International Atomic Energy Agency

Opportunities and Challenges of Large-Scale Nuclear Energy Development

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Nuclear Power Technology Development Section

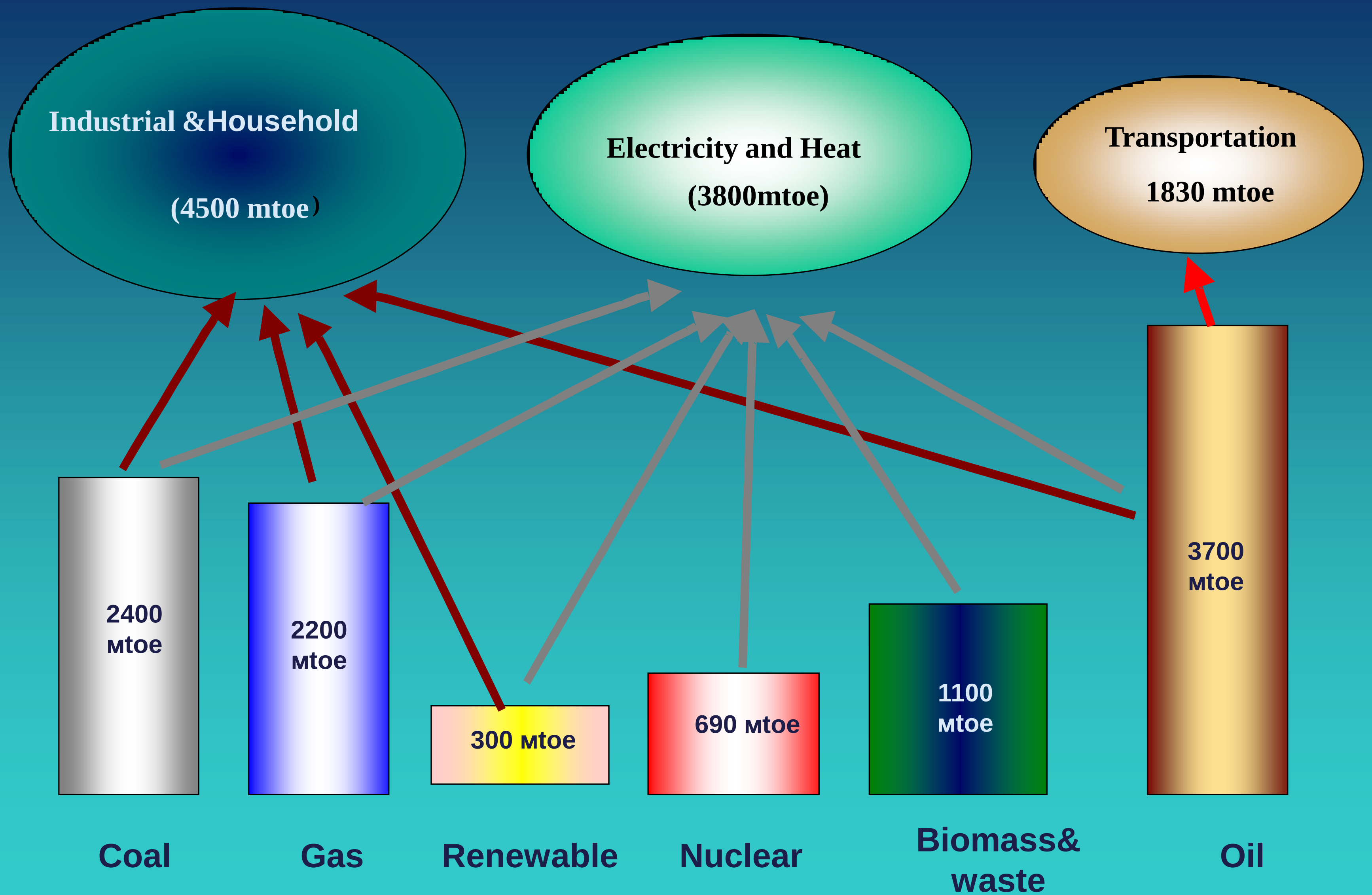
Department of Nuclear Energy

Joint ICTP/IAEA Workshop

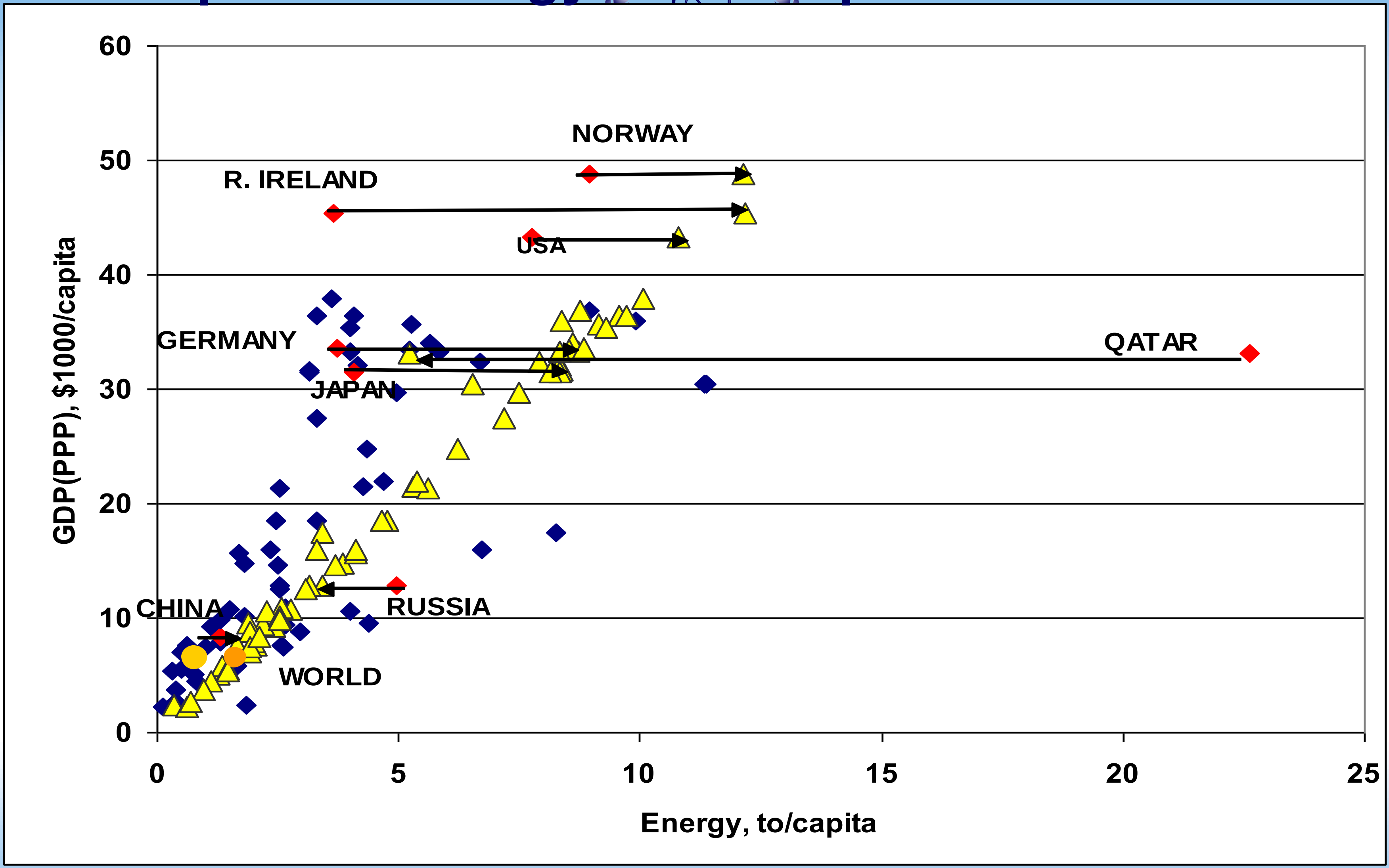
"Research Reactors for Development of Materials and Fuels for Innovative Nuclear Energy Systems"

6-10 November 2017, ICTP, - Trieste, Italy

Energy resource distribution.



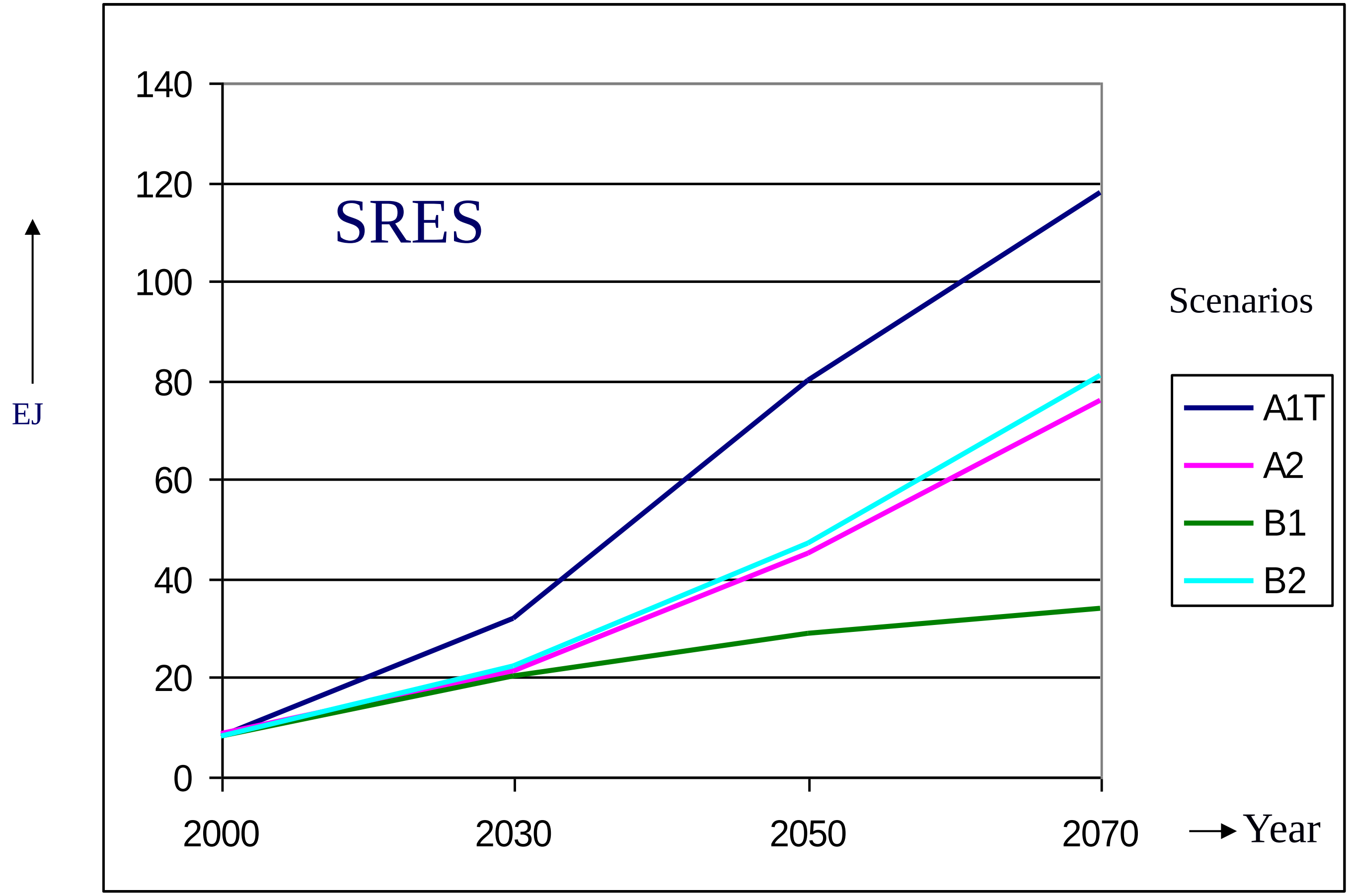
Specific energy consumption in the world



Consumption of primary energy resources

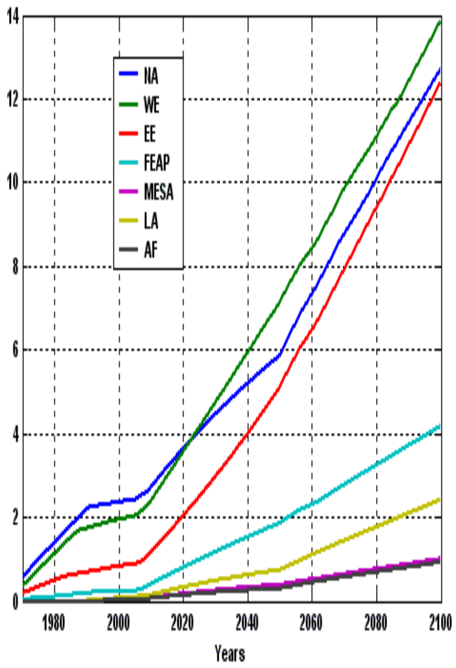
Energy consumption

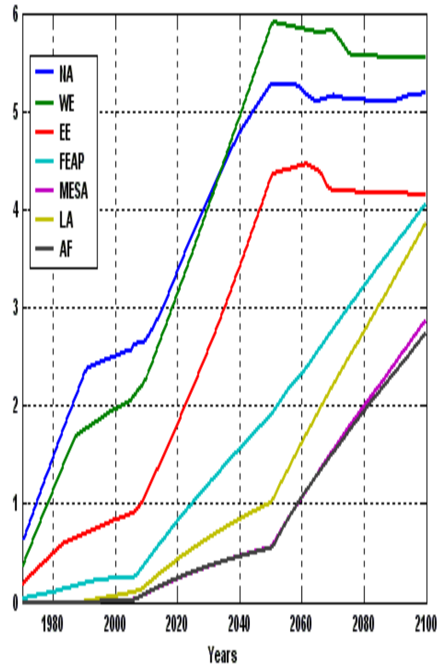
Nuclear electricity production (EJ) for the four selected SRES scenarios



Global future energy scenario+national power strategies (time frame–100 years)

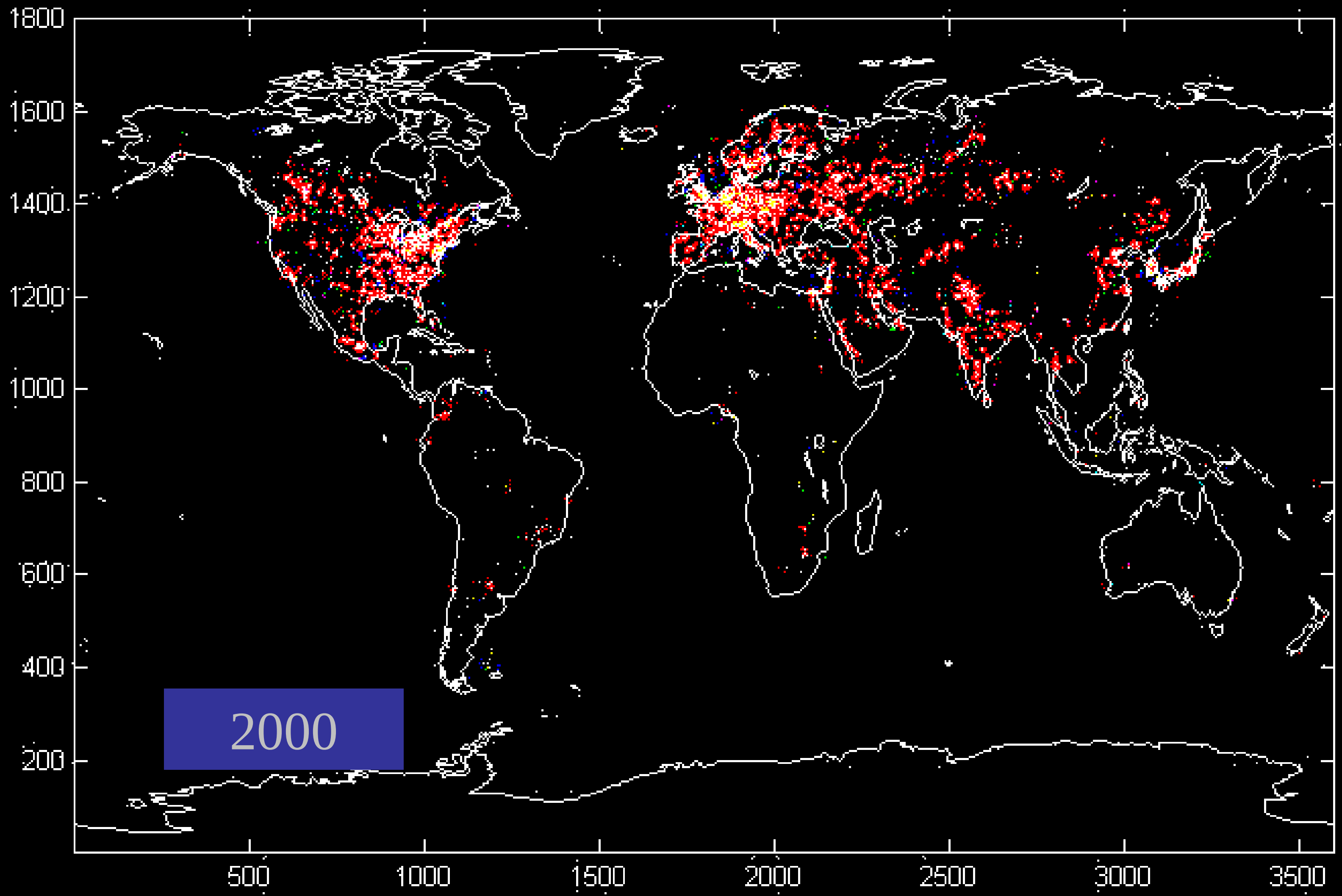
Electricity generation,
MWh per capita



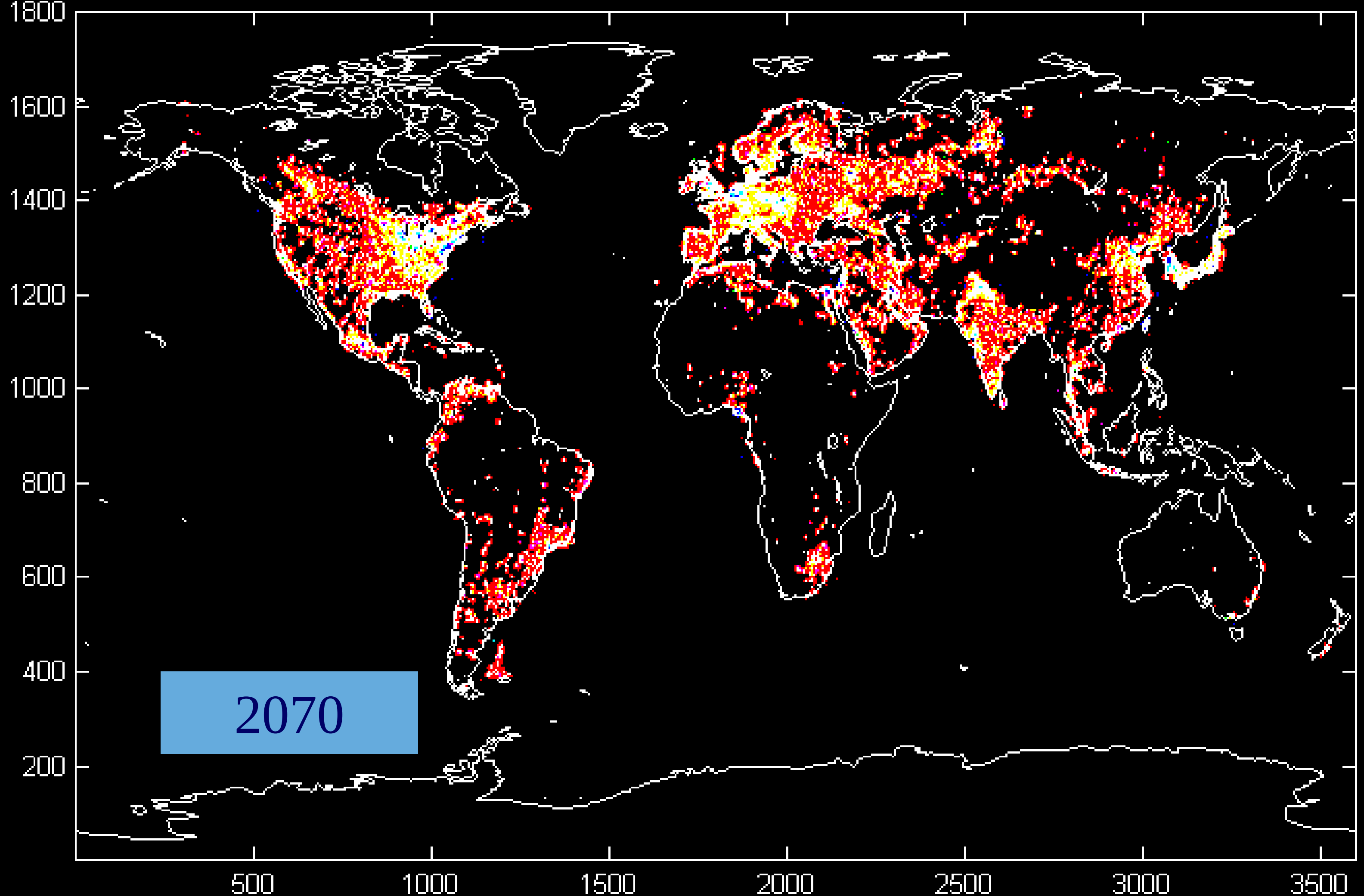


Electricity generation per capita:

NA-North America;
WE-Western Europe;
EE- Eastern Europe;
FEAP-Far East Asia (China, Korea, Japan);
MESA-Middle East & South Asia (Near East, India);
LA-Latin America;
AF- Africa



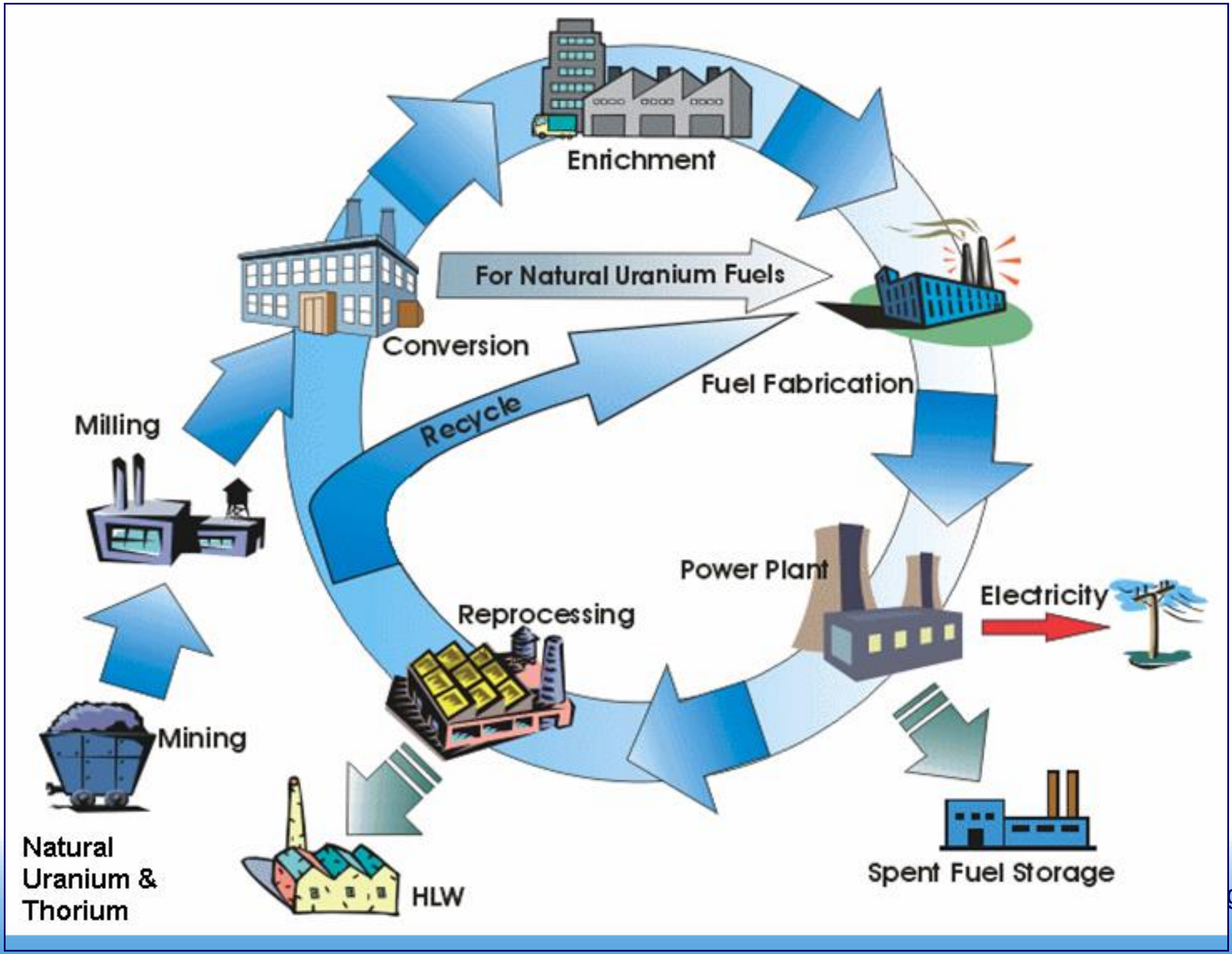
Source: IIASA



Source: IIASA

Definition of nuclear energy system (NES), long-term strategies, NE sustainable development, scenario studies

Nuclear Energy System (NES) includes all components (Facilities)



Innovative NES:

- **will position NP to make Major Contribution to Energy Supply in the 21st Century.**
- **includes Innovative and Evolutionary Designs.**
  - Innovative design (= advanced design) incorporating radical conceptual changes in design approaches or system configuration in comparison with existing designs.
  - Evolutionary design (= advanced design) incorporating small to moderate modifications with strong emphasis on maintaining design proveness**.**
- **includes all Components: Mining and Milling, Fuel Production, Enrichment, Fabrication, Production (incl. all types and sizes of reactors), Reprocessing, Materials Management (incl. Transportation and Waste Management), Institutional Measures (e.g. safe guards, etc.).**
- **includes all Phases (e.g. cradle to grave)**

Why long-range strategies?

Nuclear energy *strategies*

- Strategy
  - Medium- to long term
  - Beyond one single NPP
    - In technical terms: cover whole nuclear energy system (all facilities)
    - In planning terms: cover whole nuclear energy programme (all projects)
  - Structured hierarchy of national planning documents in some countries
    - Link to national sustainable development plan
- Two components
  - Quantified (typically up to 30 years)
  - Descriptive (all timeframes)

Why are long-term strategies important? (2)

- Because key drivers for nuclear are long-term
  - Climate change and environment (50 to 100 years plus)
  - Competitor fossil fuel / availability (20 to 100 years)
  - Objective of energy security
  - Population growth plus energy intensity (two generations, 50 years)
- Because technical lifetimes are long-term
  - One nuclear power plant (15+40/60+15 years)
  - Full nuclear energy programme (plus 40 years)
  - Including spent fuel and waste (centuries)

Why are long-term strategies important? (3)

- Because becoming a "welcome member of the nuclear family" takes time
  - Nuclear is a sector with many issues to be considered
  - A soft factor, but most relevant
  - Trust, suppliers, governmental agreements, reputation ...
- Because national sustainable development plans are long-term
  - Education, urbanization, agriculture, industrialization, health… (50 years)
  - Industrial and infrastructure development (15 to 30 years)
  - Building or transferring nuclear knowledge, HR, education (15 to 40 years)

UN Concept of Sustainability and INPRO

UN General Concept of Sustainable Development
including sustainable development
of ENERGY supply

- Economic Dimension
- Environmental Dimension
- Social Dimension
- Institutional Dimension

Sustainable development of Nuclear Energy

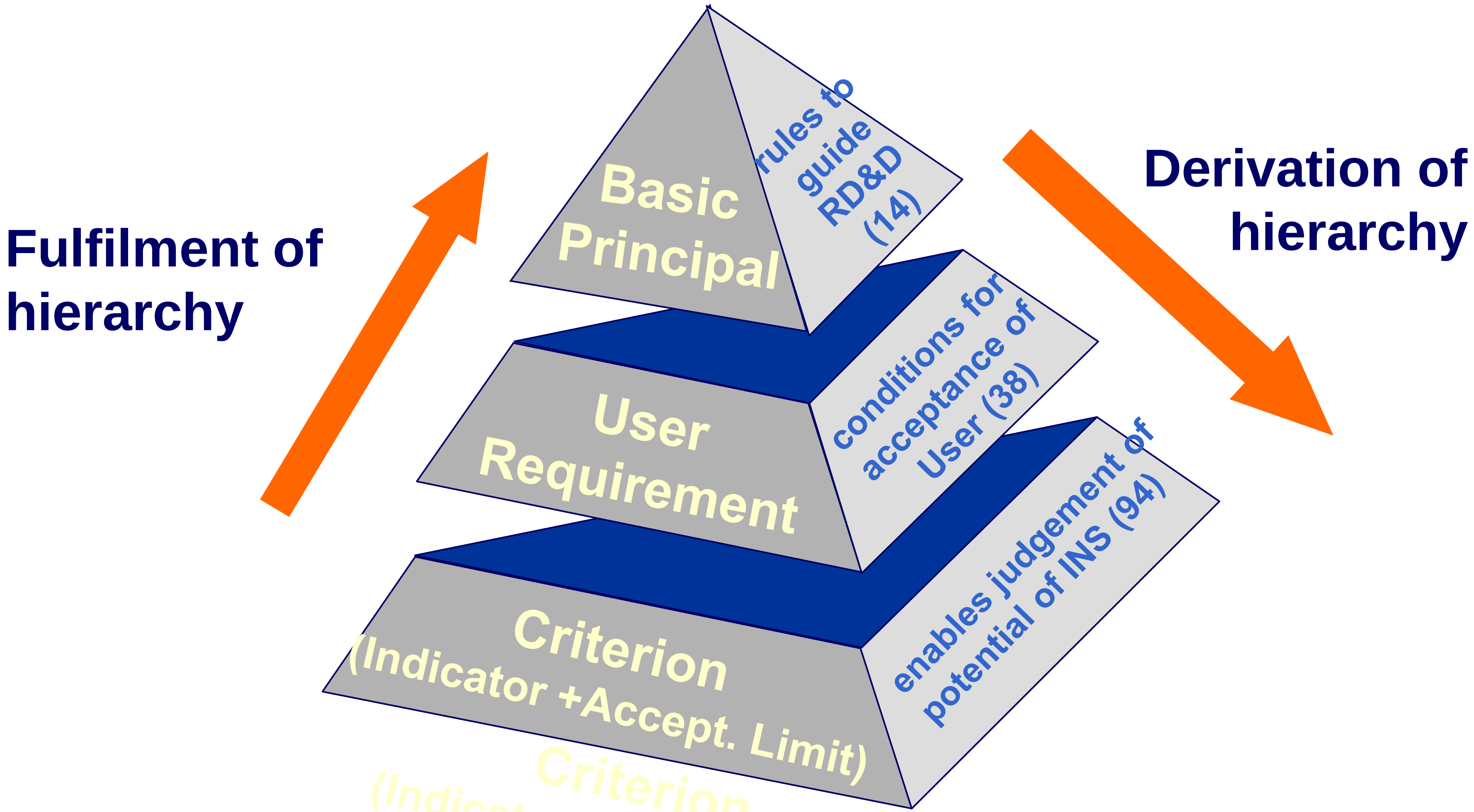
- Economics
- Environment
- Waste Management
- Safety
- Proliferation Resistance
- Infrastructure

INPRO Objectives and Methodology:
MODELLING of energy systems
Assessment using a holistic approach
Decision on Innovative Nuclear Energy System (INS)

- Energy supply is fundamental to sustainable development of the world
- Sustainable energy supply needs significant contribution by NE
- INPRO assures that NE is available in a sustainable manner in the 21st century
- INPRO addresses all dimensions of the concept of Sustainability

General features of INPRO Methodology (1)

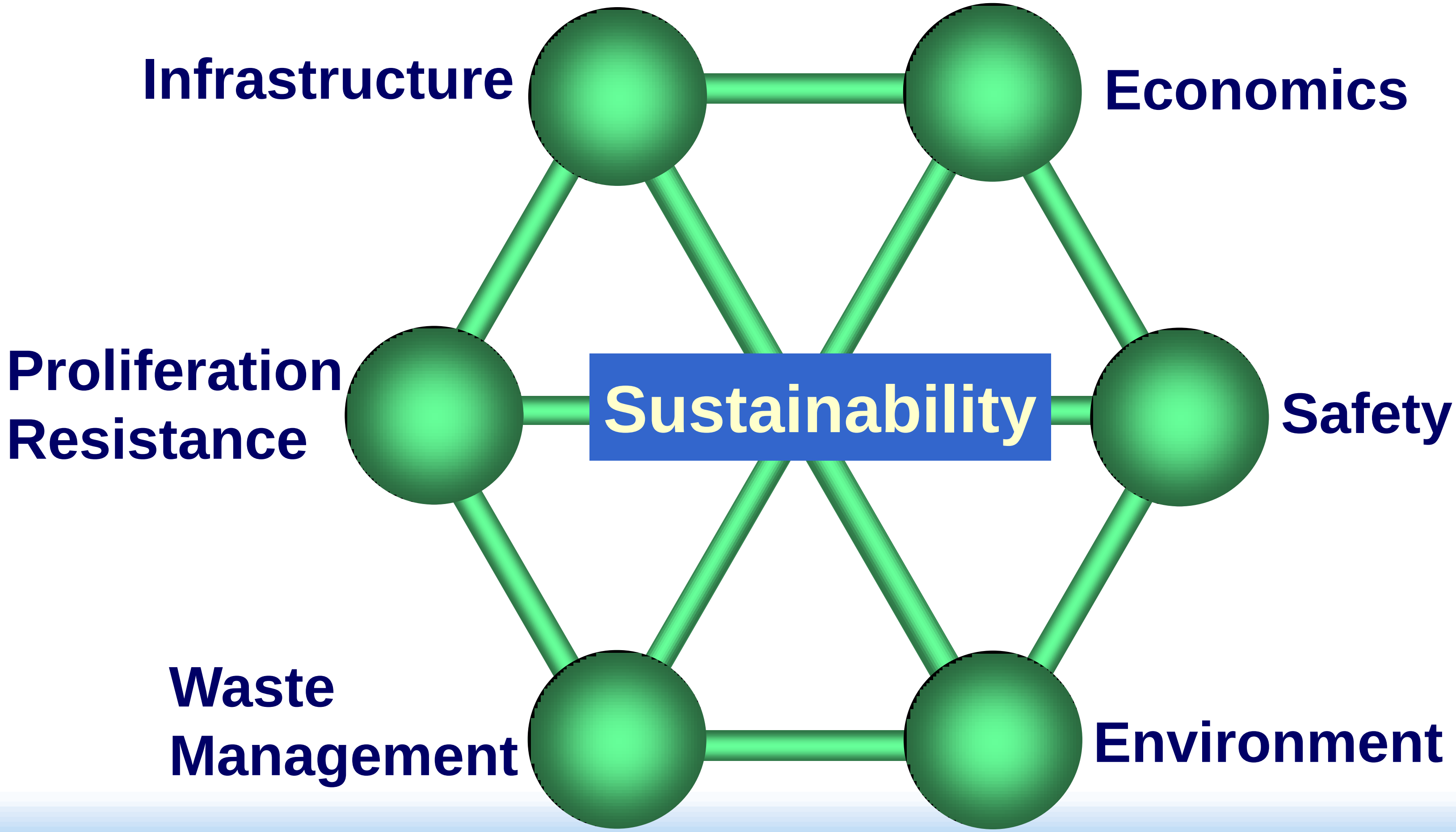
INPRO Hierarchy of demands on INS



Set of basic principles, user requirements and criteria is defined in the areas of sustainability, economics, environment, safety, waste management, proliferation resistance, infrastructure

General features of INPRO Methodology (2)

Holistic approach to assess INS in six areas* to assure its sustainability

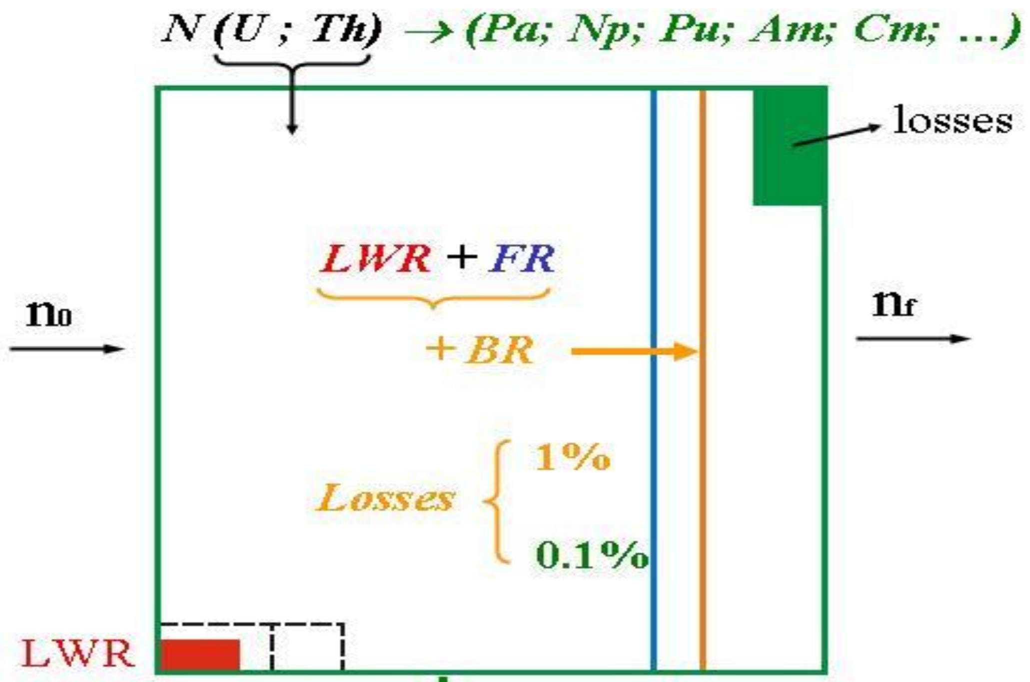


*:Physical Protection will be included

Opportunities and challenges for large-scale global nuclear energy development

presented by the global balance of demands and resources

Physical basis for Innovative NES sustainable development



k_{ef} { 1 / 0.95

Neutron gain : $NG = (n_f - n_0)/N$

	FR	LWR
U - 238	0,62	0
U - 235	0.88	0.62
Th-232	0.39	0.24

NE visions/scenarios analysis for sustainability

- Global/regional/national visions & implementing strategy for decision-makers on the existing & future role of NE for sustainability

- Translate visions of nuclear expansion into technological and policy scenarios that can guide and help coordinate strategies for R&D and NPP deployment.

INPRO study

Analyse O**pportunities and Challenges for Large-scale Global NE** to define responses that have to be done today in institutional and technology development areas:

- to facilitate global NE use in medium term and
- to prepare basis for NE to play an important role for global sustainable development.

Why INPRO needs global analysis?

- **To understand boundary conditions for INS assessments at national level (global energy demand; economic data; resources; environmental issues; non-proliferation; safety)**
- **To estimate role of NE for sustainable development at global level**
- **To define effective institutional and technology development responses having global impact**

NE Specific Challenges

Large scale global NE development may face some nuclear specific challenges in areas such as:

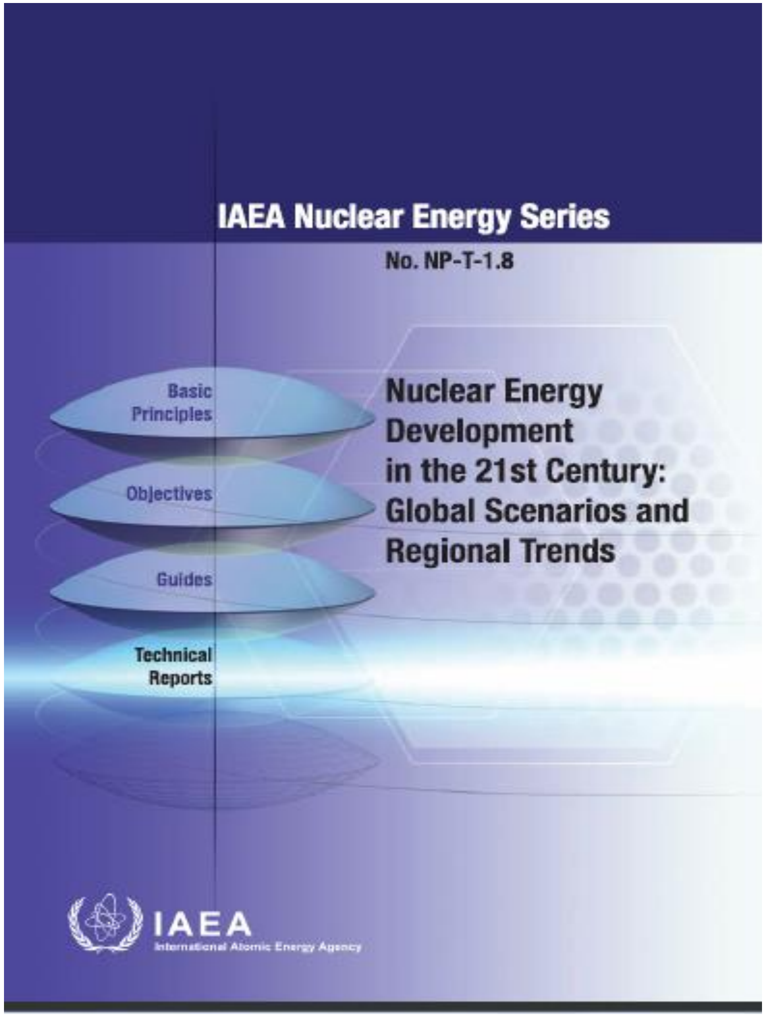
- **Natural resource availability (Pu–internal resource)**
- **Assurance of proliferation resistance**
- **Assurance of safe nuclear waste management**
- **Nuclear safety assurance**
- **Specific NE environmental issues**

A need for dynamic NE modelling

Understanding NE challenges Modelling needs

- Geographic coverage - regional and global
- Time horizon – 21st century, benchmarks at 2030 and 2050
- Areas of analysis – nuclear energy system
- Type of nuclear energy services - electricity, transport, heating, desalination and other
- Areas of concern (resources, PR, waste management, infrastructure, safety? environment? other?)
- Key Indicators and criteria to measure success in addressing NE specific challenges
- NE computer model with detailed fuel cycle description applicable for analysis of economics, infrastructure, resources, waste and PR challenges.

Scenario studies using the IAEA tools



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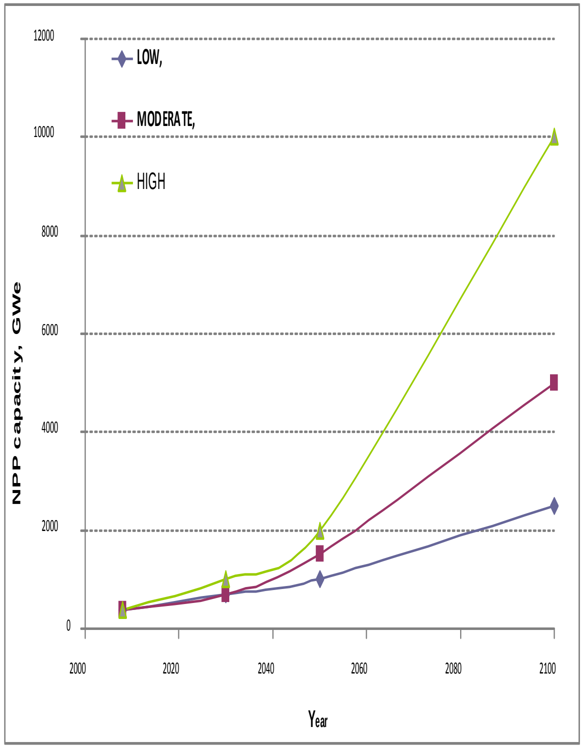
Scenarios for the INPRO study



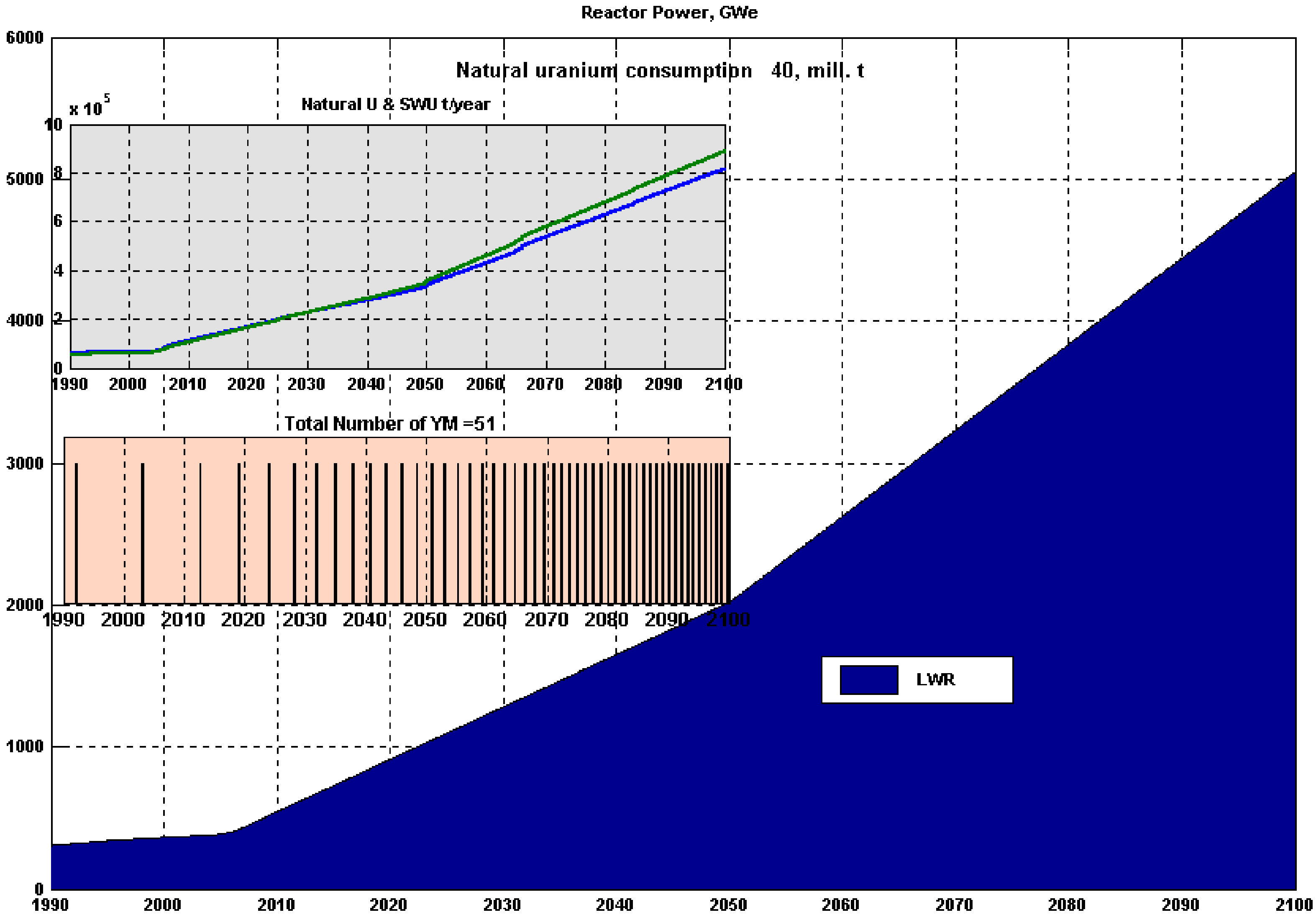
	Installed Capacity (GW_e)	Installed Capacity (GW_e)	Installed Capacity (GW_e)
Year	Low Growth	Moderate Growth	High Growth
2007	371.64	371.64	371.64
2030	500	600	700
2050	1000	1500	2000
2100	2500	5000	10000

Opportunities for Nuclear Energy

- **Limited amounts of available fossil fuels**
- **Rates of economic growth**
- **Ecological constraints**
- **Extension of the effective use of potential fossil resources**
- **Huge amount of U-238 and Th-232**
- **Experience in Nuclear Power Technology**

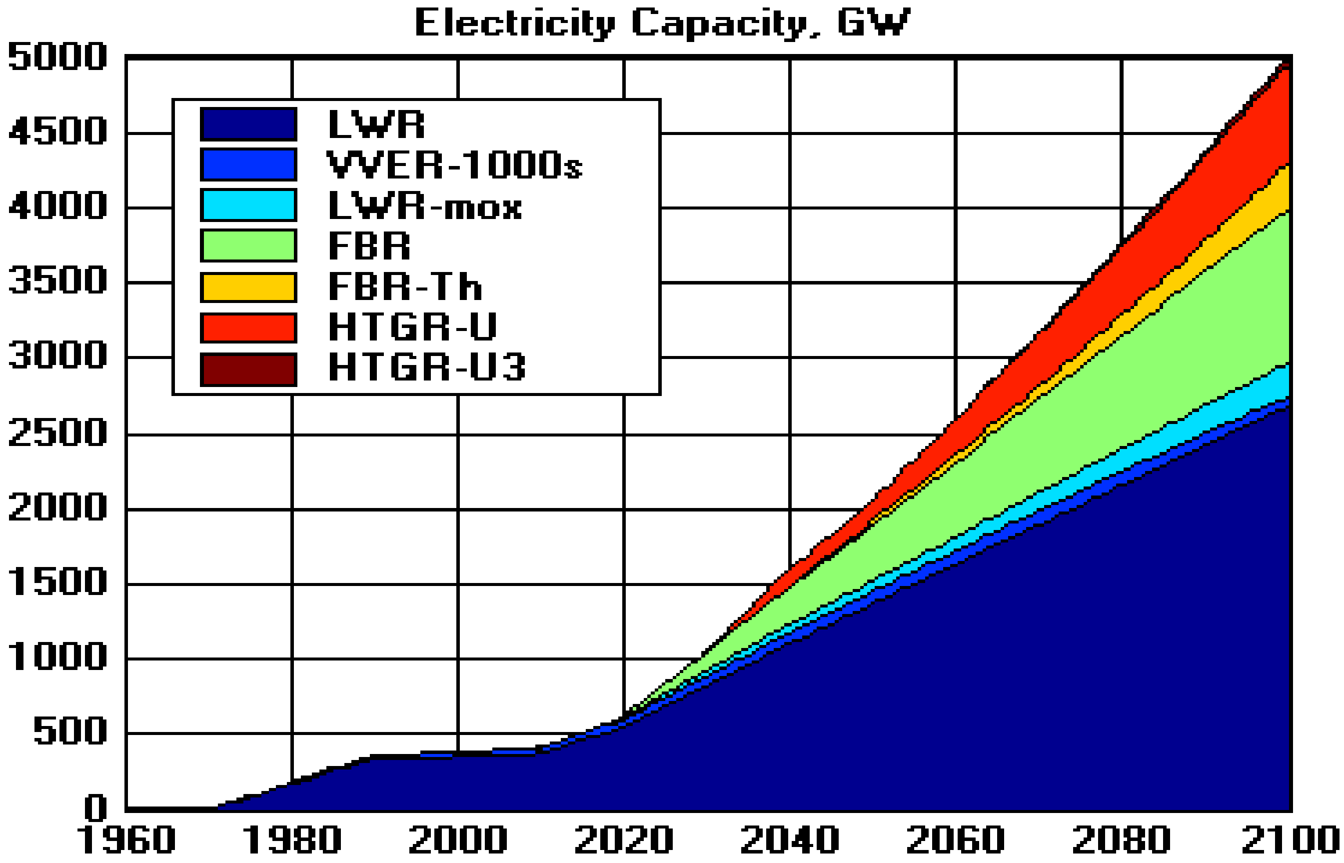
No sustainable NE development with open NFC

Uranium Consumption and Repositories in Large-Scale Development of NE in Open NFC



Possible structure of NE

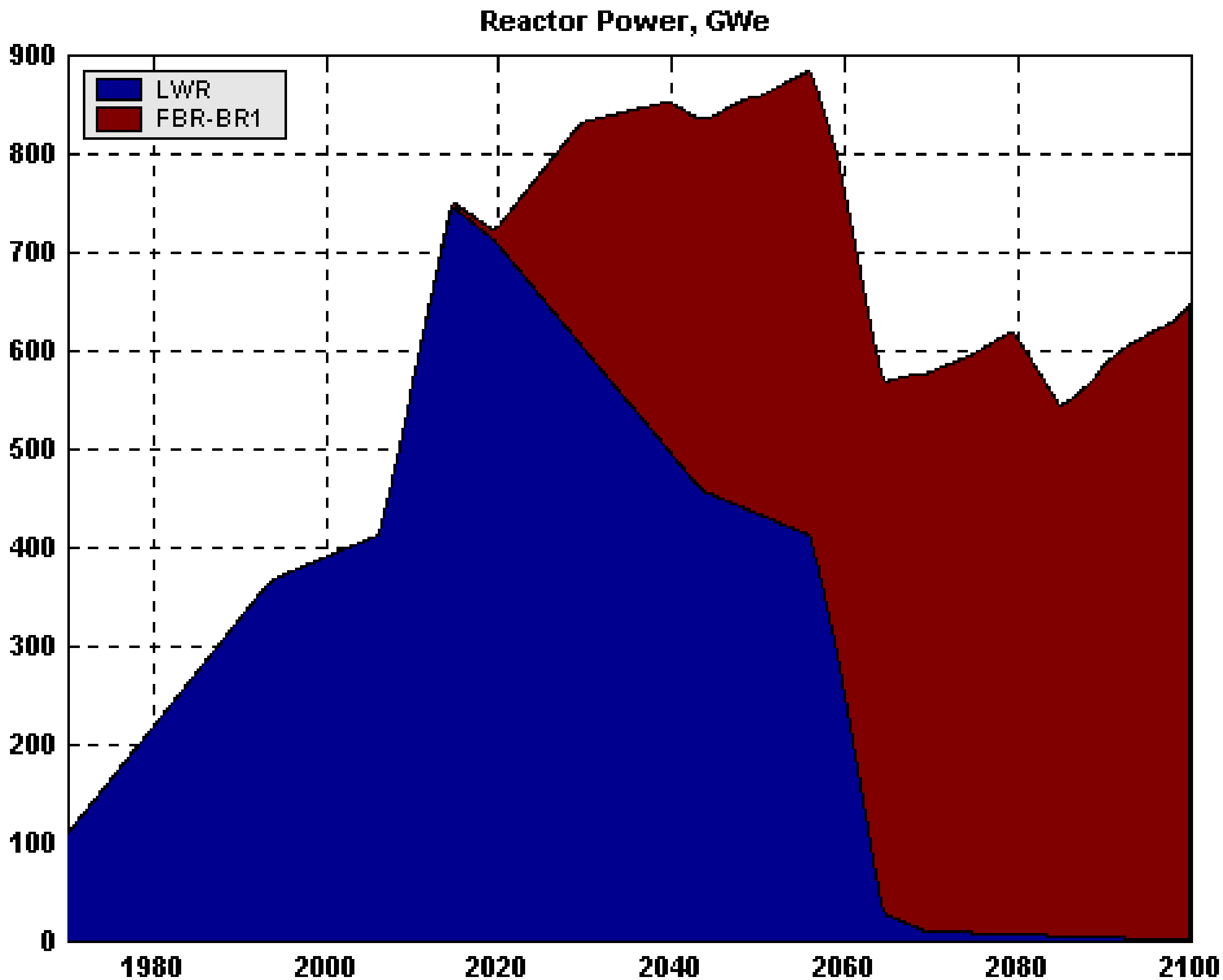
if 30% of electricity in 2100 is produced by nuclear



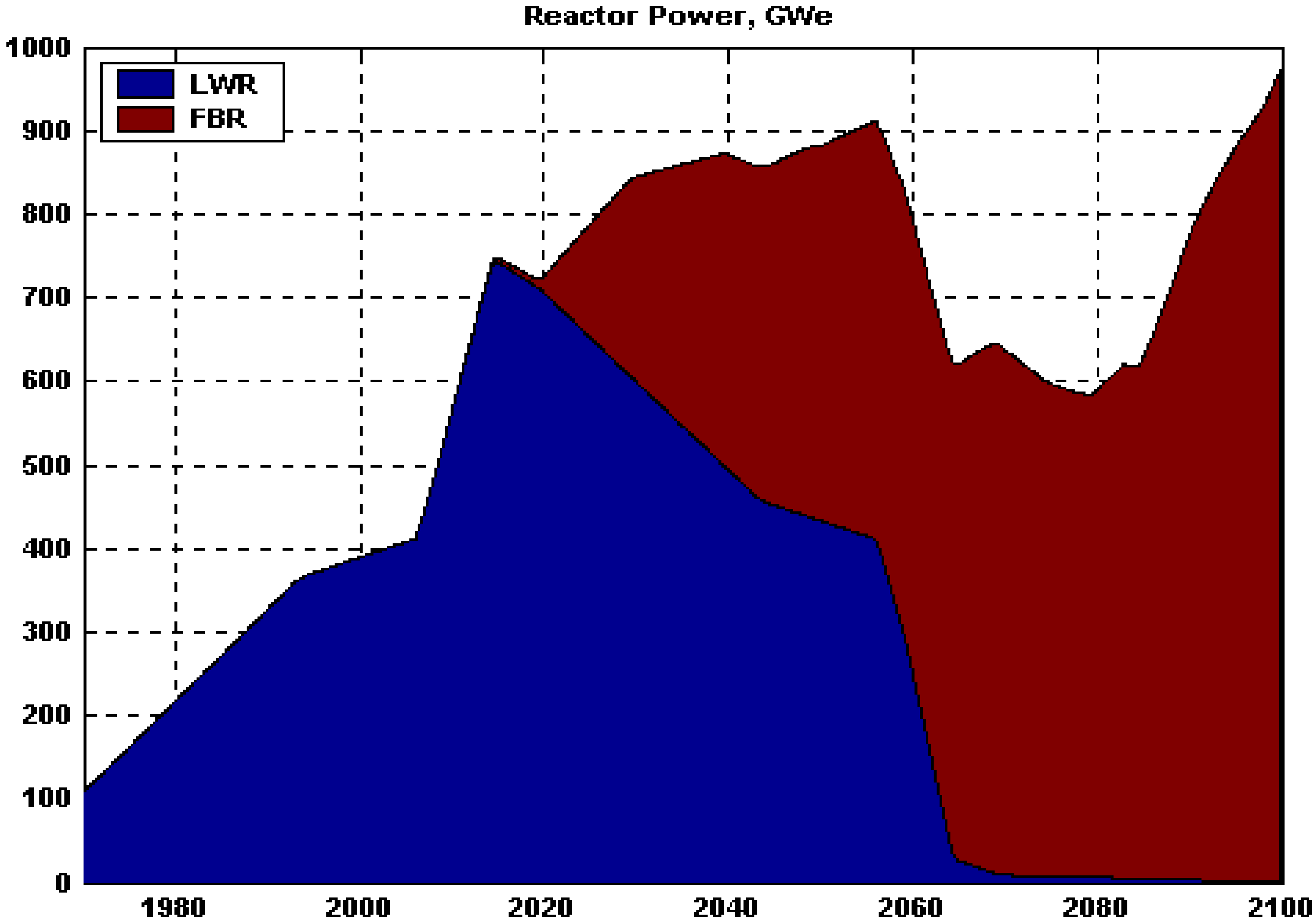
Natural U consumption   22 mln t

Installed capacities of INS: LWR, FR (2020)

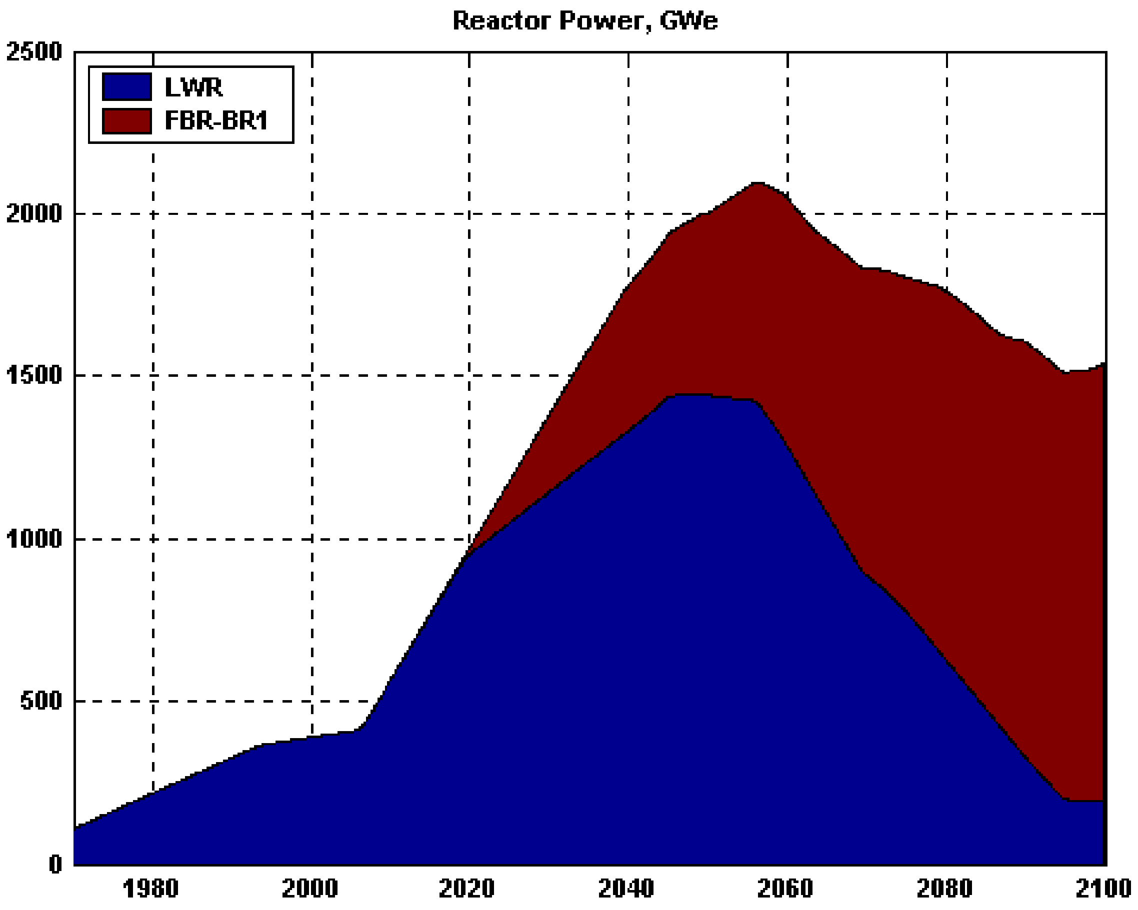
Uranium – 6 mln t, BR=1.05



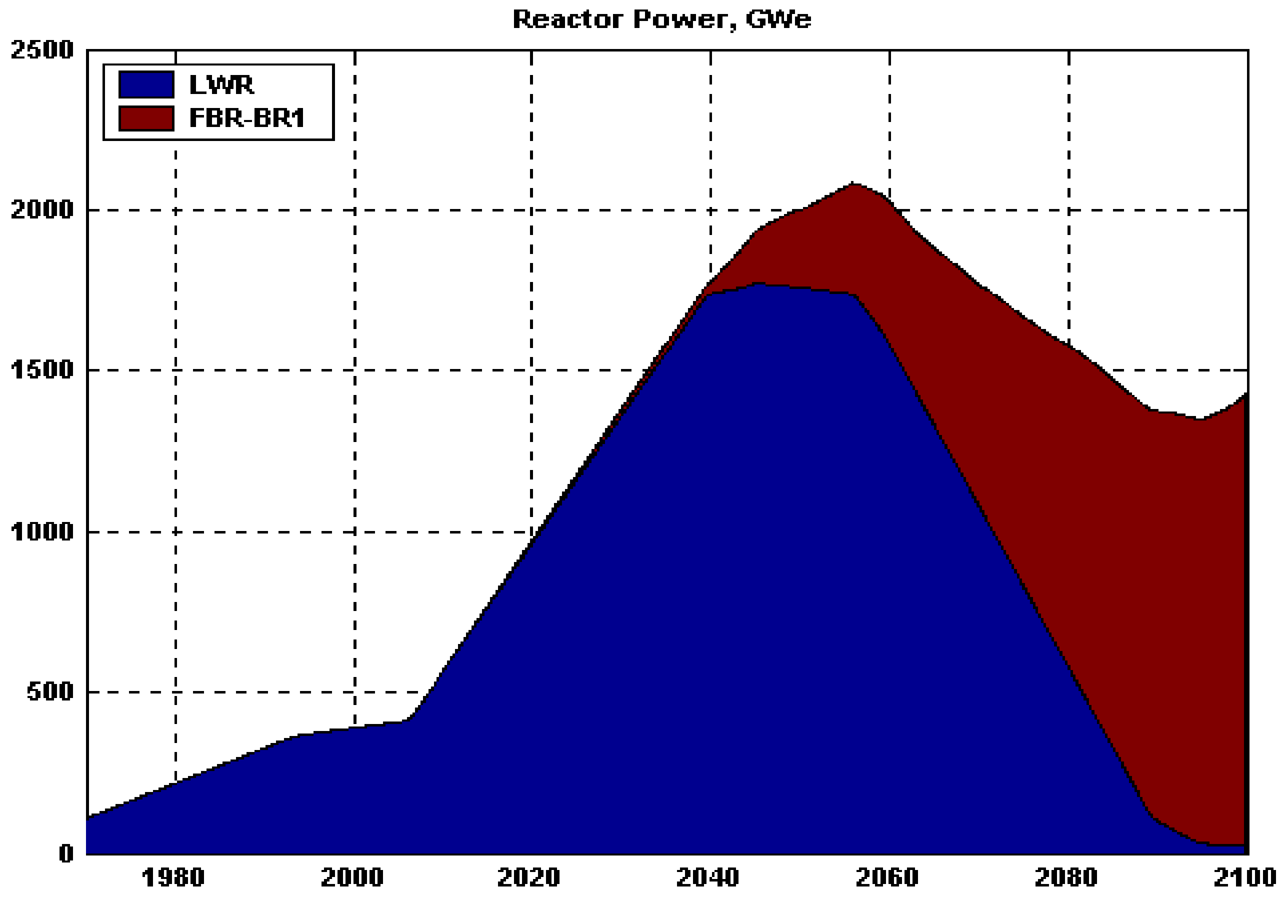
Installed capacities of INS: LWR, FR (2020)
Uranium – 6 mln t, BR=1.6



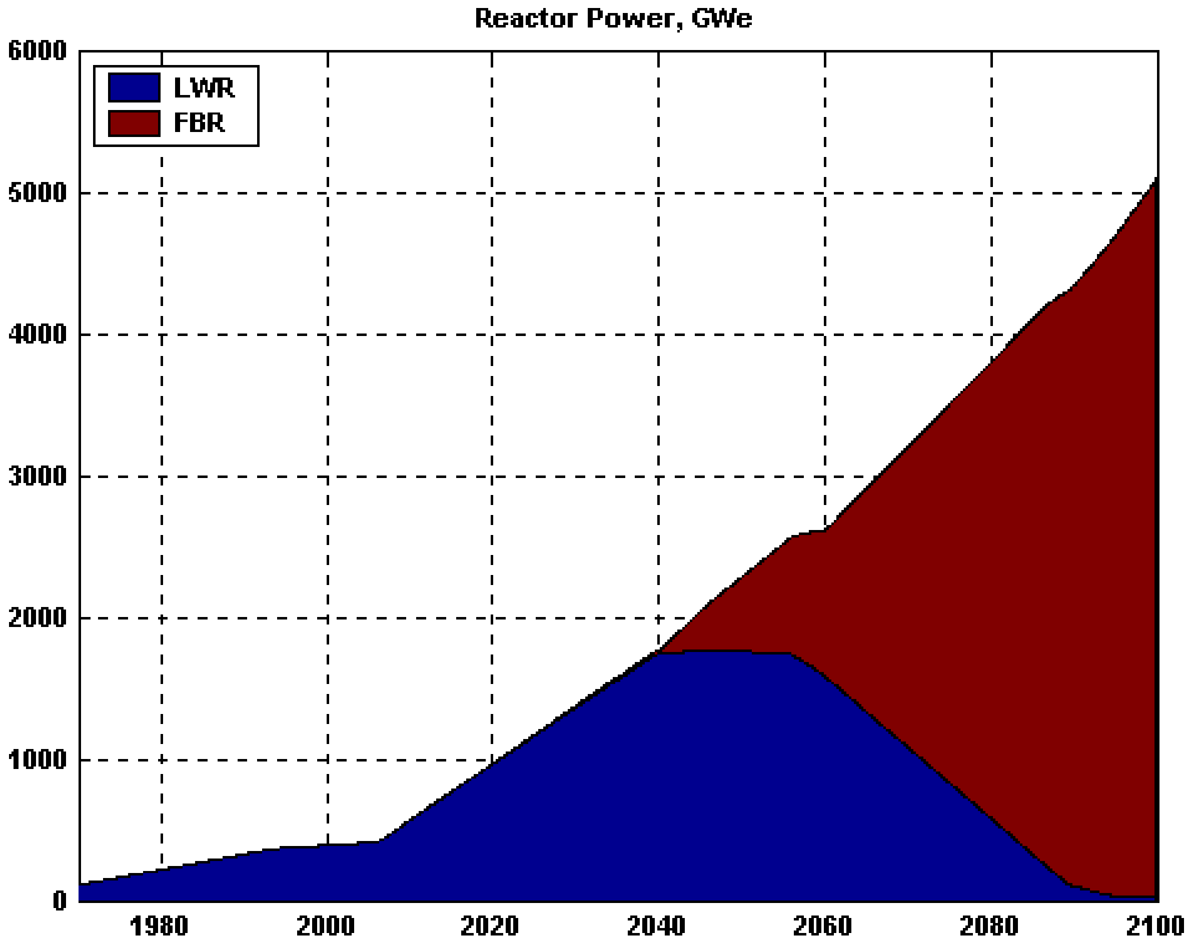
Installed capacities of INS: LWR, FR (2020)
Uranium – 16 mln t, BR=1.05



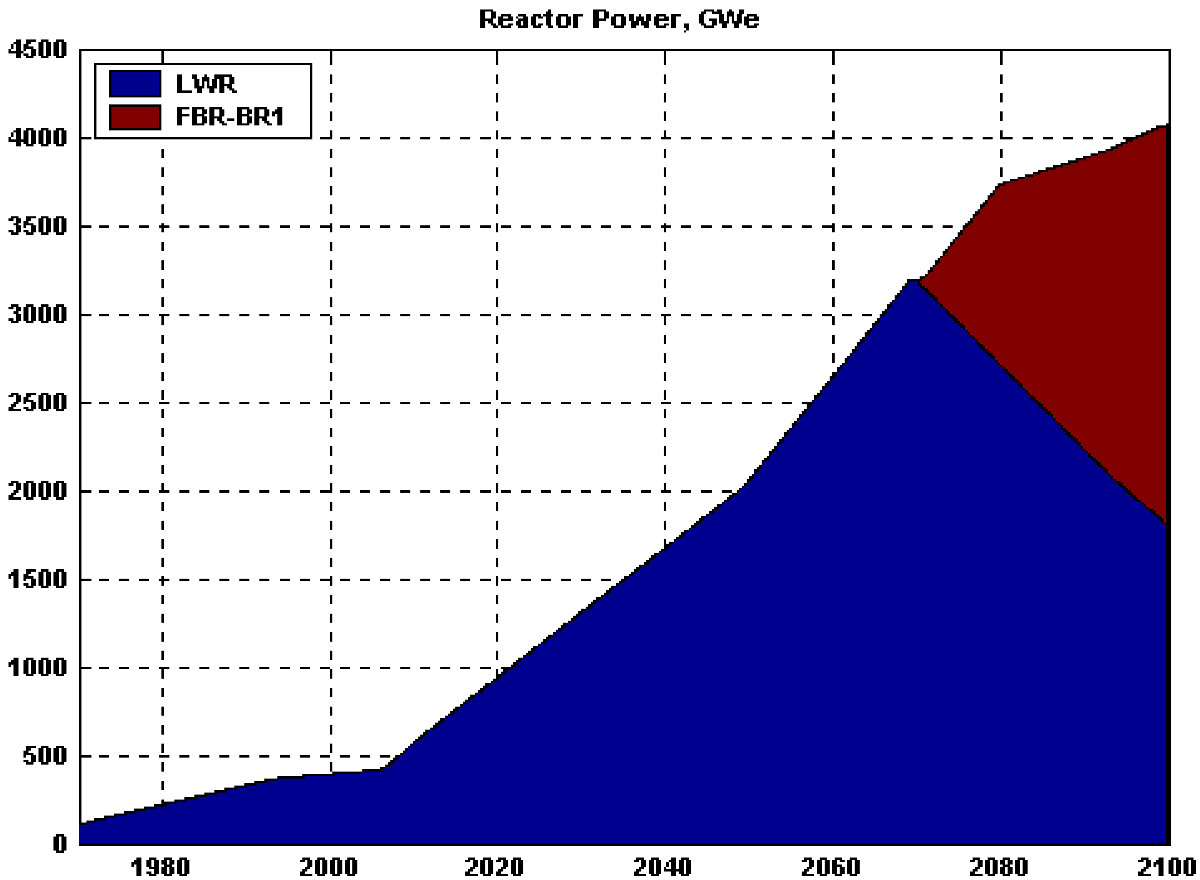
Installed capacities of INS: LWR, FR (2040)
Uranium – 16 mln t, BR=1.05



Installed capacities of INS: LWR, FR (2040)
Uranium – 16 mln t, BR=1.6



Installed capacities of INS: LWR, FR (2070)
Uranium – 40 mln t, BR=1.05



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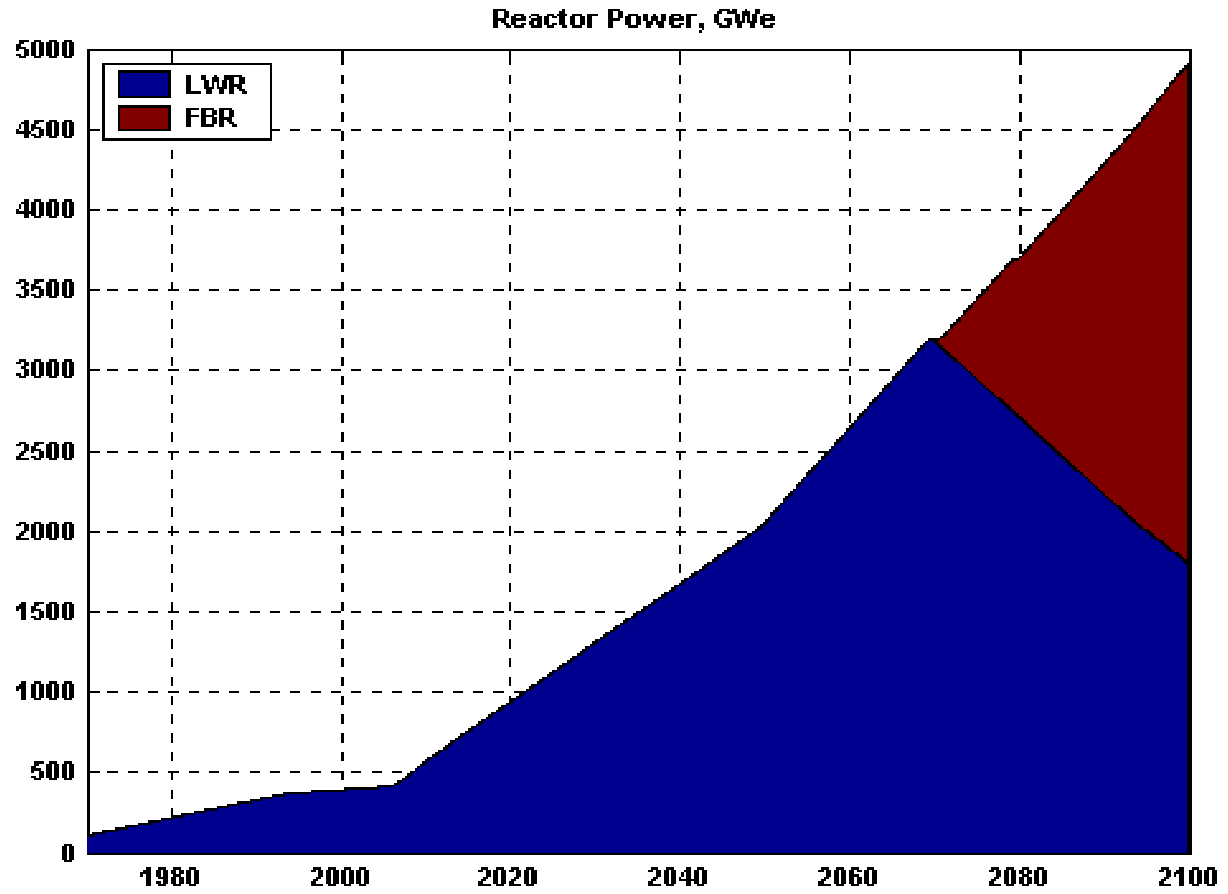
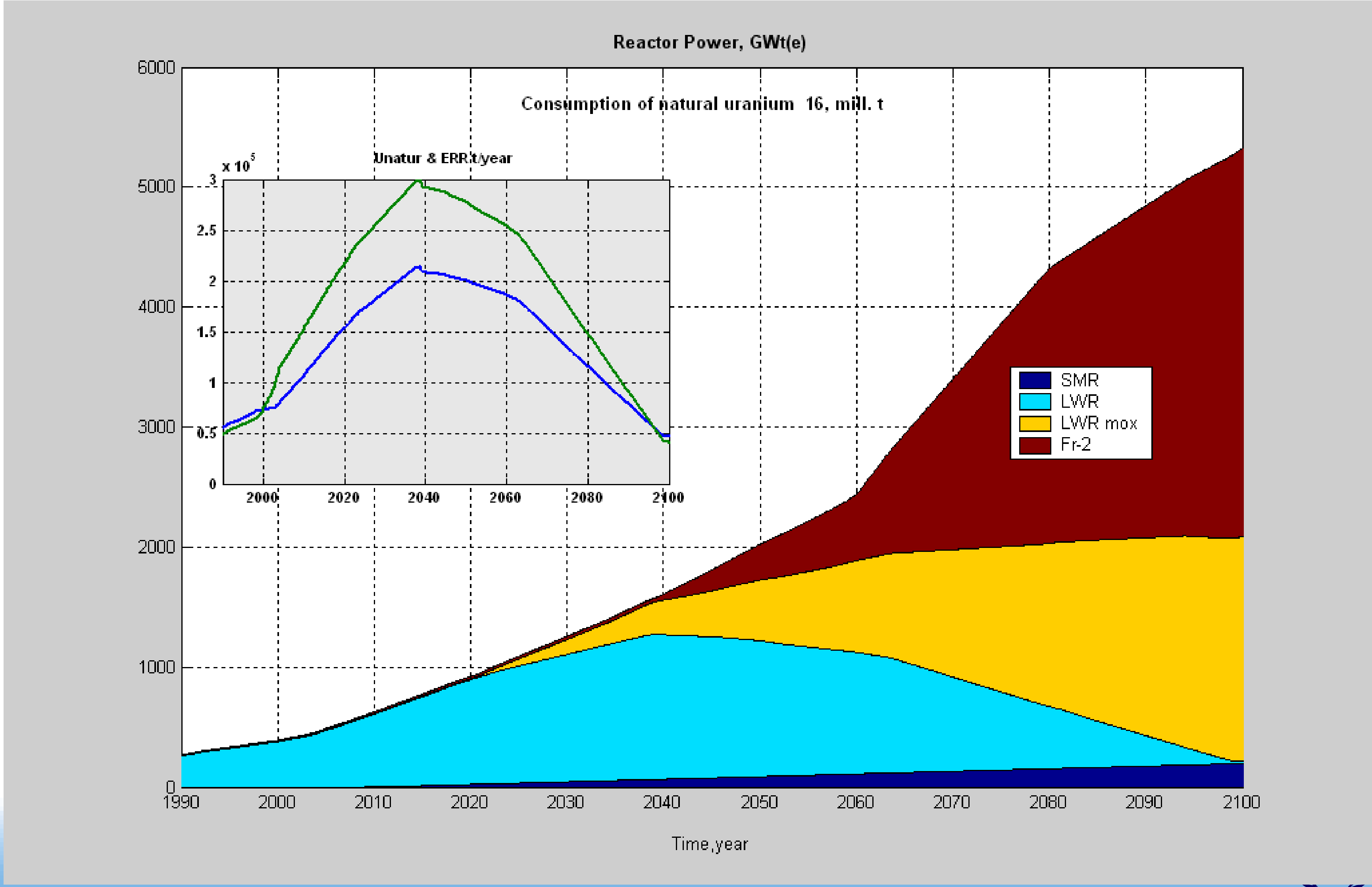
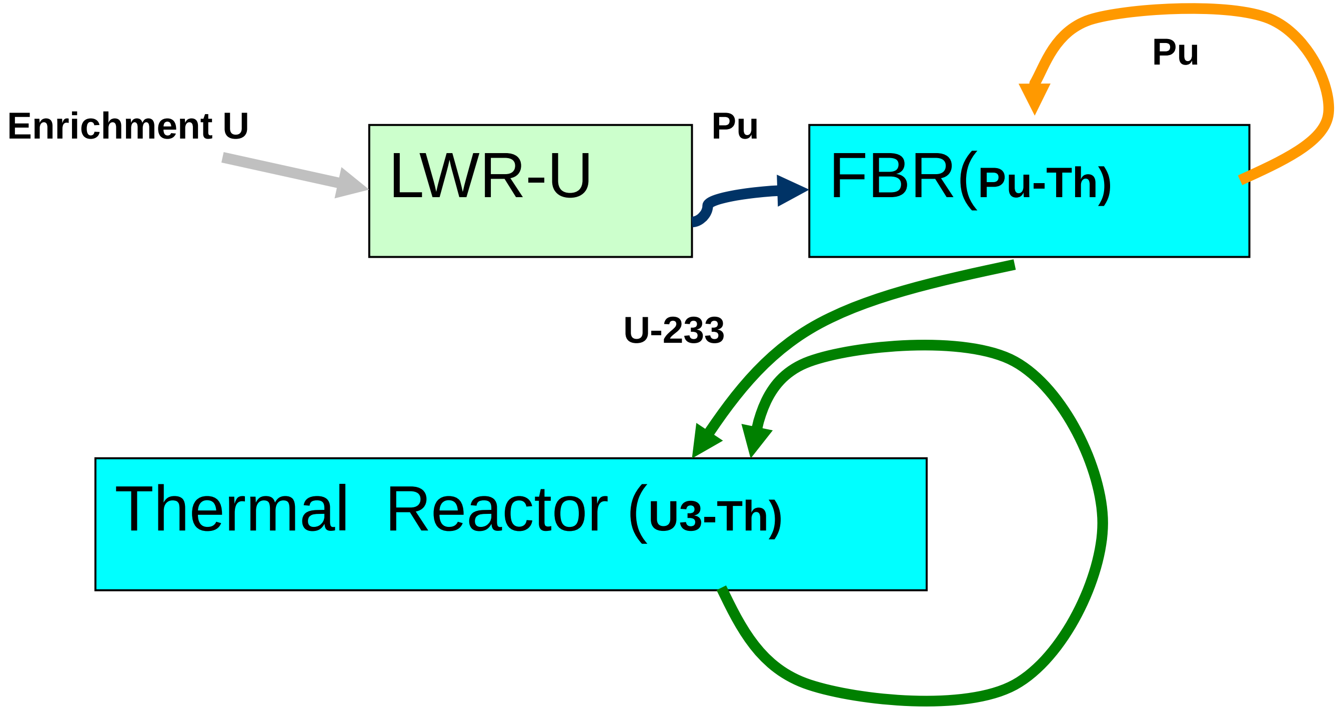
Installed capacities of INS: LWR, FR (2070)
Uranium – 40 mln t, BR=1.6



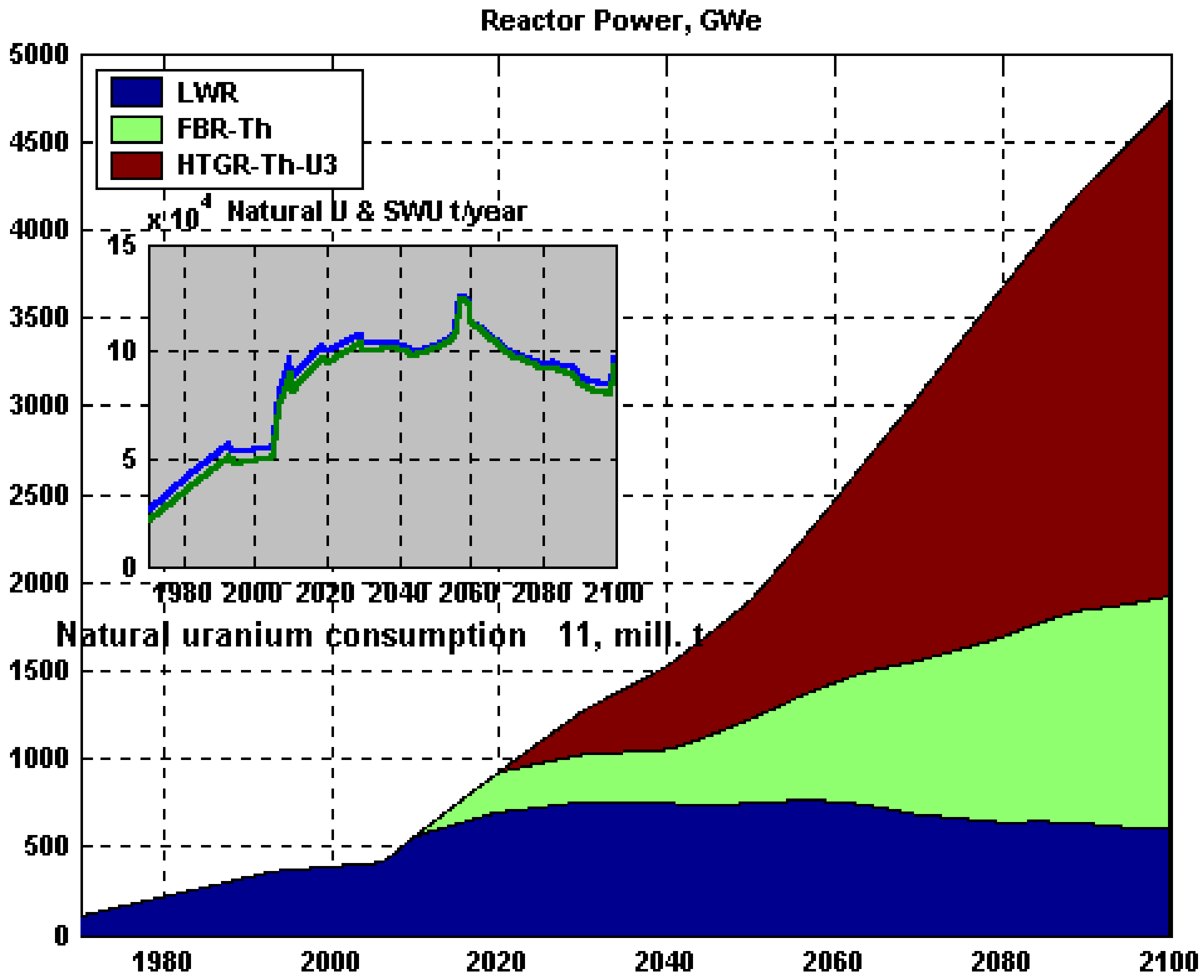
Example of sustainable INS based on LWR, FBR (BR=1.6) +LWRs + small and middle capacity reactors (SMR)



U-Th-Pu closed fuel cycle

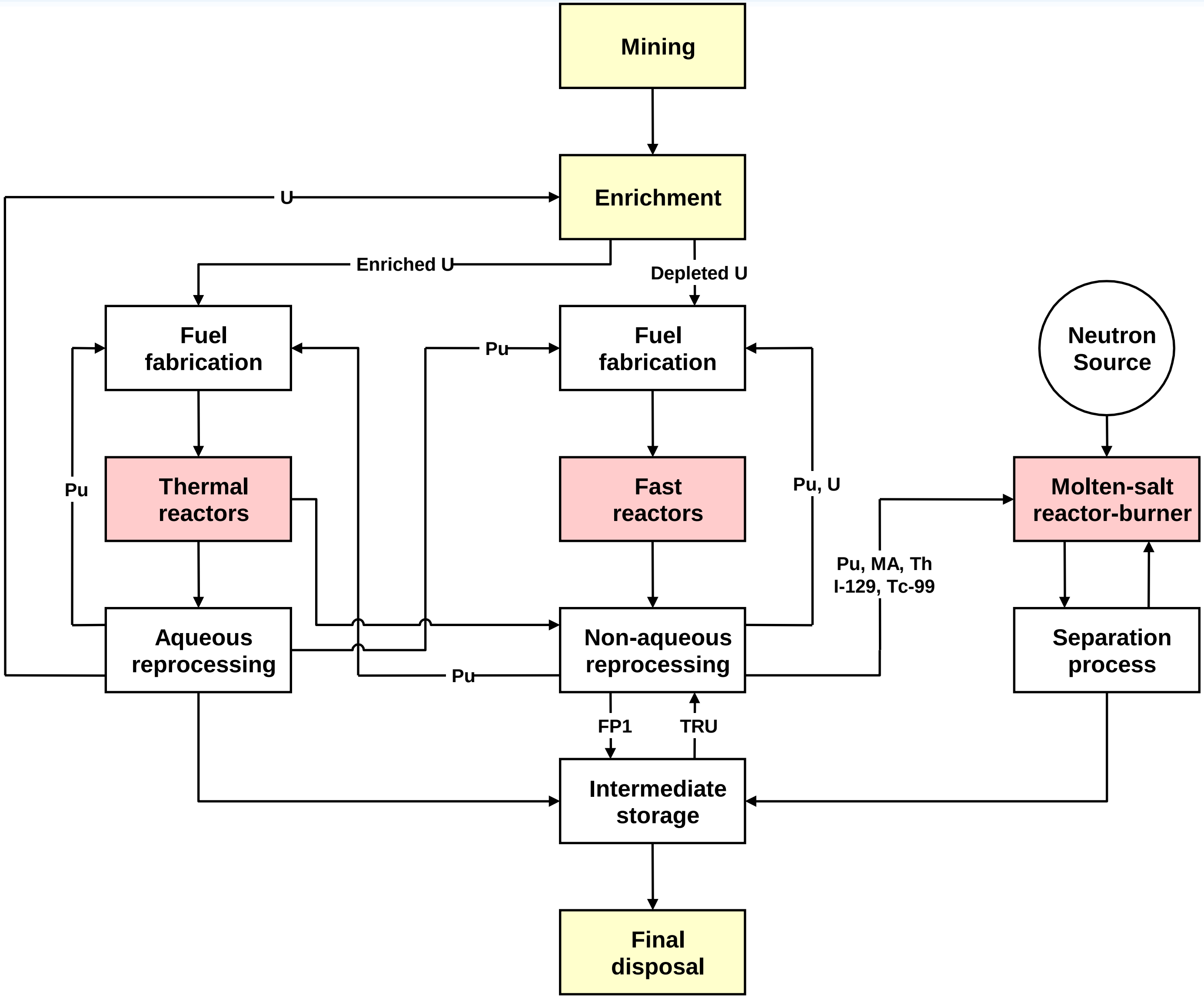


Closed fuel cycle: LWR(U); FR(core-U-Pu, blanket-Th); HTGR(Th-233U)
Total consumption of natural Uranium – 11 mln t

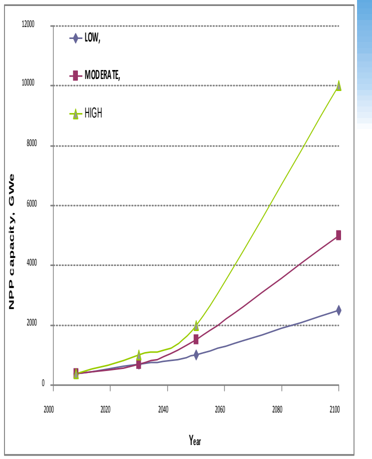


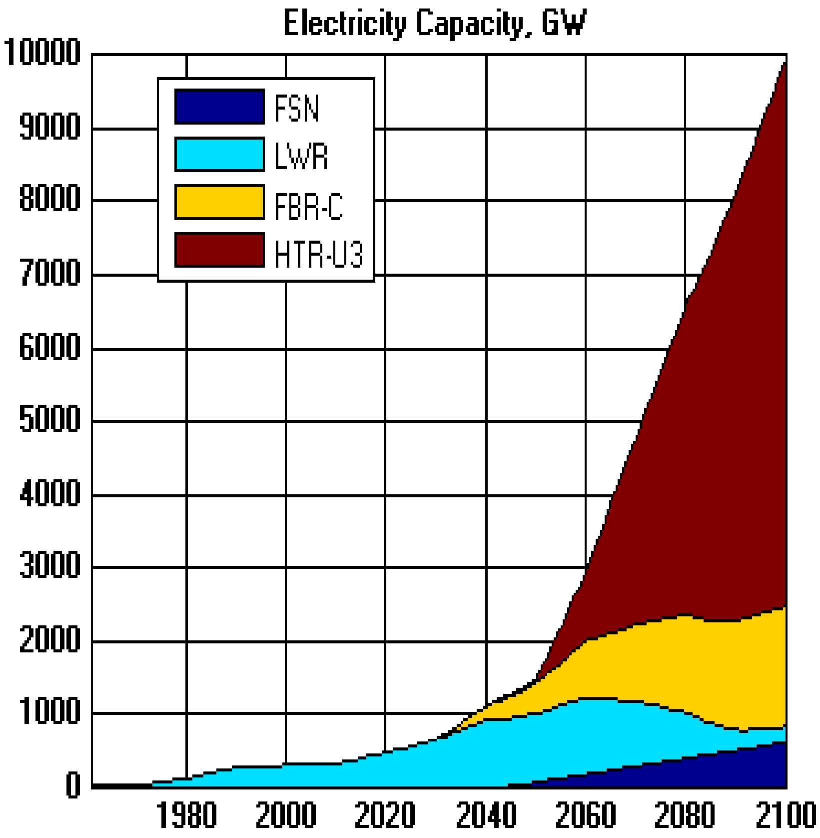
Agency

Example of INS -Multi component nuclear energy system (RRC “Kurchatov institute”, Russia)



Fusion Neutron Sources (FNS) for HIGH scenario





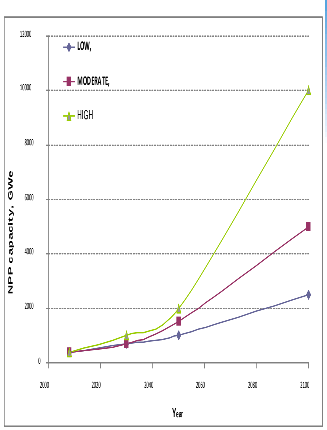
Structure of nuclear energy with FNS under MAX scenario

FNSs in the system would be small (below 10%)

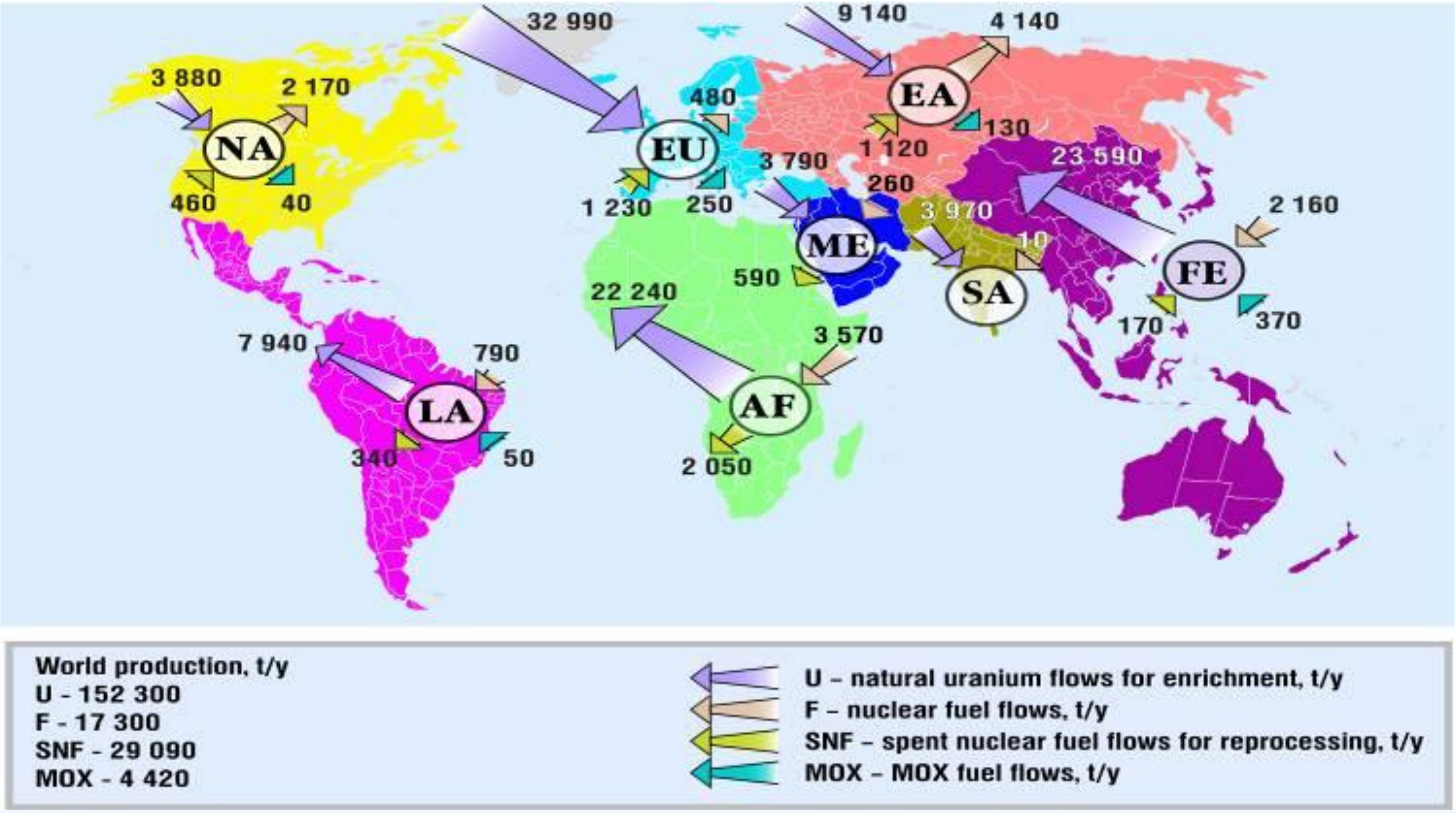
FNSs could be built in a very limited number of countries,

e.g. in the states hosting International Fuel Cycle Centers (IFCC)

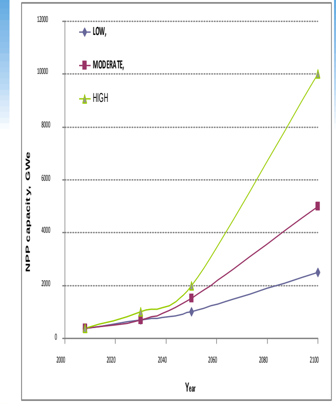
Scenario studies
Calculations / Examples

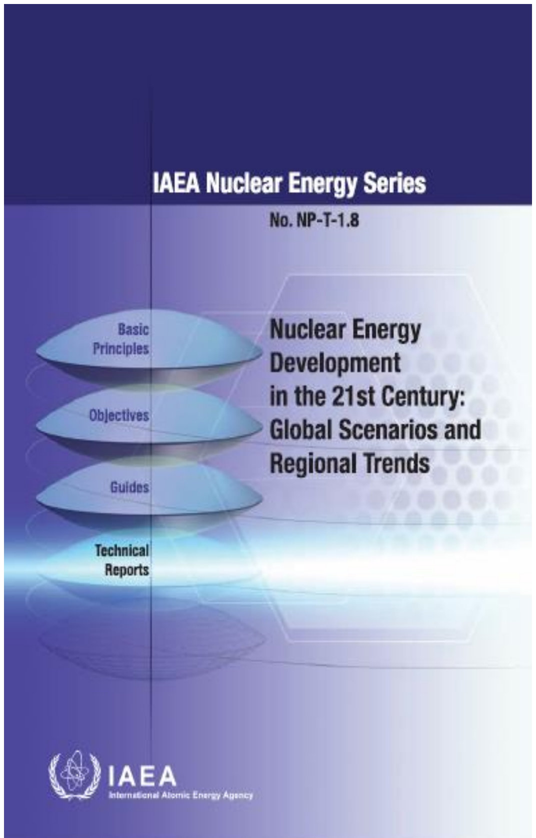


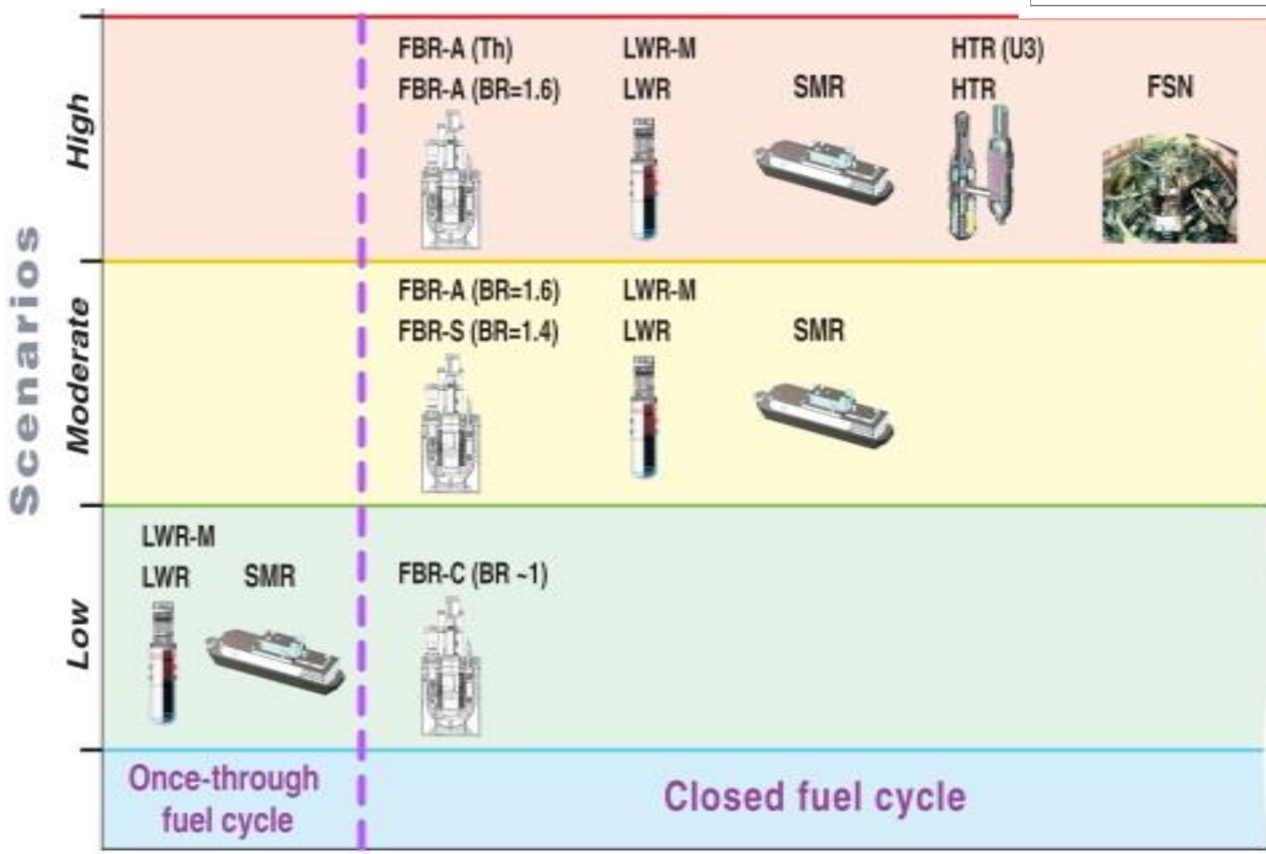
- Interregional flows of uranium, fresh, spent
- and MOX fuel under 'high' scenario (2050)



Scenario studies using the IAEA tools







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Advanced Reactor Timelines (WCR, SMR)

WCR Deployment Timeline

Generation I

Dresden-1, BWR
General Electric

Early prototypes

- **Calder Hall** GCR
- **Douglas Point** PHWR/CANDU
- **Dresden-1** BWR
- **Fermi-1** SFR
- **Kola 1-2** PWR/VVER
- **Peach Bottom 1** HTGR
- **Shippingport** PWR

MHS-NENP-NPTDS-May2015

Generation II

Calvert Cliffs, PWR
Westinghouse

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville** 1-2 PWR
- **Fukushima** II 1-4 BWR
- **Grand Gulf** BWR
- **Kalinin** PWR/VVER
- **Kursk** 1-4 LWGR/RBMK
- **Palo Verde** PWR

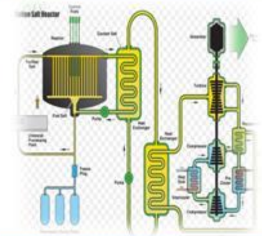
Generation III/III+

AP1000, Westinghouse PWR *NuScale, iPWR-SMR*

Evolutionary and Advanced Passive designs

- **ABWR** GE-Hitachi, Toshiba
- **ACR1000** AECL CANDU PHWR
- **AP1000** Westinghouse PWR
- **APR1400** KHNP PWR
- **APWR** MHI PWR
- **ATMEA1** Areva, MHI, PWR
- **EPR** AREVA PWR
- **ESBWR** GE-Hitachi Nuclear Energy
- **Small Modular Reactors**
  - B&W **mPower** PWR
  - Holtec **SMR-160** PWR
  - India BARC **AHWR**
  - KAERI **SMART** PWR
  - **NuScale** PWR
  - **Westinghouse SMR** PWR
- **VVER-1200** (AES2006) Gidropress PWR
- **ACC1000** (Hualong One) CNNC & CGN

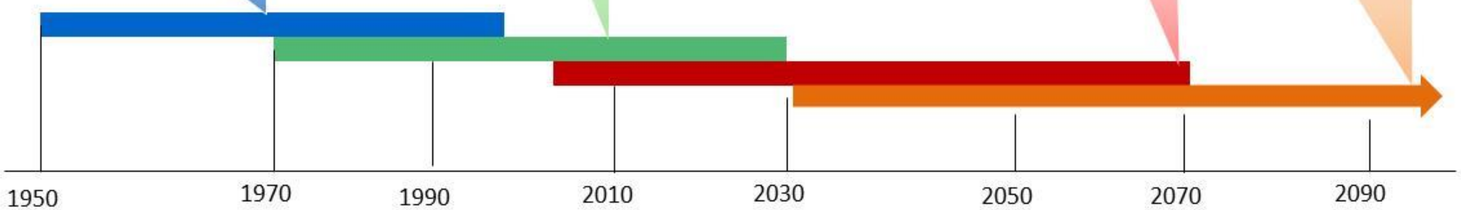
Generation IV



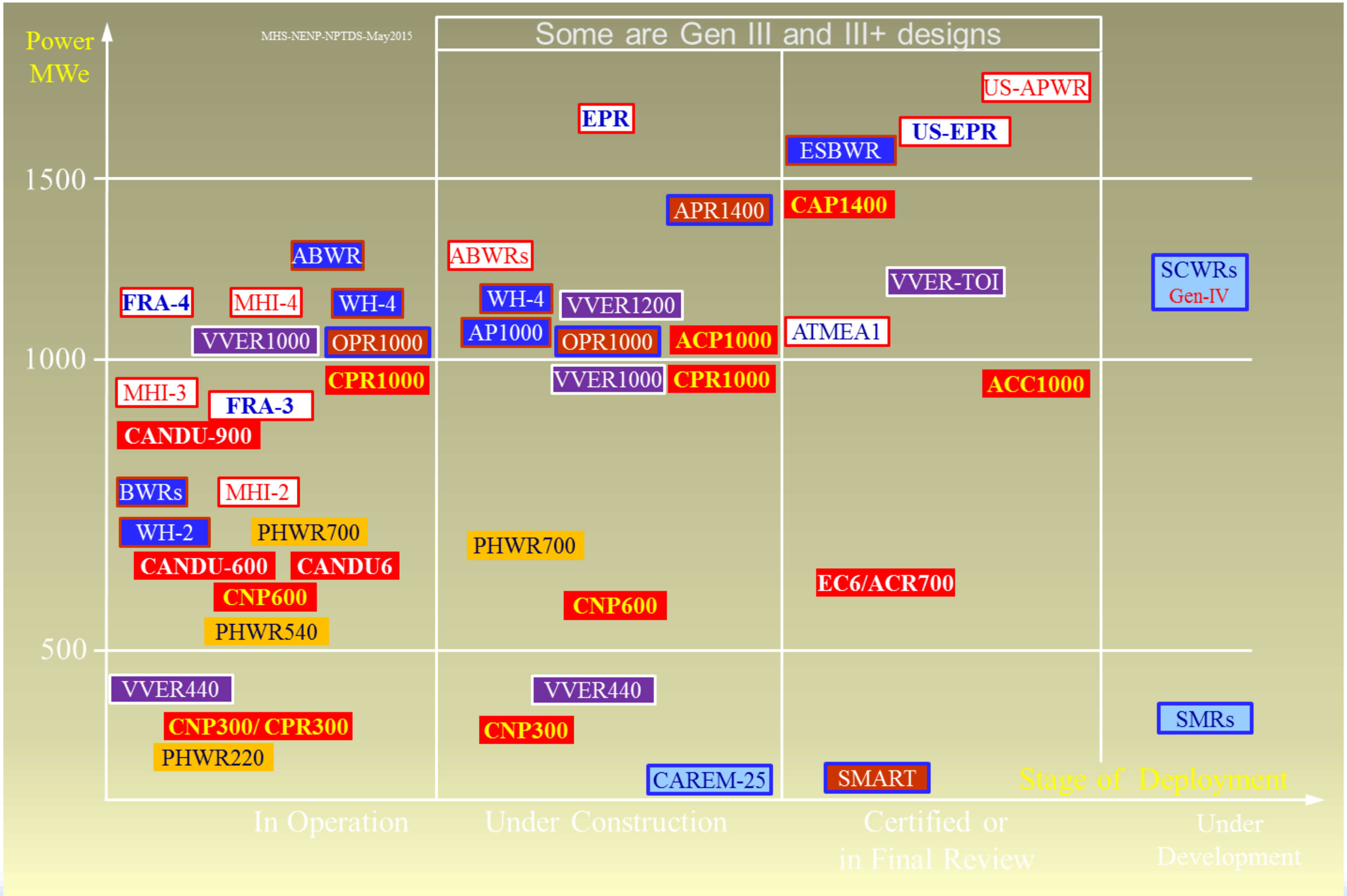
Molten Salt Reactor

Revolutionary designs

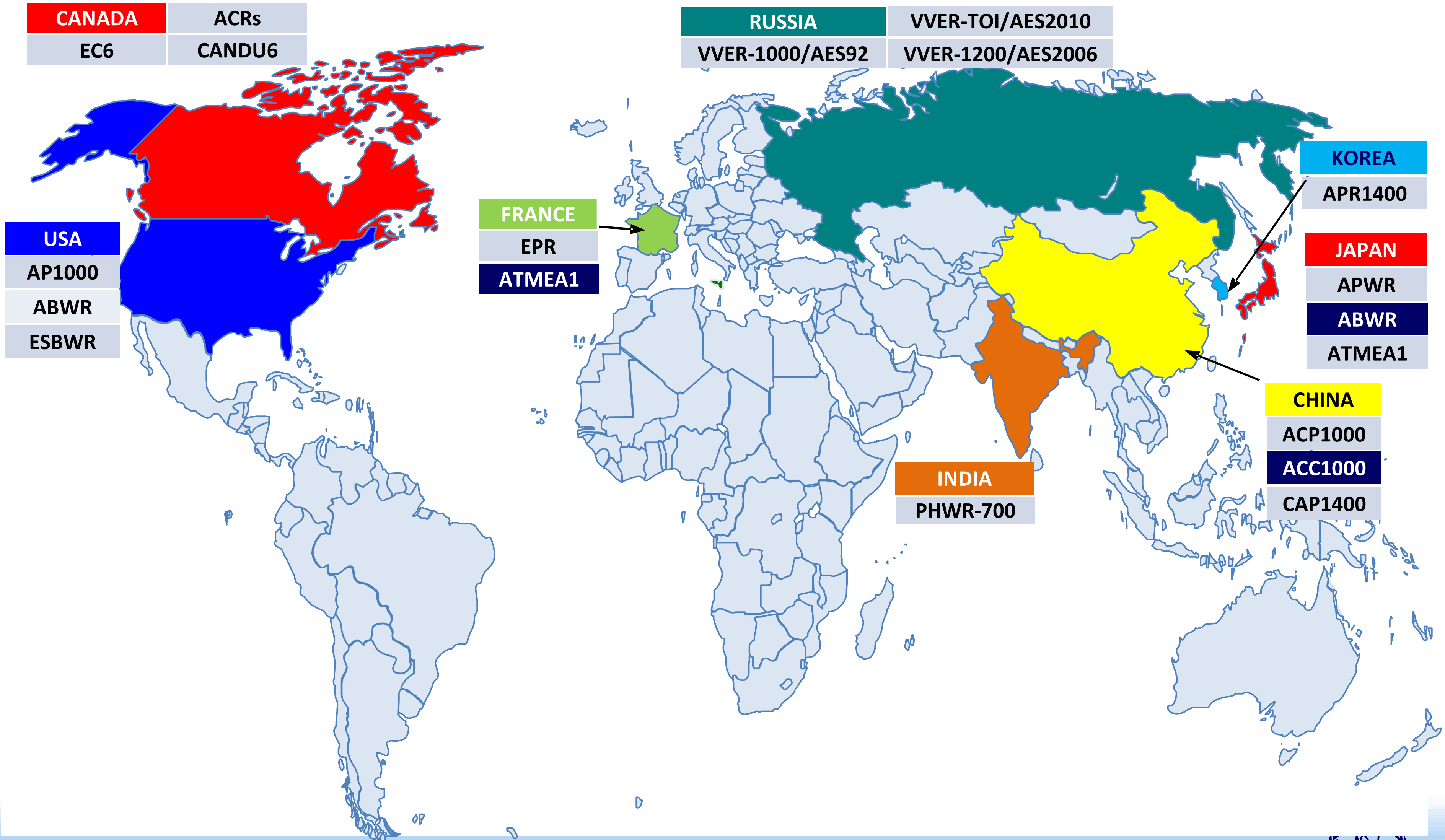
- **GFR** Gas-cooled Fast reactor
- **LFR** Lead-cooled fast reactor
- **MSR** Molten salt reactor
- **SFR** Sodium-cooled fast reactor
- **SCWR** Supercritical water cooled reactor
- **VHTR** Very high temperature reactor



WCR Development & Deployment Status

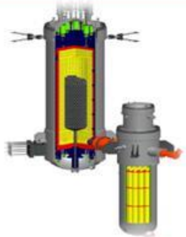


Global Map of Advanced Water Cooled Reactor Developments

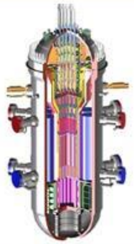


SMR Deployment Timeline

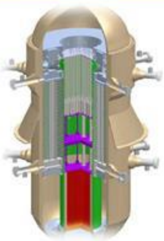
Immediate Deployable	Near-term Deployable	Mid-term Deployable




HTR-PM, HTGR — *China* | *CAREM-25,* iPWR — *Argentina*




SMART, iPWR — *Republic of Korea* | *NuScale,* iPWR — *United States of America*

Flexblue, Marine-based — *DCNS, France* | *IRIS,* iPWR — IRIS Internat. Consortium

Under Construction or Certified Design

- **KLT-40S**
  OKBM Afrikantov, Russian Federation
- **HTR-PM**
  INET, China
- **CAREM-25**
  CNEA, Argentina
- **SMART**
  KAERI, Republic of Korea

Detailed Design or under Certification Review

- **RITM-200**
  OKBM Afrikantov
- **PRISM**
  GE-Hitachi Nuclear Energy
- **PBMR-400**
  PBMR, Inc.
- **BREST300-OD**
  RDIPE
- **4S** Toshiba
- **SVBR-100** AKME
- **ABV-6M**
  OKBM Afrikantov
- **ACP100** CNNC
- **AHWR300** BARC
- **NuScale**
  NuScale Power Inc.
- **mPower**
  B&W Generation mPower
- **Westinghouse SMR**
  Westinghouse Corp.
- **GTHTR300**
  JAEA

Conceptual Design for Future Deployment

- **Flexblue** DCNS
- **IRIS**
  IRIS International Consortium
- **DMS**
  Hitachi-GE Nuclear Energy
- **IMR**
  Mitsubishi Heavy Industries
- **VVER-300**
  OKB Gidropress,
- **VK-300**
  RDIPE
- **SMR160**
  Holtec International
- **HTMR-100**
  STL
- **SC-HTGR**
  AREVA
- **G4M**
  Gen4 Energy Inc.

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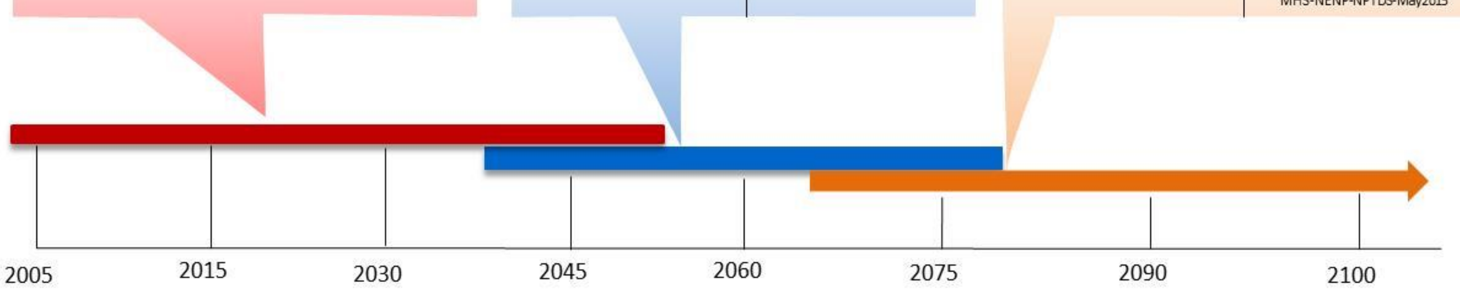
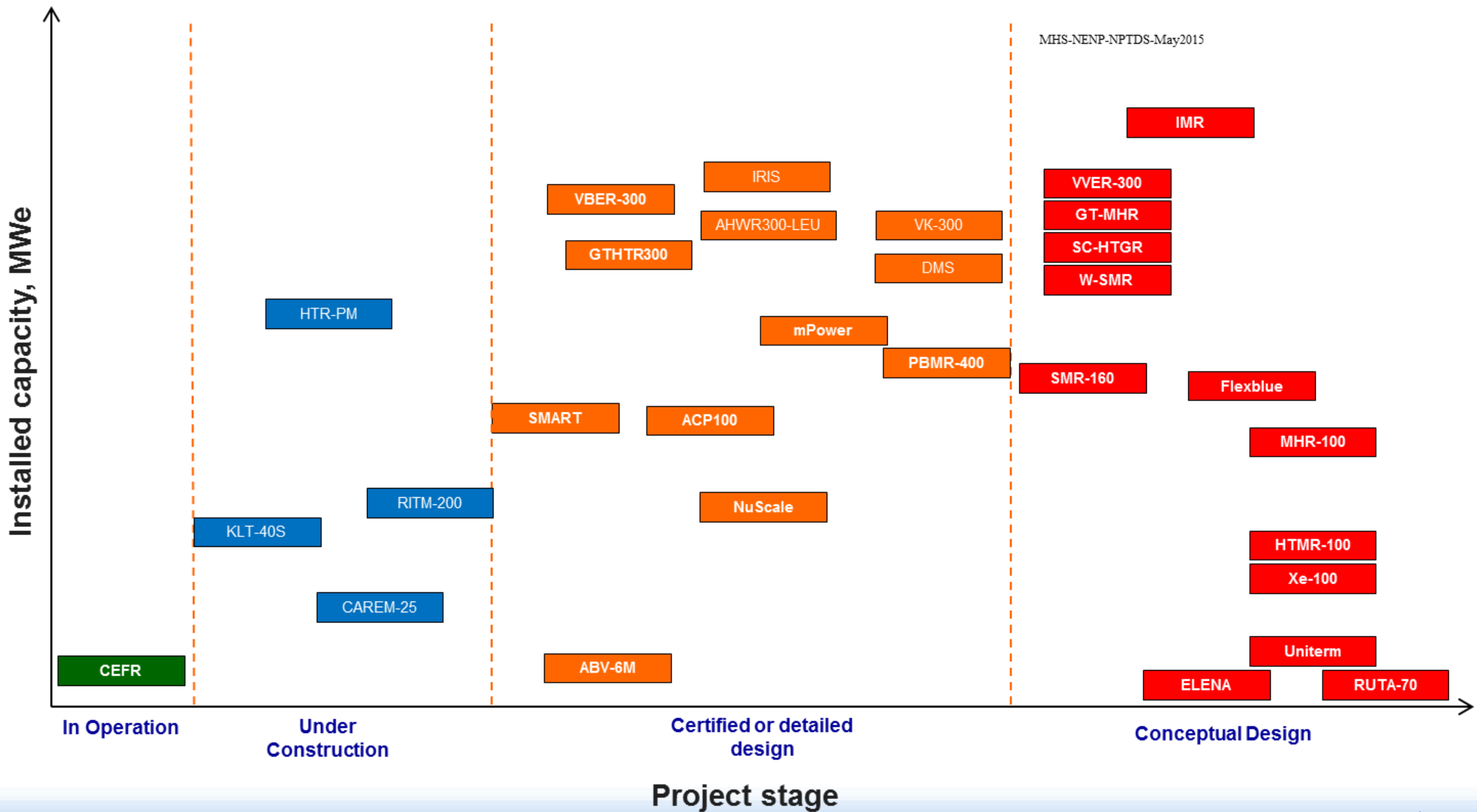
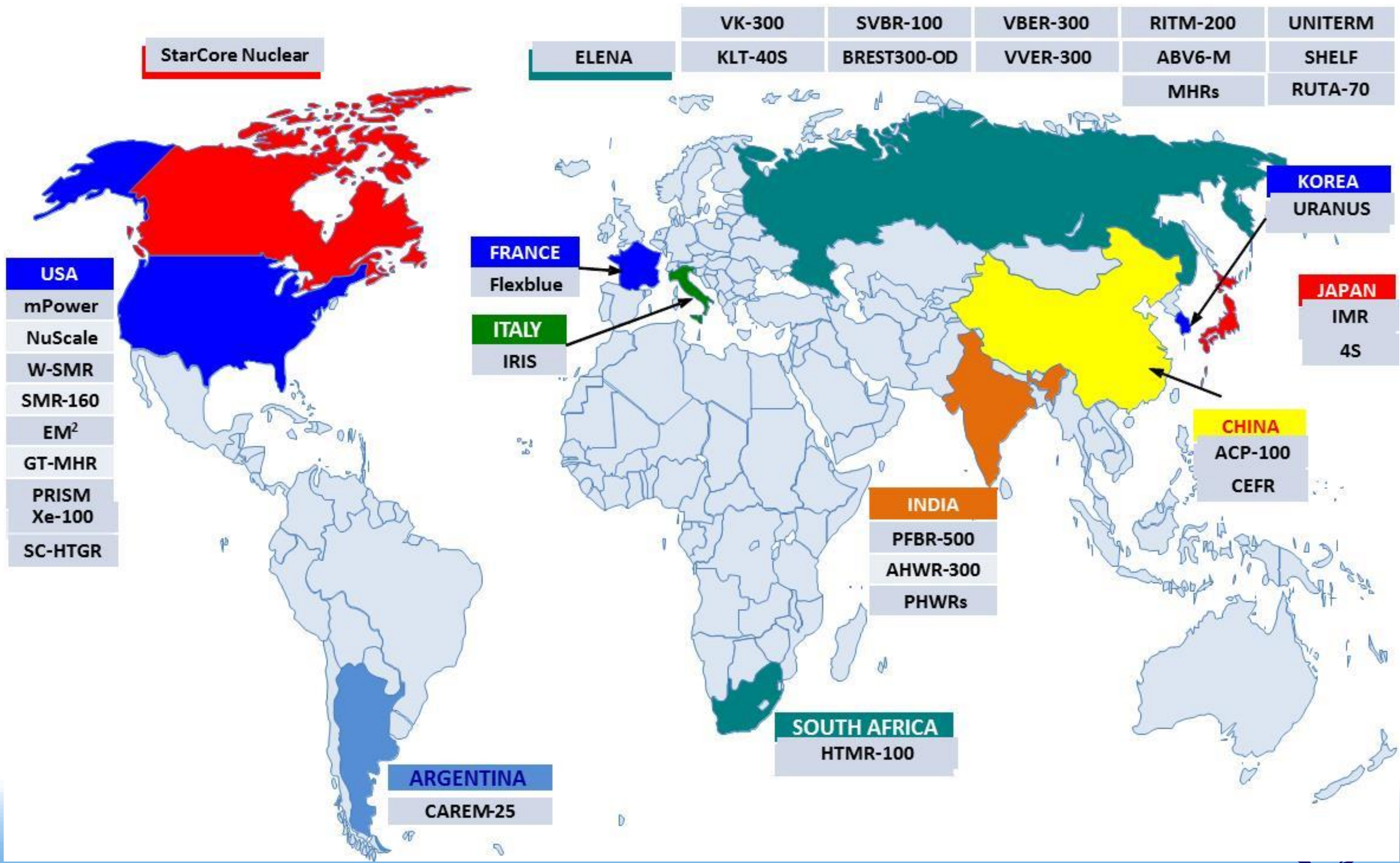


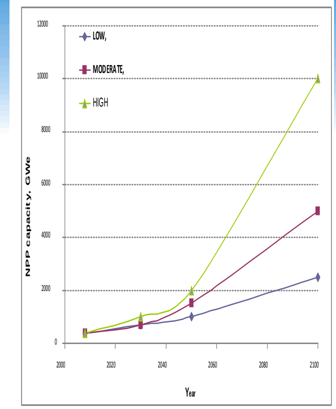
SMR Development & Deployment Status

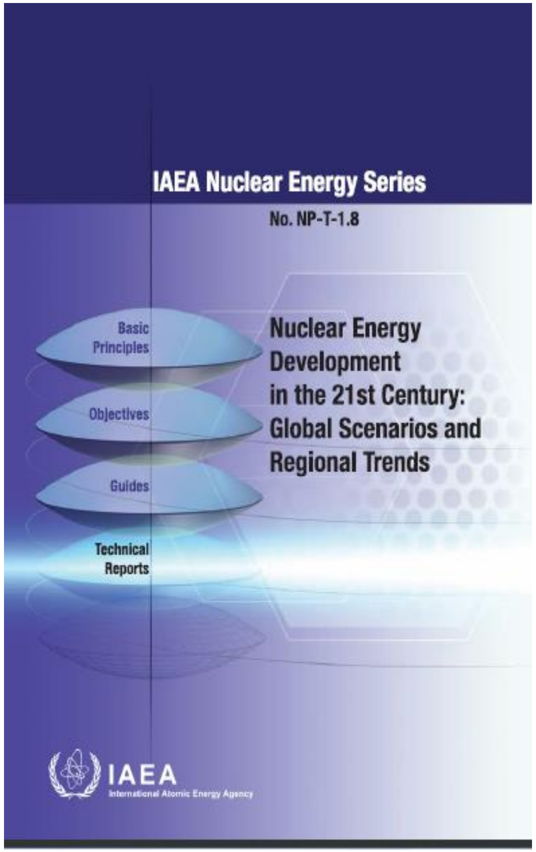


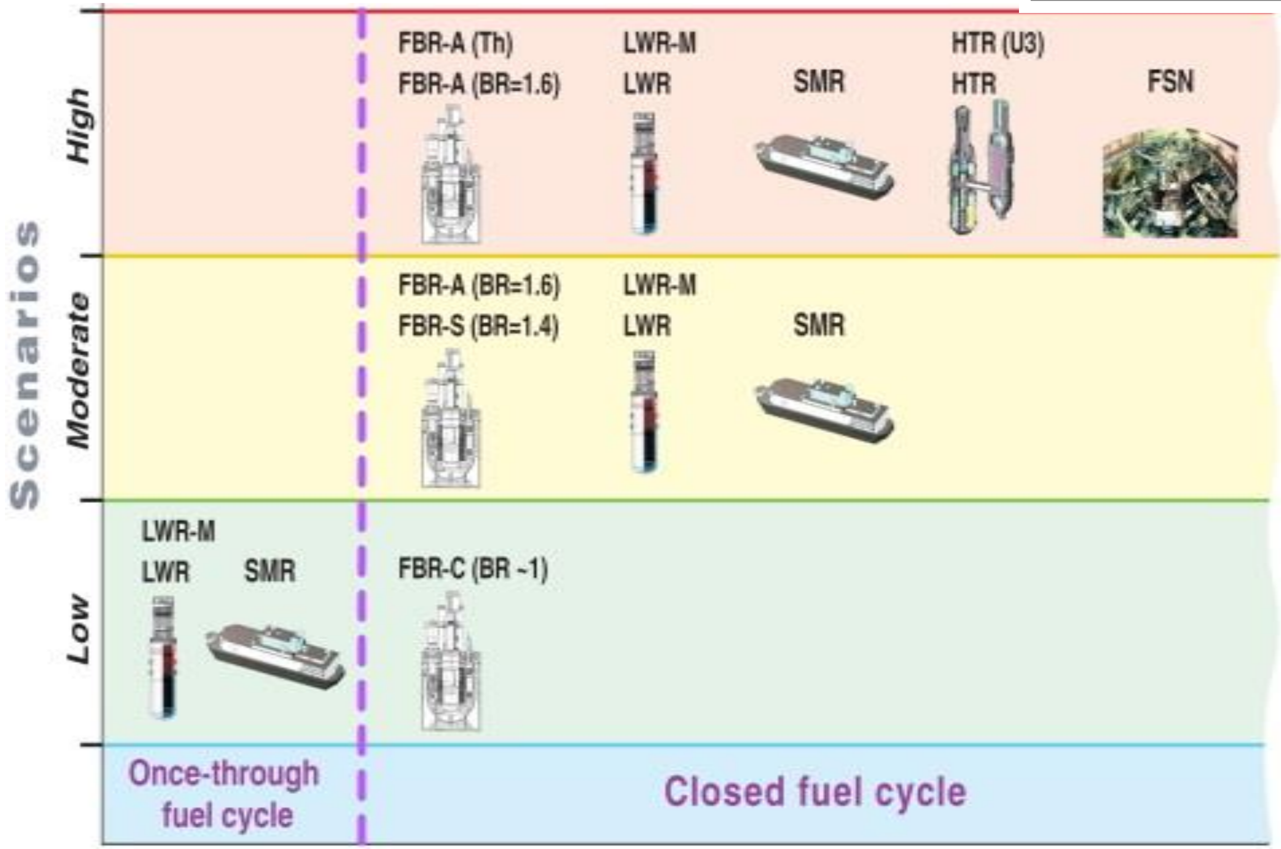
Map of Global SMR Technology Development



Scenario studies using the IAEA tools







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Nuclear Power Technology Development Programme Areas & related web pages

Fast Reactors
http://www.iaea.org/NuclearPower/FR/

Non-Electrical Applications (Desalination, Cogeneration Hydrogen production)
http://www.iaea.org/NuclearPower/NEA/

Water-cooled Reactors (PWR, BWRs..)
http://www.iaea.org/NuclearPower/WCR/

Heavy Water Reactors
http://www.iaea.org/NuclearPower/WCR/

Super Critical Water Reactors

Plant Simulators, training
http://www.iaea.org/NuclearPower/Simulators/index.html

High Temperature Gas Cooled Reactors
http://www.iaea.org/NuclearPower/GCR/

Small Modular and Medium-sized Reactors
http://www.iaea.org/NuclearPower/SMR/

Thank you for your attention