INPRO – SYNERGIES Workshop
Dialogue Forum on Drivers and Impediments for Regional Cooperation on the Way to Sustainable NES

Towards Sustainable Nuclear Energy Systems: A Collective Approach

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INPRO – SYNERGIES Workshop
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July 30th – August 3rd 2012
The energy challenges for our society

- Despite various efforts with regard to energy demand management, the global energy demand is soaring
- Contributing to climate change

Ref: IEA Energy Outlook 2010

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>1973</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Energy</td>
<td>6,115 Mtoe</td>
<td>12,267 Mtoe</td>
</tr>
<tr>
<td>Electricity</td>
<td>3,724 Mtoe</td>
<td>5,170 Mtoe</td>
</tr>
</tbody>
</table>

*Other includes geothermal, solar, wind, heat, etc.

Primary energy demand growth:
- + 1.5%/an × 1.35 × 2.1
- + 2%/an × 1.49 × 2.7
Our current Energy system is not sustainable to face the energy and climate challenges

Growing energy demand

- A 50% increase by 2030

Declining oil and gas feedstock

Unequal economic growth

- Developing countries
- OECD

Greenhouse gases emissions

- A 50% reduction by 2050


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Energy demand is fueled by two major criterias:

Population will increase by 2 billion people by 2030

- Population (in billion)
  - 2005: 8.0
  - 2010: 7.5
  - 2015: 7.0
  - 2020: 6.5
  - 2025: 6.0
  - 2030: 7.0

- 25% increase by 2030

Human Development will increase energy intensity

- Human Development Index
- kWh/cap
- Russia
- France
- India
- Japan
- USA
- Canada
- Norway
- Ivory Coast

Energy demand will increase by 50% by 2030

- Energy demand (in Gtoe)
  - 2005: 18
  - 2010: 16
  - 2015: 14
  - 2020: 12
  - 2025: 10
  - 2030: X1.5

Electricity demand will be multiplied by 2.5 meanwhile

Sources: UN population forecast 2008, IAE WEO 2009
Fossil fuel reserves and price uncertainty put at stake energy independance in various countries

Fossil fuels are becoming scarce

The globe will see oil production peak in 2020 about a decade earlier than most official government predictions. Prices are increasingly volatile.

Sources slide: Association Study of Peak Oil & Gas, 2007 et BP statistical review 2008

... while the levels of energy dependency remain high

Sources slide: Association Study of Peak Oil & Gas, 2007 et BP statistical review 2008

August 2009 – Birol : Chief Economist IEA
Major challenge towards sustainability
Reducing the GHG-emissions per TWh used

Without any change in the way we convert primary energy into energy services, a massive increase of GHG-emissions is to be expected.

In addition, the initial higher investments required to switch towards « zero-emission » energy technologies might not be viable in all markets.
Nuclear energy as part of a sustainable energy future

- Impediments towards a wider use of nuclear energy, i.e.
  - Economic competitiveness isn’t a given in all energy markets;
  - Safety remains the key objective to be guaranteed to the world’s population and only the application of the best international safety requirements can be a minimal condition to assure this worldwide;
  - Long-term radioactive waste management has been and remains a socio-political issue, despite scientifically proven final solution, i.e. geological disposal;
  - Non-proliferation of nuclear knowledge and nuclear materials given the potential dual nature of nuclear technology;
  - Natural resource availability and especially the timely and economical competitive supply-demand balance of natural uranium to feed today’s essentially $^{235}$U-driven nuclear energy systems.

- While many of these impediments were manageable in a “GWe-level” and slow growth world nuclear energy system, a potential tomorrow’ “TWe-level” in a global sustainable energy future and/or a regionally rapid growth world nuclear energy system may be jeopardized by these impediments.
Sustainability on global level recognizing differences on local level

Ref: Luc Van Den Durpel, D.C. Wade, et al., Global INPRO-SYNERGIES Workshop, July 30th – August 3rd 2012, Vienna, IAEA

INPRO-SYNERGIES Workshop, July 30th – August 3rd 2012, Vienna, IAEA

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<table>
<thead>
<tr>
<th>Client categories</th>
<th>Developed Regions</th>
<th>Transitioning Regions</th>
<th>Developing Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Industrial Situation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Industrial Infrastructure</strong></td>
<td>Robust</td>
<td>Significant</td>
<td>Lacking</td>
</tr>
<tr>
<td><strong>Labor Market</strong></td>
<td>Skilled, expensive</td>
<td>Skilled, less expensive</td>
<td>Less skilled, inexpensive</td>
</tr>
<tr>
<td><strong>Access to Capital</strong></td>
<td>Robust</td>
<td>Constrained</td>
<td>Constrained</td>
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<tr>
<td><strong>Energy Market organization</strong></td>
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<tr>
<td><strong>Liberalized/deregulated</strong></td>
<td>Yes</td>
<td>Yes/No</td>
<td>No</td>
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<tr>
<td><strong>Investors energy market</strong></td>
<td>Private</td>
<td>Private/Government</td>
<td>Government/Private</td>
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<tr>
<td><strong>Investment criterion</strong></td>
<td>Shareholders value creation</td>
<td>Cost-of-ownership</td>
<td>Capital requirements</td>
</tr>
<tr>
<td><strong>Nuclear Power Plants</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear deployment</strong></td>
<td>Initially high, replacement market, later-on small</td>
<td>Small, but steadily growing</td>
<td>Small but fast growing</td>
</tr>
<tr>
<td><strong>Nuclear technology generation</strong></td>
<td>Gen-II and III, gradual introduction of Gen-IV in a replacement market</td>
<td>Gen-II and III, Some Gen-IV introduction as part of regional fuel cycle service centre</td>
<td>Gen-III and Gen-IV</td>
</tr>
<tr>
<td><strong>Emplaced grid and favored plant size</strong></td>
<td>Large</td>
<td>Small to Large</td>
<td>Small</td>
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<tr>
<td><strong>Energy services</strong></td>
<td>Electricity, Hydrogen</td>
<td>Electricity, Process Heat Water Desalination</td>
<td>Electricity, Process Heat Water Desalination, Hydrogen</td>
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<tr>
<td><strong>Fuel cycle Infrastructure</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>SNF-inventory already existing and in the pipeline, i.e. current fissile material working inventory</strong></td>
<td>Large</td>
<td>Small</td>
<td>Very small</td>
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<tr>
<td><strong>Current access to indigenous enrichment and fuel fab facilities</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Current access to indigenous reprocessing and “hot” fuel fab facilities</strong></td>
<td>Yes – for MOX as waste management time delay</td>
<td>Some</td>
<td>No</td>
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</tbody>
</table>
A « millenium » view on nuclear energy

INPRO-SYNERGIES Workshop, July 30th – August 3rd 2012, Vienna, IAEA
A simple systems view on a nuclear energy system from the perspective of fissile material balance

![Diagram of nuclear energy system with labels and reactions](Image)

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CR'\_F

Reactor

M^e\_fi
M^i\_fi
M^u\_fi
M^s\_fi

Uranium utilization rate

Conversion ratio (CR)

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Reactor conversions ratio versus system’s conversion ratio

\[ CR_R = \frac{\text{Net fissile mass in used fuel}}{\text{Fissile Mass consumed}} \]

\[ CR'_R = \frac{\text{Net fissile mass in used fuel}}{\text{Initial fissile mass invested}} \]

\[ \xi = \text{"Fissile Recyclability Factor"} \]

Nuclear energy systems conversion \( CR'_s \) ratio becoming:

\[ CR'_s = \frac{M_{fi}^s}{M_{fi}^e} = \frac{(1 - \xi) \cdot CR'_R}{1 - \xi \cdot CR'_R} \]

\[ \frac{M_{fi}^e}{M_{fi}^e} = \frac{CR'_R}{1 - \xi \cdot CR'_R} \]
Impact on $CR'_R$ as function of fissile material use
CR'_S as function of CR'_R and ξ

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$M_{\text{fi}}^{o}/M_{\text{fi}}^{e}$ as function of $\text{CR'}_R$ and $\xi$
Nuclear energy systems main trends

Nuclear Energy System

Nuclear Power Reactors
- Large-size LWRs
- Longer fuel cycle lengths
- Life-time management (materials)

Key Development Drivers
- Safety
  - Higher BUs and fuel reliability
  - MOX parity
- Economics
  - Robust waste management based on vitrification

U/Pu-management
- Single-Pu and URT recycling
- Multi-Pu recycling

Nuclear Fuel Cycle

Increased Economic Competitiveness
- Operational Flexibility
  - Fuel cycle flexibility with respect to U-requirements and Used Fuel and HLW management
  - Used MOX management

2010
- Severe accident prevention and mitigation
- Improved construction schedule and cost
- Extended design life-time

2030
- Further reduction in CAPEX
- Flexible core-load schemes (UOX to partial or full 100% MOX)
- Multi-recycling of U and Pu

LWR-competition with ‘newcomer’ designers
- From GWe to TWe world
- NPP-park

2050
- Competitive U-availability?
- HLW Waste management
- Diversity in fuel cycle options by clients as hedge
- Alternative U/Pu/Th cycle

Improved Sustainability
- Minor Actinide Management

2080
- Facilitating multi-Pu recycling in LWRs
- Valorising DU / URT towards full sustainability

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HLW = High Level Waste
“Though all this is interesting for some countries able to afford such thinking”

For most of us ... the questions today and tomorrow relate to

- “How to integrate nuclear energy in our energy mix?”
  - Technical expertise, resources, investment and competitiveness
- “Once having nuclear, what’s our options space in nuclear fuel cycle to deal with possible impediments while assuring best performance for nuclear locally?”
  - Fuel supply assurance
  - Used fuel management (interim storage, recycling, ...)
  - Ultimate waste management
- “Once having a larger nuclear energy park, what new options become envisageable?”
  - “Generation-IV”
  - Market-specific nuclear reactors (HTGR, SMR, ...)
  - Fuel cycle installations and services

The question becomes essentially how international/multi-regional approaches open the options space for each country compared to a stand-alone approach and how this may facilitate deployment rate and/or energy independence, security of supply, financial investment/risks, ....?
A variety of synergies?

- Security of supply
- Financing risks
- Non-proliferation limitations
- Economies of scale

- Regional fuel cycle centers, waste management
- Inter/intra-regional transfers of nuclear materials?

- Regional interim storages
- Inter/intra-regional transfers of nuclear materials?

- Regional waste disposal sites
- Inter/intra-regional transfers of nuclear materials?

- Safety, knowledge, shared NPPs projects
- Inter/intra-regional transfers of nuclear materials?

- Security of Supply
- Inter/intra-regional transfers of nuclear materials?

- Regional waste disposal sites
- Inter/intra-regional transfers of nuclear materials?

- R&D, Long-term vision and risk sharing (FOAK), economies of scale (SYNERGIES-enabling)
- Inter/intra-regional transfers of nuclear materials?
A « millenium » view on nuclear energy

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Strategic options for us all and each Member State embracing nuclear energy

If nuclear energy is demanded to deliver a growing share of the future energy demand, seven main goals for future nuclear energy systems deployment are deemed necessary, i.e.:

- **G1. Cap the amount of used fuel storage**, e.g. limit the amount of spent fuel to be disposed off to approximately today’s stock of SF worldwide (0.6 Mt), i.e. equivalent to 6 regional fuel cycle centers with geological disposal capacity);
- **G2. Minimize the volume of repository space needed per additional TWhe energy generated**, i.e. limit heat load in repositories;
- **G3. Make it economically attractive**, i.e. limit financial risks;
- **G4. Serve the different energy markets**, i.e. small versus large nuclear power plants, low and high temperature reactors, ...  
- **G5. Manage non-proliferation concerns**, i.e. employ intrinsic and extrinsic barriers;
- **G6. Drastically reduce the need for long-term stewardship of waste**;
- **G7. Make better use of scarce natural resources**, i.e. natural uranium and thorium.
The means to achieve these may require international collaboration and governance

The means to achieve these seven goals are known and subject of many R&D-programs worldwide, i.e.:

- **M1. Reprocessing of SF to serve goals G1 and G7;**
- **M2. Remove some of the actinides from waste to be disposed of by recycling these in reactors, i.e. serving goals G2 and G6;**
- **M3. Allocate fissile materials for maximum added value in appropriate reactors serving goal G3;**
- **M4. Deploy different reactors and probably regional fuel cycle centers for goal G4;**
- **M5. Minimize out-of-pile inventories and use institutional frameworks for goal G5.**
So, how to seek optimal goal-setting using international approaches for means?

<table>
<thead>
<tr>
<th>Goal / Means</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
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<tbody>
<tr>
<td>G1</td>
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<tr>
<td>G2</td>
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<tr>
<td>G7</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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</tbody>
</table>
Main questions within INPRO-SYNERGIES Project

**How may these impediments be addressed such that nuclear energy may fulfill a role as worldwide applicable sustainable energy technology recognizing the differences in energy markets in various world regions and providing the avenues to address these impediments conveniently?**

- How to synergistically facilitate local economic competitiveness of nuclear energy systems with global sustainability?
- How to merge government’s actions with a vision towards nuclear sustainability with commercial NPP and fuel cycle services?

**How may different regional nuclear energy system deployment scenarios be meshed together by use of various nuclear technology options and collaborative approaches such that the sustainability character of nuclear energy worldwide but also locally is maximized or enabled?**
Main basic motivations for INPRO-SYNERGIES

Rendering the nuclear option possible or keeping it open

- Energy independency / security of supply (energy & resources)
- Reducing/avoiding impediments:
  - Fuel supply assurance
  - Long-term used fuel stewardship
  - Ultimate waste management

Transition towards sustainable NES

- R&D and FOAK towards Gen-IV/GEN-\(\chi\) reactors and fuel cycles
SYNERGIES Task 1
Activities and structure

Evaluation of Synergistic Collaborative Scenarios of Fuel Cycle Infrastructure Development

Task 1.1
Description of motivations and options for SYNERGIES (enlarging options space)

Task 1.2
Scenarios simulation with regional fuel cycle centers and/or multinational services

Task 1.3
Assessment of the drivers & impediments towards SYNERGIES

Task 1.4
Evaluation of SYNERGIES options and recommendations

Provide MS description of options and the how/when’s (tech roadmaps)

Illustrative scenarios allowing quantified assessment of win-win’s

Technical-economic assessment of drivers & impediments and identification of synergistic approaches

What IAEA and governments could/should do to make it happen
## Task 1 Regional scenarios

<table>
<thead>
<tr>
<th></th>
<th>Fissile constrained</th>
<th>Fissile in excess</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>U/Pu</strong></td>
<td></td>
<td>US</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Russia</td>
</tr>
<tr>
<td><strong>U/Pu</strong></td>
<td>China</td>
<td>France (EU)</td>
</tr>
<tr>
<td><strong>U/Pu/Th</strong></td>
<td>India</td>
<td></td>
</tr>
</tbody>
</table>

In addition, specific scenario-cases for some Member States
Nuclear energy demand

(very) near-term
- Synergies among infrastructures, fuel cycle, security of supply facilitating decision-making for new nuclear / first steps in collaboration based on existing possibilities

Till about 2030
- Based on MS-scenarios

2030 – 2050:
- IAEA/PESS, water desalination, process heat, ...
- GAINS

> 2050:
- GAINS scenarios (links to Task 2)
- High Global Vision scenario (10 TWe scenario) (to be done in Task 2)

Contributions by various Member States

E.g. ADRIA (ENEA, I), Kurchatov (Russia), ...
Thank you