IAEA
International Atomic Energy Agency

Global Scenarios for Nuclear Energy and Role of Innovative Nuclear Energy Systems

Alexander Bychkov, IAEA / INPRO

Joint IAEA-ICTP Workshop on Physics and Technology of Innovative Nuclear Energy Systems

12-16 December 2022, ICTP, Trieste, Italy

IAEA
INPRO
International Project on Innovative Nuclear Reactors and Fuel Cycles

Sustainable Development Goals (SDGs) and Role of Nuclear Power

Sustainable Development Goals (SDGs)

IAEA

1 NO POVERTY – End poverty in all its forms everywhere

2 ZERO HUNGER – End hunger, achieve food security and improved nutrition and promote sustainable agriculture

3 GOOD HEALTH AND WELL-BEING – Ensure healthy lives and promote well-being for all at all ages

4 QUALITY EDUCATION – Ensure inclusive and quality education for all and promote lifelong learning

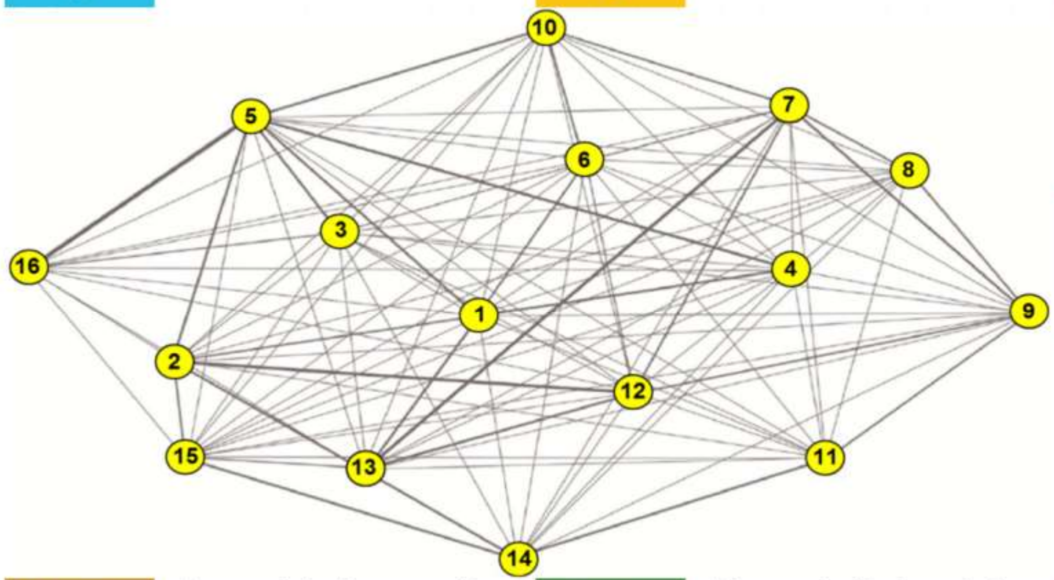
5 GENDER EQUALITY – Achieve gender equality and empower all women and girls

6 CLEAN WATER AND SANITATION – Ensure access to water and sanitation for all

7 AFFORDABLE AND CLEAN ENERGY – Ensure access to affordable, reliable, sustainable and modern energy for all

8 DECENT WORK AND ECONOMIC GROWTH – Promote inclusive and sustainable economic growth, employment and decent work for all

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE – Build resilient infrastructure, promote sustainable industrialization and foster innovation



10 REDUCED INEQUALITIES – Reduce inequality within and among countries

11 SUSTAINABLE CITIES AND COMMUNITIES – Make cities and human settlements inclusive, safe, resilient and sustainable

12 RESPONSIBLE CONSUMPTION AND PRODUCTION – Ensure sustainable consumption and production patterns

13 CLIMATE ACTION – Take urgent action to combat climate change and its impacts

14 LIFE BELOW WATER – Conserve and sustainably use the oceans, seas and marine resources

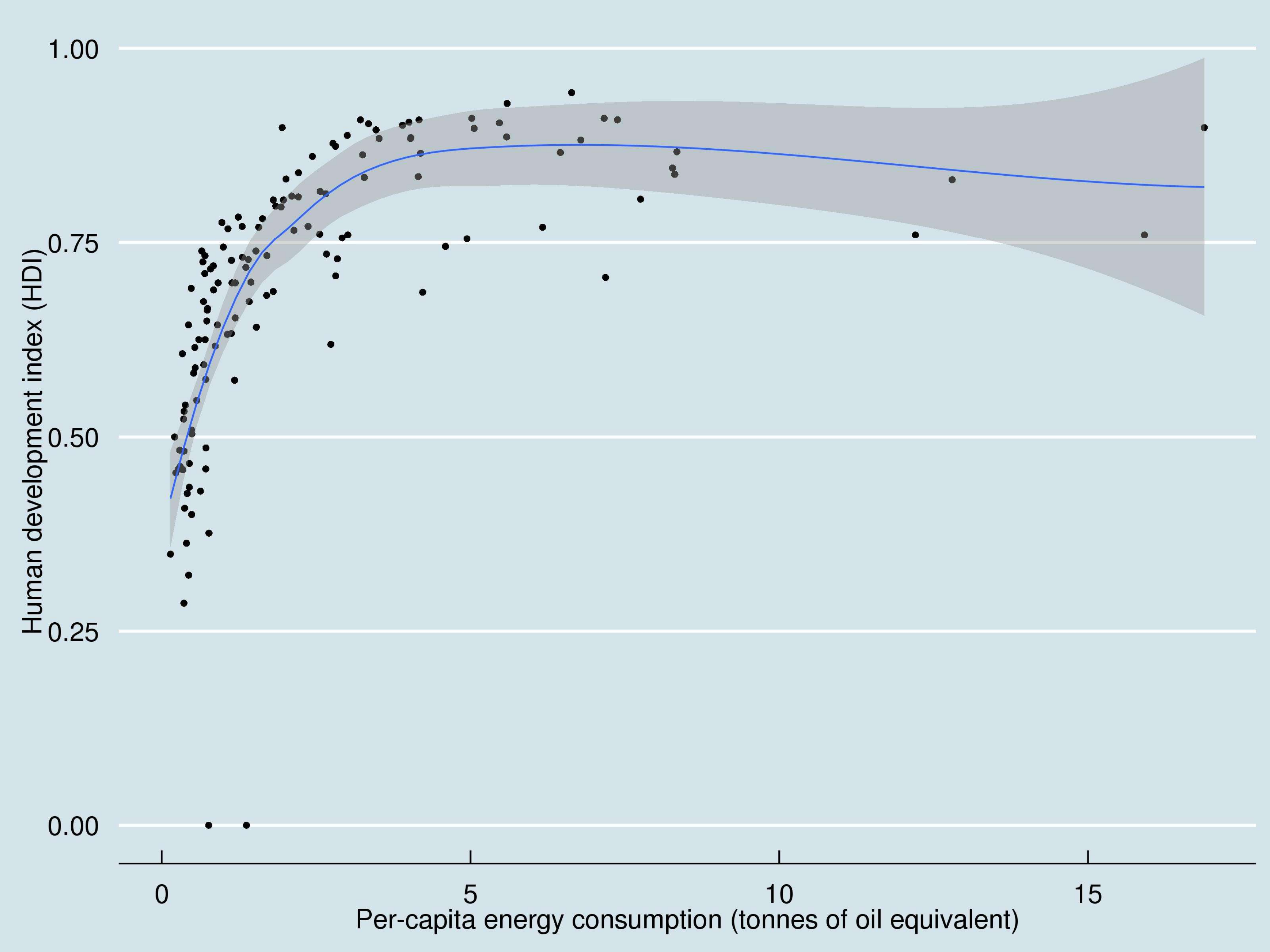
15 LIFE ON LAND – Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss

16 PEACE, JUSTICE AND STRONG INSTITUTIONS – Promote just, peaceful and inclusive societies

17 PARTNERSHIPS FOR THE GOALS – Revitalize the global partnership for sustainable development

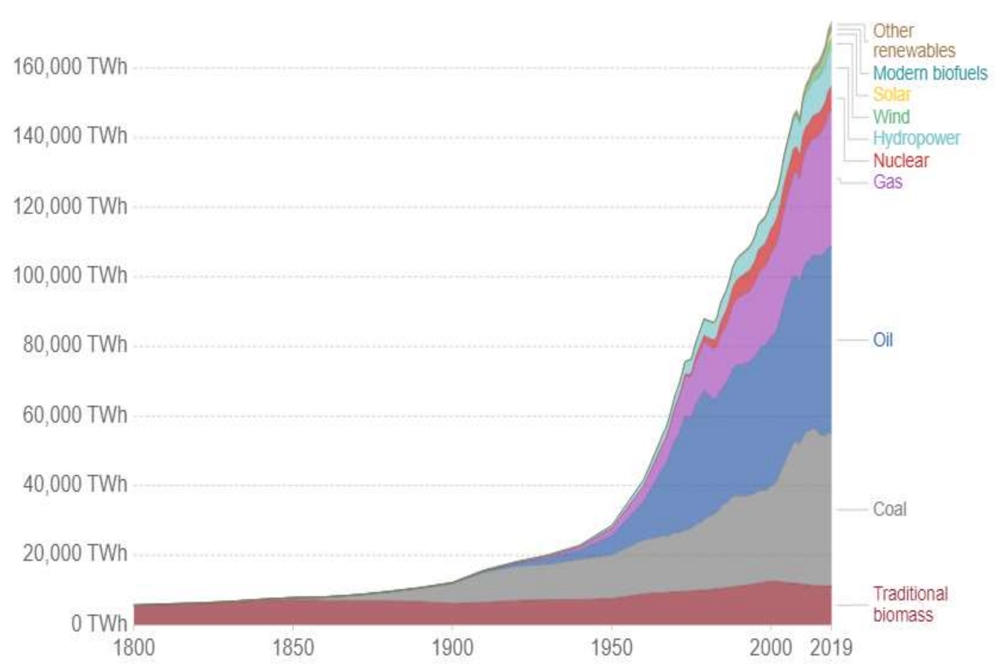
SUSTAINABLE DEVELOPMENT GOALS

Energy and Human Development

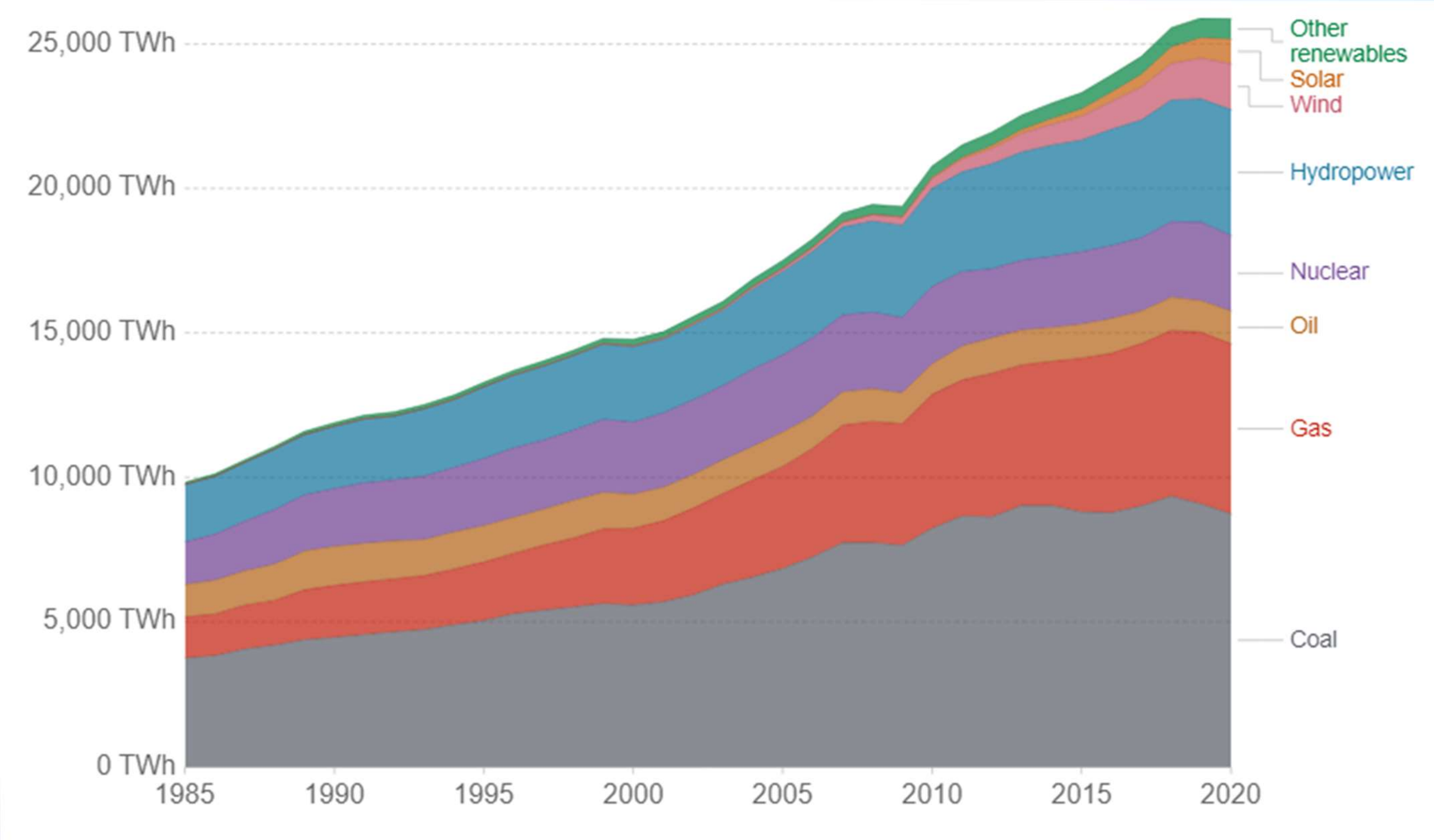


Points to Note from Evolution of Energy Consumption

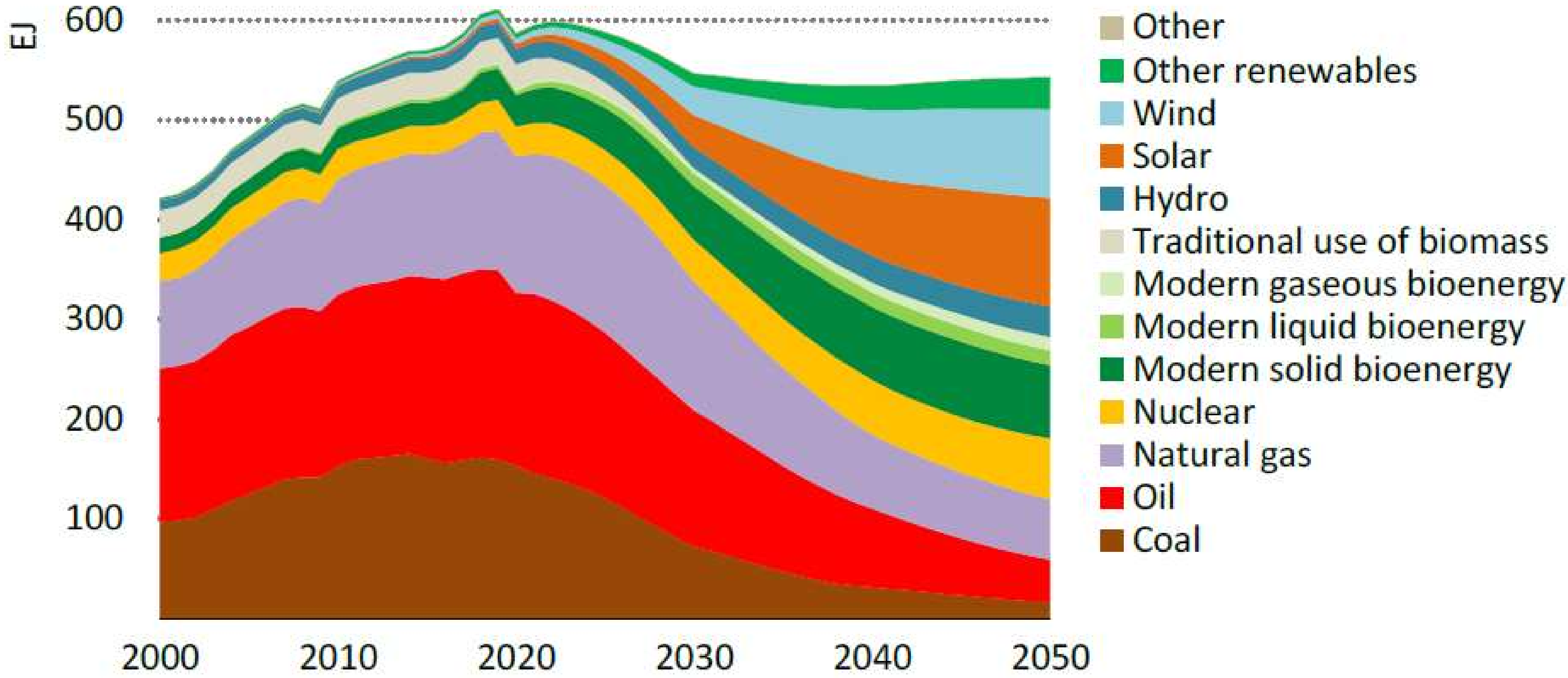
- **Growth in Energy Demand**
- **Changes in Energy Mix**
- **High Dependence on Fossil Fuels**



World Electricity Generation Mix

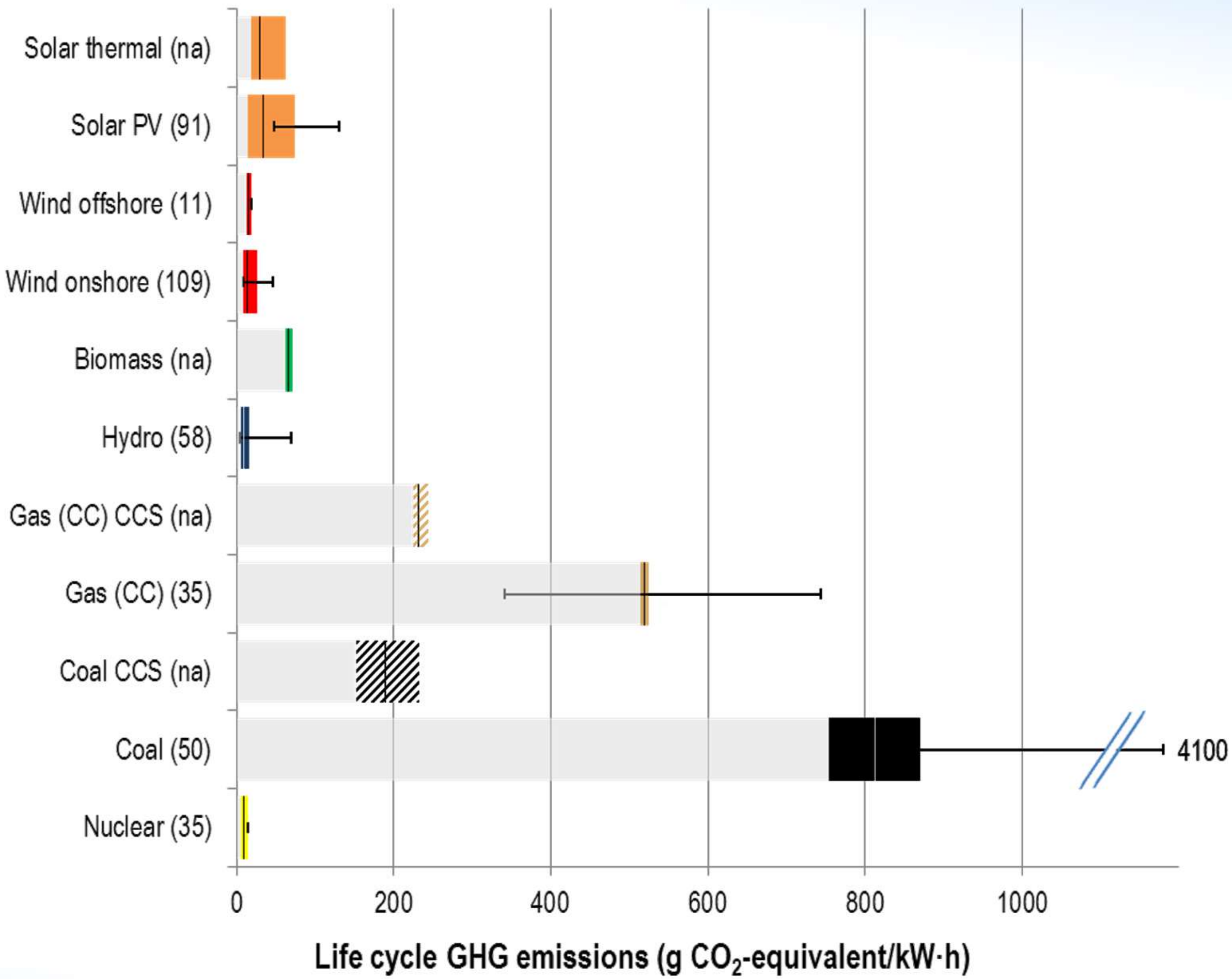


World Primary Energy in Net Zero Path



IEA 2021

Nuclear: Low Carbon Source of Energy



Source: IAEA, CCNP 2018

IAEA
International Atomic Energy Agency

Current Status of Nuclear Power

Nuclear Power Reactors in the World
Current status: December 2022

IAEA

422 NUCLEAR POWER REACTORS IN OPERATION

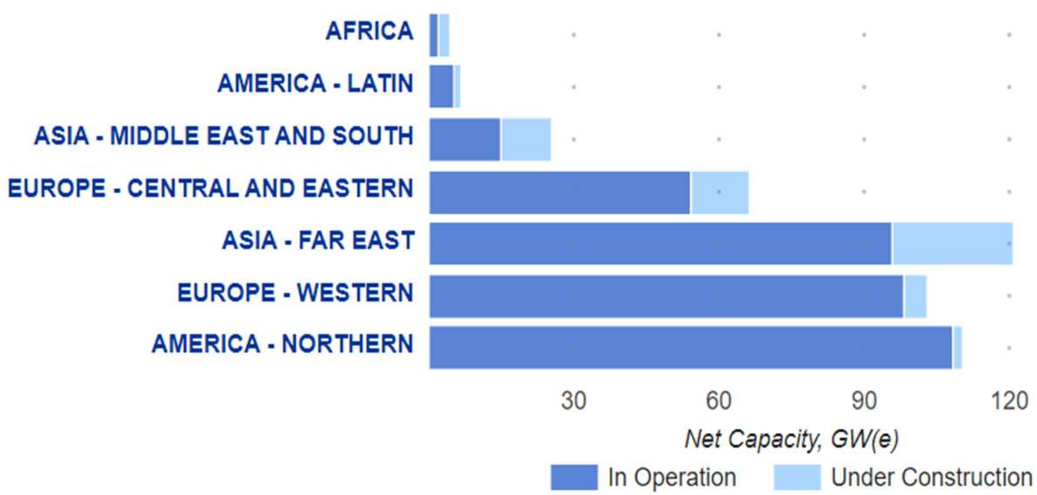
378 314 MW_e TOTAL NET INSTALLED CAPACITY

57 NUCLEAR POWER REACTORS UNDER CONSTRUCTION

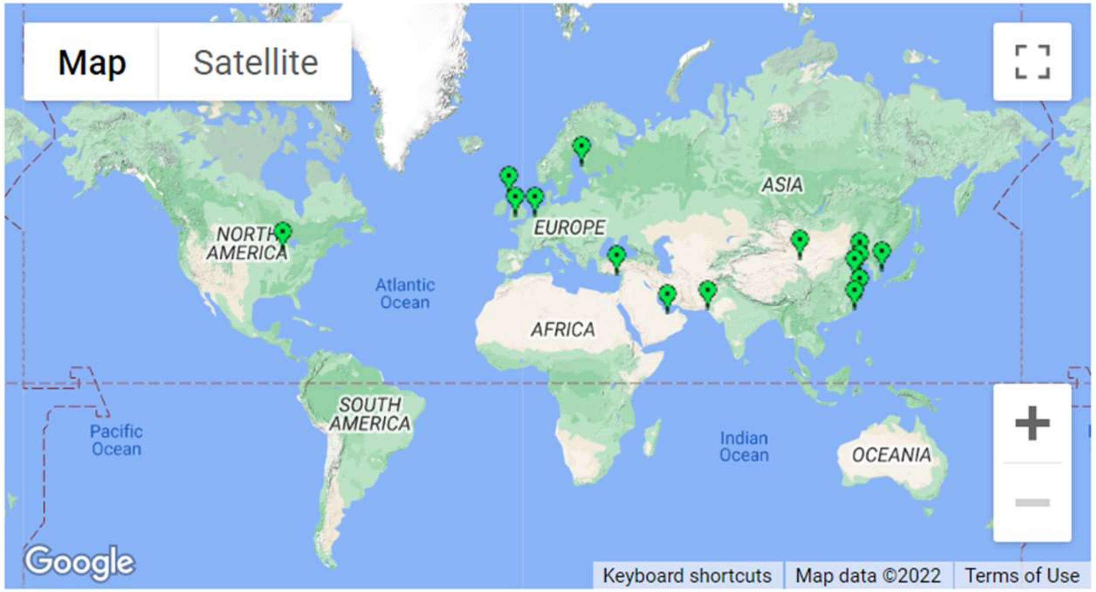
58 858 MW_e TOTAL NET INSTALLED CAPACITY

19 372 REACTOR-YEARS OF OPERATION

REGIONAL DISTRIBUTION OF NUCLEAR POWER CAPACITY



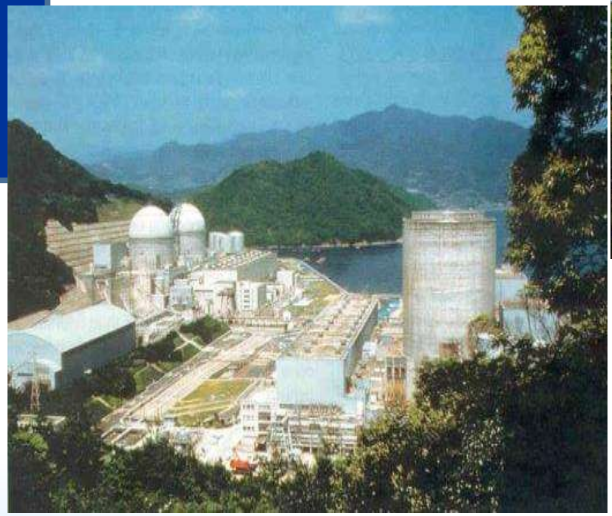
NPP Status Changes (2022)



Current status: December 2022

In operation
422 nuclear power reactors [378,3 GW_e]

USA	92
France	56
China	55
Russia	37
S. Korea	25
India	22
Canada	19
Japan	17

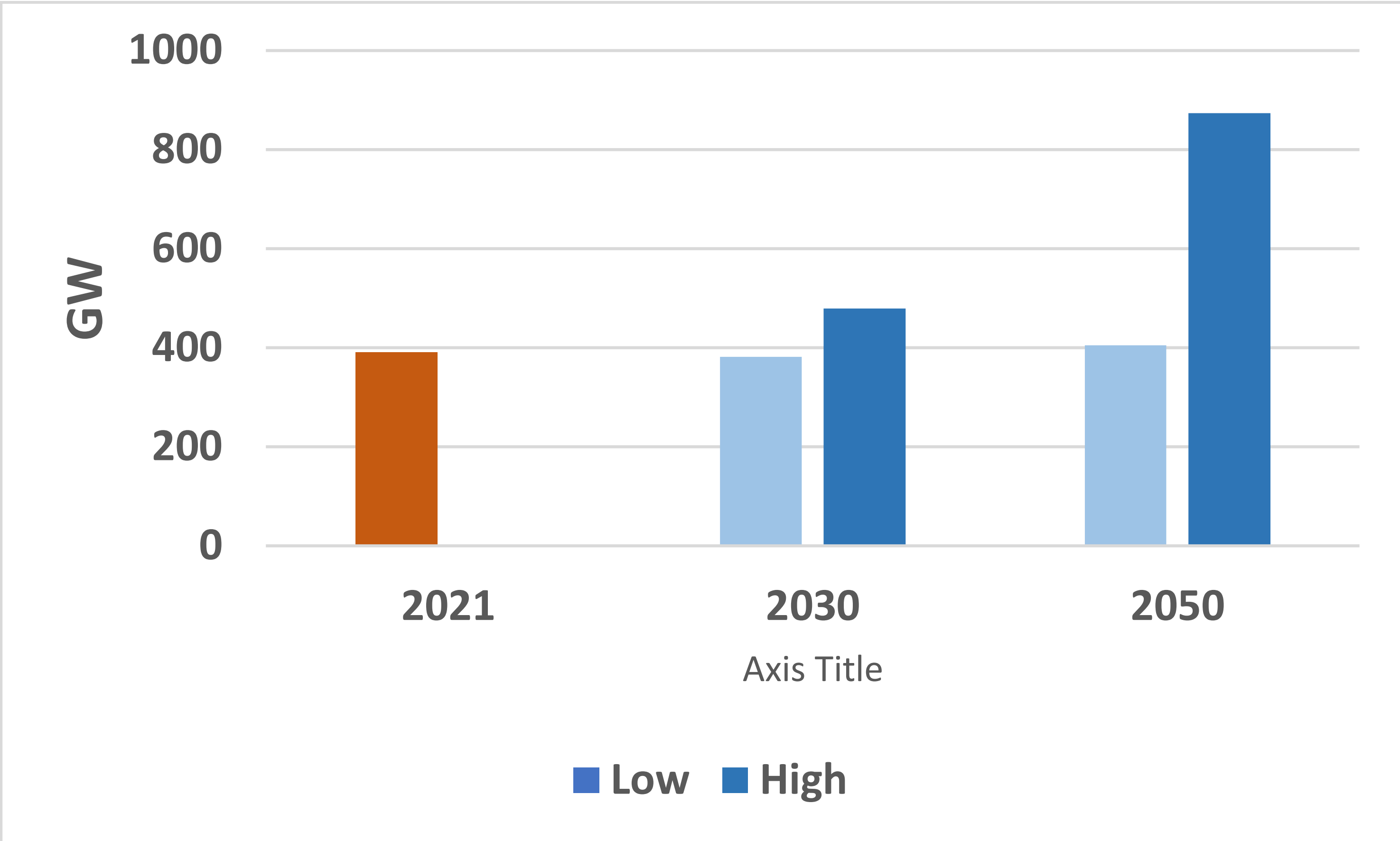


Current status: December 2022
Under-construction

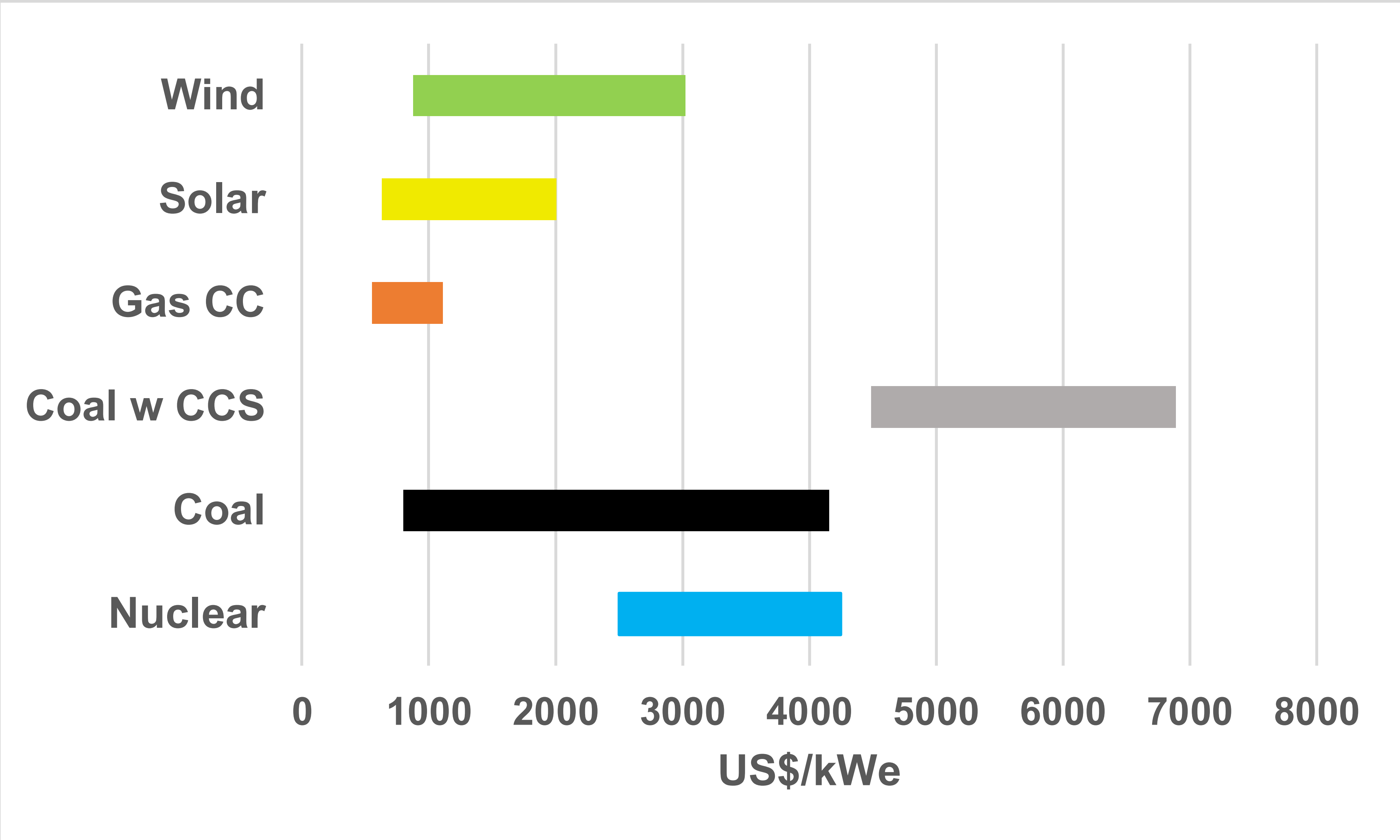
57 Power Reactors
Under-construction

• China	18
• India	8
• Russia	4
• Turkiye	4
• S. Korea	3
• Egypt	2
• USA	2
• UK	2
• Bangladesh	2

World Nuclear Power Capacity Projections, IAEA 2022

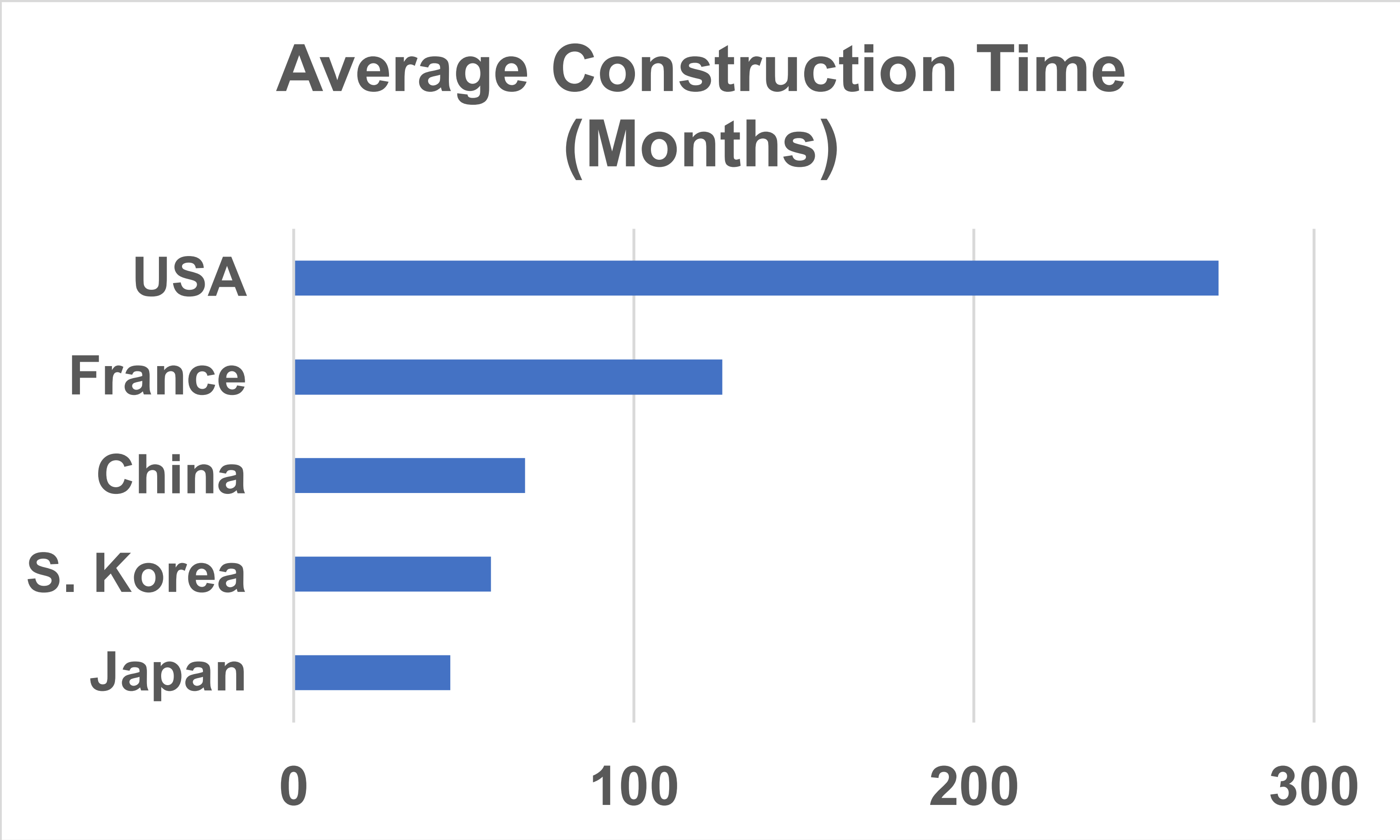


Overnight Capital Costs

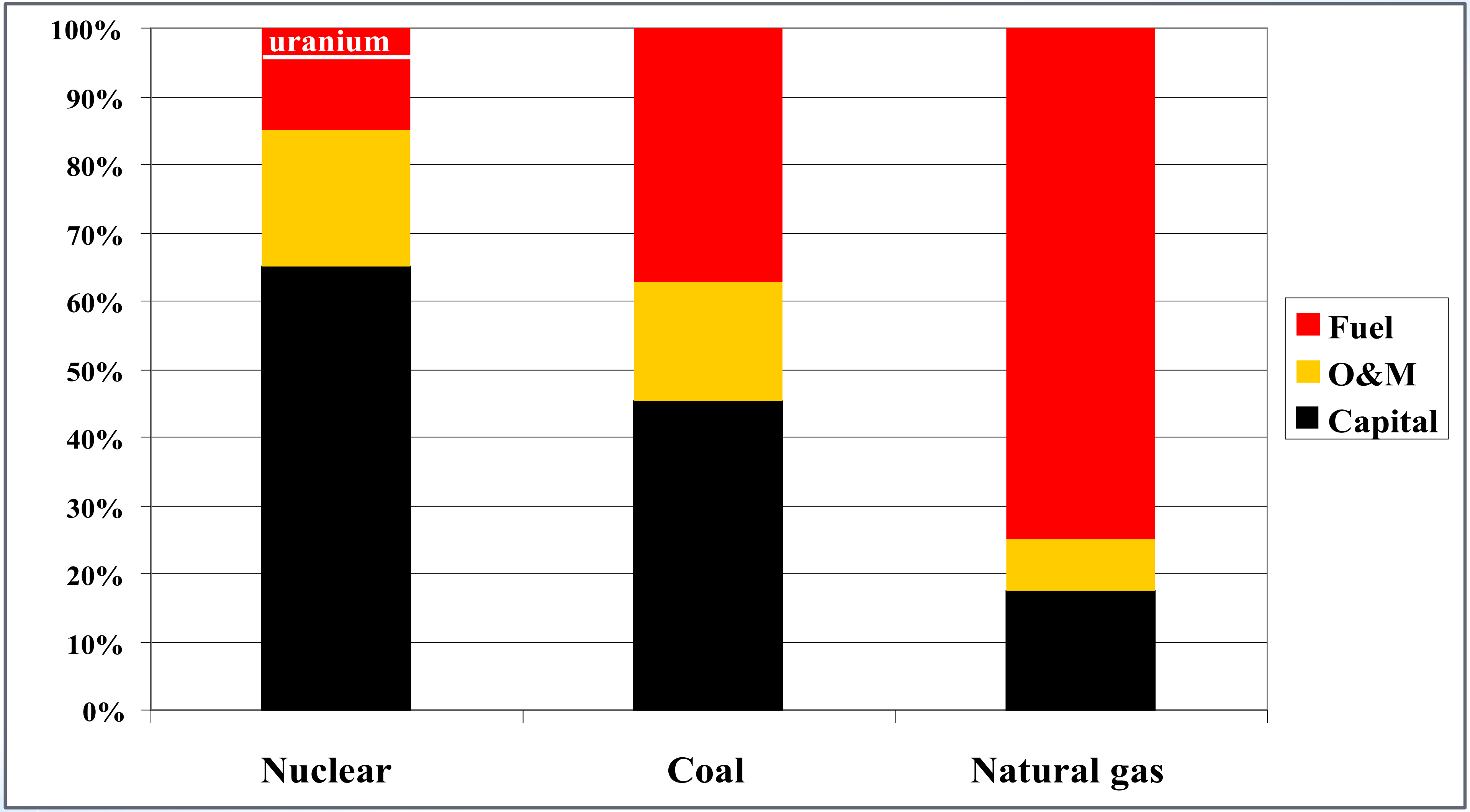


NEA/IEA, 2020

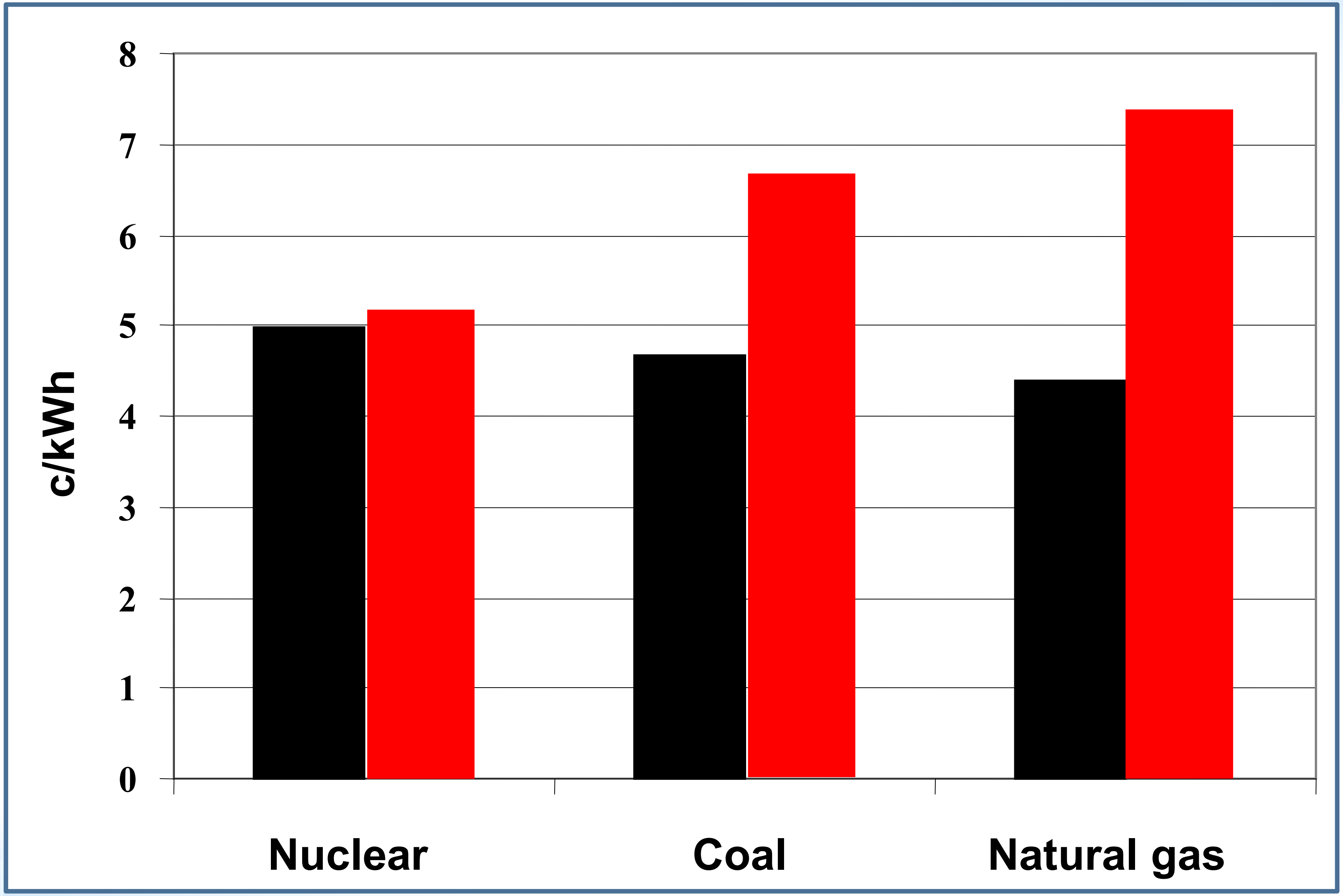
Construction Period for an NPP



Generation cost components of different options



Impact of a doubling of fuel prices



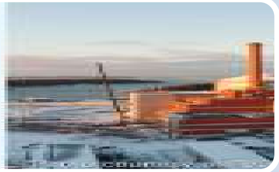
Drivers for Nuclear Power Projects

- Diversifies supply
- Emits virtually no GHG and no air pollutants
- Contributes to energy security (plentiful and geographically diversified uranium resource)
- Offers predictable generation costs (low share of fuel cost in overall cost structure)
- Offers stable and reliable base-load electricity
- Has socio-economic benefits (high level skills and knowledge, industrial development, increased human capital…)

IAEA
International Atomic Energy Agency

Nuclear Innovations and Scenarios for Nuclear Power and Fuels Cycle Development

Nuclear Power Deployment Evolution



Generation I	Generation II	Generation III / III+	Generation IV
Early Prototypes	Commercial Power Reactors	Evolutionary Designs	Innovative Designs
Various coolants / moderators	Mostly Water Cooled Reactors	Improvements to operating water cooled reactors	Innovative Nuclear Energy Systems

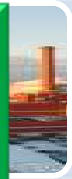
Past Innovations resulted in successful nuclear energy deployment today

Potential for significant improvements (innovations) to make meaningful contribution to sustainable development goals

1950 1970 1990 2010 2030 2050 ………………………?

The Future?

- Reactors
  - Water, gas, metal and salt cooled, double the range of thermal efficiencies
  - Large and small modular units
- Fuel resource
  - Diverse and indefinite supply
  - U, U/Pu, Th/U-233
- SNF inventory in equilibrium with reactor fleet capacity
- Multinational fuel cycle facilities
- HL waste and limited direct SF disposal
  - National and regional repositories in operation
  - Minor actinides incinerated and disposed
- Nuclear contributing to all energy sectors
- Trade in front end and back end services



Generation IV

Innovative Designs

Innovative Nuclear Energy Systems

1950 1970 1990 2010 2030 2050 ……………………….?

Potential Scenarios to 2150

- Scenario I:
  - Nuclear Power and fuel cycle options are implemented as they are today
- Scenario II:
  - Nuclear Power significantly increases to include electric and non-electric applications, and fuel cycle options evolve towards multirecycling
- Scenario III:
  - Nuclear Power is gradually phased out by 2050 and final disposition strategies pending implementation in 2150

Adapted from presentation by Christophe XERRI, Director, Division of Nuclear Fuel Cycle, Waste Management, and Research Reactor (2019 International Conference on the Management of Spent Fuel from Nuclear Power Reactors)

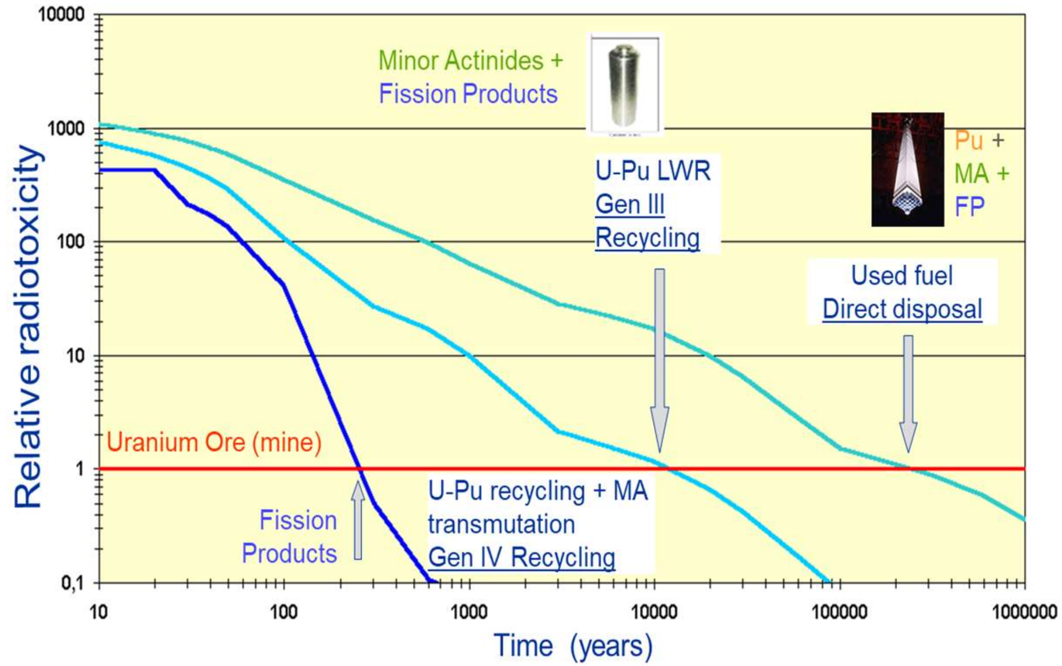
Scenario I

- Nuclear Power and fuel cycle options are implemented as they are today
  - Improved reactor designs
  - Advanced fuels (e.g., higher burnup, accident tolerant fuel, etc)
  - Enhancement of fuel cycle facilities safety and efficiency with final disposition routes in place
  - Disposal facilities for SF and HLW under operation
  - Some countries with small nuclear programmes using international services for recycling and possibly disposal
  - Political agreements between countries to build and deploy common facilities for waste management

Innovation has a role, especially for expanded deployment (necessary to address immediate climate concerns)

Scenario II

- Nuclear Power significantly increases to include electric and non-electric applications, and fuel cycle options evolve towards multirecycling
  - Advanced and innovative reactors deployed
  - Expansion into non-electricity markets
  - Environmentally friendly innovative fuel cycles
  - Fully closed fuel cycle (recycling valuable materials)
  - Natural resources preservation
  - Waste burden minimized
  - Flexible to adapt to any policy evolution
  - Multinational cooperation - fuel cycle front and backend



Innovation has a role; "preferred" scenario for sustainability and for meeting sustainable development goals

Scenario III

- Nuclear Power is gradually phased out by 2050 and final disposition strategies still pending implementation in 2150
  - SF accumulating in storage (mainly dry storage) at orphan sites
  - No or scarce support facilities for maintenance and re packaging if needed
  - Until final disposal, there is need for:
    - Ageing management programmes
    - Monitoring and inspection techniques
    - Knowledge preservation
    - Records preservation
    - Skilled professionals
    - etc

Innovation has a role disposition remaining liabilities; international cooperation beneficial to countries adopting this scenario

IAEA
International Atomic Energy Agency

Global Scenarios for Nuclear Energy and its International Architecture: INPRO Project

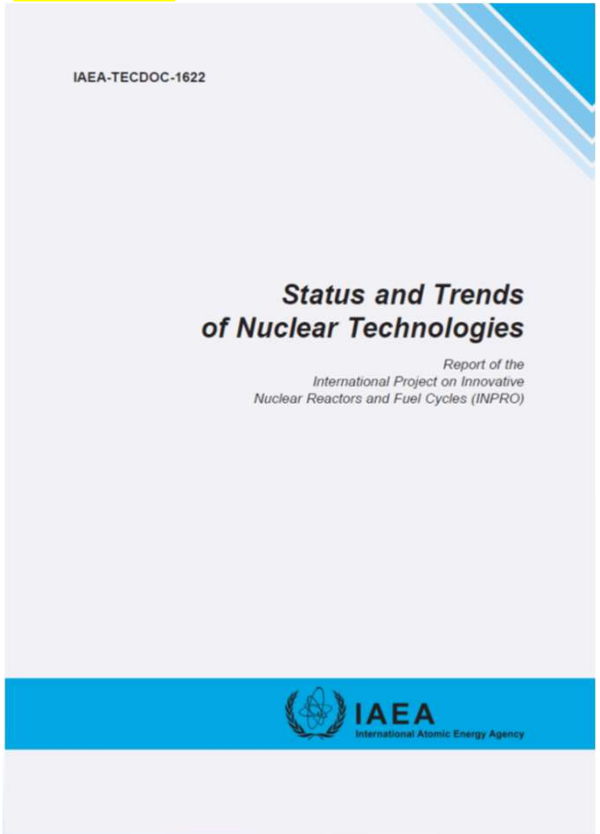
INPRO Area “Global scenarios”

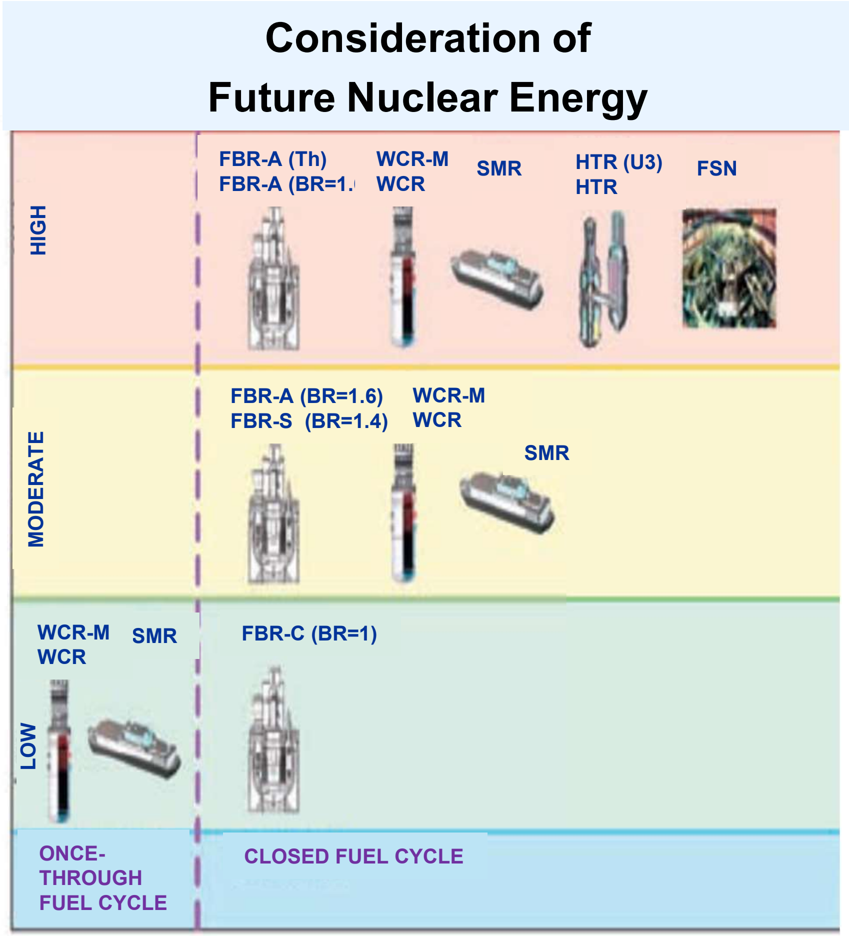
The objective of the INPRO Area **“Global scenarios**” is to develop global and regional nuclear energy scenarios, using developed scientific-technical analysis tools that lead to a **global vision of sustainable nuclear energy development** in the current century and beyond

Over the past decade this task has successfully implemented a number of collaborative projects with broad participation of Member States – INPRO Members targeted at providing the support to interested Member States **in formulating national strategies for enhancing nuclear energy sustainability**

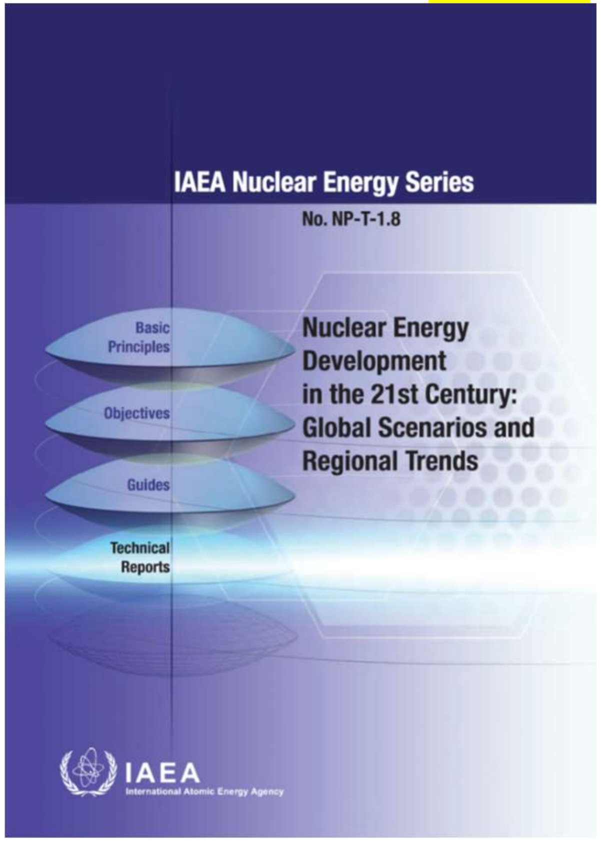
INPRO’s general overviews of innovative nuclear reactors and fuel cycle technologies in MSs

2009





2010



Assessment of NES based on a Closed Nuclear Fuel Cycle with Fast Reactors – Joint Study

A Joint Study was started in 2005 and completed in 2007 within the INPRO.

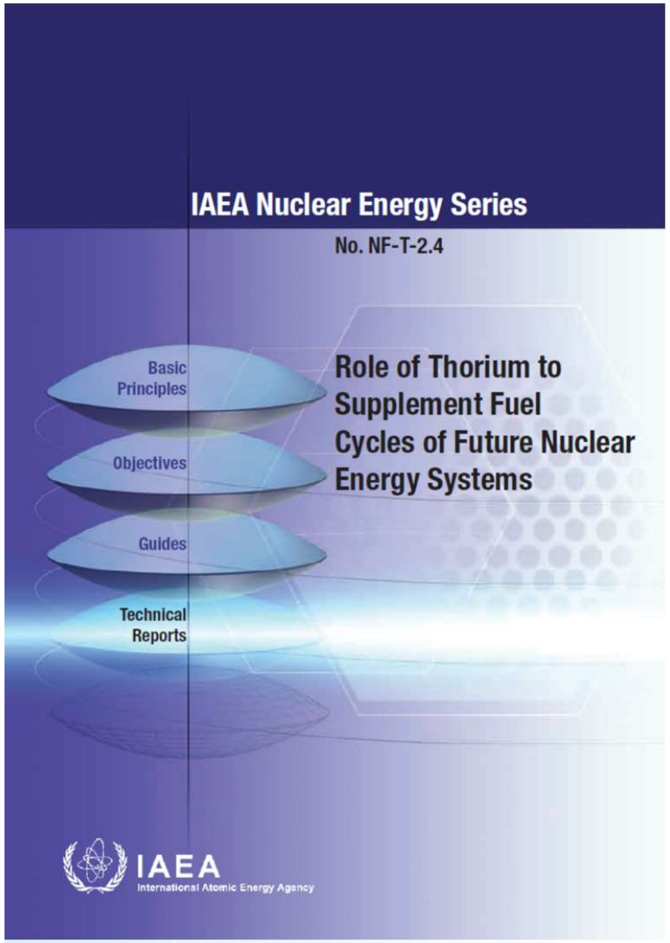
Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation, and Ukraine participated in this study.

The objectives were to assess a nuclear energy system based on a closed fuel cycle (CNFC) with fast reactors (FR) regarding - ***Sustainability, Determine milestones for the nuclear energy system deployment, and Establish frameworks for, and areas of, collaborative R&D work.***

The assessment was carried out in accordance with requirements of INPRO methodology and guiding documents of the Joint Study developed and approved by the participating parties.

Multi-component systems for Th-based NP and FC

2012



- Multi-component Systems with Th-^{233}U.
- Transition from ^{235}U and U-Pu systems to hybrid NP or to Th-based NP
- Reducing of MA amount
- Prospective: Th-based fuel cycle for SMRs and MSR.

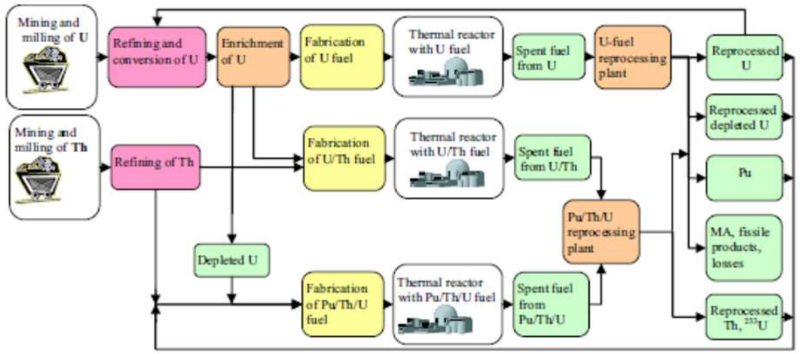


FIG. 4.9. Closed fuel cycle based on water cooled thermal reactors using thorium and/or ^{233}U (with spent fuel reprocessing and recycling of plutonium and ^{233}U).

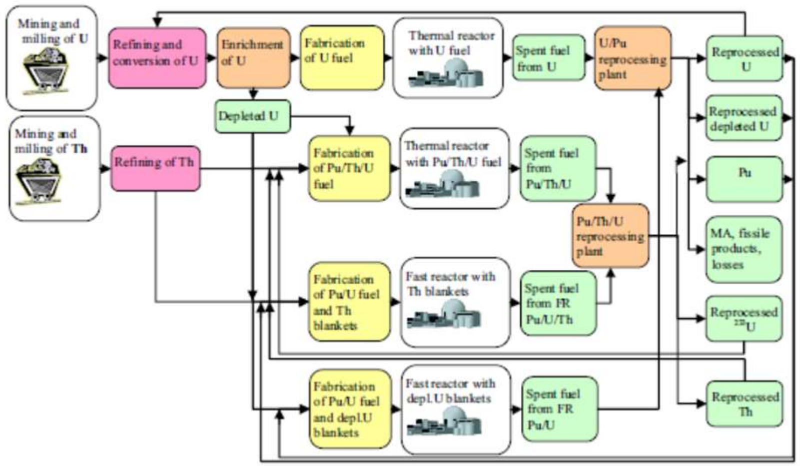


FIG. 4.10. Closed fuel cycle based on thermal and fast reactors using thorium and/or ^{233}U (with spent fuel reprocessing and recycling of ^{233}U and plutonium).

Member States' needs in developing transition scenarios towards sustainable NESs

IAEA

- **Developing transition scenarios to sustainable nuclear energy** at national, regional or global level - an essential part of the scientific research work **supporting the decision-making process** for national nuclear energy programmes
- While many States and international organizations have already performed relevant studies, it is increasingly recognized that more efforts are needed to **harmonize national decisions on technical, institutional and political issues** which are raised by transition to a nuclear energy system with enhanced sustainability features
- Several IAEA Member States have expressed interest in **joint modelling of regional and global trends toward a sustainable nuclear power supply**, taking into account the potential of technical innovations and bi-lateral or multilateral cooperation (including nuclear trade)

INPRO collaborative projects GAINS and SYNERGIES

- Responding to Member States needs, 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 INPRO collaborative project **"Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability" (SYNERGIES)** has systematized options to enhance nuclear energy sustainability applied the analytical framework to national NES evolution scenarios with regional cooperation

Analytical framework for nuclear energy evolution scenario evaluation regarding sustainability:

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

These projects have also shown enhanced sustainability may be achieved both, through innovations in technologies and/or changes in policies and through enhanced cooperation (nuclear trade) among countries, including the technology holder and technology user countries. Internationally recognized bodies responsible for defining sustainable energy policy on a global scale could also play a role here.

Major long-term sustainability enhancement issues

In terms of the scope of the GAINS and SYNERGIES projects (focused on the material flow and economic analysis), the major long-term sustainability enhancement issues addressed were as follows:

a) *Progressive accumulation of spent nuclear fuel that creates a burden for future generations*

b) *Non-effective use of natural fissile resources that in the future might create problems related to fissile resource non-availability*

c) *Presence of direct use materials (plutonium) in spent nuclear fuel - proliferation resistance issues and security concerns in the case of direct disposal of spent nuclear fuel*

d) *Huge investments required to develop and deploy innovative technologies for nuclear power*

e) *Risks related to global spread of sensitive technologies of uranium enrichment and spent fuel reprocessing*

- Not all the countries using or planning to use nuclear energy can address indigenously all the sustainability issues listed above.
- Even if technically possible for some of countries, it would not be economic to solve all the sustainability issues in isolation.
- The majority of countries would thus have or opt to rely on imported 'off the shelf' nuclear energy technologies and supply of nuclear fuel and other services and would increasingly demand regional or/and international cooperation among countries.

International Architecture of Innovative NP and NFC

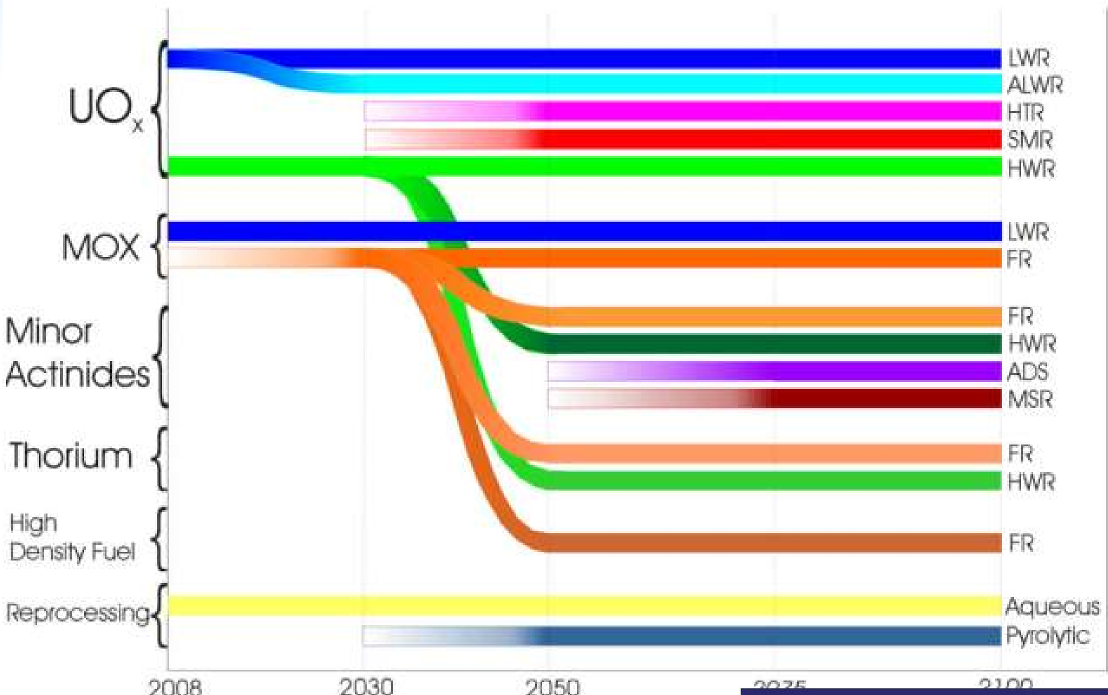
GAINS considered four architectures for NES:

I. Homogeneous “business-as-usual” (BAU) NES based on LWRs (94%) and HWRs (6%), operated in a once through fuel cycle, and a closed nuclear fuel cycle with fast reactors and thermal reactors

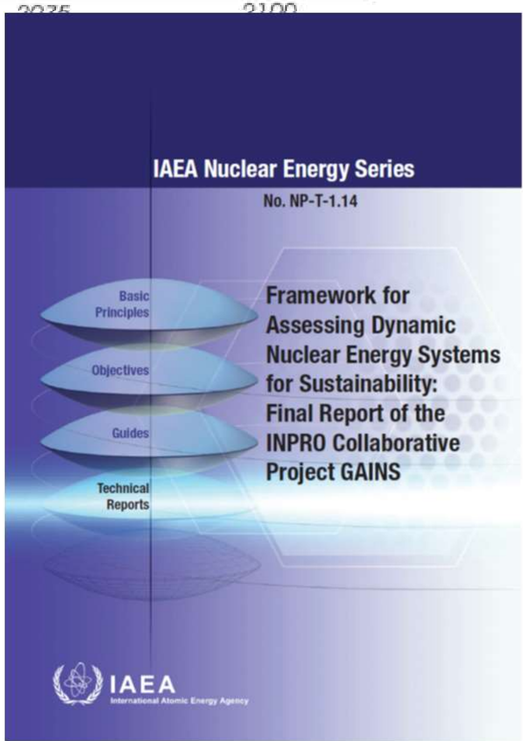
II. Heterogeneous system: closed nuclear fuel cycle with fast reactors and thermal reactors in NG1; once through fuel cycle with thermal reactors in NG2; and thermal reactors with minimal nuclear fuel cycle infrastructure in NG3

III. Minor actinide (MA) reducing components (accelerator driven systems – ADS or molten salt reactors - MSR)

IV. Thorium fuel cycle with fast reactors and thermal reactors

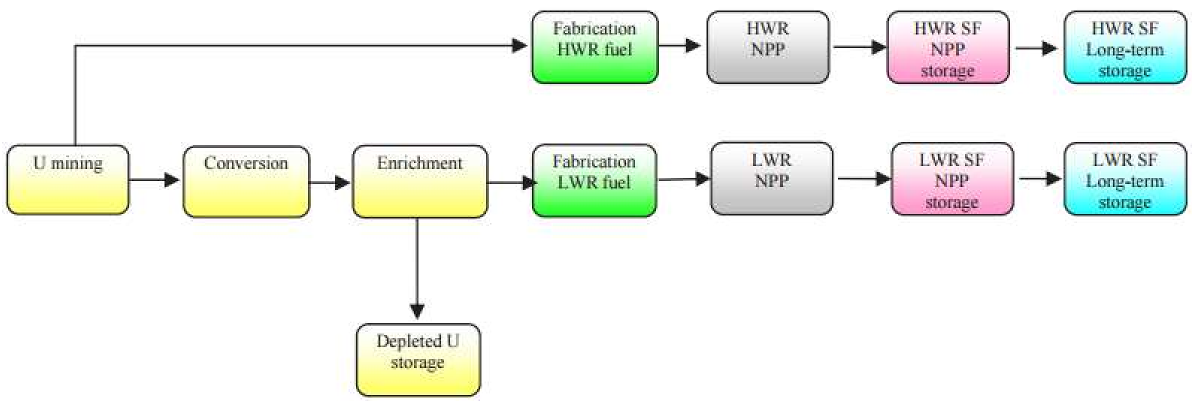


Set of reactor and fuel types and expected timeframes for deployment

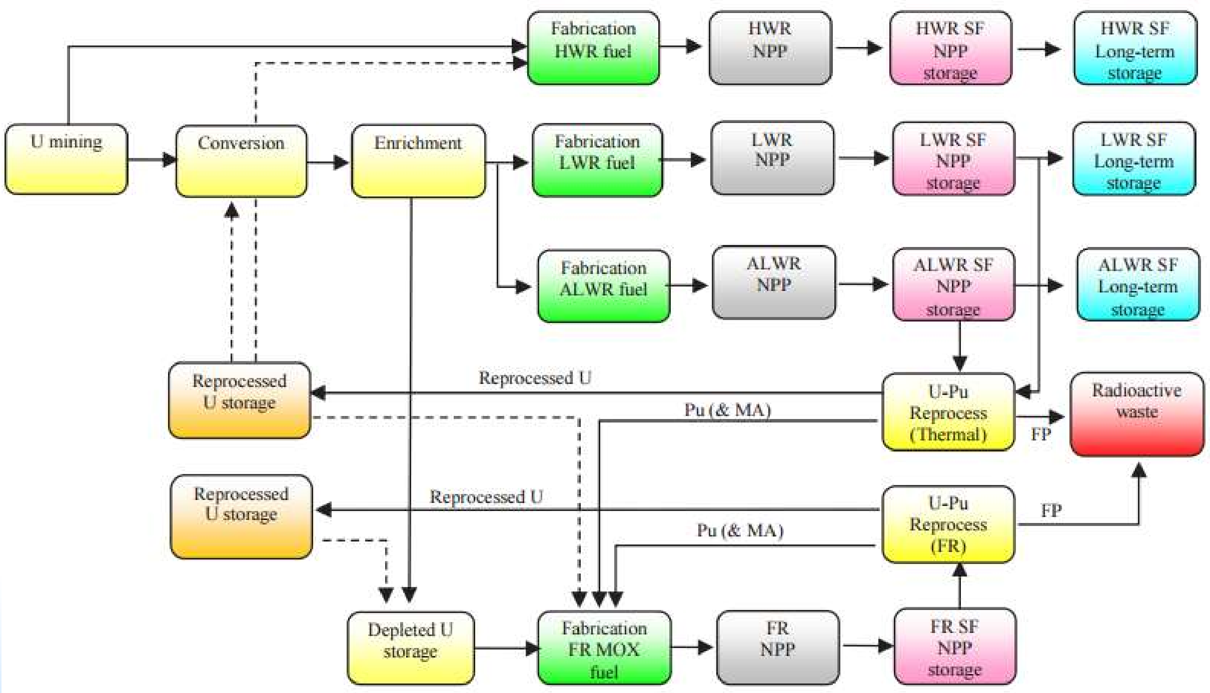


2013

Associated nuclear fuel cycle schemes (examples)



Once-through fuel cycle system (BAU scenario)

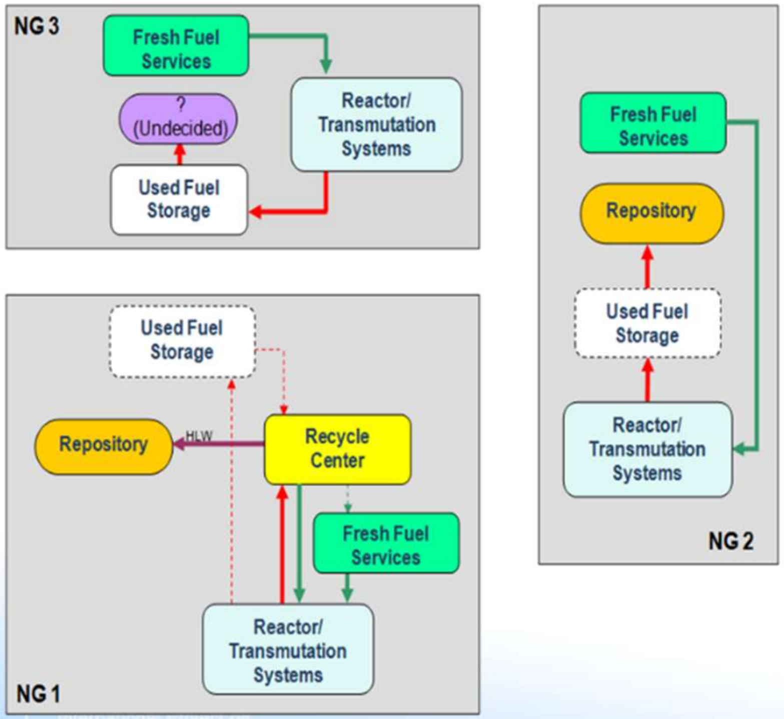


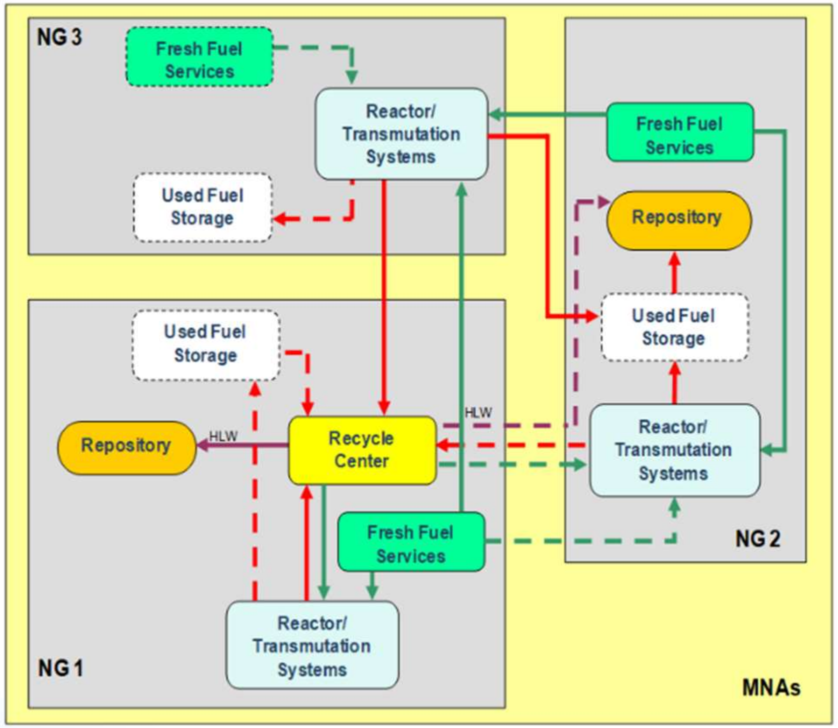
Once-through fuel cycle system combined with fast reactor closed fuel cycle system

International Architecture of Innovative NP and NFC: analytical framework

The most significant elements of this framework that might be applied within an integrated analysis of the performance and sustainability of national NES scenarios are as follows:

- Homogeneous and heterogeneous world models comprising groups of non-personified non-geographical countries with different policies regarding the nuclear fuel cycle
- Metrics and internationally verified tools for assessing material flows and key performance indicators associated with NES deployment scenarios
- An internationally verified database with characteristics of existing and advanced nuclear reactors and relevant NFCs needed for a detailed material flow analysis





GAINS-templates to calculate KIs and EPs

IAEA

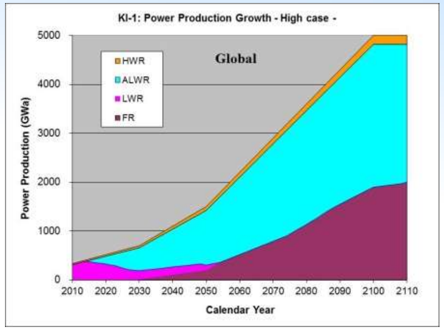
Scenario
- Nuclear power growth
- Reactor data
- Fuel cycle options

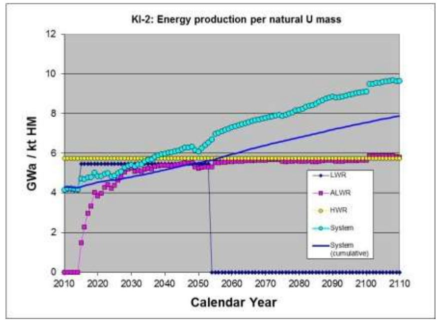
KIs and EPs

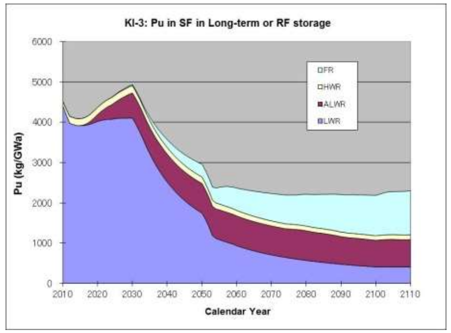
Fuel cycle codes
Mass flow analysis

GAINS template

Output



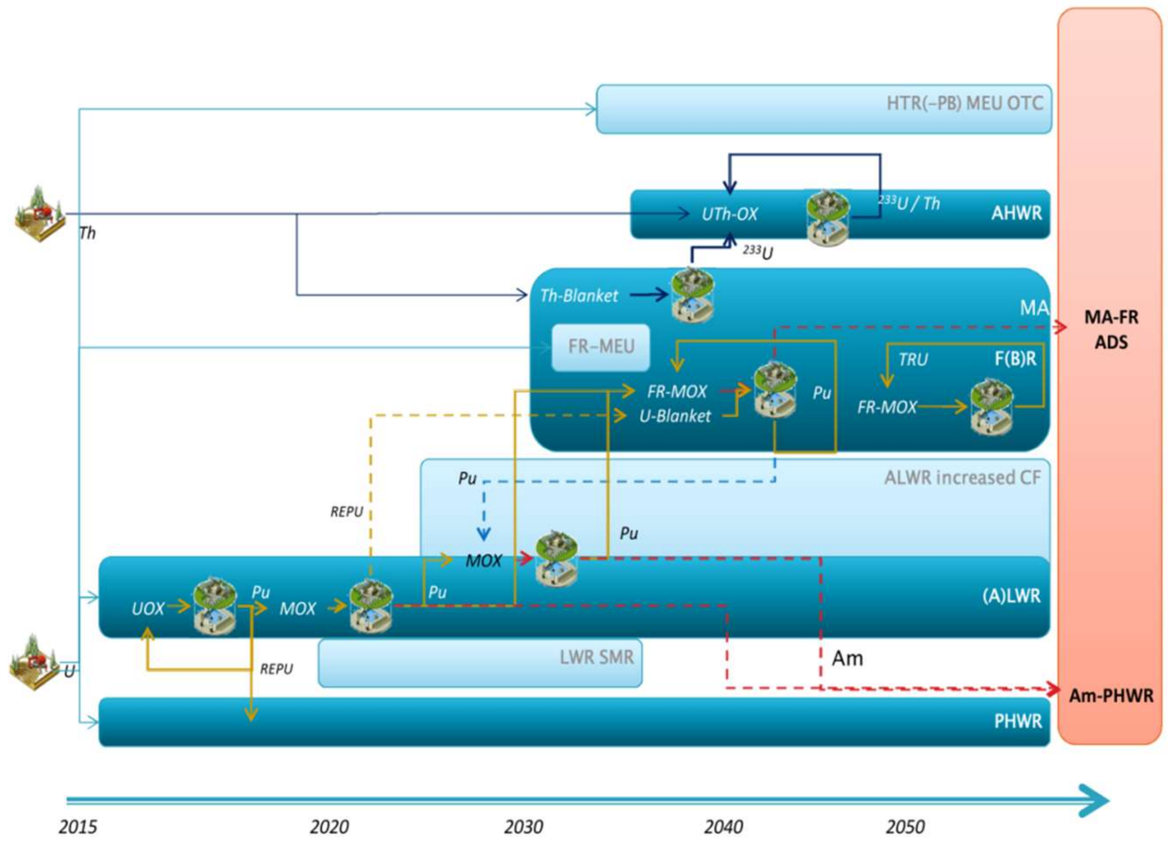




Technological options for NES sustainability enhancement

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

- *Once-through NFC*
- *Recycle of SNF with only physical processing*
- *Limited recycling of SNF*
- *Complete recycle of SNF*
- *Minor actinide or minor actinide and fission product transmutation*
- *Final geological disposal of all wastes* (obligatory for all above mentioned options)

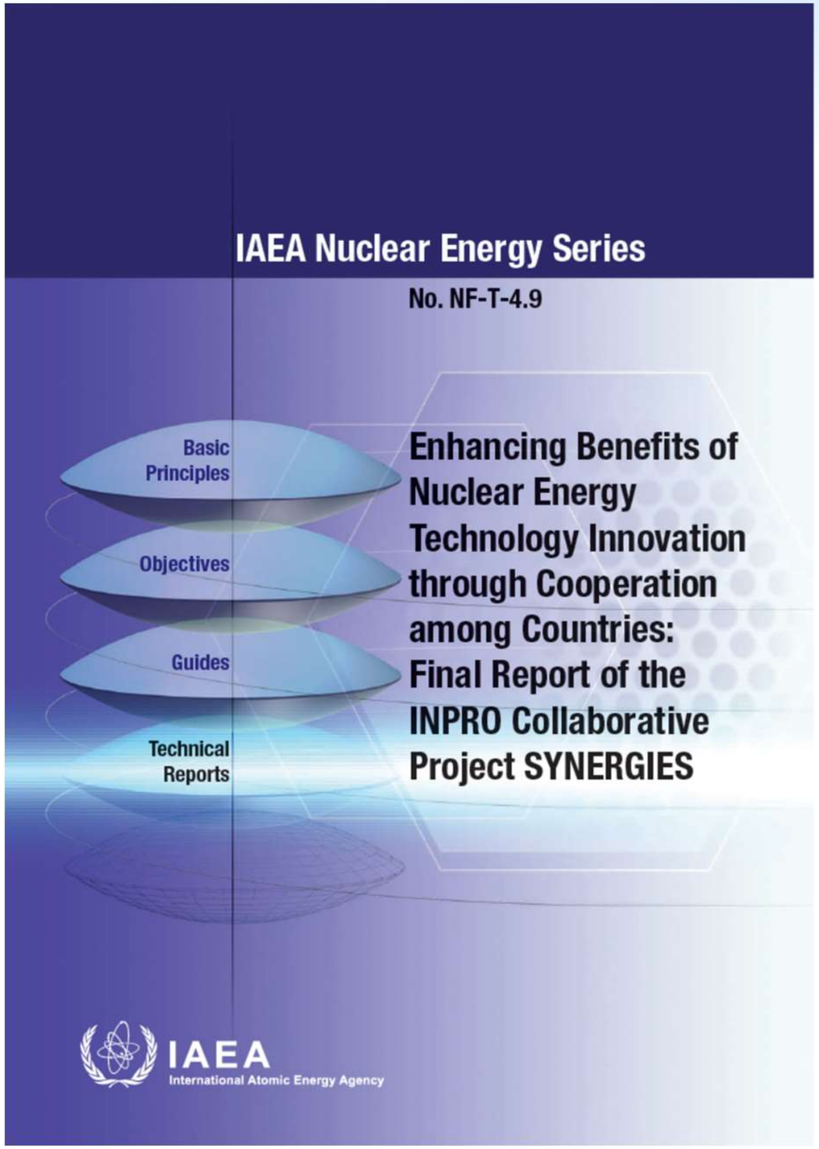


Overall view of the synergies among the technologies considered in the SYNERGIES project

Options for NES sustainability enhancement

IAEA

- Synergies within the context of nuclear energy are those actions that a country or a group of countries may undertake to facilitate the deployment of the NESs with enhanced sustainability
- Enhanced sustainability may be achieved via:
  - Innovations in technology and changes in policy
  - Increased collaboration (nuclear trade) among technology holder and technology user countries



2018

Drivers for collaboration (1)

- **Economic competitiveness** of nuclear energy has been identified as the primary driver for cooperation among countries. **The technology user countries** and, especially newcomer countries, look for the solutions with minimum economic and financial costs
- On the other hand, the **technology developer countries**, who are running large and costly research, design and demonstration (**RD&D**) programmes on innovative nuclear reactors and fuel cycles, look at strategic and business growth in anticipated national and world markets
- The **synergistic collaboration between technology developers and users** could help exploit the economic benefits associated with the economy of scale of fuel cycle facilities and the economy of accelerated learning.
- The **motivations of technology holder countries to pursue innovations** in nuclear reactors and fuel cycles are inherently affected by the availability and cost of natural resources (e.g., uranium) and the situation with the progressive accumulation of spent nuclear fuel from thermal reactors operated in a once through fuel cycle.
    - The known commercial practice (the European Union's LWR spent fuel commercial reprocessing and MOX fuel supply for a single recycle in LWRs) indicates such collaborations are currently undertaken by more wealthy and experienced users

Drivers for collaboration (2)

- Other potential drivers for synergistic cooperation in sustainable NES, as identified in the SYNERGIES case studies, could be related to the solution of some public acceptance or social issues, such as:
    - the **control of plutonium inventories** in storage to reduce proliferation and security concerns, **minimization of the amount of HLW** to simplify siting acceptable geological disposal solutions with minimum environmental impacts and footprints,
    - considerations of **increased energy independence** (non-reliance on natural uranium with its potentially volatile price), and
    - **preservation of natural resources** (e.g. natural uranium for countries with large targeted nuclear programmes).
- The SYNERGIES case studies indicate that some of the above-mentioned drivers may actually 'work' when the relevant disadvantages in economics are relatively small (a few per cent of the LUEC).
- In the case of larger increases of global nuclear energy with the associated potential of resource insufficiencies, HLW accumulation and increased proliferation and security concerns, one could expect these public acceptance and social related drivers to work more effectively for synergistic collaboration targeted at nuclear energy sustainability.

Impediments to collaboration

- *National laws in some Member States prohibiting spent fuel transport across national borders*
- *Non-available or insufficiently elaborated institutional procedures to govern nuclear fuel/ HLW transactions and price formation mechanisms for such transactions*
- *National laws that permit the return of ultimate waste (e.g., fission products and minor actinides) only of the same isotopic content as in the originally exported fuel – this would hamper the operations of a large fuel cycle back end service provider or an international fuel cycle centre for which it would be non-expedient to reprocess spent fuel individually for each customer*
- *Regional directives narrowing the competition for reprocessing services, and, potentially many others*

Timely overcoming the above-mentioned impediments of institutions and infrastructure is a necessary step to enable synergistic collaboration among countries towards sustainable nuclear energy.

The first step here would be to investigate the scope of legal and institutional issues in interested technology holder, technology user and newcomer countries more specifically and with higher degree of detail.

Near and medium-term actions towards enhanced nuclear energy sustainability

IAEA

- Near and medium-term actions are needed to continue to ensure and improve the longer-term sustainability of global nuclear energy. Near and medium-term actions for technology development are focused on developing and demonstrating enabling technologies for the sustainability improvement options.
- Use of these technologies in synergistic activities to assist other less developed programmes would further advance global sustainability. A key challenge for all advanced nuclear technologies is to improve economic performance
- Looking forward to managing growing SNF inventories in the near to medium term, geological repositories need to be opened for SNF disposal or reprocessing capacities need to be expanded and geological repositories opened for disposal of HLW.
- The successful opening and operation of one or more repositories is likely to reduce public uncertainties about nuclear waste and improve the associated social attitudes concerning specific repository projects, enabling more rapid deployment later, including potentially the deployment of regional repositories accepting waste from multiple countries. Depending on waste acceptance criteria, the start up of repositories may also influence decisions on direct disposal versus reprocessing of SNF.

Major findings of GAINS and SYNERGIES

Nuclear energy sustainability can be enhanced by innovations in nuclear energy technology, as well as by collaboration (nuclear trade) among countries. Collaboration could amplify the positive effect of technology innovation in achieving globally sustainable nuclear energy.

Potential benefits of collaboration among countries:

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

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

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

IAEA
International Atomic Energy Agency

Thank you!

a.bychkov@iaea.org

https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro