tree



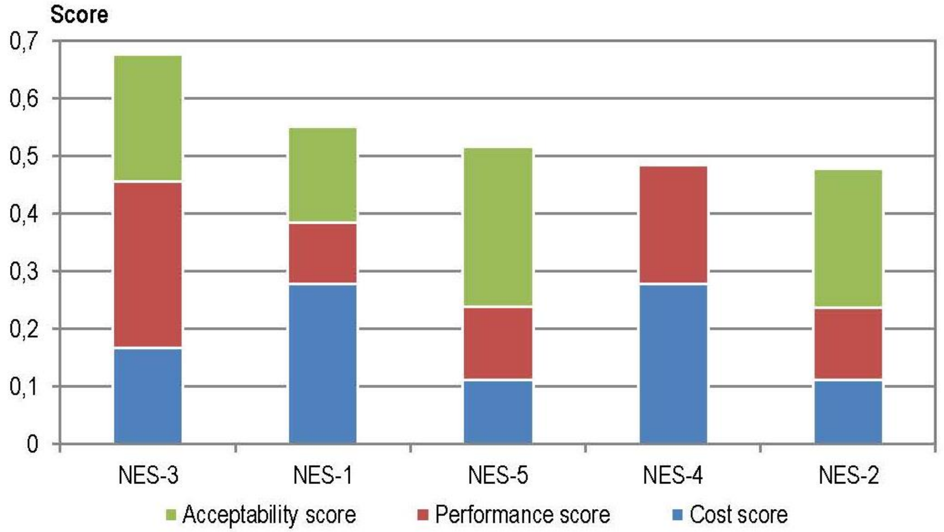
KIs	weights
E.1	0.167
E.2	0.167
WM.1	0.083
PR.1	0.028
PR.2	0.028
PR.3	0.028
ENV.1	0.083
S.1	0.017
S.2	0.017
S.3	0.017
S.4	0.017
S.5	0.017
M.1	0.111
M.2	0.111
M.3	0.111

Five NESs: ranking results

Overall score	NES-1	NES-2	NES-3	NES-4	NES-5
Multi-attribute value function	0.550	0.478	0.677	0.483	0.516

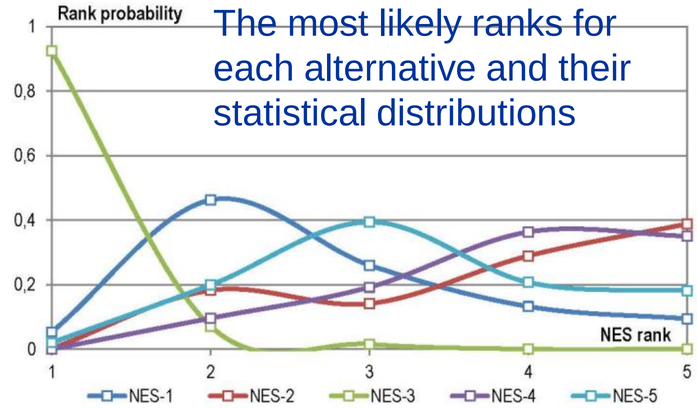
High-level objectives scores	NES-1	NES-2	NES-3	NES-4	NES-5
Cost	0.278	0.111	0.167	0.278	0.111
Performance	0.106	0.126	0.288	0.206	0.127
Acceptability	0.167	0.241	0.222	0.000	0.278

Areas' scores	NES-1	NES-2	NES-3	NES-4	NES-5
Economics	0.278	0.111	0.167	0.278	0.111
Waste management	0.000	0.083	0.083	0.042	0.042
Proliferation resistance	0.028	0.009	0.074	0.056	0.032
Environment	0.028	0.000	0.083	0.056	0.028
Country specifics	0.050	0.033	0.047	0.053	0.025
Maturity of technology	0.167	0.241	0.222	0.000	0.278



Five NESs: sensitivity analysis

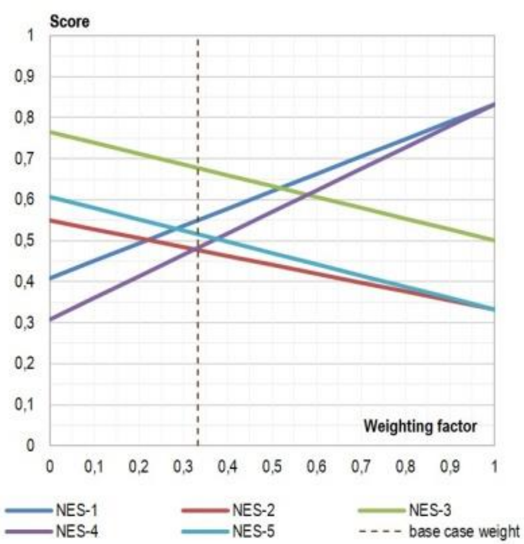
Impact of single-attribute value function shapes on ranks



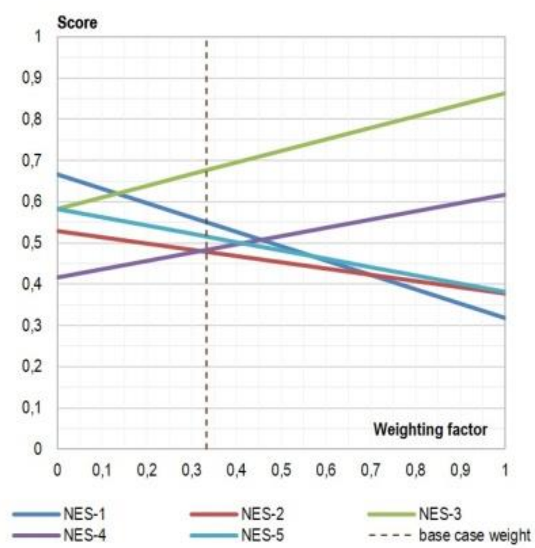
- To demonstrate the sensitivity of the ranking results to the forms of single-attribute value functions, a special statistical analysis was carried out using randomly chosen generation of single-attribute value functions and building a statistical ranks distribution of each considered alternative.

Linear weights approach to weights sensitivity analysis

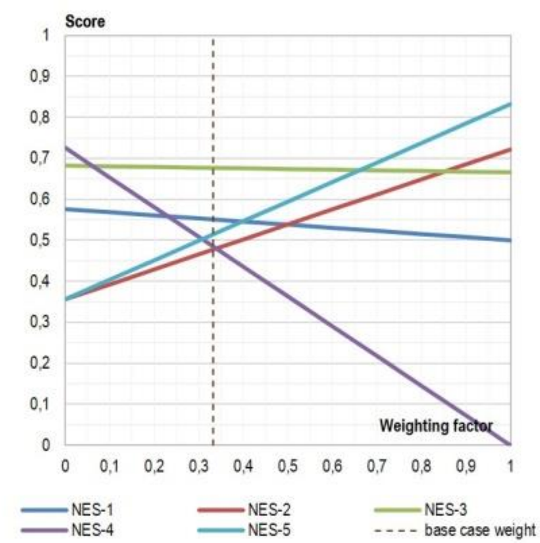
'Cost' weight



'Performance' weight

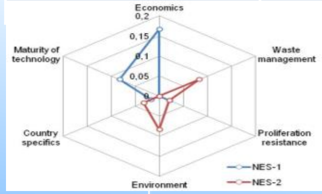


'Acceptability' weight



Two NESs: performance table

High-level objectives	Area	KI abbr,	Qualitative evaluation		2-point scoring scale		10-point scoring scale	
			NES-1	NES-2	NES-1	NES-2	NES-1	NES-2
Cost	Economics	E.1	x		1	0	9	1
		E.2	~	~	0	0	6	5
Performance	Waste management	WM.1		x	0	1	2	9
		WM.2		x	0	1	1	10
		WM.3		x	0	1	2	10
	Proliferation resistance	PR.1	x		1	0	10	2
		PR.2		x	0	1	1	10
		PR.3	~	~	0	0	2	3
		PR.4	~	~	0	0	4	3
	Environment	ENV.1		x	0	1	1	9
	Country specifics	CS.1	~	~	0	0	8	7
		CS.2	~	~	0	0	7	6
		CS.3	x		1	0	10	1
		CS.4		x	0	1	1	10
		CS.5		x	0	1	2	9
Acceptability	Maturity of technology	M.1	~	~	0	0	6	5
		M.2	~	~	0	0	0	0
		M.3	~	~	0	0	2	3
		M.4	x		1	0	9	2

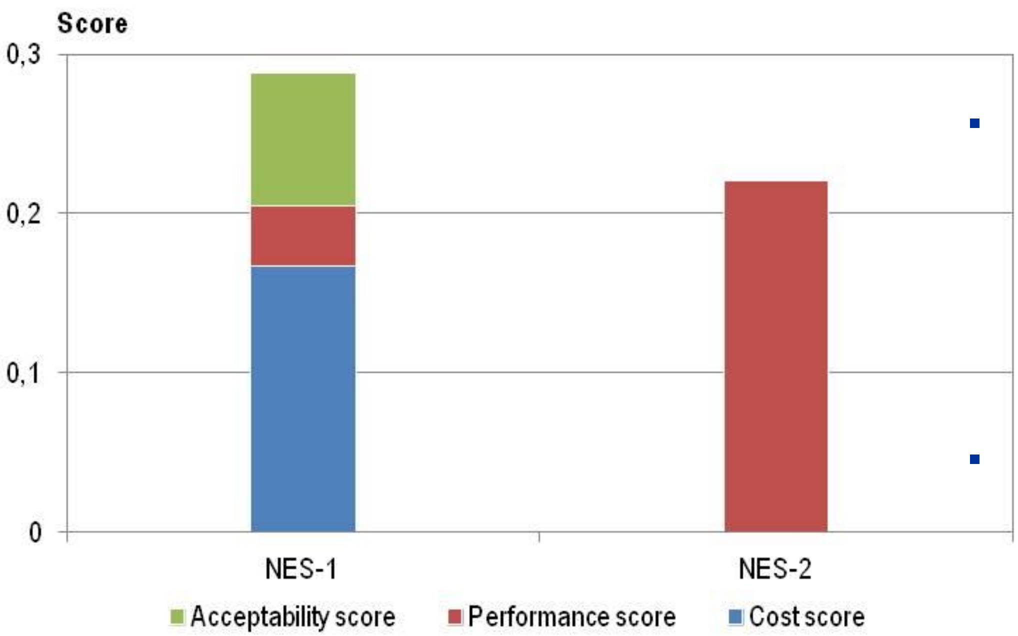


x – a pointer for the NES which provides the best performance on a corresponding KI
~ – a pointer of a KI on which both NESs have comparable performance

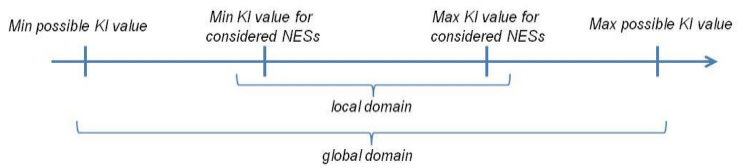
Two NESs: ranking results

NES options	Overall scores			
	2-point scoring scale		10-point scoring scale	
	Local domains	Global domains	Local domains	Global domains
NES-1	0.288	0.288	0.592	0.440
NES-2	0.221	0.221	0.325	0.368
Δ (NES-1 – NES-2)	0.067	0.067	0.267	0.072

Ranking results for 2-point scoring scale



- When two NESs are compared with local domains, the ranking results are not sensitive to the form of single-attribute value functions
- The same is true for global domains of single-attribute value functions within a 2-point scoring scale

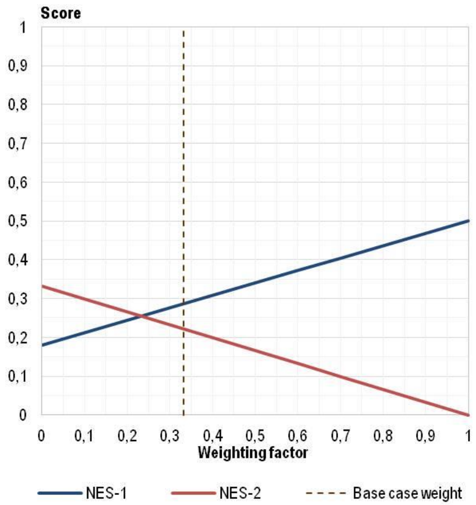


- If global domains and a 10-point scoring scale is used, the probability that the first alternative would have the first and second ranks would be equal to 77% and 23%, respectively

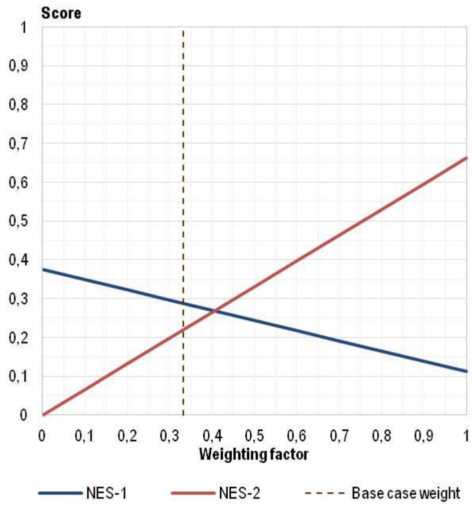
Two NESs: sensitivity analysis

Linear weights approach to weights sensitivity analysis

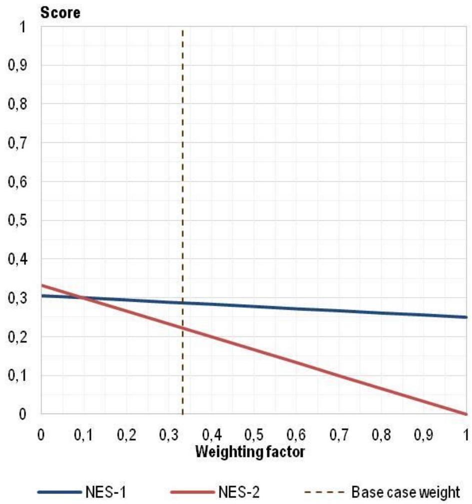
‘Cost’ weight



‘Performance’ weight



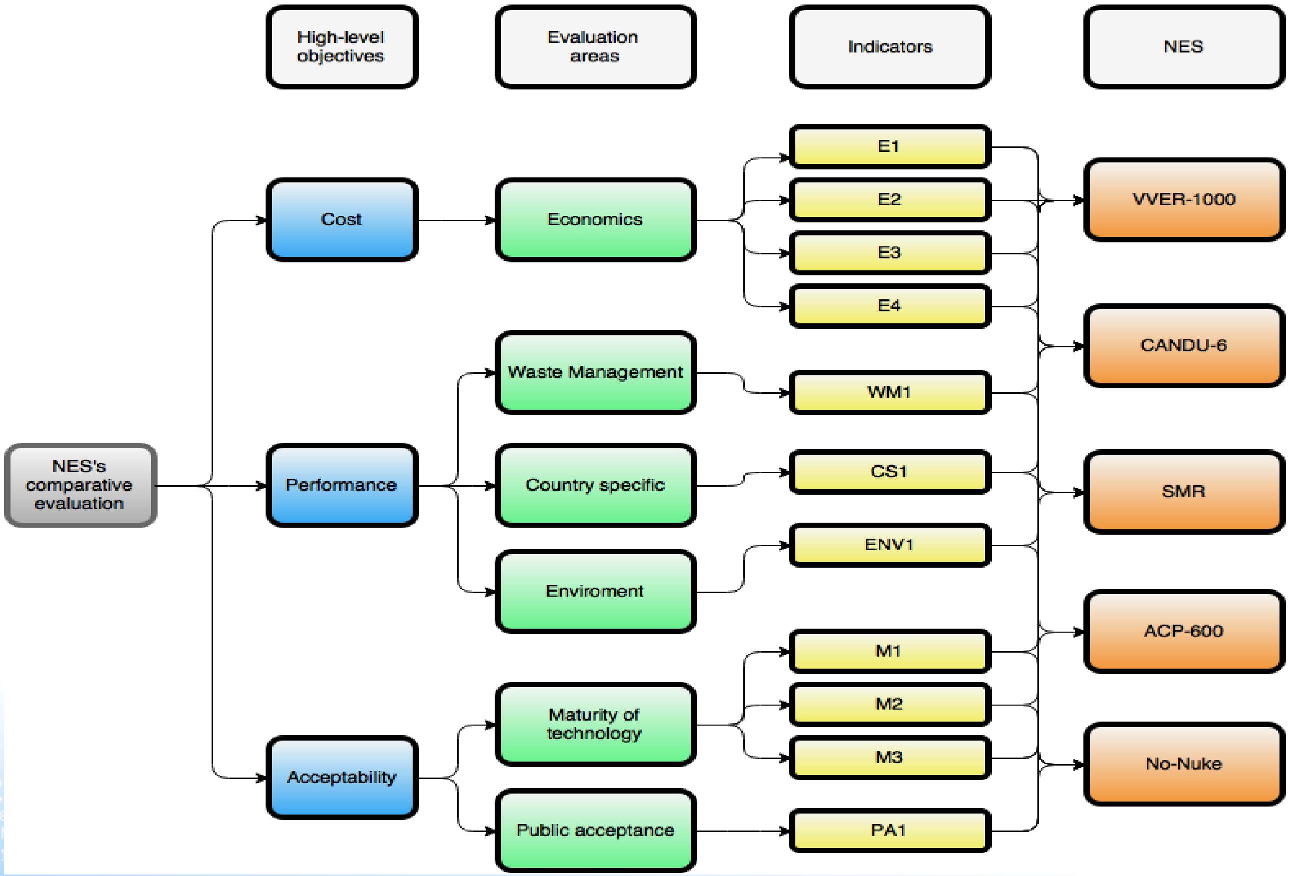
‘Acceptability’ weight



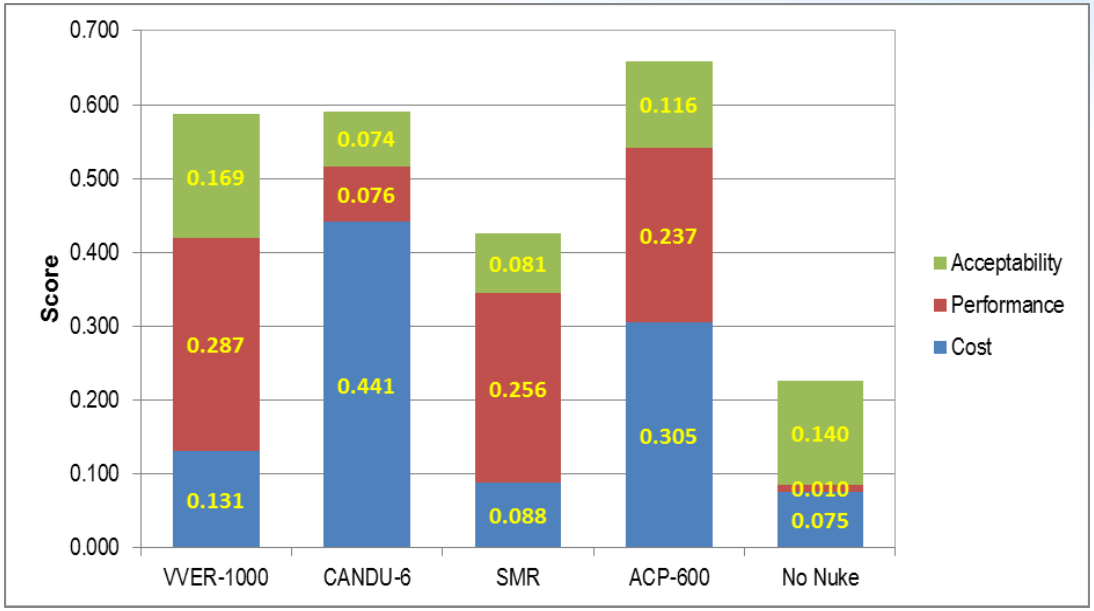
Case study from Armenia (1)

The overall objective was to clarify and select the most attractive nuclear option for Armenia. The main nuclear (i.e., WWER-1000, CANDU-6, SMR (small modular reactor) of 360 MW(e) and ACP-600) and thermal generation expansion plans have been evaluated in this study.

The structure of the objectives tree in the Armenian case study



Case study from Armenia (2)



‘Cost’ : 0.5
‘Performance’: 0.3
‘Acceptability’: 0.2

The most desirable alternative for implementation in Armenia is a medium sized reactor ACP-600 with an overall score of 0.658. The differences in alternatives CANDU-6 and WWER-1000 can be considered as indistinguishable according to the scores of multi-attribute value functions; these options take the second and third places, respectively. The worst case for energy system development is No Nuke scenario, which has significantly low ranking value (0.225).

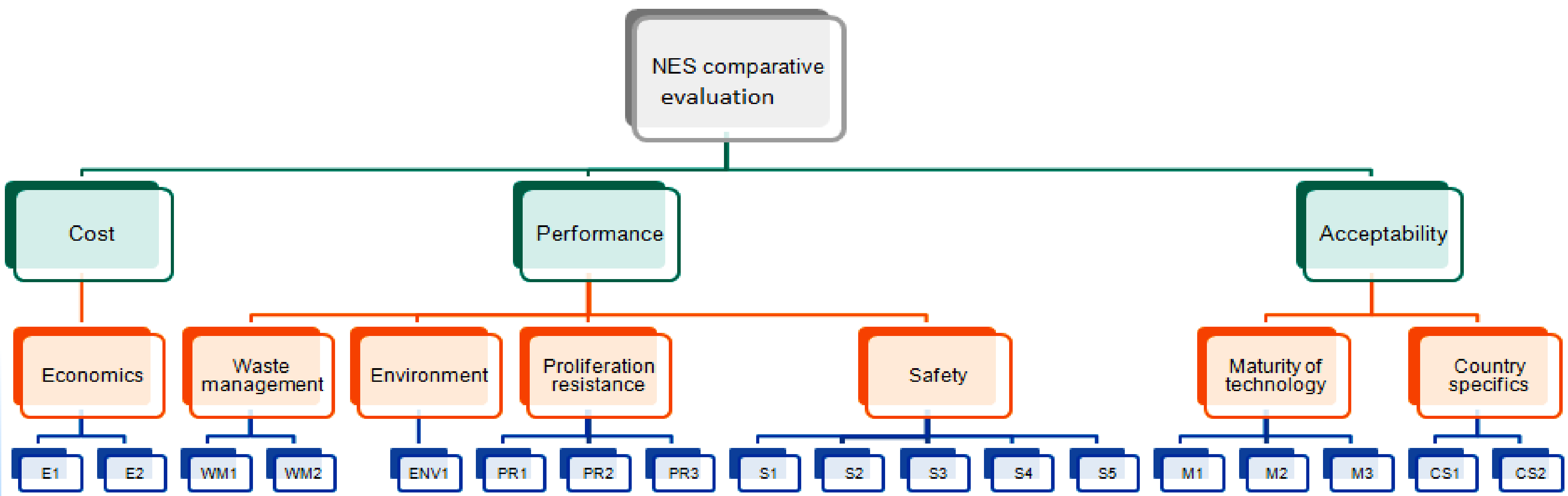
For the ranking results interpretation, it is necessary to decompose multi-attribute value functions into individual components in accordance with the specified structure of objectives tree. CANDU-6 has the best rank for Cost (0.441) followed by ACP-600 (0.305). At the same time, CANDU-6 has the lowest rank of Performance and Acceptability in nuclear options, whereas WWER-1000 takes the best rank.

Case study from Romania (1)

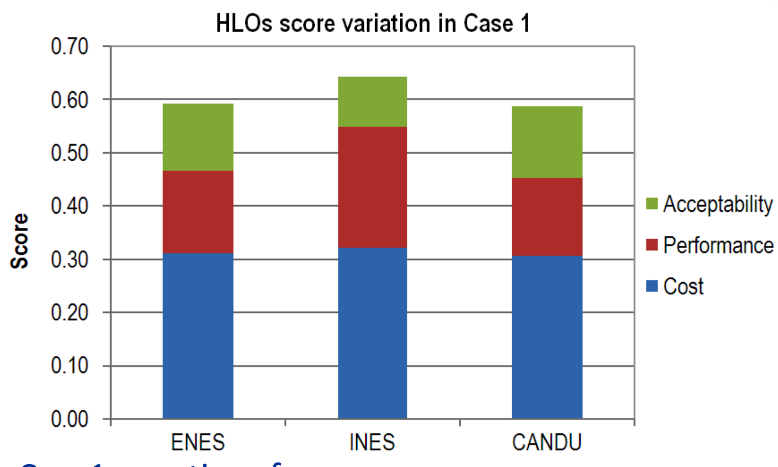
The study performed by the expert team from Romania addressed the following specific objectives:

- To evaluate ENES (PHWR) and INES (LFR) together with the already existing/operating NES technology (CANDU 6), based on specific key indicators (key indicators developed under the framework of the KIND project) and taking into consideration the country specifics;
- To examine the robustness of the obtained results by performing sensitivity analysis.

The structure of the objectives tree in the case study from Romania

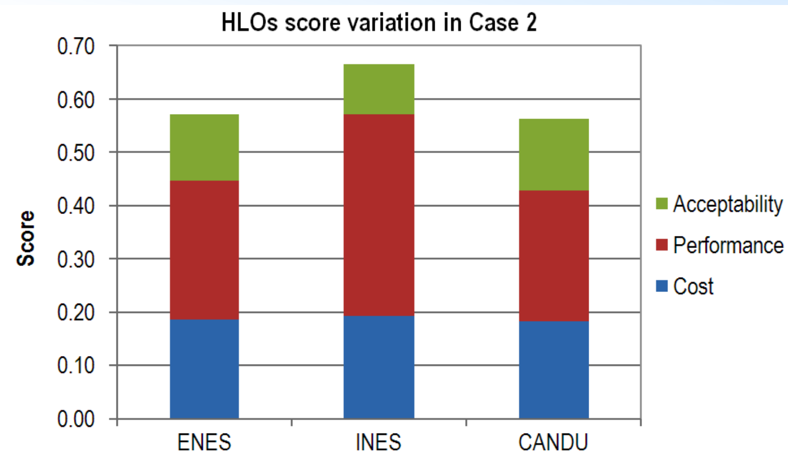


Case study from Romania (2)



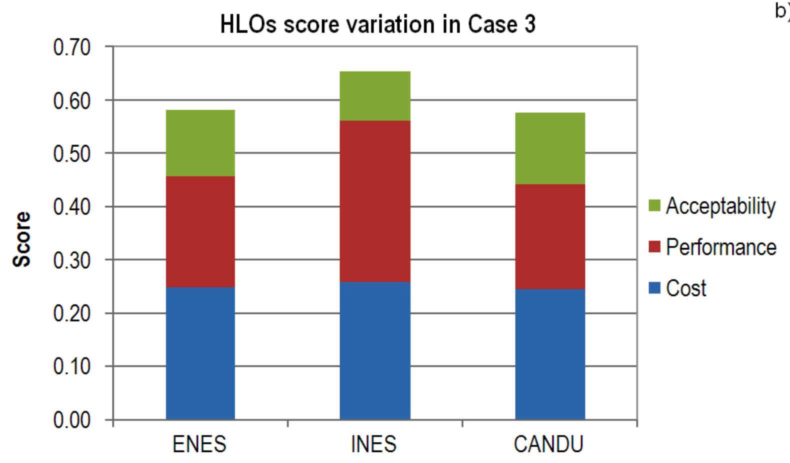
a)

Case1 — ratings for HLOs: cost 50%, performance 30%, acceptability 20%



b)

Case2 – ratings for HLOs: cost 30%, performance 50%, acceptability 20%



c)

Case3 – ratings for HLOs: cost 40%, performance 40%, acceptability 20%

Innovative NES technology appears to be more attractive than the evolutionary NES technology.

The CANDU NES technology has the lowest overall scores

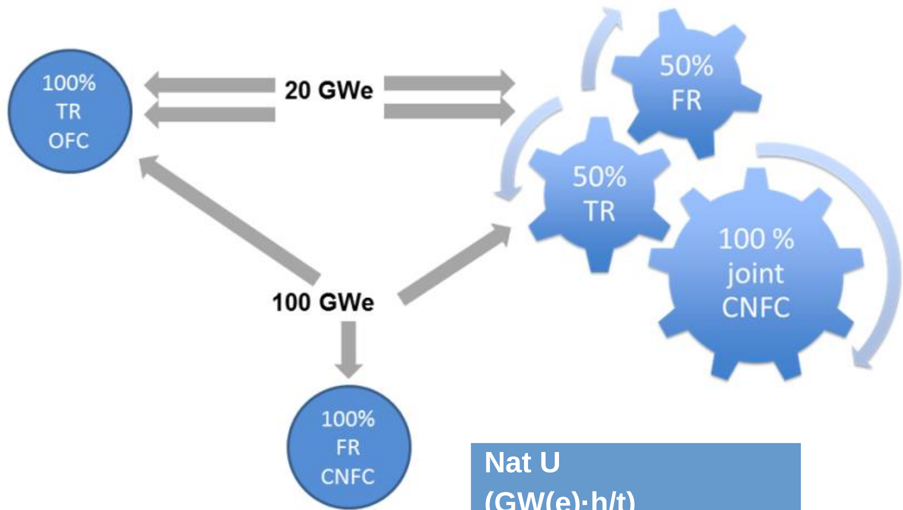
Parameter	CANDU	ENES	INES
Reactor type	PHWR	PHWR	LFR
Fuel type	Natural UO_2	Slight enriched UO_2	MOX

Case studies from Russia (1)

Two case studies have been performed by Russian experts under the KIND project on comparison of NESs based thermal and fast reactors with closed nuclear fuel cycle.

The following types of reactors were considered in the case study:
Thermal reactor (TR) technologies TR1, TR2 and TR3 have the same technical features regarding natural uranium consumption and spent fuel generation but different levelized unit fuel cost in the fuel cycle back end.

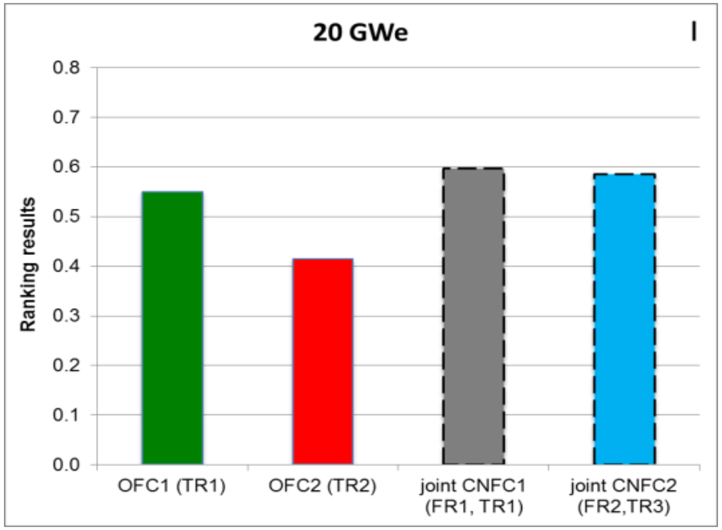
There are two types of fast reactor (FR) technologies under consideration in the current study. The first fast reactor FR1 is considered as near term deployable reactor. As a new technology, LUEC is higher than TR. The fast reactor FR2 is a concept project with improved safety in design and more attractive LUEC. FR1 consumes MOX-fuel; FR2, depending on the system under consideration, consumes MOX or enriched uranium fuel.

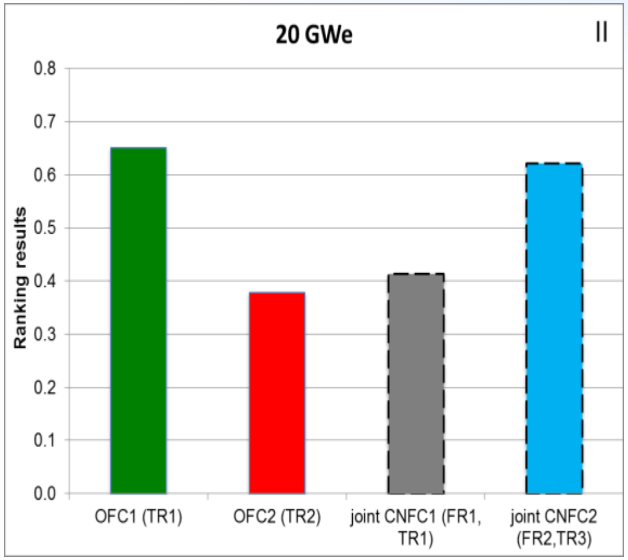


Nat U (GW(e)·h/t)
LUEC (US $/MW(e)·h)
Wastes (t/TW(e)·h)
TtMature (years)
R&D refund (billion US $)

Case studies from Russia: Ranking results

Ranking results for different weighting options





KI Final weight	1 Nat. U	2 LUEC	3 Wastes	4 TtMature	5 R&D refund
Option I	0.15	0.25	0.3	0.25	0.05
Option II	0.15	0.5	0.2	0.1	0.05

Option I focuses on 'Wastes' key indicator , In this case, the potential of OFC1(TR1) will be lower than that of the joint CNFC1 (FR1, TR1). This result indicates that an acceptable solution to the problem can be found in the fuel cycle back end in case of cooperation among the technology holder and the technology user countries. Option II allows to postpone decisions regarding the final stages of the NFC, such as long term interim storage of SNF. An open NFC 1 based on thermal reactors TR1 (OFC1(TR1)) acquires the highest score/potential with the value 0.65. This is an option where the best cost makes the best alternative.

Case study from Thailand

IAEA

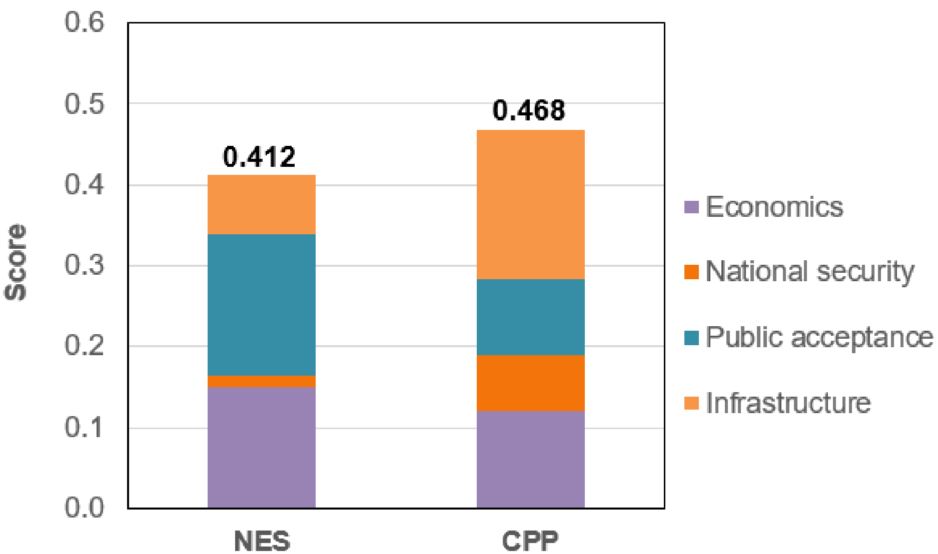
The objective of the study was to apply a set of KIs (tailored to address the needs of newcomer countries) for comparative evaluation of NES and a non-nuclear energy system (non-NES). The KI set enveloped the four areas: economics, national security, public acceptance and infrastructure.

The structure of the objectives tree in the Thailand case study

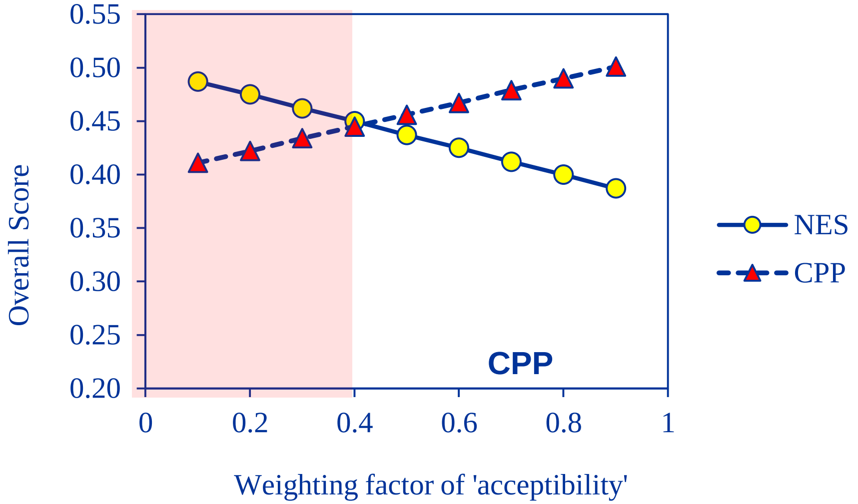
Area title	Key indicator
Economics	Levelized unit electricity cost (LUEC)
	Cash flow
National security	Degree of dependence on supplier(s)
Public acceptance	Survey of public acceptance
	External cost
	Risk of accident
Infrastructure	Status of legal framework
	Status of State organizations
	Availability of infrastructure to support owner/operator
	Government policy
	Availability of human resources

Case study from Thailand: Ranking results

Structure of area scores for NES and CPP for Option 1



Structure of area scores for NES and CPP for Option 2



For a case when NES is less attractive than coal power plant (CPP) the ratio of the HLO weighting factors ‘Economics’ to ‘Acceptability’ was 0.3/0.7

The sensitivity analysis has to be performed by varying the ratio of the high-level objective weighing factor and fixing the weighting factors of the evaluation area and the indicators

Exercise on comparative evaluation of NESs (part II)

Compared NES:

1. NES1 (evolutionary NES - ENES)
2. NES2 (innovative NES - INES)
3. NES3 (advanced NES - ANES)

Performance table and weighting factors

Evaluation areas / Key Indicators	Goal	ENES	INES	ANES
Economics Levelized energy product or service cost	Min	2	5	3
Waste management Specific radwaste inventory	Min	9	1	6
Environment The amount of useful energy produced by the system from a unit of mined natural uranium	Max	2	9	4
Country specific Socio-economic impact	Max	2	5	3
Maturity of technology Time needed to mature the technology	Min	1	4	2

Evaluation areas / Key Indicators	Weights
Economics Levelized energy product or service cost	0.200
Waste management Specific radwaste inventory	0.200
Environment The amount of useful energy produced by the system from a unit of mined natural uranium	0.200
Country specific Socio-economic impact	0.200
Maturity of technology Time needed to mature the technology	0.200

Indicators $\{x_i\}$ i=1,……n ,

NESs, $\{NES_j\}$ j=1,……m ,

Performance table:

$$X = \begin{pmatrix} x_{11} & \dots & x_{1n} \\ \dots & \dots & \dots \\ x_{m1} & \dots & x_{mn} \end{pmatrix}$$

Single linear value function

$min \le x_i \le max$ $0 \le u_i(x_i) \le 1$

$$u(x) = \frac{x - x^{min}}{x^{max} - x^{min}}$$ Increasing value function

$$u(x) = \frac{x^{max} - x}{x^{max} - x^{min}}$$ Decreasing value function

Weights w_i, $w=\{w_1, w_2, \dots w_n\}$

$\Sigma w_i=1$

Additive value function

$G_j=\Sigma w_i \times u_i(x_i)$

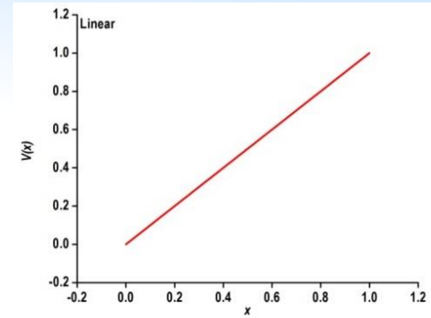
$G=\{G_1, G_2 \dots G_m\}$

Remark on increasing/ decreasing value functions

IAEA

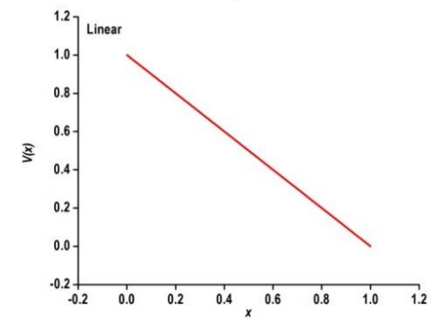
Increasing value functions

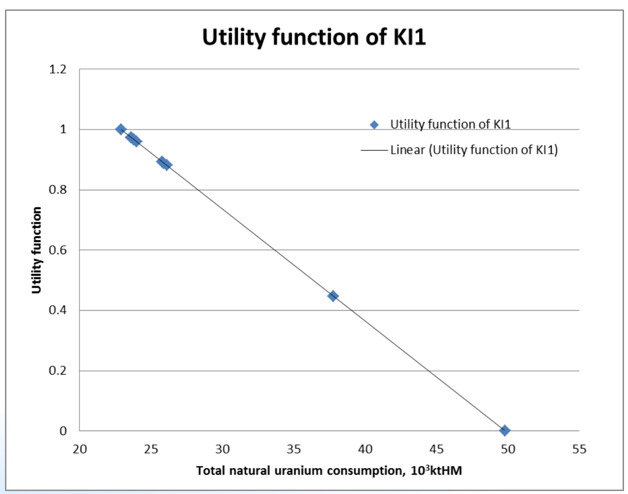
$$u(x) = \frac{x - x^{\min}}{x^{\max} - x^{\min}}$$



Decreasing value functions

$$u(x) = \frac{x^{\max} - x}{x^{\max} - x^{\min}}$$





Ranking result

NES/ KI	Goal	NES1	NES1	NES1
1	Min	2	5	3
2	Min	9	1	6
3	Max	2	9	4
4	Max	2	5	3
5	Min	1	4	2

Increasing value function

$$u(x) = \frac{x - x^{\min}}{x^{\max} - x^{\min}}$$

Decreasing value function

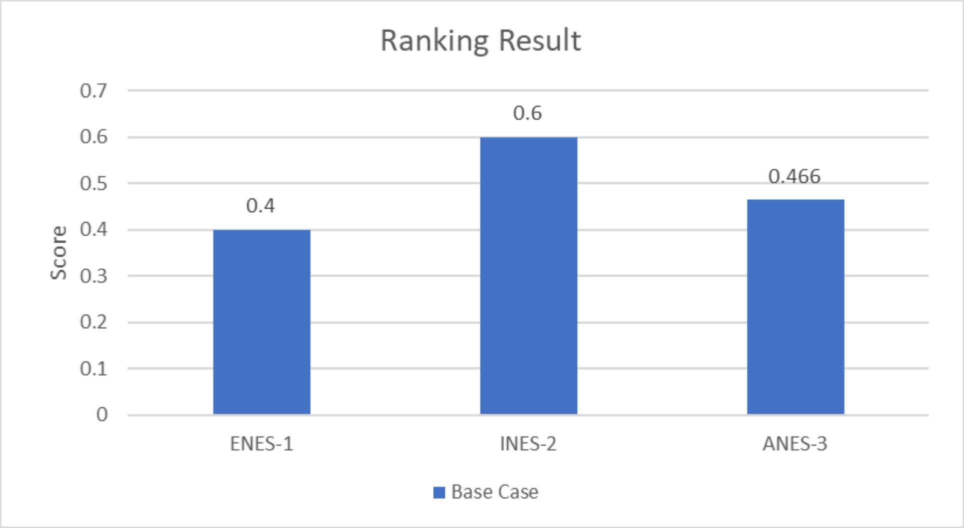
$$u(x) = \frac{x^{\max} - x}{x^{\max} - x^{\min}}$$

NES/ KI		NES1	NES1	NES1
1		1.000	0.000	0.667
2		0.000	1.000	0.375
3		0.000	1.000	0.286
4		0.000	1.000	0.333
5		1.000	0.000	0.667

$\otimes$

Weights
0.200
0.200
0.200
0.200
0.200

G={0.400, 0.600, 0.466 }



Performance table and weighting factors

Evaluation areas / Key Indicators	Goal	ENES	INES	ANES
Economics Levelized energy product or service cost	Min	2	5	3
Waste management Specific radwaste inventory	Min	9	1	6
Environment The amount of useful energy produced by the system from a unit of mined natural uranium	Max	2	9	4
Country specific Socio-economic impact	Max	2	5	3
Maturity of technology Time needed to mature the technology	Min	1	4	2

Evaluation areas / Key Indicators	Weights
Economics Levelized energy product or service cost	0.500
Waste management Specific radwaste inventory	0.125
Environment The amount of useful energy produced by the system from a unit of mined natural uranium	0.125
Country specific Socio-economic impact	0.125
Maturity of technology Time needed to mature the technology	0.125

Ranking result ?

THANK YOU
for your attention!

Technological options for enhancing nuclear energy sustainability

- Once-through NFC: this is currently the most widespread, although not the only option realized in the majority of countries using nuclear energy. The reactors currently operated in a once-through nuclear fuel cycle include multiple light water reactors (LWRs), gas-cooled reactors (GCRs), heavy water reactors (HWRs) but at further stages could include additional reactor types, some of which could achieve high fuel burn-up with savings in natural uranium consumption and a reduction in specific radioactive waste production.
- Recycle of SNF with only physical processing: This option provides for a single recycle of spent nuclear fuel (SNF) from reactors of a particular type in nuclear reactors of another type, with no chemical reprocessing applied. It could help to a small extent save natural uranium resources and reduce SNF volume for final disposal, while avoiding the use of proliferation sensitive chemical reprocessing technology. The technological readiness of such an approach is rated high; however, it has so far never been implemented in practice.
- Limited recycling of SNF: This enhancement option includes chemical reprocessing and is a step in improving resource utilization and reducing the waste burden. Limited recycle reduces SNF volumes, slightly improves resource utilization, and keeps fertile fuel resources more accessible for later options of sustainability enhancement, thus offering some flexibility for long term management of nuclear materials. This option is commercially realized as single mixed oxide (MOX) fuel recycle in LWRs.
- Complete recycle of SNF: With the use of a closed nuclear fuel cycle and breeding of fissile material, all natural resources of fissile (^{235}U) and fertile (^{238}U) uranium and (^{232}Th) thorium could eventually be utilized through the conversion of all fertile nuclear materials into fissile with their subsequent fission. This enhancement option realizes full utilization of the energy potential of nuclear fuel. It also reduces the long-lived radiotoxicity burden of HLW by up to an order of magnitude, especially through keeping plutonium out of the waste. Within this option both, fast and thermal reactors of different types are being considered, including sodium (SFR) and heavy liquid metal cooled (HLMFR) fast reactors, fast gas cooled reactors (GCR), LWRs, HTGRs, molten salt and liquid (non-fuel) salt reactors, etc.
- Minor actinide or minor actinides and fission products transmutation: A closed nuclear fuel cycle with recycling of all actinides and final disposal of only fission products would provide the maximum benefits for combined resource utilization and waste hazard minimization. This enhancement option builds on the technologies of the previous options, but also requires the development and deployment of minor actinide reprocessing/partitioning, minor actinide-bearing fuels/targets and remote fuel/target fabrication technologies. A couple of decades ago an option to transmute, along with minor actinides, also long-lived fission products was considered. As it was found that long term radiotoxicity of long-lived fission products is much less than that of the minor actinides, further research along this trend faded. The nuclear installations associate with this option may include commercial or dedicated fast reactors of different types, as well as accelerator driven systems (ADS) and molten salt reactors (MSRs).
- Final geologic disposal of all wastes: Final geological disposal of SNF/high level waste (HLW) applies to all sustainability enhancement options mentioned above. To be sustainable, each generic fuel cycle option mentioned above must be amended by final geologic disposal either of SNF, or of some combinations of minor actinides and fission products, or of fission products only.

Introduction in International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

IAEA

Membership-based **International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)** increases international cooperation on global nuclear energy sustainability, long term strategies and institutional and technical innovations for nuclear energy development and deployment. INPRO supports activities in the following main areas: global scenarios; innovations; sustainability assessment and strategies; and policy and dialogue.

- **Global scenarios**
  - Activities are focused on developing 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.
- **Innovations**
  - In close collaboration with Member States, INPRO investigates innovative nuclear energy technologies and institutional arrangements that support the development of sustainable nuclear energy in Member States in the current century, and disseminates good practices.
- **Sustainability assessment and strategies**
  - Activities aim at assisting Member States in developing sustainable, long-range, national nuclear energy strategies and related deployment decision-making through the application of the INPRO Methodology in Nuclear Energy System Assessments conducted by Member States.
- **Dialogue and outreach**
  - The INPRO Section provides an international venue for Member States' guidance, for policy coordination and for coordination with other international organizations and initiative. Dialogue Forums on Global Nuclear Energy Sustainability bring together technology holders and users to exchange ideas and information on long-range nuclear energy system strategies, global nuclear energy scenarios and related technical and institutional innovations. The work also focuses on developing and implementing outreach and training activities in support of the services provided by the INPRO Section to Member States.

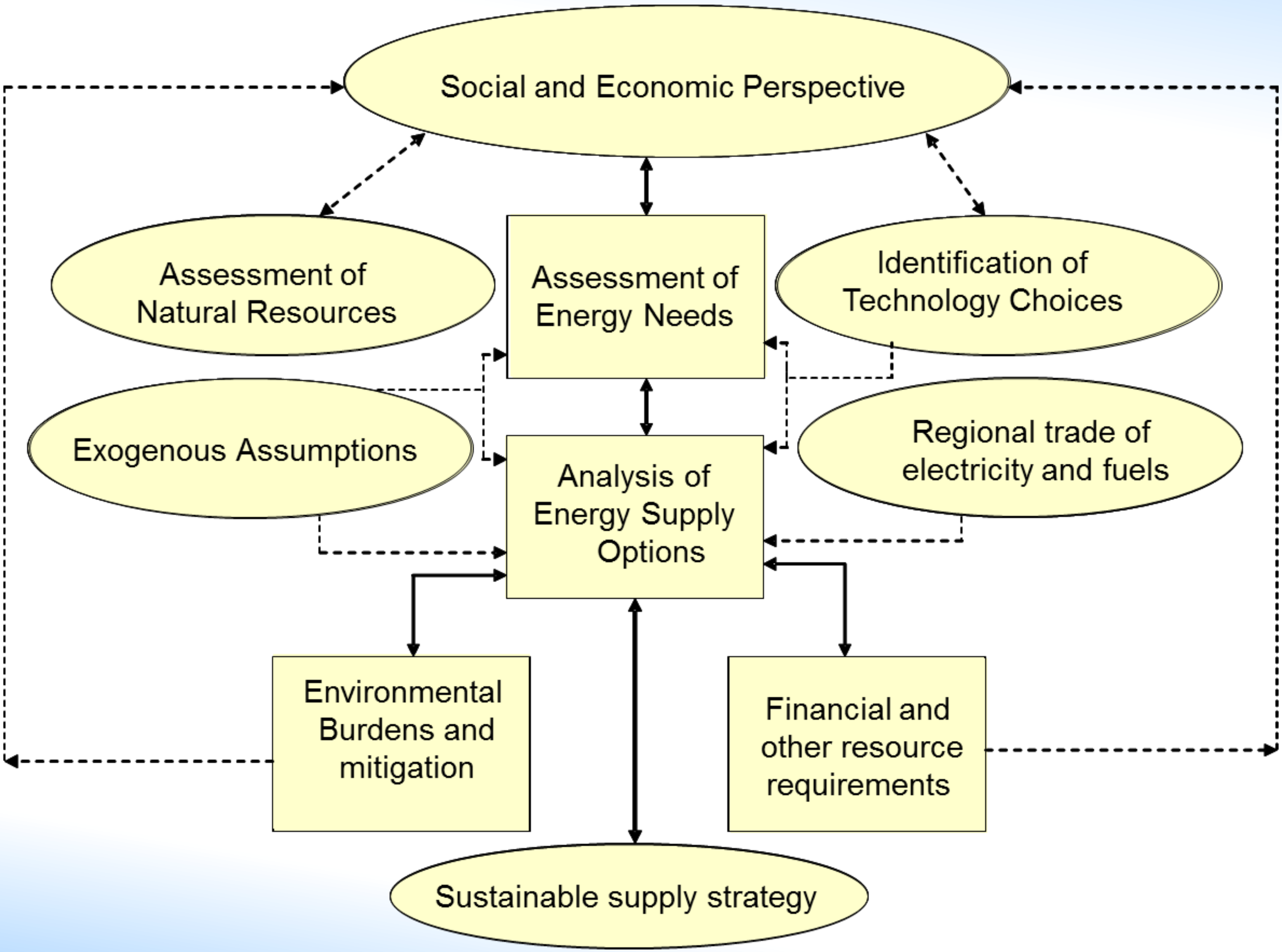
Collaborative enhancements

IAEA

- ***National indigenous technology development*** – nuclear energy technologies developed indigenously (development of National intellectual property) as part of a national nuclear RD&D program as opposed to those imported from a supplier State, If these technologies are integrated into larger systems such as whole reactors, facilities or a set of facilities, they may combine both national indigenous technologies and imported technologies into a single NES construct, This is a common situation in many advanced nuclear supplier States,
- ***Bilateral agreement*** – generically known as an agreement for co-operation on peaceful nuclear energy, 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, Typically a country may conclude one or several of these bilateral agreements depending on the needs of its industry for imports and exports of materials, equipment, services and intellectual property, This is the most common type of co-operation agreement,
- ***Multilateral agreement*** – 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, Such agreements may also act as umbrellas to create broader nuclear governance institutions within the block of countries such as development of a Secretariat that manages common minimum expectations on regulations, a semi-independent inspection regime, group ownership of nuclear materials and control and security of supply, etc, It could also be an umbrella agreement that is narrow to trade and co-operation on a single part or critical technology underpinning the nuclear industry (sensitive fuel cycle technology is a current example),

I. Energy system planning

Framework for Long Term Energy Assessment



Developing Infrastructure for Enhanced NES Sustainability

- The IAEA Milestones document (Milestones in the Development of a National Infrastructure for Nuclear power, IAEA Nuclear Energy Series No, NG-G-3,1 (Rev1), IAEA, Vienna, 2015) provides guidance in establishing an adequate infrastructure for the first nuclear power plant for decision-makers developing a national nuclear power programme in the near term
- For achieving and enhancing long-term NES sustainability the INPRO Manual on infrastructure (Nuclear Energy Series No, NG-T-3,12, 2014), in particular, recommends that:

"UR6: Regional and international arrangements:

- Regional and international arrangements should provide options that enable a country with an NES to minimize the infrastructure for a nuclear power programme"

- As shown on the previous slides, developing infrastructure for regional and international arrangements may require long time it needs to be taken into account when developing pathways to achieve and enhance sustainability of national NES