Interregional Workshop on Aspects of Modelling and Simulation in Gen-IV Type SMR Development

IAEA-ROSATOM

«A Perspective on Large-Scale Development of Nuclear Energy in the 21 Century»

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Background to the problem statement

- **"Millennium summit" UN, September 6-8, 2000 President of Russia Vladimir Putin:** "Development of large-scale energy based on new nuclear technologies will save the planet's organic resources for their non-energy use by present and future generations, to stabilize and further reduce the impact of the greenhouse effect, economically and environmentally optimal to ensure the growth of global energy consumption.»

- **The anniversary session of the UN in September 2015, Vladimir Putin:**

"... among the problems that affect the future of all mankind, such a challenge as global climate change. ...We need qualitatively different approaches. It should be about the introduction of fundamentally new, nature-like technologies that do not cause damage to the surrounding world, but exist with it in harmony and will restore the balance between the Biosphere and the Technosphere disturbed by man.

Sustainable development

In brief, the definition of sustainable development involves three approaches to the analysis of sustainability and sustainable development:

- (1) current development should be consistent with the objective of meeting current needs with minimal environmental impact and in an economically acceptable manner;
- (2) current R & D, design and creation of innovative power unit and technology programs should be developed and supported within trends that lead to technological and institutional changes that serve as a platform for future generations to meet their needs;
- (3) meeting current needs should not jeopardize the ability of future generations to meet their needs.

Place of NE in the overall picture of economic activity

Power industry is:

On the one hand – the branch of economic activity.

On the other hand - the power part of the control system mechanism for obtaining and distributing natural goods;

“The system of transformation of all potential resources in the total capital of society" V. V. Bushuev

Problems of modern NP

Modern NP cannot be considered as basis of sustainable development for the following reasons:

•Inefficient fuel utilization (the effective resource is less, than of oil and gas);

•Degradation of neutron potential (consumption of uranium - 235, absence of nuclear fuel breeding);

•Accumulation of waste products proportionally energy production (there comes that moment when the electricity tariff will not be sufficient for SNF and RW management);

•Limitation of scales and regions of use;

•Increase of threat of uncontrollable use of nuclear materials.

Some boundary conditions of the problem statement

- **Nuclear power is the only existing large-scale energy reserve.**
- Reproduction of the modern NE structure does not solve energy problems. It is necessary to organize a full-scale fuel cycle to use the energy resource of U-238 and Th-232.
- It is impossible to single out any one of the directions of development of nuclear technologies that would solve all the tasks facing nuclear power.
- We do not know the totality of all the conditions and requirements that will arise in the future and will determine the choice of the structure of nuclear power and the selection of nuclear power plants, and this choice is not for us.
- **The existing and developing reactor directions do not have the necessary and sufficient set of characteristics, physical and mathematical models, experimental and technological bases for the creation of a nuclear power system that meets the requirements of sustainable development.**

Boundary conditions of INS development in 21 Century :

- International projects (INPRO, Generation 4, GNEP, international NFC centers), new opportunities for use of global experience and large scales of involved resources
- Globalization of the markets of energy and finance: economic risks; political risks
- The end of great geological discovery epoch - rise in price of uranium and all other resources
- Complication and increase in scales of the systems demanding the qualified highly paid staff (demographic restrictions)
- Creation of integral systems - «from cradle to grave»

International Innovative projects (INPRO) of the IAEA on the development of nuclear power plants and nuclear fuel cycle for innovative future nuclear energy system (INES)

The INPRO methodology is a tool that can be used:

- To analyze the INES for its ability to meet the requirements of sustainable development;
- To compare different INES to find preferred or optimal INES meeting the requirements of a given state;
- To determine the research, development and demonstration facilities required to improve existing installations and new construction of missing components INES.

The assessment should include all components of the INES system in order to:

- **gain a holistic vision**
- **and ensure that the system meets the requirements of sustainability.**

INPRO methodology

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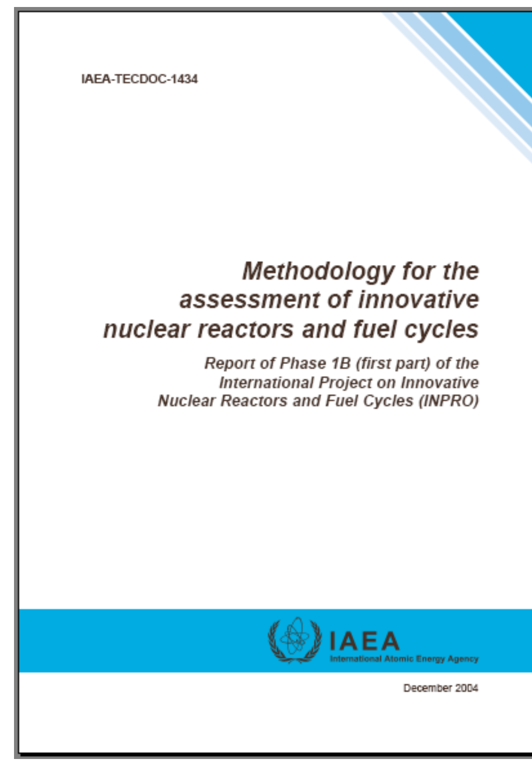
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Methodology for the assessment of innovative nuclear reactors and fuel cycles

Report of Phase 1B (first part) of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

IAEA
International Atomic Energy Agency

December 2004

Innovative Nuclear Energy Systems (INES)

encompasses all systems that will position nuclear energy to make a major contribution to global energy supply in the 21st century.

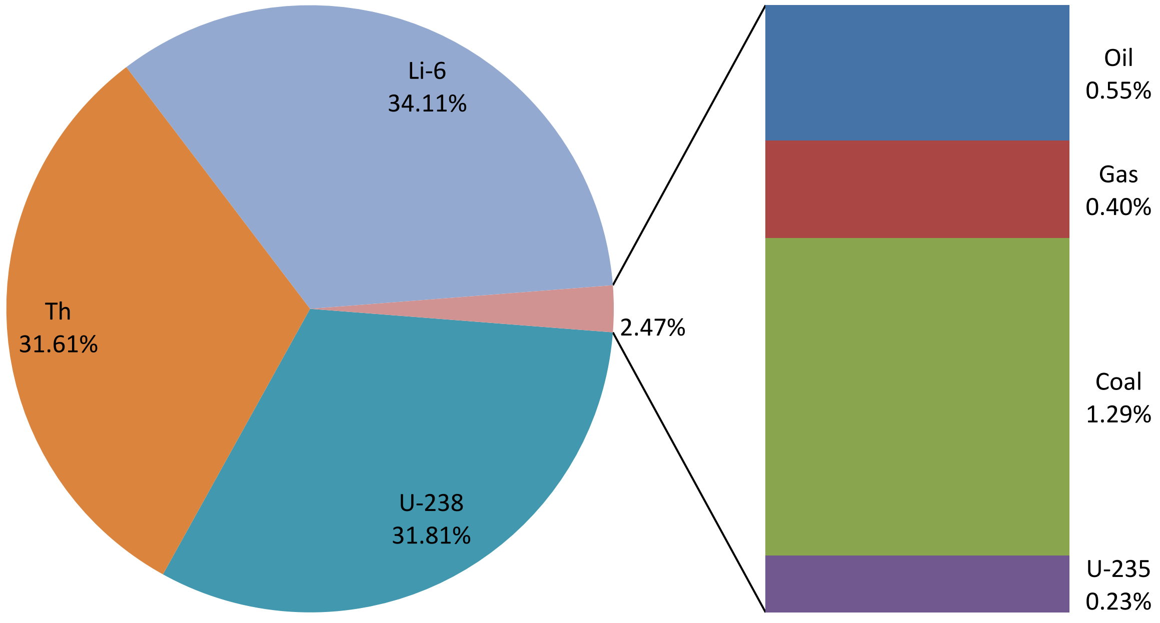
Future systems may include evolutionary as well as innovative designs of nuclear facilities:

- Evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design to minimize technological risks.
- Innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. These systems may comprise not only electricity generating plants, but include also plants (of various size and capacity) for other applications, such as:
  - high-temperature heat production,
  - district heating and sea water desalination, to be deployed in developed regions as well as in developing countries and countries in transition.

Large-scale nuclear power as a basis for sustainable development:

- Nuclear energy resource is more than oil and gas;
- Multiproduct;
- Multicomponent;
- Consequences of large-scale development: more expensive uranium and RW management;
- Different phases of development (initial, mature, final).

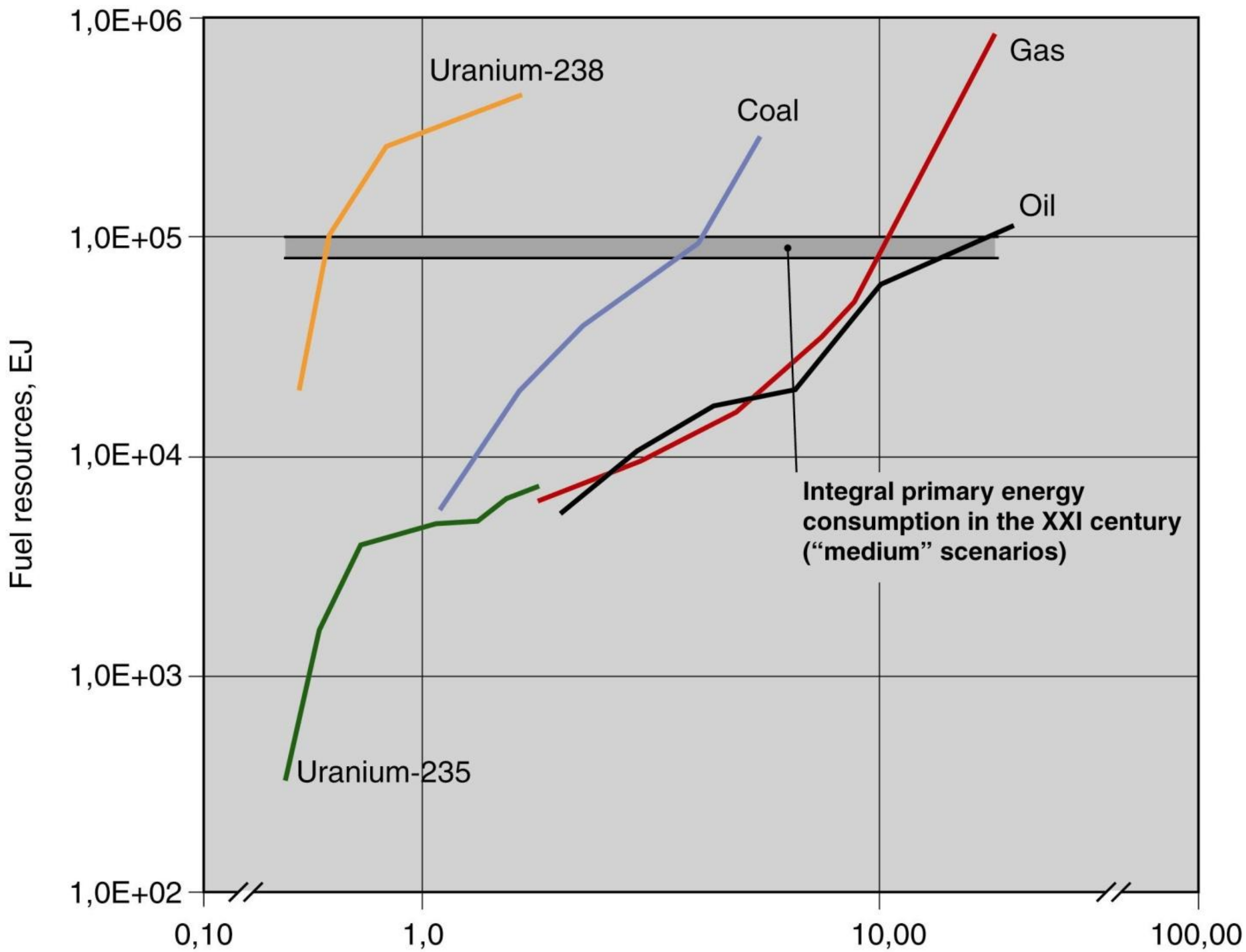
Global distribution of energy resources



Initial assumption:

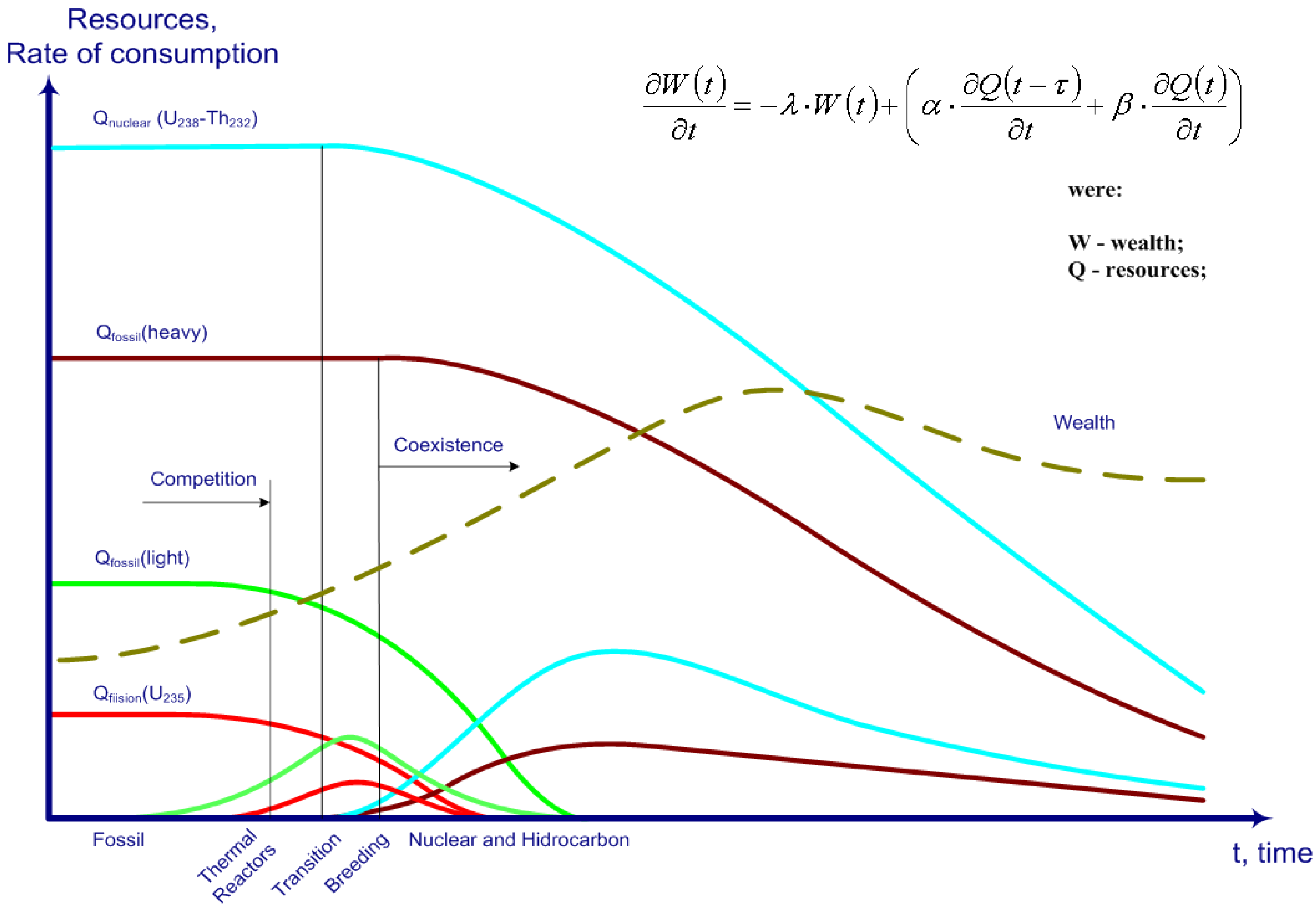
- according to “ U red book” it is assumed that world resources of thorium amount to 7 million tons;
- tritium is produced only from lithium-6, the world's lithium resources are taken according to U.S. Geological Survey

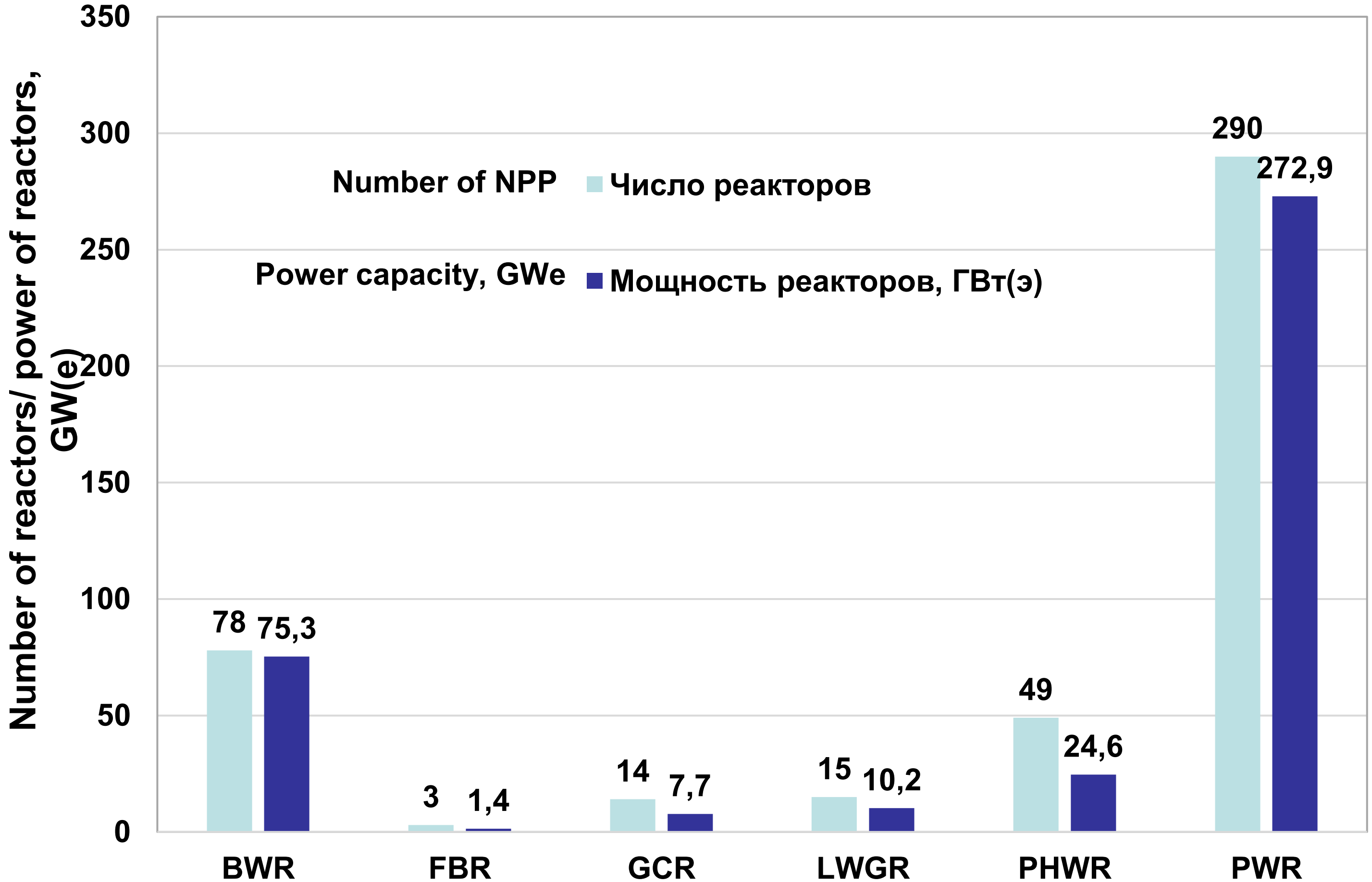
Energy resources' availability depending on their extraction costs



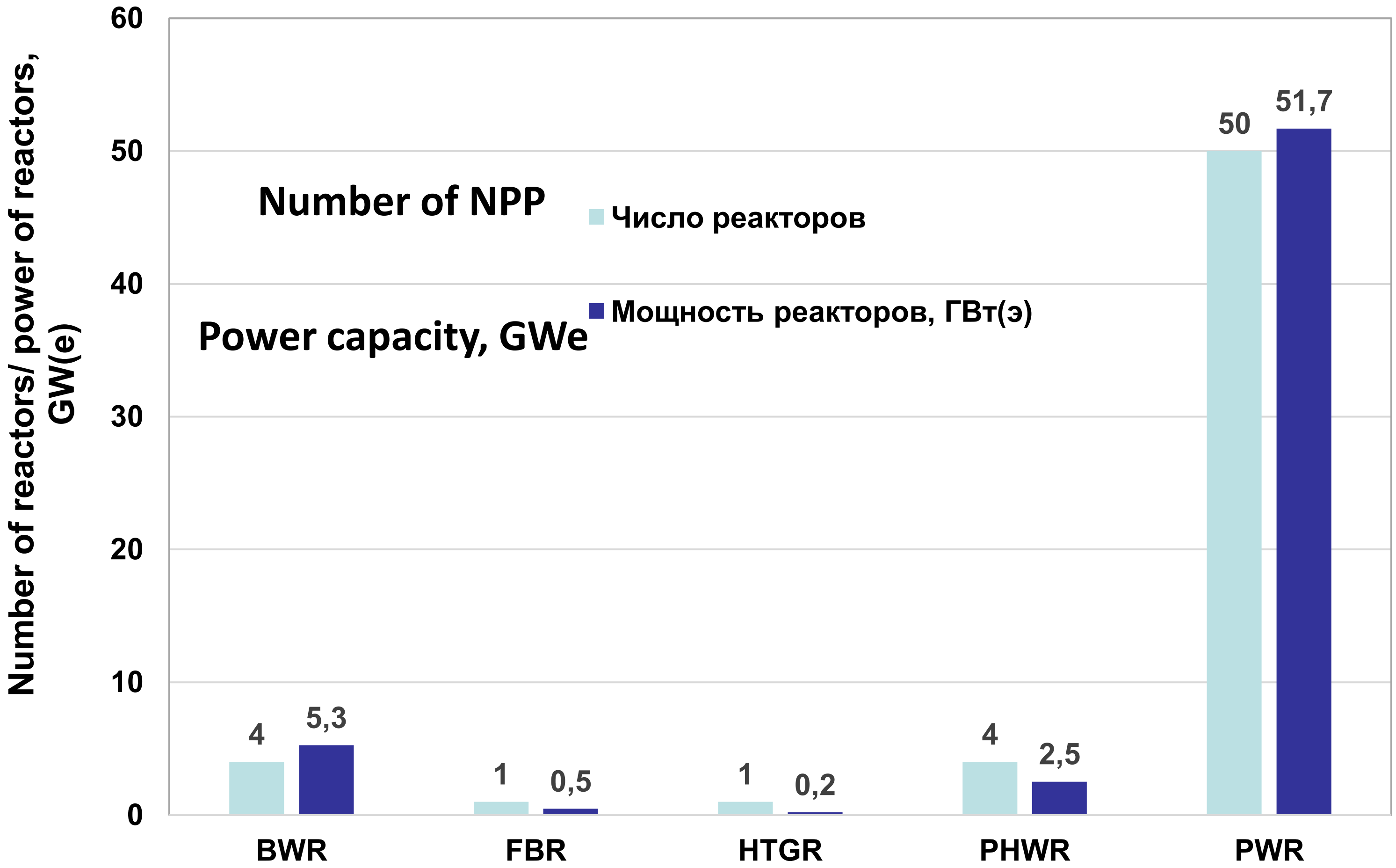
Extraction costs, relative units

The scheme of transition from the competition of energy technologies to their mutually agreed coexistence





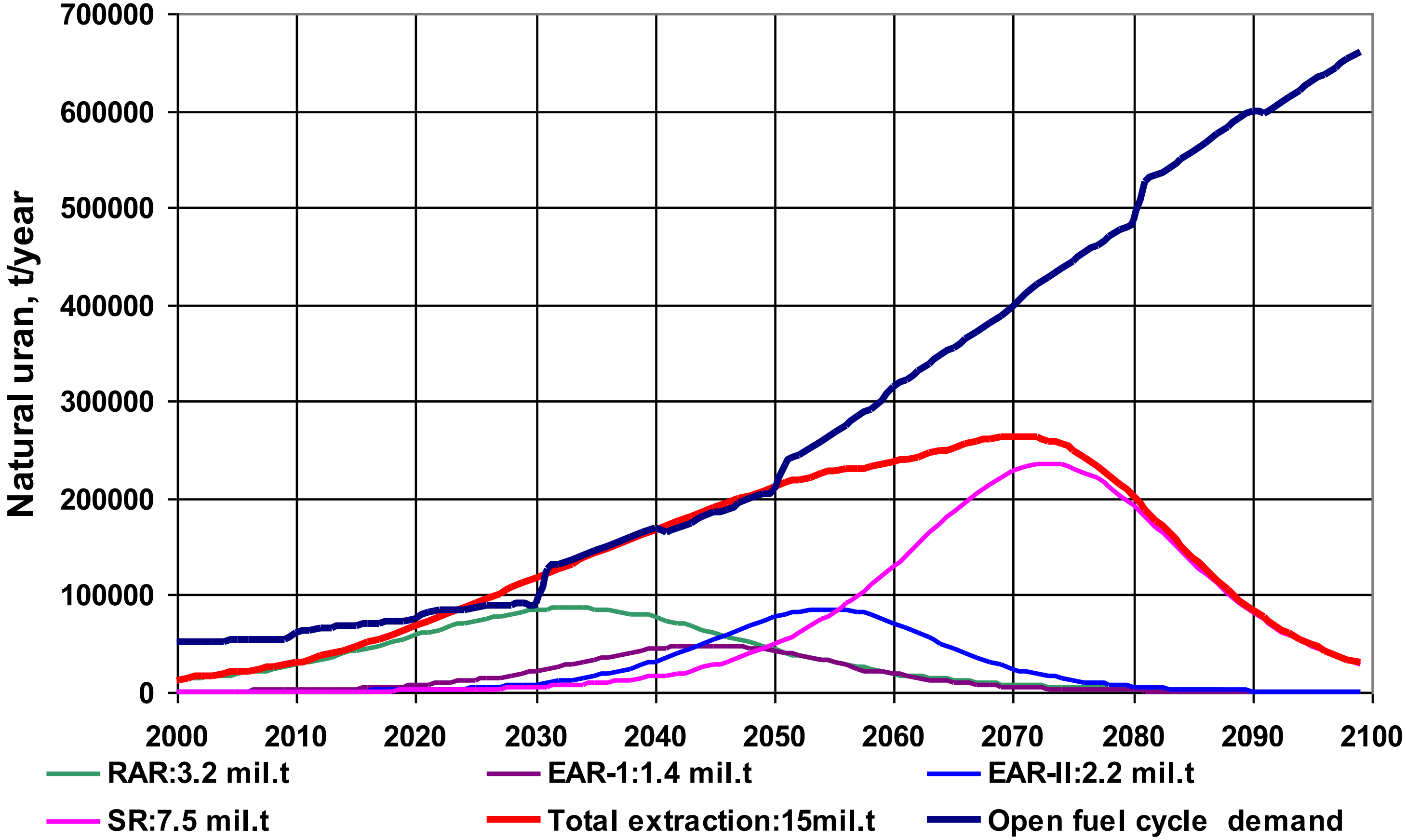
Number and capacity of reactors of various types operating in the world (according to IAEA/PRICE as of March 1, 2017).)



Number and capacity of reactors of various types under construction in the world (according to IAEA/PRICE as of March 1, 2017).)

Open fuel cycle
2030 y. – 600 GWe   2050 y - 1500 GWe

Uranium demand and annual extraction potential .



Potential solutions to problems for NE

	TR	FR	MSR	TR+ FR	TR+FR+ MSR
Various fields of use (regions, technologies)	+	-	-	+	+
Resource efficiency (uranium 235, uranium 238, thorium)	-	+/-	+	+\-	+
Disposal of minor actinides (Pa, Np, Am, Cm,...)	-	-	+	-	+
Recycling of plutonium and minor actinides at the final stage of development of NE system.	-	-	+	-	+

Open nuclear fuel cycle

There are two types of resources in the NE:

- U-235 as a source of neutrons (neutron potential) and energy (creation of a controlled and self-sustaining neutron field with simultaneous energy production)
- and U-238 and Th-232 as energy sources (which in the neutron field can turn into Pu and U-233 and provide, under certain conditions, a regime for maintaining the neutron potential of the NE system).

In the open NFC it is considered to use of U-235.

In this case the NE cannot claim to be an energy technology capable of solving the problems of energy security and sustainable development, as it faces the same institutional, economic and "geological" problems as other technologies based on the use of exhaustible organic resources.

Closed nuclear fuel cycle

In order for the NE to be able to solve the tasks set for it (within the framework of the INPRO international project) to participate in ensuring sustainable development, it must switch from uranium 235 to the use of uranium 238 and thorium 232.

Effective use of U-238 and Th-232 requires removal of fission products from the neutron field. It seems to be inherent for liquid-fuel reactors (MSR), but in solid-fuel reactors it is connected with the organization of the external fuel cycle. The fewer fission products there are in the neutron field, the more efficiently nuclear fuel can be used.

The closure of the NFC for MA slightly increases the neutron potential of the NE system, but can significantly help in solving the problems of radioactive waste disposal, especially if a political (legal) decision is not made for a long time on:

- what (for which nuclides the closure of the NFC is necessary),
- in what quantity (burn up depth, losses level),
- how and where it can be buried (placed in the final state that does not require further control).

User requirements
Basic principals
Guides, rules

Energy source
U-238
Th-232

Neutron source
U-235
D
Li

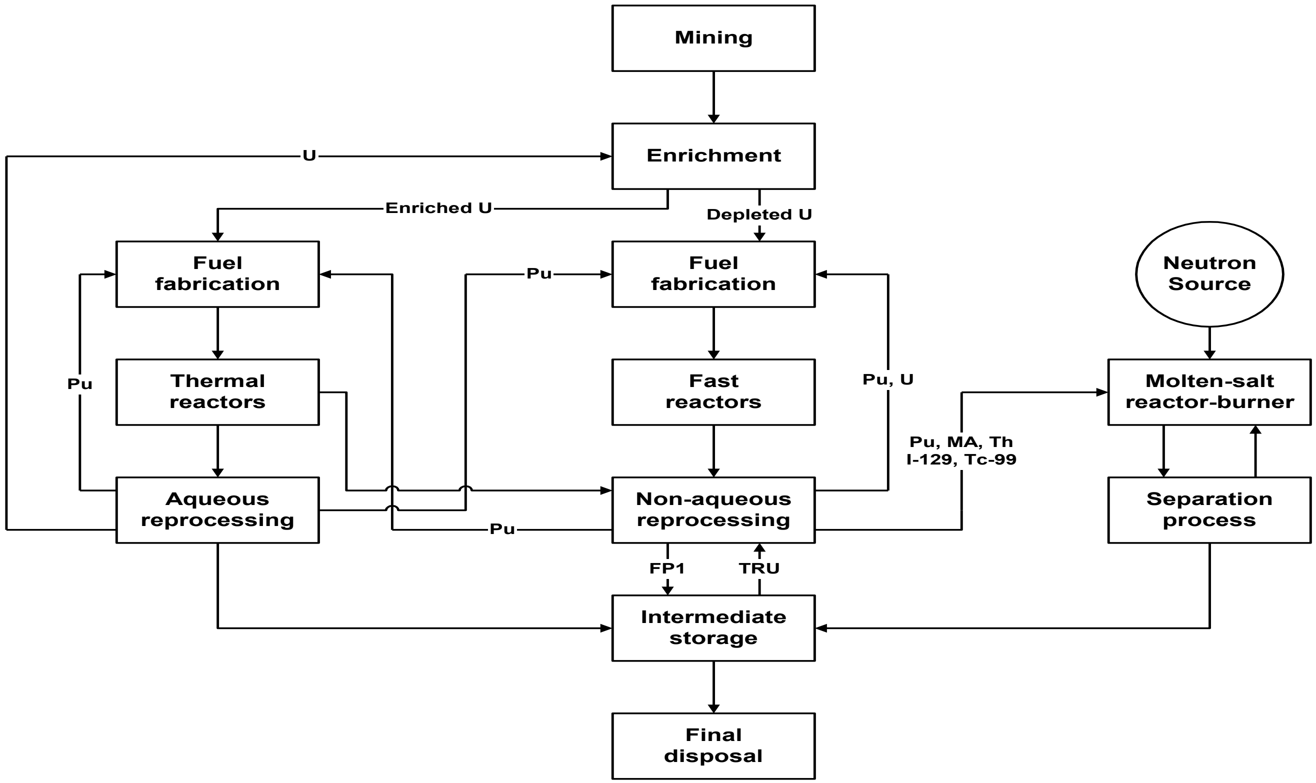
INES:

- NFC enterprises
- Thermal reactors
- Fast reactors
- Burner reactors
- Fusion neutron source

Fission products,
Useful radio
nuclides,
Energy

Non nuclear recourses

“Zero” approach of Innovation Nuclear Energy System:
Multi-component nuclear power system with closed fuel cycle for all actinides, including Pu, MA and dangerous long-lived fission products (principle of coexistence)



Multicomponent system, along with the possibility of implementing various fuel schemes in reactors, creates ample opportunities for maneuver in the structure of the nuclear fuel cycle, which can compensate for the possible risks in reasonable time periods

Role of different reactor types

- Thermal neutron reactors: energy generation for various consumers (electricity, district heating, technologies, hydrogen); wide capacity range (SMR – regional/autonomous applications, large reactors – grid applications); operation in load maneuvering mode; flexible fuel cycle (Pu, U, Th);

- Fast neutron reactors (FR): basic energy generation; fuel breeding (Pu, U-233); nuclear fuel cycle closing by U, Pu and minor actinides;

- Liquid-fuel reactors (MSR) intended for minimizing the amounts of minor actinides within the system could be required by 2050 at the earliest, in case no acceptable ways would be found by then to dispose of minor actinides or utilize them in solid-fuel reactors.

- Fusion neutron sources (FNS): increasing the rates of Th-232 and U-238 involvement in the nuclear fuel cycle; increasing the neutron potential of the NES; most likely, FNS would be required in the maximum nuclear energy development scenario;

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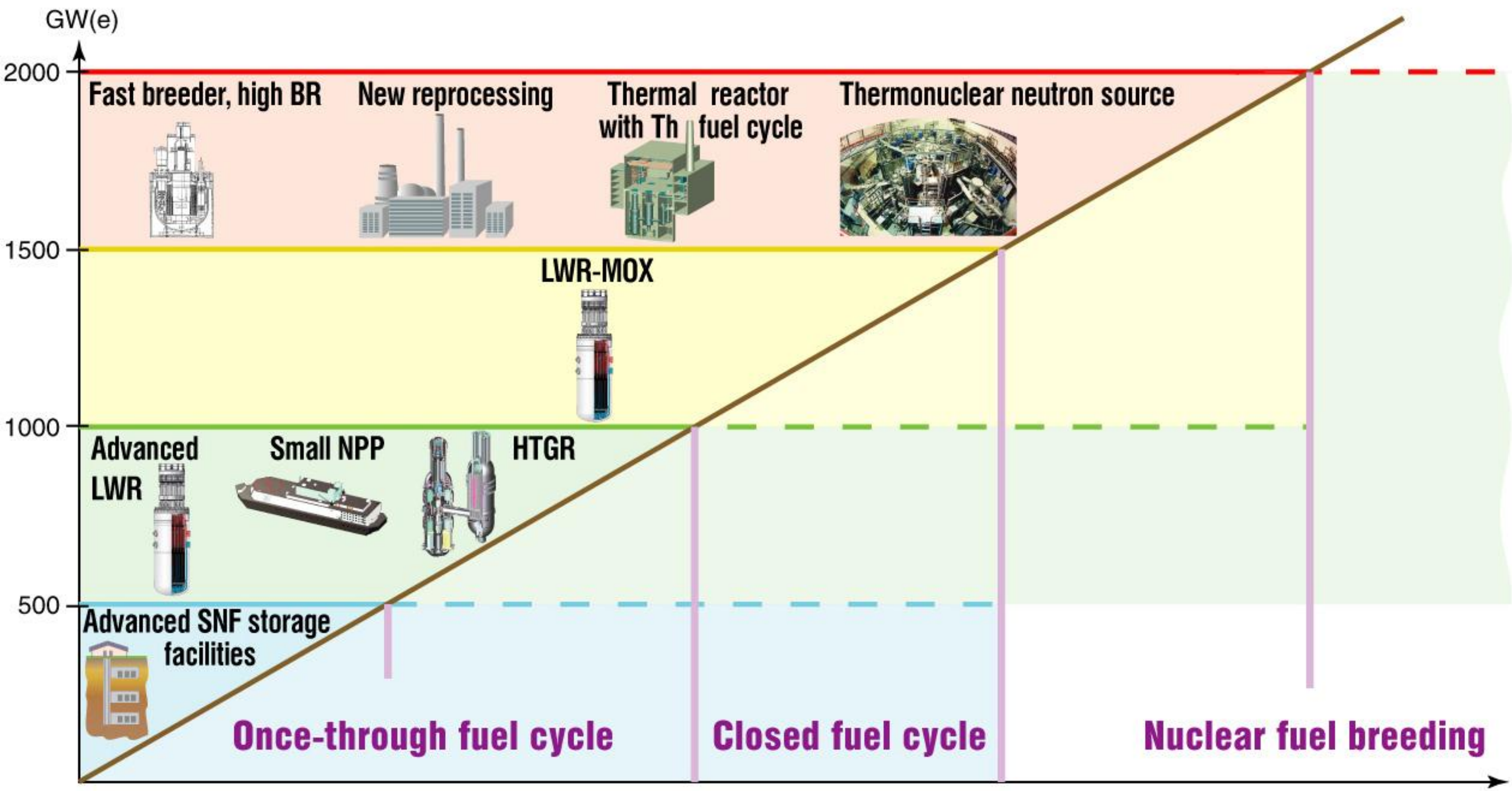
Required innovations depending on the level of the world nuclear energy development (by 2050)



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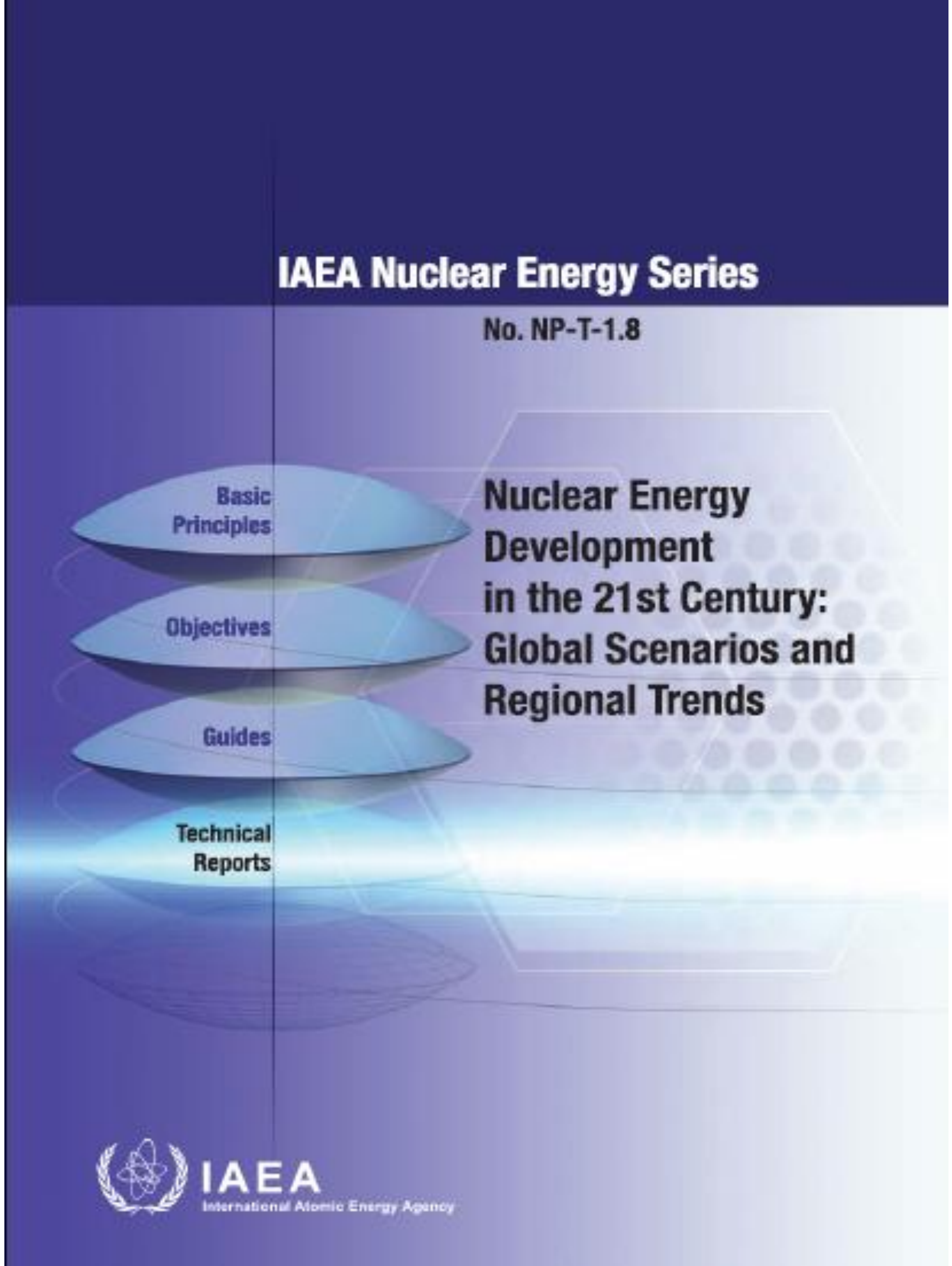
Difference of neutron balance for Reactor and INES

- **The potential of neutron balance in a reactor at fissioning of uranium-235 and 233, plutonium 239, 241 is defined by size (uranium-235: ν-1-α = 2.5 – 1 – 0.3 = 1.2).** The excess of neutrons in the reactor makes it possible to use them to facilitate the solution of problems of ease of operation, safety and economic efficiency.

- **The potential of neutron balance in system AE at use of all uranium-238 or thorium-232 is defined by size (Pu 239: ν-1-α-1 = 2.9 – 1 – 0.3 – 1 = 0.6).** When solving the problem of nuclear fuel breeding, the task of realizing the necessary neutron balance in the system becomes much more complicated - all those measures (absorption in special absorbers, blocking the interaction of neutrons with uranium-238 and thorium-232) that were acceptable for obtaining energy from fissile nuclides become ineffective. The role of "external" neutron sources (electro-nuclear, thermonuclear) is significantly increasing

Technical problems of Nuclear power

- Neutron field control and management – practically solved;
- Control and management of energy generation - practically solved;
- The control and management of energy remove requires innovative approaches;
- Energy transformation requires innovative approaches;
- Control and management of nuclides compositions and nuclides flows requires the greatest investment of resources, time and knowledges, without solving this problem, nuclear power cannot become the basis of sustainable development.


IAEA Nuclear Energy Series
No. NP-T-1.8
Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends
Basic Principles
Objectives
Guides
Technical Reports
IAEA
International Atomic Energy Agency

Power in the Economy of the 21st Century.

E.Velikhov, A.Gagarinsky, S.Subbotin, V.Tshibulsky

The features of the potentials of nuclear energy

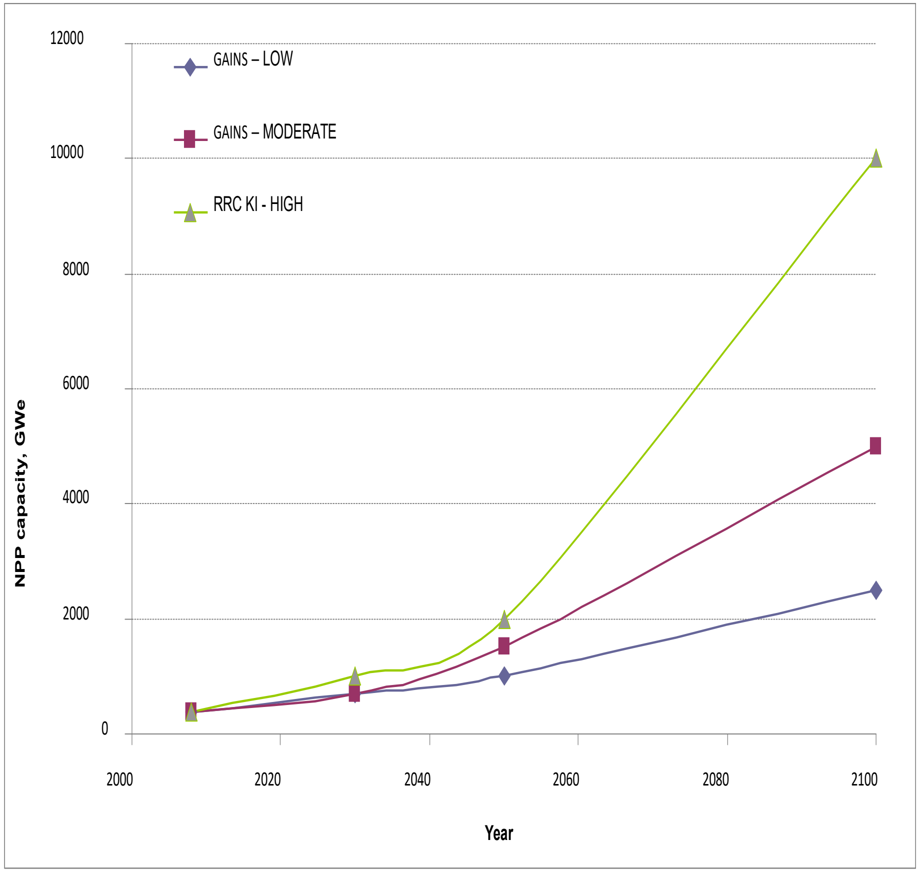
The possibility of using NE potentials for solution of sustainable development problems and solving the problems of energy security largely depend on the successes and failures of other energy technologies. The possible scale of the use of nuclear power sources and the rate of its development depend on it.

Specialists in the field of nuclear energy within their traditional competencies cannot influence it, relying only on the level of technical measures and solutions.

The nuclear industry should have the appropriate competencies necessary to position the potential of this technology in the public consciousness, economic and legal spaces at the appropriate levels.

Nuclear technology brings with it more opportunities for economic activity than simply expanding the energy base.

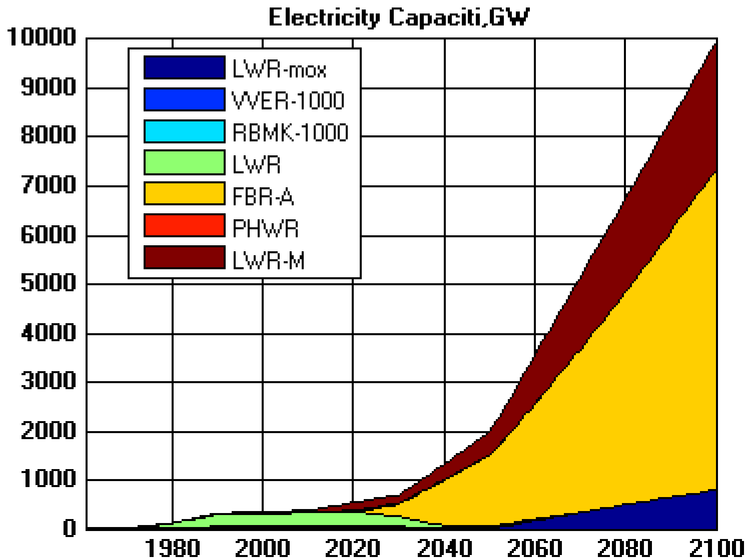
World nuclear energy development scenarios

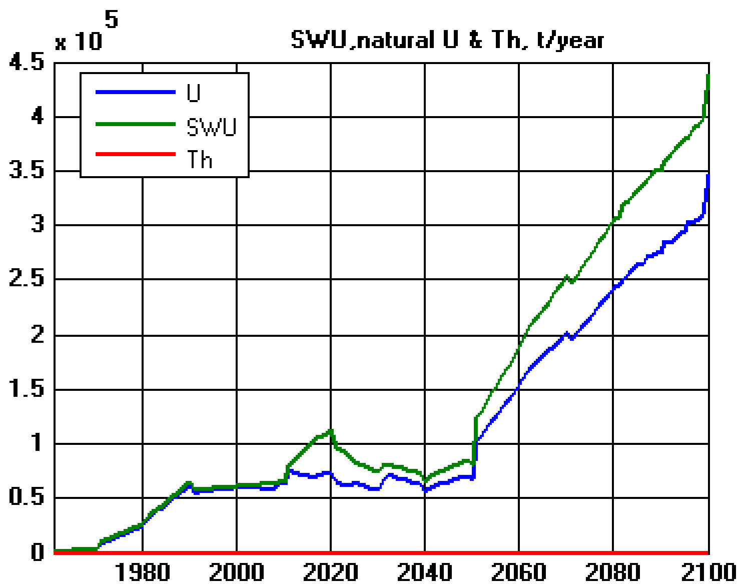


World nuclear energy development scenarios are considered not as "forecasts for the future", but as an illustration and identification of opportunities for innovative nuclear energy systems to make their considerable contribution to the sustainable development of the world.

Low - the share of nuclear energy in energy production by the end of the century about 6%
Moderate - share of nuclear energy in energy production by the end of the century 12%
High - share of nuclear energy in energy production by the end of the century 25%

Scenario MAX: 2000GW in 2050 10000GW in 2100





FBR-A: BR=1.6

Burn up LWR-M – 60 GWd/t

Surplus Pu is used in LWR-MOX

Consumption of natural uranium up to 2100

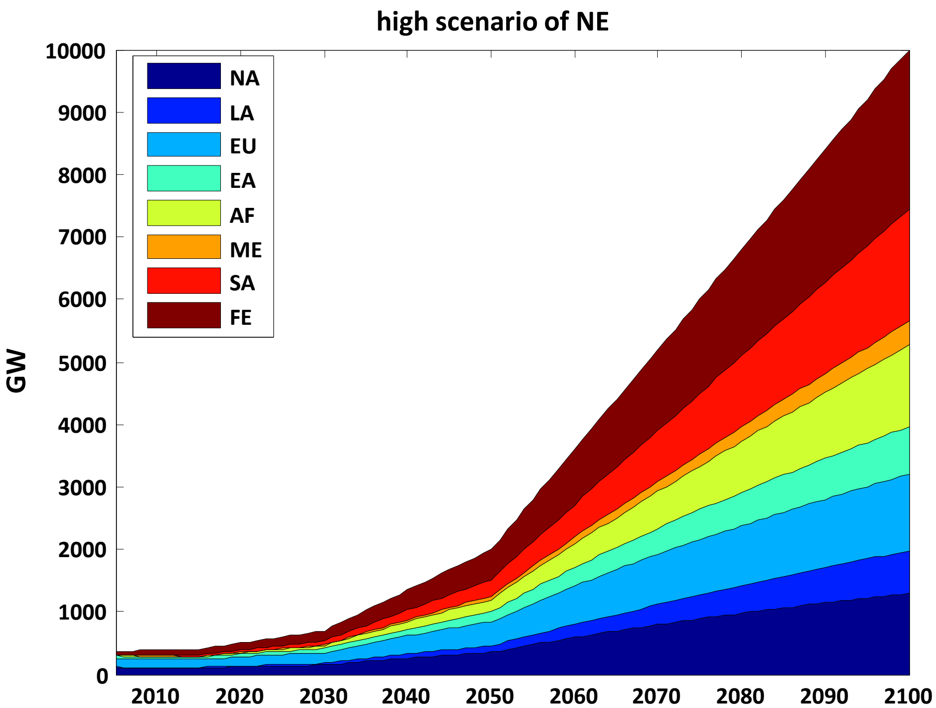
15.5 million t

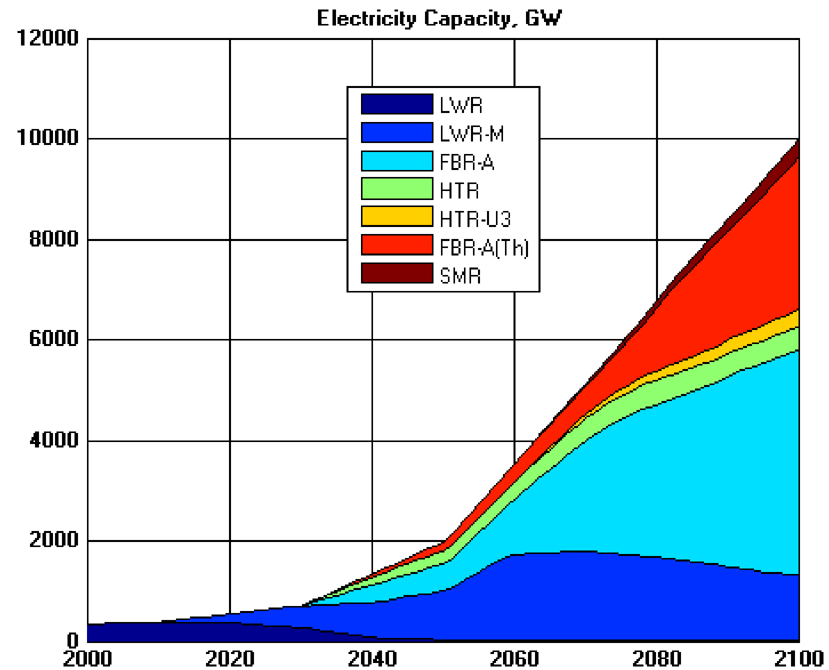
Volume fuel reprocessing :

2050г:-20000 tSF/year

2100г.-60000 tSF/year

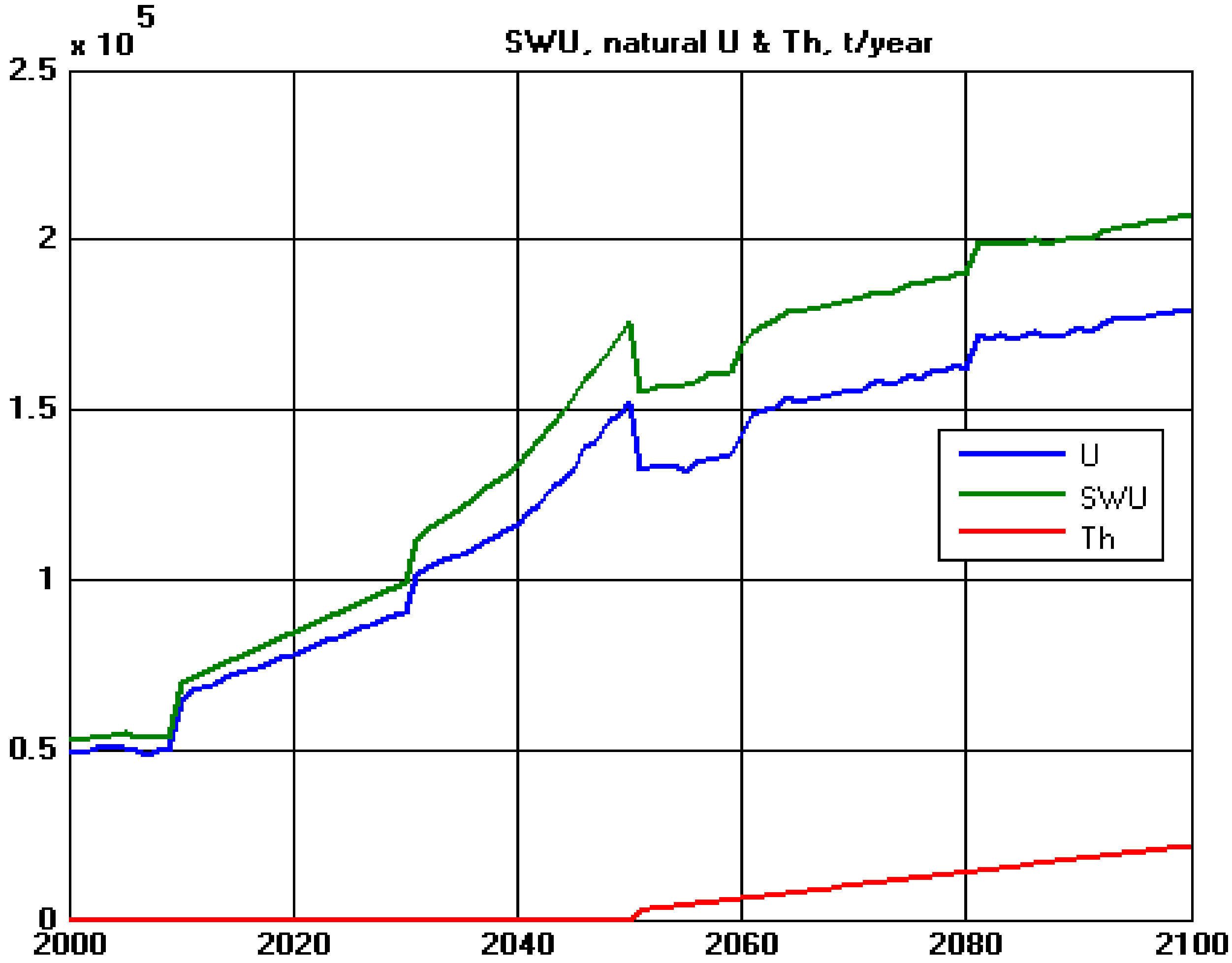
The maximum scenario (the share in the energy mix is about 25%)





It is necessary to close the fuel cycle on the basis of fast reactors with extended fuel reproduction, the share of fast reactors by the end of the century will be more than 80%

Uranium mining and separation work for the maximum scenario

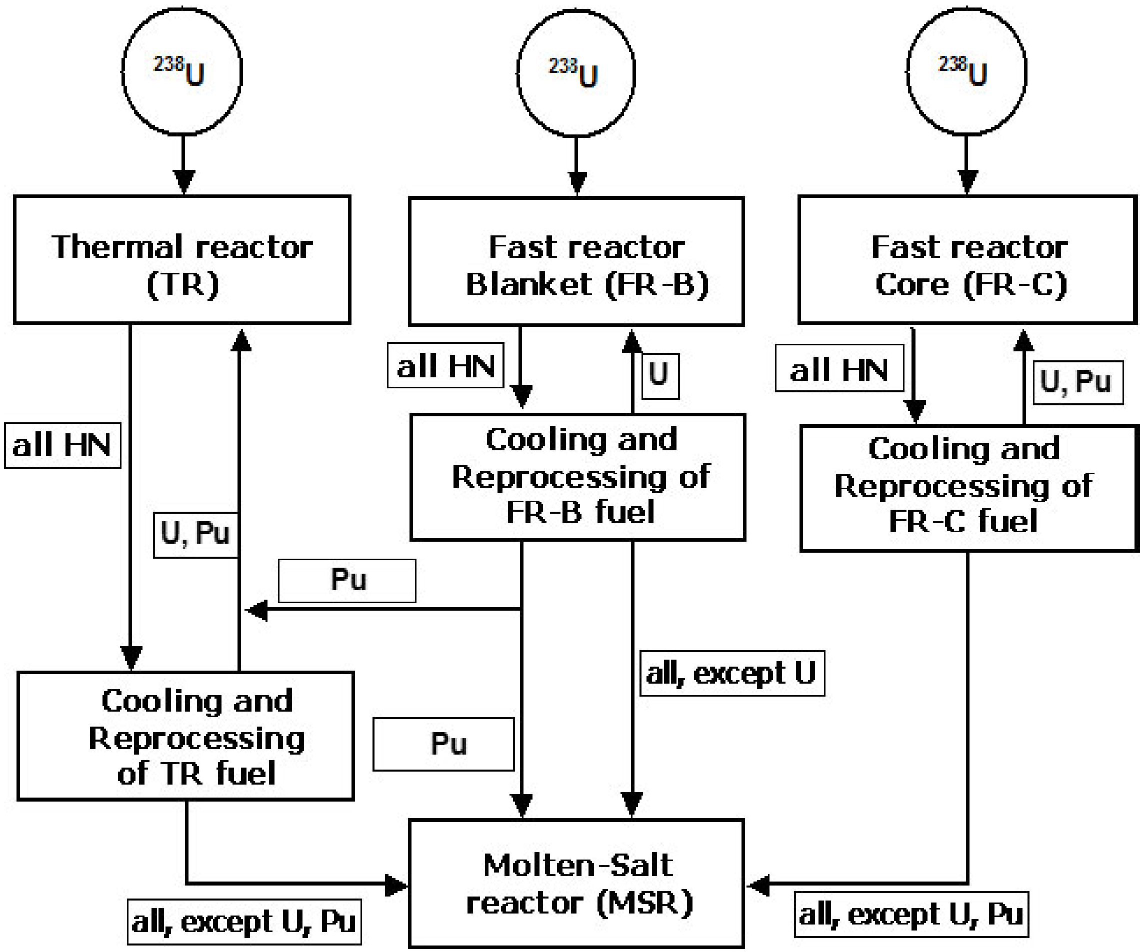


The development of efficient breeders on the basis of fast spectrum neutron reactors:

- at the initial stage - specific loading of plutonium into the reactor to a minimum (up to 3–4 t per GWe), breeding ratio of 1.2–1.3; duration of the external fuel cycle for plutonium is not more than 5–6 years;

- after 15–20 years, the plutonium breeding level in a fast reactor has to be raised up to 1.5–1.6; duration of the external fuel cycle for plutonium is not more than 3 years

Structure of INES for uranium-plutonium nuclear fuel cycle



Share of reactor power in the system

59% TR

33% BR

8% MSR

The amount of fuel for 1 GW(e)

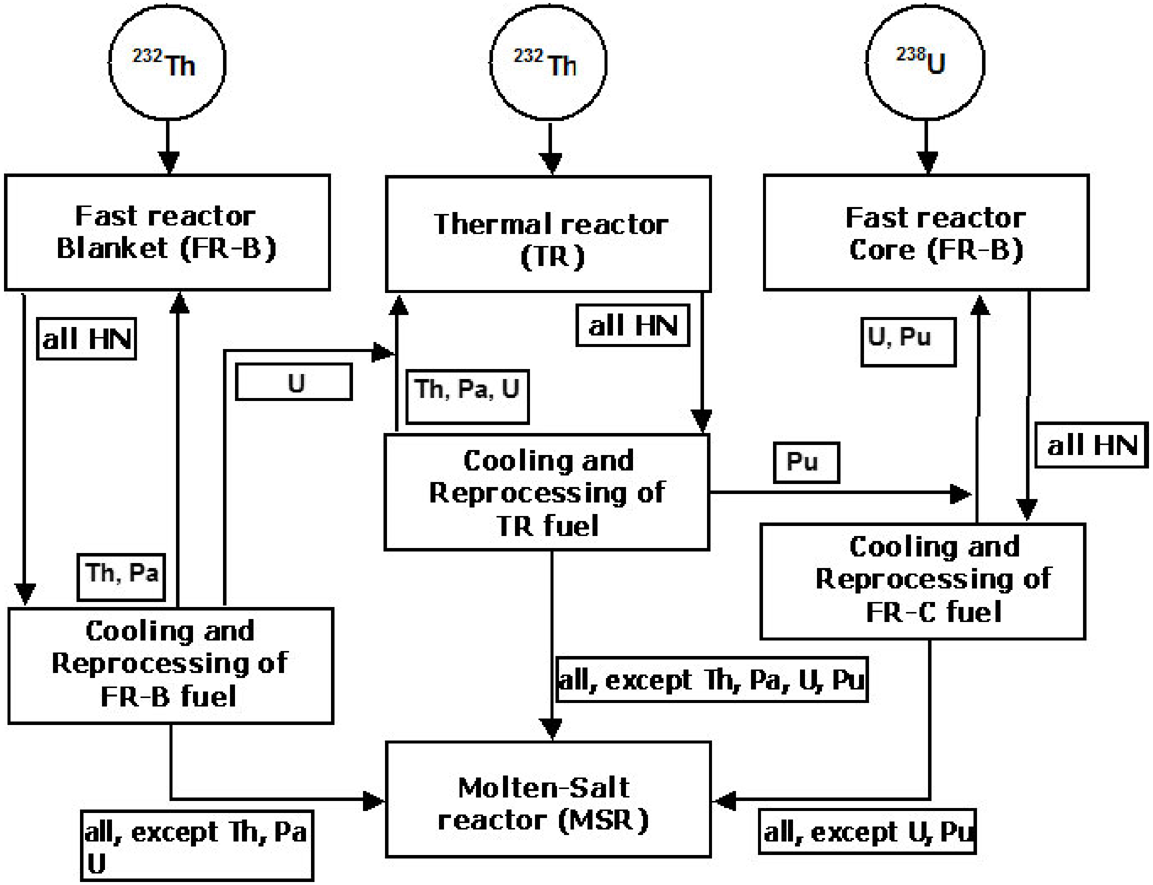
Total in INES

285.0 t

In the external NFC

175.3 t

Structure of INES for uranium-plutonium-thorium nuclear fuel cycle



Share of reactor power in the system

88% TR

9% BR

3% MSR

The amount of fuel for a INES for 1 GW(e)

Total in INES

136.2 t

In the external NFC

87.8 t

Scenarios with Fusion Neutron Source

Problems with the delay in the development of FR are forced to consider scenarios with Fusion neutron source and introduction of thorium into the NE system.

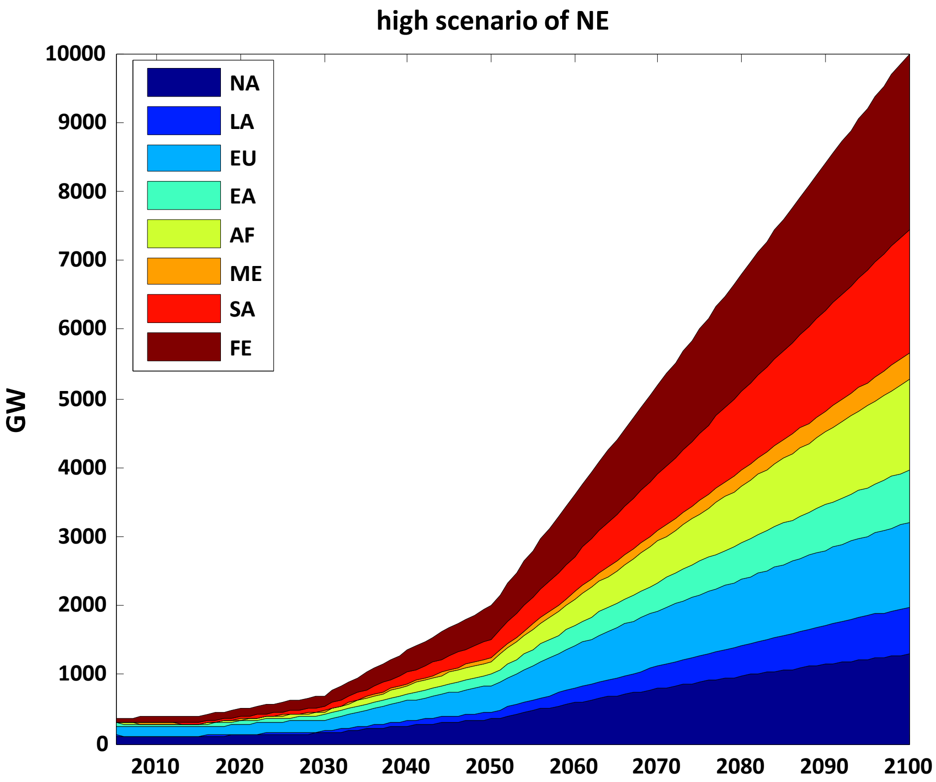
This group of scenarios is divided into several areas:

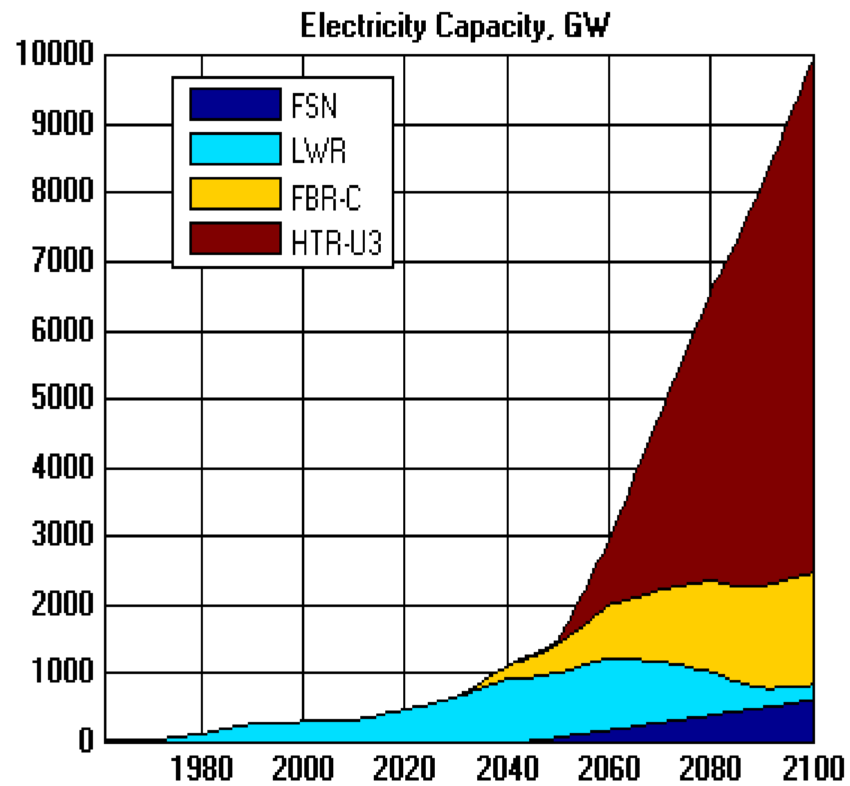
- Production of tritium in FNS
- Partial production of tritium in FNS and TR
- Production of tritium in TR
- Molten salt blankets
- Solid fuel blankets

Nuclear fuel Production Potential in fission reactors and in fusion neutron source

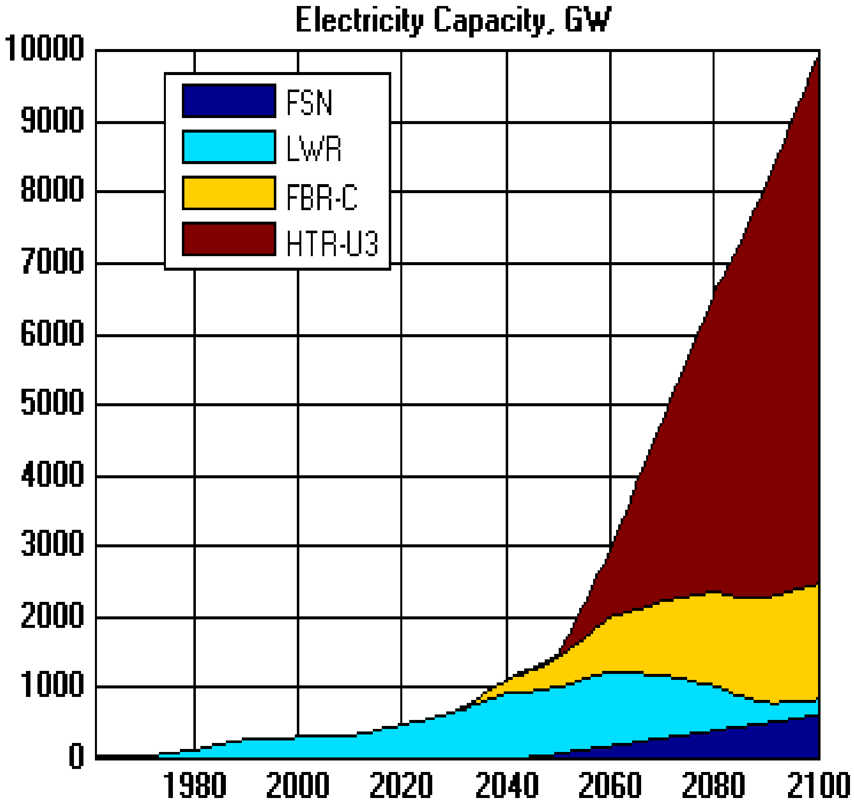
	FR	FNS
Pu (U-233), kg/GW(e) year	270	2000

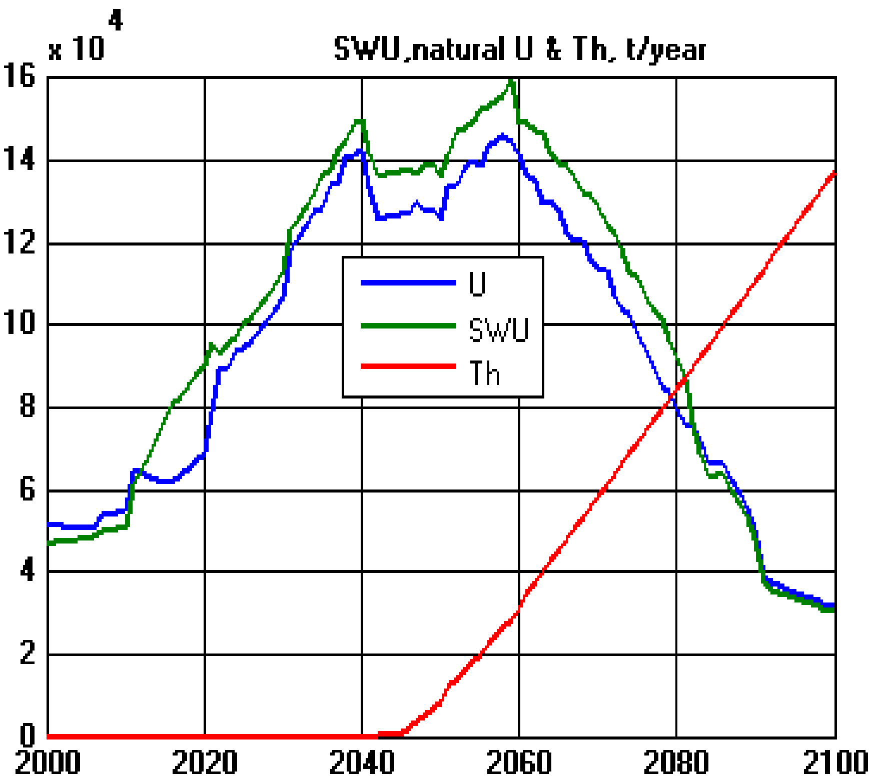
Maximum scenario for development of INES (IAEA) with FNS





Maximum scenario for development of INES (IAEA) with FNS





The power share of FNS in INES is less than 10%

Problems of transition to the second stage of INES development

- The principal point is the use of U-235 both as a source of neutrons and as a source of energy. Without it, all other troubles are meaningless. If there is no cheap and affordable U-235, there will be no need for effective specialists, except those who will be engaged in the decommissioning of nuclear power plants.
- Another basic point: it is necessary to learn how to use effectively uranium 238 and thorium 232 for energy production. It is proposed to use FR and closed nuclear fuel cycle, and to develop FNS.
- It is possible to consider nuclear energy as a necessary part of the whole energy system
- It can be proposed as a basic principle – the goal of NE development is to improve photosynthesis efficiency - but it is difficult to take assistance and financial resources from agriculture for the development of INES.

Difficulties of implementation scenarios with FR and FNS

- The theorem of possibility of creating fast neutron reactors and closed nuclear fuel cycle technologies is convincing for specialists with a technical thinking, but it is not sufficient to make appropriate decisions in the economic field of solving the problems of nuclear power plant development.
- And the fact that FNS is quite attractive from an economic point of view and the fact that many States allocate sufficient funds for its development, does not yet lead to the proof of the theorem of its feasibility.

Features of transition period for INES development:
The evolution from competition and survival of individual NPP to a nuclear power system that meets the requirements of sustainable development.

Until the NE system has been developed and experience gained in its operation, one should not expect the emergence of sustainable requirements or regulations, and it is necessary to rely on the analysis based on study of possible scenarios for development of both the NE system and changes in the conditions and objectives of its development, which helps to develop recommendations:

- Forecast goals and objectives for different periods of time and different possible conditions;
- Anticipate changes in the conditions of occurrence of risks and threats;
- Find solutions to identified and predicted problems and using various opportunities and resources to do so;

at the same time, bearing in mind that the dangers and threats are realized themselves, and the opportunities need to work in advance.

The mechanism of INES development

The problem should proceed from the basic economic principle of sustainable development INES (INPRO): Energy and related products and services from INES should be available and affordable, or in other words, INES must be technically feasible using economic methods, because there is no other methods of its large-scale implementation.

At the same time, based on the fact that the fundamental premise of the classical economy is that wealth and living standards grow as a result of the pursuit of long-term personal benefits by market participants (A. Greenspan), it is necessary to rationally set the task of developing the INES as a system, so that its structure, scale and goals can become interesting to almost all those interested producers and consumers of nuclear energy services who now see each other as competitors or opponents.

Basic physical principles of sustainable development of INES, the meeting of which requires the closure of NFC

- The risk is proportional to the power of nuclear power rather than to the integrated power generation (NFC closure for all hazardous radionuclides);
- Neutron efficiency of INES must increase (breeding and external neutron sources);
- Minimization of life time (number) of hazardous radionuclides in the system (different types of reactors in the nuclear power system);
- Effective use of radionuclides, including the use of all of the produced/extracted heavy nuclides (closing of nuclear fuel cycle for all actinide);

Priority benefits in the near term

In the field of nuclear technology, it is necessary to assess both benefits and risks at very long-time intervals, significantly exceeding the time of responsible decision-making.

On the basis of available models and databases that allow assessing both benefits and risks, decisions that are now being made are fundamentally more focused on possible gains.

This priority is due to the facts that:

- first of all, those who make decisions will receive the benefits (even if they later turn out to be erroneous), and the consequences of neglecting the risks fall on the shoulders of a fundamentally larger circle of individuals, the state, society as a whole or the whole of humanity;
- risks are more distant in time compared to the times of expected gains, and this leads to greater uncertainty in both the models and variables that are used to assess risks compared to the models and variables for assessing benefits;
- specialists have a kind of clear vision of what they are specialists in, but they do not have sufficient knowledge in the field of all kinds of risks, because risk assessments require a wider set of theories, hypotheses, principles, databases than is available to any individual or even to firms and corporations.

Priority of risks in the long term

But, if now we need to make decision on a distant future in which there are no our real interests in obtaining of individual benefits for obvious reasons, the situation and the emphasis could be seriously changed, because the consequences of decisions can be catastrophic, and the gains are not significant and generalized. And preferences in the choice of solutions for future technologies can be shifted from now profitable technologies to minimum risky technologies.

The problem of complex systems development

- We are just at the beginning of the era of nuclear power. If we are going to consume effectively both uranium 238 and thorium 232, then nuclear era can last at least several thousand years.
- One should not rely for INES on evolutionary processes, on trial and error, and hope that the main thing is good practice based on a detailed study of current tactical steps. There is a well-known maxim of the great Chinese military thinker Sun Tzu that tactics without strategy are just vanity before defeat.
- The computers made it possible to use fundamentally more complex financial processes in the economy, it gave an impetus to economic development, but also revealed various contradictions and problems due to the organization of structures of greater complexity that are no longer comprehended by the human mind and require measures to ensure the security of economic and financial processes at a new level of development of the global economic system.

INES problems

- The scale and rate of INES development will determine the set and level of the problems that nuclear power must solve in order to fulfill their mission.
- The now offered variety of solutions ranges from obviously sufficient at a low level of demand for nuclear power, to those levels for which there are no solutions in the field of nuclear power not only on the tables of designers, but even in their heads.
- Since we are in the field of fundamental uncertainty in the scale and rate of INES development, we need to identify the problems at the level of projections to be addressed in different situations and to evaluate those resources required for their solution or decision making when we receive clarity with the future scale and pace.
- Separately, there is a problem of preparing resources for the expected time of decision-making. Among the resource problems, the most important, in addition to the available sources of neutrons in the form of uranium 235, plutonium, uranium 233, is the training of appropriate specialists with the necessary set of theories to adequately assess the situation, taking into account past experience and available resources and trends in the development of various technologies that are already or will be related to the fate of nuclear power plants.

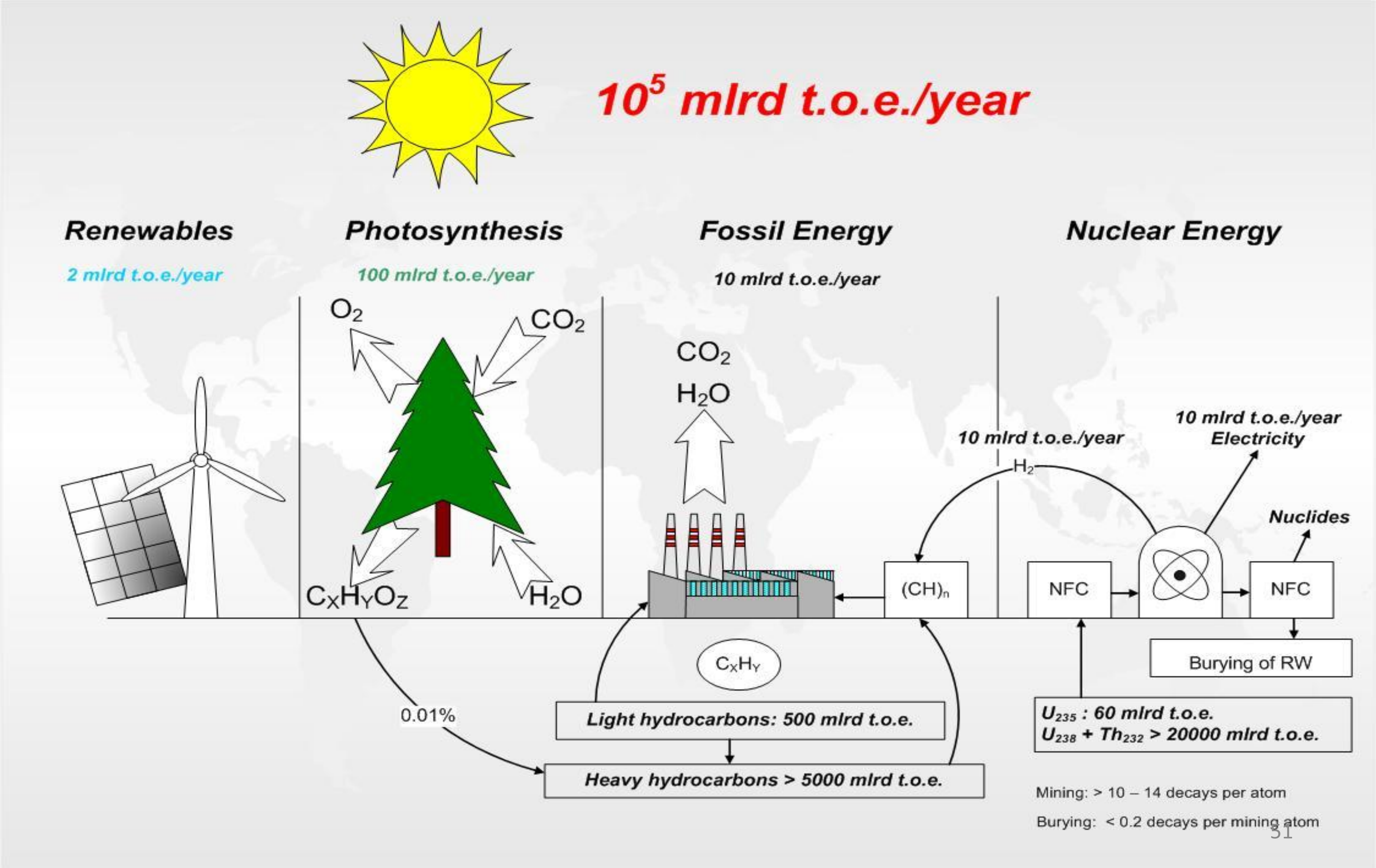
Summary

- Only nuclear energy can be a real Challenger for the role of a future large–scale energy source, and in such a configuration that it fully and timely solves the main problem of the modern world - the elimination of resource scarcity.
- In conditions of deficit of fissionable nuclides, especially at the stage of rapid growth of nuclear power capacity, fusion neutron source can be used as the most effective sources of neutrons for the production of fissionable nuclides from raw nuclides (uranium-238 and thorium-232), the involvement of which in energy production is a necessary condition for the sustainable development of nuclear power.

Summary

- Energy is the power part of the natural process control system. Sustainable development is not so much about strengthening governance as it is about understanding more about what we are managing and for what purposes.
- Nuclear Power gives new qualities that we still need to understand and develop appropriate new concepts and new images that are available not only for understanding by NP system specialists, but also for those who can contribute to its "implantation" in a sustainable economic process, taking into account environmental constraints.
- In principle, nuclear power plants and nuclear technologies with appropriate organization of their use can allow us not only to improve the efficiency of "photosynthesis", but also to make timely decisions more adequately at the level of new theories.

Asymptotic view on Sustainable Energy Future



Thank you for attention!