GENERATION IV CONCEPTS: EURATOM

BREAKTHROUGH TECHNOLOGIES TO IMPROVE SUSTAINABILITY, SAFETY & RELIABILITY, SOCIO-ECONOMICS AND PROLIFERATION RESISTANCE

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Nomenclature – Acronyms and Abbreviations

ALFRED	Advanced Lead Fast Reactor European Demonstrator (project)
ALLEGRO	Gas Cooled Fast Reactor demonstrator (project)
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
BOOT	Build-Own-Operate-Transfer
CAPEX	CAPital EXpenditures
DG	Directorate General (33 departments in the European Commission /EC/)
E&T	Education & Training
EFSI	European Fund for Strategic Investments
EGE	European Group on Ethics in Science and New Technologies
EMWG	Economics Modelling Working Group (GIF methodology)
ENEN	European Nuclear Education Network
ENSREG	European Nuclear Safety Regulators Group
ESNII	European Sustainable Nuclear Energy Industrial Initiative
EIT	European Institute of Innovation and Technology
ETIP	European Technology and Innovation Platforms (stakeholder groups)
EU	European Union (27 member states)
EUR	European Utility Requirements
Euro	European currency (1 Euro = 1.11 US Dollar, average over year 2020)
FISA	series of Euratom conferences on RTD and JRC results in fission safety
GIF	Generation-IV International Forum
INPRO	IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles
ISAM	Integrated Safety Assessment Methodology (GIF)
JHR	Jules Horowitz Reactor (CEA Cadarache, south-eastern France)
JRC	Joint Research Centre (“science for policy”, EC Directorate General)
KSC(A)	Knowledge, Skill and Competences (Attitudes)
LERF	Large Early Release Frequency
LUEC	Levelized Unit Energy Costs
MA	Minor Actinides (e.g. neptunium (Np), americium (Am), curium (Cm))
MEUR	Million euros (see Euro value 2020 above)

MS	Member State
MYRRHA	Multipurpose Hybrid Research Reactor for High-technology Applications (accelerator-driven system under construction at SCK-CEN, Mol, Belgium)
NC2I	Nuclear Cogeneration Industrial Initiative (part of SNETP)
NGEU	Next Generation EU fund 2020
NGO	Non-Governmental Organization
NPP	Nuclear Power Plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons (IAEA 1970)
NRG	Nuclear Research and Consultancy Group (Petten, the Netherlands)
NUGENIA	Nuclear Generation II & III Association (part of SNETP)
PALLAS	Research reactor (thermal neutrons) under construction in Petten (NL)
PIRT	Phenomena Identification and Ranking Table
PR&PP	Proliferation Resistance and Physical Protection group (GIF methodology)
RATEN-ICN	Regiei Autonome Tehnologii pentru Energia Nucleara – Institutul de Cercetari Nucleare - Pitesti (national nuclear institute of Romania)
R&D	Research and Development
RD&DD	Research – Development & Demonstration – Deployment
RSWG	Risk and Safety Working Group (GIF methodology)
RTD	Research and Technological Development (one of the DGs in the EC)
3S	Safety, Security and Safeguards (nexus - 3 disciplines related to nuclear)
SCK-CEN	Studiecentrum voor Kernenergie – Centre d'Étude de l'énergie Nucléaire (nuclear research centre, Mol, Belgium)
SDG	Sustainable Development Goals – 17 in total - UN 2030 Agenda (2015)
SET Plan	"Strategic Energy Technology" Plan (EU, 2008)
SMR	Small and Medium nuclear power Reactors (also called "Modular")
SNF	Spent Nuclear Fuel
SNETP	Sustainable Nuclear Energy Technology Platform (ETP)
SRA	Strategic Research Agenda
STC	Scientific and Technical Committee (Euratom Treaty - Articles 4, 7 and 8)
TMI	Three Mile Island
TSO	Technical Safety Organization (usually associated with nuclear regulator)

« Se défier du ton d'assurance qu'il est si facile de prendre et si dangereux d'écouter »

"Beware of the tone of assurance that is so easy to take and so dangerous to listen to".

Charles Coquebert de Montbret, scholar and state clerk, professor of mining statistics at the École des mines, Paris, 1755-1831 (Journal des mines n°1, Vendémiaire An III – i.e.: September 1794 - http://annales.org/)

Abstract

A significant part of the Euratom research and training programme is devoted to Generation-IV nuclear energy systems, which are scheduled for industrial deployment before 2045. A number of Euratom projects are thus focusing on innovative reactor technologies and fuel cycles, aligned with the Generation-IV Technology Roadmap. They share the objectives of the Generation-IV International Forum (GIF) :

1. sustainability (in particular, optimal utilization of natural resources and waste minimization) including decarbonisation of the economy and security of supply
2. safety and reliability (through design, technology, regulation and culture)
3. economics (industrial competitiveness, integration in low-carbon energy mix) together with social aspects (in particular, easy access to affordable energy for all)
4. proliferation resistance and physical protection (aligned with the Non-Proliferation Treaty, IAEA 1970).

In doing so, the Euratom research and training programme naturally contributes to the achievement of the main objectives of the EU's energy and climate policy, namely:

- towards secure, sustainable, competitive and affordable energy systems - the EU Energy Union Package (2015)
- towards a European climate-neutral economy by 2050 - the EU Green Deal (2020).

KEYWORDS:

EU; Euratom research, innovation and training; nuclear fission; science for policy; Generation-IV reactor systems; safety; sustainability; competitiveness; social acceptance

1. INTRODUCTION: "EU ENERGY UNION" (2015) AND "EU GREEN DEAL" (2020) – GOING CLIMATE NEUTRAL BY 2050 - EURATOM CONTRIBUTION

Total of 106 nuclear power reactors in the EU (= 26 % of gross electricity production)

The European Union (EU) [1] covers a total land area of over 4,23 million km² and has a combined population of approximately 450 million inhabitants as of June 2021 (27 Member States /MS/ - reminder: the United Kingdom withdrew on 31 January 2020).

In the EU, nuclear fission falls under the Euratom Treaty ("European Atomic Energy Community", signed in 1957 in Rome) [2] which is one of the founding Treaties of the EU.

[1] "Fact Sheets on the European Union" (European Parliament) – designed to provide non-specialists with a straightforward overview of the EU's policies - https://www.europarl.europa.eu/factsheets/en/home

[2] "Consolidated version of the Treaty establishing the European Atomic Energy Community (Euratom)" OJ C 327, 26.10.2012: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:12012A/TXT
- see also "50 years of the Euratom Treaty - Communication from the Commission to the Council and the European Parliament" COM/2007/0124/, 20 March 2007 – (EU Monitor's view on how to improve future action) - https://www.eumonitor.eu/9353000/1/j4nvhdfcs8bljza_j9vvik7m1c3gyxp/vikqhl1ogox3

Nuclear is a major contributor already today as a low-carbon technology in the EU's strategy to reduce its fossil fuel dependency and to fulfil its 2020/2030/2050/COP21 energy and climate policy objectives.

The EU is a major player in the world of nuclear fission. As of 2020, a total of 106 units are operable in 13 of the 27 of the EU Member States, that is: Belgium (7 units), Bulgaria (2), the Czech Republic (6), Germany (6), Spain (7), France (56), Hungary (4), the Netherlands (1), Romania (2), Slovenia (1), Slovakia (4), Finland (4) and Sweden (6). The 106 nuclear power reactors (104 GWe net, 15 300 tonnes uranium required yearly) account for over one-quarter of the electricity generated in the whole of the EU. Over half of the EU's nuclear electricity is produced in only one country – France (61 GWe net). Moreover, the European nuclear industry sustains more than 1.1 million jobs in the EU and generates more than 100 billion euros per year in GDP, according to a 2019 study by Deloitte.

At the end of 2019, above EU countries represented a gross nuclear electricity generation of 732 TWh (i.e., 26 % of gross electricity production in the EU). Five amongst those countries (Bulgaria, the Czech Republic, Finland, Hungary and Slovakia) operate 18 Russian-designed VVER reactors with a total electricity output of 80 TWh, which corresponds to approximately 11 % of nuclear electricity generation in the EU.

As of June 2021, it should be noted that 4 reactors are under construction in the EU (1 in Finland /EPR - 1600 MWe at Olkiluoto/, 1 in France /EPR - 1650 MWe at Flamanville/ and 2 in Slovakia / two V-213+ of 471 MWe each, at Mochovce 3 and 4/), while 13 reactors are planned (6 in Poland, 2 in Hungary, 2 in the Czech Republic, 2 in Romania and 1 in Finland – 16 GWe gross capacity in total) and a further 8 reactors have been proposed.

World-wide, around 10% of the world's electricity is generated by about 440 nuclear power reactors operating in 32 countries plus Taiwan, with a combined electrical capacity of about 400 GWe. In 2019, nuclear plants supplied 2657 TWh of electricity, up from 2563 TWh in 2018. As of June 2021, about 50 power reactors are being constructed in 16 countries (notably China, India, Russia and the United Arab Emirates) with a combined capacity of 57 GWe, equivalent to approximately 15 % of existing capacity. About 100 power reactors with a total gross capacity of about 110 GWe are on order or planned, and over 300 more are proposed. Most reactors currently planned are in Asia, with fast-growing economies and rapidly-rising electricity demand. It should be noted that Russia and China have taken the lead in offering nuclear power plants to emerging countries (approximately 30 in total), usually through state-owned nuclear companies with finance and fuel services.

** District heating and industrial heat applications world-wide*

It is worth discussing non-electric applications of nuclear fission in the world. Russia, several East European countries, Switzerland and Sweden have all had nuclear-fuelled district heating schemes. Heat from nuclear power plants has also been sent to industrial sites in several countries. In 2019, 71 nuclear power reactors in 11 countries utilized 2146 GWh (gigawatt-hours) of electrical equivalent heat to support non-electric applications of

nuclear energy such as for district heating, process heat supply (including chemicals refinement and hydrogen production) or seawater desalination purposes. As nuclear power plants supplied 2657 TWh of electricity world-wide in 2019, non-electric applications represent only 0.8 ‰. About 88% of that heat was supplied by 57 reactors in Europe and 12% by 14 reactors in Asia. Further, 10 reactors supported seawater desalination (using 48 GWh), 56 reactors supported district heating (1871 GWh) and 32 reactors supported industrial heat applications (1248 GWh). Source: IAEA and WNA.
NB - In Europe, the low carbon hydrogen production through electrolysis using nuclear power could be the most economical way to achieve the hydrogen productivity levels foreseen by the EU Hydrogen strategy (as part of the EU Green Deal 2020).

** Good health and well-being (SDG 3 – 2030 Agenda, United Nations /UN/ 2015)*

The 17 Sustainable Development Goals (SDGs) are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental. The use of nuclear technology in medicine (SDG 3) has become one of the most widespread uses of nuclear energy in the non-electric sector [3]. Nuclear techniques play an important role in diagnosing and treating various health conditions, in particular non-communicable diseases. Reminder - The fission of uranium-235 (U-235) produces a spectrum of fission products including Molybdenum-99 /Mo-99/ (as well as I-131 and Xe-133). More than 80% of all nuclear medicine Single Photon Emission Computerized Tomography (SPECT) scans used each year to detect diseases like cancer and cardiovascular diseases require Technetium-99m (Tc-99m) – the most widely used radioisotope in radiopharmaceuticals. Tc-99m is the decay product of Mo-99, which is mainly generated in research reactors (usually using proliferation-sensitive "highly enriched uranium" /HEU/).

EU's ambition to become the world's 1st major economy to go climate neutral by 2050

Euratom is not isolated in the EU policies. Nuclear fission is part of the European energy mix [4], together with the two other primary energy sources: renewable and fossil.

Remember Article 194 of the Lisbon Treaty [5] (signed in 2007, entered into force in 2009):

> *"Union policy on energy shall aim, in a spirit of solidarity ...: .. Such measures shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply".*

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3 IAEA website - 17 Sustainable Development Goals (SDGs) set out in the UN 2030 Agenda – nuclear development in areas such as: energy, human health, food production, water management and environmental protection - https://www.iaea.org/about/overview/sustainable-development-goals

4 EC DG (Directorate General) ENERGY programmes related to Nuclear safety; Radioactive waste and spent fuel; Radiation protection; Decommissioning of nuclear facilities; Safeguards to avoid misuse; Security (non-proliferation and physical protection) : http://ec.europa.eu/energy/en/topics/nuclear-energy

5 Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A12007L%2FTXT
(in general, summaries of EU Legislation: http://eur-lex.europa.eu/browse/summaries.html)

The EU energy and climate strategy during the coming decades is defined in the "EU Energy Roadmap 2050" (issued in 2011) which originally proposed several scenarios towards a low-carbon economy, based on a balance between sustainable development, security of supply and industrial competitiveness. Two messages are important for the nuclear fission sector at horizon 2050. Firstly, one of the "decarbonisation scenarios" is based on a 20 % share of electricity generation by nuclear fission, which represents an equivalent operating capacity of 127 GWe, to be compared to today's total nuclear generation of 104 GWe. Secondly, the general conclusion for all "decarbonisation scenarios" (still valid today) is that electricity will play a much greater role than now (almost doubling its share in final energy demand, from 21 % today to 40 % in 2050).

The "EU Energy Union Package" (2015): secure, sustainable, competitive and affordable energy

In February 2015, EC President Jean-Claude Juncker (in office during 2014-2019) presented the overall EU energy strategy in the "Energy Union Package".[6], aiming at building an energy union that gives EU consumers - households and businesses - secure, sustainable, competitive and affordable energy.

The above Energy Union Package is based on five closely related and mutually reinforcing objectives:

- *Security, solidarity and trust* - diversifying Europe's sources of energy and ensuring energy security through solidarity and cooperation between EU countries
- *A fully integrated internal energy market* - enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers
- *Energy efficiency* - improved energy efficiency will reduce dependence on energy imports, lower emissions, and drive jobs and growth
  (NB: in the EU in 2019, the dependency rate was equal to 61 %, which means that more than half of the EU's energy needs were met by net imports)
- *Climate action, decarbonising the economy* - the EU is committed to the 2015 Paris Agreement *(NB : draft in December 2015 and formal entry into force on 4 November 2016)* and to retaining its leadership in the area of renewable energy
- *Research, innovation and competitiveness* - supporting breakthroughs in low-carbon and clean energy technologies by prioritising research and innovation to drive the energy transition and improve competitiveness.

Here are two excerpts related to nuclear fission in the above 2015 Energy Union Package:

[6] ENERGY UNION PACKAGE / Communication from the EC to the European Parliament, The Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank (COM(2015) 80, Brussels, 25.2.2015) *"A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy"* - http://www.consilium.europa.eu/en/policies/energy-union/

- *putting the EU at the forefront of ... all innovative energy technologies ..., including ...the world's safest nuclear generation, is central to the aim of turning the Energy Union into a motor for growth, jobs and competitiveness.*
- *The EU must ensure that ... it maintains technological leadership in the nuclear domain, including through ITER, so as not to increase energy and technology dependence.*

An important preliminary step in the European Energy policy was made on 13 January 2015, when the EU adopted the "*European Fund for Strategic Investments*" (EFSI) [7], which is at the very heart of the 315 billion euros Investment Offensive of EC president J C Juncker. The EFSI was the central pillar of the Investment Plan for Europe in the mid-2010s. EFSI aimed originally to tackle the lack of confidence and investment which resulted from the economic and financial crisis, and to make use of liquidity held by financial institutions, corporations and individuals at a time when public resources were scarce. The EFSI was mobilising public and private investments in the real economy in areas including infrastructure, energy efficiency and renewable energy, research and innovation, environment, agriculture, digital technology, education, health and social projects. To reach these goals, the Commission works together with the European Investment Bank (EIB), which is also used to help small businesses to start up and to grow.

A few years later (in 2018), the European Commission presented an updated strategic vision showing how it could lead the way to climate neutrality by investing in realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for an equitable transition. This was the subject of the EC Communication "*A Clean Planet for all*" which stated, in particular, that "*renewable energies together with a nuclear power share of ca. 15%, (…) will be the backbone of a carbon-free European power system" in 2050* [8].

Moreover, as far as nuclear is concerned, the following messages could be derived from the above 2018 EC Communication "*A Clean Planet for all*":

- nuclear will remain an important component in the EU 2050 energy mix
- the capacity of nuclear in 2050 could be between 99 and 121 GWe
- in the baseline, hydrogen use develops only for road transport and industry.

NB : According to Foratom (the Brussels-based trade association for the nuclear energy industry in Europe), in the longer run with 15% nuclear generation foreseen in 2050, most of the existing fleet will have to be renewed.

[7] EC priority - Investment Plan - https://ec.europa.eu/info/strategy/priorities-2019-2024/economy-works-people/jobs-growth-and-investment/investment-plan-europe/european-fund-strategic-investments-efsi_en

[8] "A Clean Planet for all - A EU strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" COM (2018) 773 - https://ec.europa.eu/clima/policies/strategies/2050_en and "EC Staff Working Document supporting in-depth analysis" (393 pages) - Brussels, 28/11/2018 – https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

The 2020 (fifth) report on the State of the Energy Union COM (2020)950 [9] is the first such report since the adoption of the European Green Deal (European Parliament, 15 January 2020, discussed further down). It looks at the energy union's contribution to Europe's long-term climate goals. It highlights how the "Next Generation EU" recovery plan can support EU countries through a number of flagship funding programmes, especially through energy-related investments and reforms.

Here is an excerpt of this 2020 report on the Energy Union, related to nuclear fission:

> *On nuclear safety and security, the EU has a comprehensive framework that covers the full nuclear life cycle, including the safe and responsible management of spent fuel and radioactive waste. The Commission has continued to carefully monitor the implementation of this framework in Member States. The EU has also continued to promote high levels of nuclear safety outside the EU, particularly in neighbouring countries that operate or plan to build nuclear power plants. This includes support in conducting stress tests and follow up to promote proper and transparent implementation of recommendations.*

The EU Green Deal (2020): towards a European climate-neutral economy by 2050
On 1 December 2019, Ms Ursula von der Leyen, the current President of the European Commission (in office until the 2024 elections), took office with a new programme focused on six main priorities: 1) a European Green Deal; 2) an economy that works for people; 3) a Europe fit for the digital age; 4) a protection of the European way of life; 5) a stronger Europe in the world; and 6) a new push for European democracy.

On 11 of December 2019, The EC issued a communication that sets out the European Green Deal [10] for the European Union and its citizens, towards a European climate-neutral economy by 2050, aimed at mobilizing at least 1 trillion euros of public/private investment over the course of ten years to achieve net zero greenhouse gas emissions for EU countries as a whole. Several initiatives have been launched by the EC in the frame of the implementation of this EU Green Deal. The most important initiative is the EC's proposal to cut greenhouse gas emissions by at least 55% below 1990 levels by 2030. This is a substantial increase compared to the existing target, upwards from the previous target by at least 40%. It is in line with the 2015 Paris Agreement objective to keep the global temperature increase to well below 2°C, and pursue efforts to keep it to 1.5°C.

Energy transition towards climate neutrality: EU's support for "green" technologies

Next Generation EU fund 2020 (NGEU): what are sustainable "green" economic activities?

The Next Generation EU (NGEU) fund is a European Union recovery package to support the Member States after the COVID-19 pandemic, thereby preparing a better future for

[9] "Fifth report on the state of the energy union", including the national energy and climate plans, EC, 14 Oct 2020 - https://ec.europa.eu/energy/topics/energy-strategy/energy-union/fifth-report-state-energy-union_en
[10] EU climate action and the EU Green Deal - https://ec.europa.eu/clima/policies/eu-climate-action_en

European next generation. Initiated by EC President Ursula von der Leyen and agreed to by the EU Council on 21 July 2020, the fund is worth 750 billion euros (in fact, 360 billion euros in loans and 390 billion euros in grants). The NGEU breaks away from the austerity policy adopted after the 2008 financial crisis as the EU's main response to economic crises. The NGEU fund will be tied to the regular 2021–2027 budget of the EU's 2027 Multiannual Financial Framework (MFF) which amounts to 1074.3 billion euros. Hence, the comprehensive NGEU and MFF packages are projected to reach 1824.3 billion euros.

The EU has launched the above COVID-19 recovery plan for several objectives. The primary objective is to help its Member States to repair the immediate economic and social damages caused by the coronavirus pandemic.

Secondly, alongside tackling the economic and social impacts of the pandemic, the plan has other objectives. It also aims to assist the green transition, digital transformation, smart, sustainable, and inclusive growth and jobs, social and territorial cohesion, health and resilience, policies for the next generation, including education and skills.

The third objective of the NGEU is modernizing the EU infrastructure. Therefore, more than 50 % of support for the plan will be spent on modernization. Such as: research and innovation, via Horizon Europe; fair climate and digital transitions, via the Just Transition Fund and the Digital Europe Programme; preparedness, recovery and resilience, via the Recovery and Resilience Facility; and a new health programme, EU4Health.

EU green Taxonomy: technical assessment of nuclear energy with respect to the ‘Do No Significant Harm’ (DNSH) criteria

The European Commission intends to strongly link the above recovery plan NGEU to the need to fight climate change with the objective of reducing greenhouse gas emissions. The NGEU approach is in line with the objectives of the 2020 EU Green Deal, the flagship initiative to address the climate emergency that seeks to make of the EU the global leader on climate change and achieve carbon neutrality by 2050. For example, there is a general agreement on the cross-cutting lifecycle emissions threshold of 100 g CO_2 equivalent / kWh. Moreover, an overall climate target of 30% will apply to the total amount of expenditure from the MFF and NGEU in compliance with the 2015 Paris climate accord.

In this context, the EU Council and Parliament adopted in June 2020 a regulation (EU-2020/852 - the so-called “EU green Taxonomy”) that establishes the general framework for determining whether an economic activity qualifies as environmentally sustainable. The purpose is to define the degree to which an investment may be environmentally sustainable. The regulation empowers the Commission to establish, for each of the environmental objectives laid down in that regulation, the technical screening criteria for determining the conditions under which specific economic activities qualify as contributing substantially to that objective and ensuring that those economic activities do not cause significant harm (DNSH) to any of the other environmental objectives.

The EU green Taxonomy is a green classification system that translates the EU's climate and environmental objectives into criteria for specific economic activities for investment purposes. This EU green Taxonomy is the world's first-ever "green list" classification system for sustainable economic activities. As a result of this taxonomy, there is no risk of greenwashing: the industrial and economic activities are classified according to their ecological impact and investments are directed towards projects that are recognised as "sustainable" through the recognition of a "green label".

All technologies, with the exception of power generation activities using solid fossil fuels, have been assessed based on life cycle considerations, as well as in accordance with the additional requirements that apply to so-called transition activities. Appropriate technical screening criteria have been developed including to avoid 'significant harm' (including with regard to the disposal of waste). The separate classification of energy technologies (which all together in the EU account for about 22% of direct greenhouse gas /GHG/ emissions), deserving of the green label and therefore of being financed by the NGEU, is the subject of heated debate, especially when it comes to natural gas and nuclear energy (as well as agricultural activities).

As part of the political compromise reached, neither natural gas, nor nuclear energy were explicitly included or excluded from the first list (the so-called first Delegated Act). The Commission stated in April 2021, that it will issue by the end of 2021 a complementary Delegated Act covering nuclear energy "subject to and consistent with the results" of a review process that is underway in accordance with above Taxonomy Regulation.

A key milestone in that process was a nearly 400-page report issued in March 2021 by the Joint Research Centre (JRC), called JRC Report on DNSH [11]. JRC is the EU's technical in-house science and knowledge body. This report concludes that nuclear energy "does no significant harm" (DNSH) to the environment. Indeed, the subject JRC report states:
" *there is no science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies already included in the EU Taxonomy as activities supporting climate change mitigation* ".

With regard to nuclear waste specifically, the JRC revealed a broad scientific consensus that the EU's current disposal strategy, which places high-level, long-lived radioactive waste inside deep geologic formations, is considered an appropriately safe means of isolating radioactive waste from the biosphere in the long-term. The JRC report drew comparisons to the sequestration of carbon dioxide in carbon capture and sequestration technology, when discussing long-term disposal of radwaste in geological facilities.

Many organisations welcomed the publication of this DNSH report by JRC which provides a technical basis for the political debate to move forward on climate change mitigation solutions. *This may be a sign that science (and not politics) is finally driving the EU*

[11] "Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')", EC JRC report 124193, Petten, 29 March 2021 https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/210329-jrc-report-nuclear-energy-assessment_en.pdf

Taxonomy. This landmark JRC report is under review by two other expert groups, the Euratom Article 31 experts' group and the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER), both composed of radiation protection and public health experts. The review is targeted for completion by the end of 2021.

2. EURATOM: RESEARCH & TRAINING; SAFETY OF NUCLEAR INSTALLATIONS; HEALTH AND SAFETY (RADIATION PROTECTION); SAFEGUARDS; RADWASTE MANAGEMENT

EURATOM – Brief history (21st century challenges) and links with IAEA and OECD/NEA

The Treaty establishing the European Atomic Energy Community (the Euratom Treaty) was signed in 1957 by the six founding States of the European Union (Belgium, France, Germany, Italy, Luxembourg and the Netherlands) who joined together to form Euratom. The Euratom Treaty is dedicated to peaceful and sustainable applications of nuclear fission.

Originally, in the mid-1950's, the Euratom Treaty proposed nuclear power plants (NPPs) as part of the solution to the energy crisis in Western Europe. It should be noted that, already at that time, security of energy supply was a concern. Remember the oil crisis in 1956 due to the closure of the Suez Canal. Moreover, in the fossil energy sector (in particular, in coal mines), severe accidents with many casualties were also a concern: remember still in 1956, the major mining disaster in Marcinelle, Belgium, with a total of 262 miners killed (a.o. Italian, Moroccan, Spanish, Polish, Greek and Turkish victims).

Before the European integration was finalised, there had been the Founding Treaties: the Treaty of Paris in 1951 ECSC (European Coal and Steel Community) and the two Treaties of Rome in 1957 - EEC (European Economic Community) and Euratom (European Atomic Energy Community). In 1967 they were all merged to become later the European Union. While the first two ended, Euratom is left unchanged and only was added as a protocol to the new EU Treaty (Lisbon Treaty 2009).

The Euratom Treaty had originally set highly ambitious objectives, including the "speedy establishment and growth of nuclear industries". In other words: the Treaty was developed at the end of the 1950s to foster nuclear energy with governmental funds. However, at the beginning of the 21st century, owing to the complex and sensitive nature of the nuclear sector, which touches on social acceptance in some Member States and on vital interests (defence and national independence), those ambitions had to be scaled back. Remember: *Nuclear energy is the energy that generates most emotion per MWh produced !*

Other important objectives of the Euratom Treaty are the promotion of research and dissemination of knowledge (training); safety of nuclear installations; health and safety (in particular, radiation protection in connection with ionising radiation); safeguards (security); as well as radioactive waste management. As far as security of energy supply is concerned, the Euratom Treaty is also aiming at (1) ensuring that all users in the

Community receive a regular and equitable supply of ores and nuclear fuels and (2) exercising the Community's right of ownership with respect to special fissile materials.

The Euratom Community works in synergy with its own institutional laboratories (i.e., the Joint Research Centre /JRC/) and with national programmes in the EU Member States dedicated to applications of nuclear fission and ionising radiation. Equally important is international collaboration outside the EU frontiers, in industrialized countries or in emerging countries using, considering, planning or starting nuclear power programmes.

Euratom policies of course are closely related to the two most important international organisations dedicated to nuclear fission and radiation protection:

(1) the UN/IAEA (International Atomic Energy Agency, created in 1957, headquarters in Vienna – 173 member states world-wide) and

(2) the OECD/NEA (Organisation for Economic Co-operation and Development / Nuclear Energy Agency, created in 1972, headquarters in Paris - 34 member states from Europe, North America and the Asia-Pacific region).

Of particular importance in the Euratom safeguards policy is to share the objective of IAEA: to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology. In this context it is worth recalling that the European Union (in particular, Euratom) has the power to establish legally-binding acts (Euratom Directives) with regard to the safety of nuclear facilities as well as radiation protection and security and safeguards. IAEA may only make non-binding recommendations in its Nuclear Security Reports, while the EU may impose direct sanctions on nuclear operators whenever they have been violating the nuclear safeguards framework. Similarly, the OECD/NEA helps to establish the global framework of guidance, standards and best practices through non-binding recommendations in their domain of competence.

World-wide, besides supply of energy for an ever-growing world population, a number of other challenges in the energy domain are emerging, especially the issue of sustainability in connection with the UN Sustainable Development Goal no 7 (SDG-7) which calls for "affordable, reliable, sustainable and modern energy for all" by 2030.

More generally, energy is an enabler to foster economic development and to perform many actions required for overall development of societies. SDG-7 specifically is aiming at:

(1) decarbonising the global economy (connected to protecting the environment)

(2) providing easy access to energy for all (connected to global population growth)

(3) ensuring a stable supply of affordable energy for industry and households (connected to improving economy and increasing everyone's standard of living).

The focus on sustainability in Euratom programmes goes together with a better governance structure in the decision-making process. Also important is public information and engagement in energy policy issues, notably in connection with nuclear decision making.

Euratom research, innovation and education programmes are well aware of the importance of good governance. As a consequence, the major stakeholder groups of nuclear fission and radiation protection are brought together within the "Sustainable Nuclear Energy Technology Platform" (SNETP) which is one of the so-called "European Technology and Innovation Platforms" (ETIPs) and within the "European Energy Research Alliance" (EERA) which is a key player in the European Union's "Strategic Energy Technology" (SET) Plan and the Clean Energy Transition (more information further down).

The major stakeholder groups concerned with nuclear energy in the EU are:

- research organisations (e.g., from public and private sectors)
- systems suppliers (e.g., nuclear vendors, engineering companies)
- energy providers (e.g., electrical utilities and associated fuel cycle industry)
- technical safety organizations (TSO) associated with nuclear regulatory authorities
- academia and higher education and training institutions dedicated to nuclear
- civil society (e.g., policy makers & opinion leaders), NGOs, citizens' associations.

The above stakeholder groups are instrumental, in particular, in the design of the Euratom research and innovation programmes (the current one 2021-2025 is discussed below). They encourage, in particular, the scientific community to participate in collaborative projects wherever appropriate. It is clear that, in this collaboration, the participating TSOs adhere strictly to their prescribed roles, powers and independence as a support to the national regulators in decision making. Moreover, non-EU research organisations are welcome to join Euratom projects provided that their scientific contribution brings clear added value to the project and that they pay the full costs of their participation.

It should be noted that in the EU, socio-economics is at the heart of many policies. In this context, it is no wonder that the EU Council at their meeting of 28 June 2011 requested that the EC *"organise a symposium in 2013 on the benefits and limitations of nuclear fission for a low carbon economy. The symposium will be prepared by an interdisciplinary study involving, inter alia, experts from the fields of energy, economics and social sciences"*. As a consequence, a *"2012 Interdisciplinary Study"* was launched in April 2012, composed of two parts (scientific-technological and socio-political) and published on the occasion of and presented at the 2013 "Symposium on the benefits and limitations of nuclear fission for a low carbon economy" (Brussels, 26-27 February 2013) [12].

An *Ethics study* covering all primary energy sources was also conducted in this context and was published in the proceedings of the above 2013 Symposium as well as in a separate EC/EGE document. The title of the *Ethics study* is "*Ethical framework for assessing research, production, and use of Energy*". It was issued on 16 January 2013 and referred

[12] 2012 Study – co-organised by European Commission and European Economic and Social Committee (EESC) - https://www.eesc.europa.eu/sites/default/files/resources/docs/nucf_p_wip14_17june13.pdf
and synthesis report available in the Publications Office of the EU (194 pages - free of charge) - https://op.europa.eu/en/publication-detail/-/publication/e92b20be-9163-4aee-b469-87828b10c0f1

to as “Ethics Opinion no. 27”. This *Ethics study* advocates a fair balance between four criteria in the light of *social, environmental and economic* concerns [13]. The four criteria of the *Ethics study* are: *(1) access to energy as a human right; (2) security of EU energy supply; (3) sustainability / environmental responsibility; (4) safety, imminent, indirect and long term*. The authors also insist on more science-based support for EU energy policy. For example, one of the key messages reads: *“Proper impact assessment methodologies to compare the security and safety of the energy mix instruments are necessary.”*

EURATOM legal framework – the most stringent safety requirements in the world

The EU became the first major regional actor with a legally binding regulatory framework for nuclear safety following implementation of the Euratom Directives on safety (2014), waste management (2011) and basic safety standards (2013). As a consequence, today, all 27 EU Member States meet equally high standards of safety, radiation protection, safeguards and security.

Not surprisingly, the above statements from the “Energy Union Package” (2015) regarding nuclear safety and EU technological leadership in the nuclear domain were at the heart of the three important Euratom Directives discussed below.

Particularly important are the lessons drawn from the three severe accidents that happened: during the last five decades: Three Mile Island /TMI/ 1979 in the USA (INES scale 5); Chernobyl 1986 in the former Soviet Union (INES 7); Fukushima 2011 in Japan (INES 7). *NB: INES is the “International Nuclear and Radiological Event Scale”, introduced by IAEA and OECD/NEA in 1990 as a tool for promptly communicating the safety significance of reported nuclear and radiological incidents and accidents (7 levels).*

In short, the following lessons [14] were drawn in the nuclear energy sector world-wide:

- TMI 1979 : need for more robust safety assessment methods (deterministic versus probabilistic approaches) and importance of human failures
- Chernobyl 1986 : implementation of safety culture and development of laws and regulations related to safety and health at work (IAEA and Euratom)
- Fukushima 2011 : design against beyond design basis accidents (design extension) and independence of national regulatory authorities (to be required by law).

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[13] "*Ethical framework for assessing research, production, and use of Energy*", Brussels, 16 January 2013 – EC/EGE study - https://publications.europa.eu/en/publication-detail/-/publication/44f7f1fa-eb0c-44e7-9a75-45377d5abd73/language-en - Note on EC/EGE. The *European Group on Ethics in science and new technologies* (EGE) was asked by EC President Mr. José Manuel Durão Barroso (in office from 2004 to 2014) on 19 December 2011 to contribute to the debate on a sustainable energy mix in Europe by studying the impact of research into different energy sources on human well-being.

[14] “Root Causes and Impacts of Severe Accidents at Large Nuclear Power Plants”, Lars Högberg, Ambio (courtesy of Springer), 2013 April; 42(3): 267–284 - National Center for Biotechnology Information, U.S. National Library of Medicine - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3606704/

Particularly important is the *revised 2014 Euratom Safety Directive* [15] which introduces the following legally binding requirements for the safety of nuclear installations:

- a high-level “Nuclear Safety Objective for Nuclear Installations” avoiding radioactive releases (including *the practical elimination of accident situations with core melt which would lead to large early releases) - the most stringent safety goal in the world*
- instigation of topical peer reviews by competent regulatory authorities every six years (focussing on safety issues)
- an obligation to ensure transparency of regulatory decisions and operating practices, as well as an obligation to foster public participation in the decision-making process
- definition of strong and effective benchmark criteria and requirements to guarantee the effective independence of national regulators in decision-making, own appropriate budget allocations and autonomy in implementation
- establishment of a strong safety culture (*a number of indicators are also provided*)
- an obligation to obtain, maintain and further develop expertise and skills in nuclear safety, in particular, via a special effort vis-à-vis education and training.

The latter requirement actually reads as follows: “*Member States shall ensure that the national framework require all parties to make arrangements for education and training for their staff (…)*”.

Equally important in this context are the legally binding standards regarding the health of workers and of the general public in the *2013 Euratom "Basic Safety Standards" (BSS) Directive* [16] (incorporating lessons learnt from the Fukushima accident), which provides:

- better protection of workers and of the public, also taking into account economic and societal factors, as well as of patients (e.g., radio-diagnosis and radio-therapy)
- emergency preparedness and response ("Emergency exposure situations") - *in the EU Member States there are variations in the levels of dose at which specified actions are required (evacuation, sheltering, iodate tablets, etc)*
- an obligation to ensure transparency (communication with external parties).

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[15] Council Directive 2014/87/Euratom of 8 July 2014 *amending Directive 2009/71/EURATOM establishing a Community framework for the nuclear safety of nuclear installations* - (L 219/42 OJ of the EU 25.7.2014) - EU-Euratom nuclear safety legislation - https://ec.europa.eu/energy/topics/nuclear-energy/nuclear-safety_en (in EC DG ENERGY website) including subject Euratom Safety Directive - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32014L0087

[16] “Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation”
- EU-Euratom radiation protection legislation (EC DG ENERGY website) :
https://ec.europa.eu/energy/overview-eu-radiation-protection-legislation_en including subject Euratom BSS Directive - https://ec.europa.eu/energy/sites/ener/files/documents/CELEX-32013L0059-EN-TXT.pdf

Worth noting is that the above BSS Directive includes social, legal and ethical aspects in addition to purely technical considerations. As a way of comparison, in the US approach to safety objectives until recently, the emphasis was placed on mortality and direct monetary costs of in- or off-site consequences, i.e.: Cost Benefit Analysis aspects were key (e.g., taking into account the monetary value of human life, at up to several million US $ following, for example, calculations by the US Environmental Protection Agency).

Finally, the legally binding standards regarding radioactive waste management at EU level are described in Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.

They are mostly based on the IAEA Safety Standards and propose the following general principles:

- ultimate responsibility lies with the Member State
- embrace passive safety features for long term management
- the generator of the waste to bear the cost
- export under only very strict conditions.

This Euratom waste directive also contains requirements regarding education and training.

Extended lessons were drawn world-wide from the Fukushima 2011 accident, in particular in the EU, which organised “stress tests” [17] in all European nuclear installations (i.e., 131 NPP units in 2011). This was a request from the European Council on 24/25 March 2011 (thus very shortly after the accident). These “stress tests” were defined by the EC as *targeted reassessments of the safety margins of nuclear power plants* and were developed by the *European Nuclear Safety Regulators' Group* (ENSREG). The “stress-tests”, based on a deterministic approach (postulated conditions), examined the European NPPs resilience against events like extreme earthquake or flooding, and the response in case of partial or total loss of the ultimate heat sink and/or loss of electrical power supply.

WENRA which is the Western European Nuclear Regulators' Association (a European network of chief regulators of EU countries with nuclear power plants, created in 1999), played a key role in the formulation of these stress tests. Moreover, WENRA updated its so-called 2014 reference levels, thereby increasing its requirements, especially on the topics of design extension and natural hazards (e.g., defence-in-depth approach for new NPPs), which have been integrated in many national nuclear regulations. It should be noted that many non-EU countries also conducted comprehensive nuclear risk and safety assessments based on the EU "stress test" model. These include Switzerland and Ukraine

[17] EC Communication COM(2012) 571, dated 4 October 2012 – *"EC Communication on the comprehensive risk and safety assessments ("stress tests") of nuclear power plants in the EU and related activities* " - https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52012DC0571 and follow-up implementation actions - https://ec.europa.eu/energy/en/topics/nuclear-energy/nuclear-safety

(both of which fully participated in the EU "stress tests"), Armenia, Turkey, the Russian Federation, Taiwan, Japan, South Korea, South Africa and Brazil.

In conclusion (EC, 26 April 2012), "*the stress tests have demonstrated that nuclear safety is an area where cross-border cooperation and action at EU level bring tangible benefits. Significant safety improvements have been identified in all participating countries. The total cost of the upgrades is estimated at some Euro 25 billion, averaging about Euro 190 million per reactor*." The conclusion indeed was that the level of robustness of the NPPs under investigation was sufficient but, for many plants, safety reinforcements have been defined or recommended to face the likelihood of beyond design basis (BDB) events.

These reinforcements include (see e.g., results of stress tests in Belgium, 2020 report [18]):

- protective measures against external hazards (earthquake, flooding, fire, extreme weather conditions or phenomena, oil spills, industrial accident, explosion, etc.)
- additional emergency equipment, such as pumps and generators, to support all reactors at a given site simultaneously following a natural disaster (BDB events)
- protective structures (reinforced local crisis centres, secondary control room, hardened stationary equipment, protective building for mobile equipment …),
- severe accident management provisions, in particular for hydrogen management and containment venting (in particular, emergency filtered venting systems)
- install enhanced equipment for monitoring water levels in spent fuel pools
- new "extended PSA" methodologies considering, for all reactors and spent fuel storages on a nuclear site, contributions to risk originating from single and correlated external hazards of the beyond design type
- new organizational arrangements (procedures for multi-unit accidents, external intervention teams able to secure a damaged site).

As far as risk and acceptance is concerned, it is worth mentioning the discussion in the mid-2010s about "advanced" Resilience Engineering vs "classical" Safety Management. Remember, in simple words: the goal of resilience engineering is to increase the number of things that go right rather than to reduce the number of things that go wrong, noting that the latter will be a consequence of the former. Safety cannot be seen independently of the core process (or business) of the system, hence the emphasis on the ability to function under "both expected and unexpected conditions" rather than just to avoid failures [19] . Search for causes is replaced with understanding of how the system failed in its performance.

EURATOM – Science, technology and innovation (several ambitious Framework Programmes since 1994)

[18] "National final report on the stress tests of nuclear power plants", Brussels, Belgium, 1 Sept 2020, Federal Agency for Nuclear Control (FANC) and Bel V (TSO) - https://afcn.fgov.be/fr/system/files/best-2020.pdf

[19] "The Fukushima disaster-systemic failures as the lack of resilience" by Hollnagel, Erik, University of Odense (Denmark)) and Fujita, Yushi (Technova Incorporation, Tokyo (Japan), in Nuclear Engineering and Technology, Volume 45, Issue 1, February 2013 - https://doi.org/10.5516/NET.03.2011.078

Science, technology and innovation (STI) as well as education and training are at the heart of the Euratom Treaty. Article 4.1 indeed explicitly mentions **research** and **training** as a twofold objective:
"*The EC is in charge of promoting and facilitating nuclear research activities in the MS and to complement them through a Community* ***Research*** *and* ***Training*** *programme*".

Nuclear STI in general contributes to social well-being, economic prosperity and environmental sustainability by improving nuclear safety, radiation protection, security and waste management. Euratom research and training programmes indeed are funding international projects focussing on safety improvements in Generation-II (e.g., related to long-term operation) and in Generation-III (e.g., related to severe accident management). Large efforts are also dedicated to Generation-IV developments aimed at efficient resource utilisation and waste minimisation. The implementation of geological disposal for spent fuel and high-level radioactive waste is also addressed. As regards radiation protection research, the emphasis is on better quantification of risks at low dose (in particular, in the domain of radio-diagnosis and radio-therapy) and how these vary between individuals.

More generally, the Euratom Research and Training programme (fission and fusion) has the following specific objectives since the very beginning:

- improve and support nuclear safety, security, safeguards, radiation protection, safe spent fuel and radioactive waste management and decommissioning, including the safe and secure use of nuclear power and of non-power applications of ionising radiation
- maintain and further develop expertise and competence in the nuclear field within the community
- foster the development of fusion energy as a potential future energy source for electricity production and contribute to the implementation of the fusion roadmap
- support the policy of the EU and its Member States on continuous improvements in the "3S" domain, i.e., Safety, Security and Safeguards.

Since 1994, more than 1000 research projects under the "indirect actions" in nuclear fission, safety, radioactive waste management and radiation protection have been funded within various EU Framework Programmes (FP), namely:

170 million euros in the Fourth (FP-4 / 1994-1998); 191 million euros in the Fifth (FP-5 / 1998-2002); 209 million euros in the Sixth (FP-6 / 2002-2006); 287 million euros in the Seventh (FP-7 / 2007–2013).

The programme after FP-7 was called Horizon 2020 /FP-8/ (duration 2014-2020) with a Euratom funding of 355 million euros under the "indirect actions", aligned with the three priorities of Horizon 2020: excellent science, industrial leadership, societal challenges.

Euratom funding under Horizon 2020 was approximately 92% whereas it was 54% under FP-7 – the complement was provided by the contracting parties as usual.

As far as the current "Horizon Europe" framework programme for research and innovation (/FP-9/ duration 2021-2027) is concerned, a global budget of 95.5 billion euros was agreed by the EU leaders, including new knowledge and innovative solutions across all scientific disciplines to overcome our societal, ecological and economic challenges (in particular, how to satisfy constantly increasing energy needs while fighting climate change is particularly crucial ?). This EU budget is complemented by 1.38 billion euros for Euratom research and training over five years (2021-2025) and 5.61 billion euros for the ITER project ("International Thermonuclear Experimental Reactor", CEA Cadarache, south-eastern France) over seven years (2021-2027) through a dedicated EC Decision – all amounts are in 2020 prices. The text of the Euratom research and training programme 2021-2025 in nuclear fission, safety and radiation protection under "Horizon Europe", as well as the ITER text, was adopted on 12 May 2021 [20].

> *Mariya Gabriel, Commissioner for Innovation, Research, Culture, Education and Youth, said:*
> *"The newly adopted Euratom Programme will complement Horizon Europe. It will support research and innovation in areas such as cancer treatment and diagnostics, nuclear safety and fusion.*
> *Thanks to Euratom, Europe will maintain world leadership in fusion, nuclear safety, radiation protection, waste management and decommissioning, safeguards and security with the highest level of standards."*

The objectives of the current Framework programme for Euratom research and training (2021-2025) remain the same as those for the precedent framework programme, i.e.: to improve and support nuclear safety, security, safeguards, radiological protection, safe spent fuel and radioactive waste management and decommissioning; maintain and further develop expertise and competence in the nuclear field; develop fusion energy; and support the policy of the EU and its member states in these domains.

The EU added a new objective on the safe and secure use of non-power applications of ionizing radiation. In this regard, the medical field is the most prominent and Euratom is supporting the European's Beating Cancer Plan (cf. ionising radiation used for diagnostics and therapy). There is also much potential in the application of nuclear science (in particular, ionising radiation) to fields like industry (e.g., nucleonic gauges and on-stream analysers), agriculture, environment as well as security and space.

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[20] "EU adopts Euratom Research and Training Programme", EU NEWS - 12 May 2021, Brussels, Belgium - https://ec.europa.eu/info/news/eu-adopts-euratom-research-and-training-programme-2021-may-12_en

Moreover, special efforts are being dedicated to the development of a common culture for nuclear safety and radiation protection at EU level, based on the highest achievable standards (in particular, regarding a sense of responsibility and a questioning attitude of all staff members in nuclear installations and in nuclear medicine centres). Finally, increasing attention is dedicated to threats and counter efforts in CBRNE-Cyber fields (that is: chemical, biological, radiological, nuclear, explosives and cyber risks), thereby raising awareness and education enforcing a CBRNE-Cyber security culture.

The current Euratom Programme (2021-2025) uses the same instruments and rules for participation as Horizon Europe. The breakdown of the 1.38 billion euros budget for Euratom research and training during the period 2021-2025 is as follows:

- euro 266 million for indirect actions in fission safety and radiation protection
- euro 532 million for direct actions undertaken by the EC's Joint Research Centre
- euro 583 million for indirect actions in fusion research and development.

In line with the Euratom Treaty, the Programme will run for 5 years, from 2021 to 2025, to be extended in 2025 by 2 years in order to be aligned with the EU's long-term budget (Multiannual Financial Framework 2021-2027).

Finally, the Programme puts emphasis on Europe's nuclear expertise and competences through mobility, education and training (cf. Marie Sklodowska-Curie Actions) as well as dissemination and technology transfer. Moreover, special attention is dedicated to access to research infrastructures, especially those of JRC. This will allow Europe to maintain world leadership in nuclear safety, radiation protection and waste management.

The Euratom **Research and Training** programme [21] consists of indirect and direct actions.

(1) Indirect actions are research activities undertaken by multi-partner consortia who respond to specific Euratom competitive calls-for-proposals, focusing on 2 areas
    - nuclear fission, safety, waste management and radiation protection
    - nuclear fusion research and development *(not discussed in this article).*

Indirect actions are co-funded by the Euratom budget and are carried out by private and public R&D (Research and Development) organisations in the EU Member States, in the form of collaborative projects initiated and monitored by EC DG RTD (Directorate General

[21] "Horizon Europe - Euratom Research and Training Programme" containing also Euratom Factsheets - https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/euratom-research-and-training-programme_en

Research and Innovation), Brussels [22]. Overall supervision of these projects is left to Euratom staff working with EC DG RTD to ensure that the actions are implemented properly in compliance with the contracts signed. Euratom projects under indirect actions usually involve up to 10 research organisations and have a duration of up to 4 years.

Specific objectives of the indirect actions encompass:

- supporting the safety of nuclear systems;
- contributing to the development of safe, longer-term solutions for the management of ultimate nuclear waste, including final geological disposal as well as partitioning and transmutation;
- supporting radiation protection and the development of medical applications of radiation, including, inter alia, the secure and safe supply and use of radioisotopes;
- promoting innovation and industrial competitiveness;
- ensuring the availability and use of research infrastructures of pan-European relevance;
- supporting the development and sustainability of nuclear expertise and excellence in the Union.

(2) Direct actions are funded and carried out by the Commission's Joint Research Centre (JRC) [23] which is the EC's science and knowledge service (see above mentioned Euratom Article 4.1 about research and training). They complement the research conducted at national level in the fields of nuclear safety, security, safeguards and non-proliferation. JRC also plays a central role in nuclear training and knowledge management and open access of its nuclear research facilities to EU scientists and also abroad. The institutional laboratories of the Joint Research Centre are spread over five EU countries and consist of six institutes *(1) Growth and Innovation (Seville, Spain) ; (2) Energy, Transport and Climate (Petten, the Netherlands) ; (3) Sustainable Resources (Ispra, Italy) ; (4) Space, Security and Migration (Ispra) ; (5) Health, Consumers and Reference Materials (Geel, Belgium) ; and (6) Nuclear Safety and Security (Karlsruhe, Germany).*

Specific objectives of the direct actions are very close to indirect actions and encompass:

- improving nuclear safety, including: nuclear reactor and fuel safety, waste management, including final geological disposal as well as partitioning and transmutation; decommissioning, and emergency preparedness;
- improving nuclear security, including: nuclear safeguards, non-proliferation, combating illicit trafficking, and nuclear forensics;
- increasing excellence in the nuclear science base for standardisation;
- fostering knowledge management, education and training;
- and supporting the policy of the Union on nuclear safety and security.

[22] All funding information and details on how to apply are provided in the Funding and Tenders portal: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-search .
[23] EC DG JRC - the European Commission's in-house science service (science hub): https://ec.europa.eu/jrc/

EURATOM – dissemination of knowledge - "European Nuclear Education Network"

Education and training are particularly important in the Euratom history. Remember Article 2.1 of the Euratom Treaty 1957: "*In order to perform its task, the Community shall, as provided in this Treaty: (a) promote research and ensure the dissemination of technical information; (b)* …". It is therefore not surprising that all European universities that teach nuclear fission have decided to join their efforts in the "European Nuclear Education Network" (ENEN). This is an international non-profit organization, created in 2003 (AISBL established under the Belgian law) [24]. As of June 2021, ENEN has 62 full members (from the EU Member states), 7 international members and 10 partners (mostly international organisations). The main purpose of ENEN is the preservation and further development of expertise in the nuclear field via higher education and training in Europe.

This objective is realized through the co-operation of organisations involved in the application and teaching of nuclear science and ionising radiation, including universities, research organisations, regulatory bodies and industry. ENEN has established close collaborations with major national nuclear E&T operators in Europe such as :

- the French "Institut National des Sciences et Technologies Nucléaires" (CEA-INSTN, Paris), with its own Nuclear Engineering Master level (or specialization) degree and a catalogue of more than 200 vocational training courses (22,000 teaching hours per year; 1,100 students, including 320 apprentices /30 % foreign students/) – top-level training courses in French or English upon client request

- the Belgian "SCK-CEN Academy for Nuclear Science and Technology" with the "Belgian Nuclear higher Education Network" (BNEN), a master-after-master academic programme organised through a consortium of six Belgian universities and SCK-CEN (BNEN served as a role model for the foundation of ENEN in 2003).

Moreover, the *Euratom Fission Training Schemes* (EFTS) should be mentioned, aimed at structuring Higher University Education Master of Science (MSc) training and career development. These schemes are funded through Euratom indirect actions, focussing on lifelong learning and borderless mobility: they are based on mutual recognition of learning outcomes across various countries. The concept of "learning outcomes" related to Knowledge (= understanding), Skills (= how to do) and Competences (= how to be) /altogether KSC/ is at the heart of the EFTS. This approach is aligned with the EU policy in education and culture, i.e., the "Bologna 1999" process for mutual recognition of academic grades (Erasmus) and the "Copenhagen 2002" process for continuous professional development (ECVET) across the EU Member States. *NB: Erasmus is the world's most successful student mobility programme. Since it began in 1987-88, the*

[24] "European Nuclear Education Network" (ENEN) - https://enen.eu/ + list of ENEN courses and Nuclear Masters Programs delivered by Members of ENEN - https://enen.eu/index.php/about-enen/nuclear-masters/ + Euratom overview article (2005 – 2015) by Georges Van Goethem, 30 Sept. 2015 - "Euratom Research, Innovation and Education : stakeholder needs, common vision, implementation instruments", EC DG RTD, Dir Energy – Euratom - https://enen.eu/index.php/publications/e-c-paper-by-georges-van-goethem/

Erasmus programme has provided over three million European students with the opportunity to go abroad and study at a higher education institution or train in a company.

It is no surprise that the format adopted by the IAEA training programmes is based on a concept very close to the above KSC approach. Following the IAEA definition (Safety Standard Series, 2001) [25],
competence means the ability to apply knowledge, skills and attitudes so as to perform a job in an effective and efficient manner and to an established standard.

Of particular interest regarding education and training in innovative nuclear technologies are the two following initiatives:

- a highly successful European Master in Innovation in Nuclear Energy (EMINE) promoted by EIT KIC InnoEnergy which is one of the "Knowledge Innovation Communities" (KIC) of the "European Institute of Innovation and Technology" (EIT), involving major industrial partners, such as: EDF-Framatome (FR), ENDESA (ES) and VATTENFALL (SE), CEA (FR) and universities KTH (SE), University of Catalonia (UPC, ES), INP (Grenoble, FR) and Paris-Saclay (FR)
  NB there are 8 EIT's Knowledge and Innovation Communities (partnerships that bring together businesses, research centres and universities in the EU): EIT Climate-KIC ; EIT Digital ; EIT Food ; EIT Health ; EIT InnoEnergy ; EIT Manufacturing ; EIT Raw Materials ; and EIT Urban Mobility. For example, InnoEnergy invested EUR 560 million into more than 480 products.
- a five-day "*INSTN Course on Generation IV Nuclear Reactor Systems for the future"* [26] co-organised in November 2020 by CEA-INSTN (Paris) and ENEN.

Many of above Euratom E&T actions are closely associated with the series of Generation IV webinars [27] that were launched in September 2016 and are currently offered once a month. A total of 54 webinars have been presented as of June 2021 (one-hour on-line lecture on one GIF system or cross cutting topic from top level experts with Q&A session).

3. GENERATION-IV: BREAKTHROUGH DEVELOPMENTS IN SUSTAINABILITY, SAFETY AND PERFORMANCE THROUGH MULTILATERAL COLLABORATION (GIF, IAEA-INPRO)

Generation-IV International Forum (GIF): USA, Canada, France, Japan, South Africa, South Korea, Switzerland, Euratom, China, Russia and Australia

** Innovation in nuclear fission from Generation I to IV (Euratom contribution)*

[25] "*Building competence in radiation protection and the safe use of radiation sources*" (jointly sponsored by IAEA, ILO, PAHO, WHO), IAEA 2001 - https://www.iaea.org/resources/safety-standards/search

[26] European GEN-IV course - targeted skills : (1) Acquire a general view of GIF objectives and organization; (2) Explain the rationale for the development of GEN-IV; (3) Describe the main characteristics of each system, and formulate their design, performance and safety characteristics; and (4) Discuss the technical challenges ahead - https://enen.eu/index.php/2020/09/04/instn_geniv_course/

[27] GIF webinars can be viewed at: https://www.gen-4.org/gif/jcms/c_82831/webinars - the webinars have been converted to YouTube Video: https://www.youtube.com/channel/UCEHOQ63gD01fSKbClY9XvSQ

Several generations of nuclear fission reactors are commonly distinguished (Generation-I, -II, -III and -IV).

- Generation I reactors were developed in the 1950-60s, and none are still running today. Gen-I refers to the prototype and power reactors that launched civil nuclear power, running on natural uranium. This kind of reactor typically ran at power levels that were "proof-of-concept" from 50 to 500 MWe (e.g., the graphite-moderated reactors, such as the gas-cooled Magnox /UK/ and UNGG /FR/).

- Generation-II refers to a class of commercial reactors designed to be economical and reliable, using enriched uranium. Gen-II systems began operation in the late 1960s and comprise the bulk of the world's 400+ commercial pressurized water reactors (PWR) and boiling water reactors (BWR). They are derived from US designs originally developed for naval use. However, they have also produced a legacy of significant quantities of used fuel, they require relatively large electric grids, and present social acceptance challenges in some countries.

  As far as safety is concerned, the basic concept is Defence-in-Depth (DiD – INSAG 10 report – IAEA, Vienna 1996) which aims to prevent and mitigate accidents during the entire life of nuclear facilities. The key of DiD is the creation of multiple independent and redundant layers of defence. This means that the safety and security systems in place should be able to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. DiD includes the use of stringent access controls, physical barriers, redundant and diverse key safety functions (in particular, 1 - control of reactivity, 2 - cooling of fuel elements, and 3 - activity retention), and effective emergency response measures. These reactors use traditional active safety features involving electrical or mechanical operations that are initiated automatically or which can be initiated by the operators of the nuclear reactors. DiD is a safety approach whose effectiveness must be periodically evaluated, tested, and improved upon should new concerns or challenges arise.

- Generation-III nuclear reactors are essentially Gen-II reactors with evolutionary, state-of-the-art design improvements. They have a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time. Gen-III designs have advanced safety features and set worldwide standards for the *Safety, Security and Safeguards* concept ("3S"). Improvements in Gen-III reactor technology aim to achieve longer operational life for NPPs (typically up to 60 years of operation) and fuel burn-up (also known as fuel utilization) rates of 60 GWd/tHM or more - thus reducing fuel consumption and waste production
  – NB : GWd/tHM means gigawatt-days/metric ton of heavy metal (U or Pu).

  There are a number of evolutionary improvements in the areas of safety systems (notably those related to severe accident management), fuel technology, thermal efficiency and digital instrumentation & control. The advancements of DiD to GEN-III reactors primarily address *the practical elimination of accident situations with core melt* which would lead to large early releases. Perhaps the most significant advantage of Gen-III systems over Gen-II designs is the incorporation in some of these of passive safety features that do not require active controls or operator intervention, but which rely instead on gravity or natural convection to mitigate the impact of abnormal events. As a consequence, the so-called "grace" period becomes quite substantial, so that – in some designs - following shutdown, the plant requires no active intervention for 72 hours.

- Generation-IV reactor systems are breakthrough developments, some of which still require considerable research and development efforts. Conceptually, Gen-IV reactors have all of the features of Gen-III units, as well as the ability, when operating at high temperature, to support combined heat and power /CHP/ generation (e.g., aiming at producing economical and decarbonized H_2 through thermal energy off-taking). In addition, these designs, when using a fast neutron spectrum, include full actinide recycling and on-site fuel-cycle facilities based on advanced aqueous, pyro-metallurgical, or other dry-processing options. Gen-IV options include a range of power ratings, including "batteries" of 100 MWe, modular systems rated around 300 MWe, and large plants of up to 2000 MWe. As far as DiD is concerned (i.e.: the basis of the safety philosophy of NPPs), the Gen-IV reactors as innovative design concepts take up the cause of
    - excelling in safety and reliability
    - having a very low likelihood and degree of reactor core damage
    - eliminating the "technical" need for offsite emergency response.

In this context, it is worth recalling the IAEA definition of advanced nuclear plant designs:

- "evolutionary" (Generation-III/III+): these designs emphasise improvements based on proven technology and experience. No prototype is needed for their industrial deployment. From a safety point of view, the two aims of "evolutionary" reactors are a further reduction in core damage frequency (e.g., through increased use of passive safety, wherever justified) and a limitation of off-site consequences in the event of a severe accident (e.g., by strengthening the containment function). Examples of GEN III are APR-1400 / KHNP in South Korea. Examples of GEN III+ are: EPR / EDF-Framatome in France / ; AP-1000 / Westinghouse-Toshiba in the USA / ; and VVER-1200 / OKB Gidropress under Rosatom in Russia /.

- "visionary" or "revolutionary" (Generation-IV): these designs emphasise the use of new or entirely revisited features, particularly with regard to efficient resource utilisation and waste minimisation as well as enhanced safety. Prototypes will be needed for industrial deployment. The main aim of these reactors is to integrate all *Generation-IV International Forum* (GIF) goals in the design ("built in", rather than "added" features) and, in particular, to develop a "robust" safety architecture whereby to demonstrate the "practical elimination" of severe accidents.

In 1999 a group of nine countries, led by the U.S. Department of Energy (DOE), launched an international project to select a series of nuclear systems of a "revolutionary" type that would deploy industrially before 2045. The countries involved at the beginning were (in alphabetical order): Argentina, Brazil, Canada, France, Japan, South Africa, the Republic of South Korea and the United Kingdom, and the USA. These all signed the GIF Charter in 2001, thereby creating GIF. In 2002, Switzerland too became a forum member. The Charter was originally for a duration of 10 years, but in 2011 the signatories unanimously prolonged this duration indefinitely.

The *European Atomic Energy Community* (Euratom), which represents the EU Member States, signed the Charter on 30 July 2003 by a decision of the EC pursuant to Article 101(3) of the previously-mentioned Euratom Treaty. The EU Council approved the accession of Euratom to the GIF Framework Agreement in its Decision no. 14929/05, Brussels, 2 December 2005. This accession was notified in EU Commission Decision (2006)7 of 12 January 2006. On 11 May 2006, Euratom formally acceded and thus became a Party to the GIF Framework Agreement. As far as practical implementation in the EU is concerned, Article 2 of the latter EU Commission Decision states the following:
"The Joint Research Centre is confirmed in its role as coordinator of the Community participation in GIF and thus will represent Euratom as its own "Implementing Agent" in accordance with Article III.2 of the Framework Agreement."

Accession to GIF brings with it certain obligations, including co-funding of the Nuclear Energy Agency (OECD/NEA)'s GIF technical secretariat activities. OECD/NEA is indeed the official Depositary of the GIF Framework Agreement. As a consequence, OECD/NEA is in charge of coordinating the international GIF R&D programme through various dedicated committees (see GIF website).

After establishing the GIF Roadmap 2002, the GIF members expressed a strong will to establish an international legal framework [28]. An important step at this point was the signature of the *Framework Agreement for International Collaboration on Research and Development of Generation-IV Nuclear Energy Systems* (in short, the GIF Framework Agreement or FA) – the original version of this FA was open for signature on 28 February 2005. On 26 February 2015, the GIF Framework Agreement was extended for another ten years, thereby paving the way for continued collaboration among participating countries. It is in fact an intergovernmental agreement, comparable from a legal point of view to the ITER agreement which was officially signed in Paris on 21 November 2006 by Ministers from the seven ITER countries concerned (including Euratom which represents the EU).

[28] GIF website (hosted at OECD/NEA, Paris) containing Newsletters; 2018 GIF Symposium Proceedings; Technology Roadmap; R&D Outlook Publications; as well as Annual Reports up to 2020. Information about the Generation IV International Forum in: https://www.gen-4.org/gif/jcms/c_9260/public and about technology (systems and goals) in: https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

As far as fusion is concerned, remember that China, the European Union, India, Japan, South Korea, Russia and the United States are engaged in a 35-year collaboration to build and operate the ITER experimental device, and together bring fusion to the point where a demonstration fusion reactor can be designed. During the construction phase of the project, EU has responsibility for approximately 45 % of construction costs, whereas China, India, Japan, South Korea, Russia and the United States will contribute approximately 9 % each. The lion's share (90 %) of contributions will be delivered "in-kind”.

Russia and China joined GIF in 2006. Australia joined the Forum in 2016. As a result, GIF has had eleven active members since 2016, i.e., members who have signed the Charter and signed, ratified or acceded to the above GIF Framework Agreement and are effectively contributing to GIF work. The eleven active members of GIF are: the USA, Canada, France, Japan, South Africa, the Republic of South Korea Switzerland and Euratom, as well as the People's Republic of China, the Russian Federation and Australia.

The main goal of GIF is to foster world-wide a multilateral collaborative effort involving the next generation of nuclear reactor systems (comprising power reactor and fuel cycle) by setting high-level goals and providing guidance regarding the viability and performance capabilities of the selected reactor systems.

GEN-IV concepts indeed feature extended capabilities beyond those of light water reactors and complement existing and evolutionary Gen III/III+ reactors – to be deployed up to the end of the century – by providing additional options and applications such as:

• optimisation of resource utilisation;
• multi-recycling of fissile materials/used fuel and reduction the footprint of geological repositories for high-level waste;
• low-carbon heat supply for cogeneration and high-temperature industrial applications (e.g., process steam, synthetic fuels, hydrogen production);
• enhanced integration of nuclear and other low-carbon sources.

Six innovative nuclear reactor systems were selected in 2002 after evaluation of more than 100 different designs by over 100 experts from a dozen countries world-wide, namely:

- Sodium-cooled Fast Reactors (SFR)
- Lead-cooled Fast Reactors (LFR) - or Lead-Bismuth Eutectic cooled
- Gas-cooled Fast Reactors (GFR)
- Very High Temperature Reactors (VHTR), with thermal neutron spectrum
- Molten Salt Reactors (MSR), with fast or thermal neutron spectrum
- SuperCritical Water Reactors (SCWR), with fast or thermal neutron spectrum.

Out of the six GIF systems, three are fast neutron reactors and thus have a closed fuel cycle to maximise the resource base and minimise high-level wastes to be sent to a repository (which makes them "sustainable"). They utilise fast neutrons, generating power from plutonium while making more of the same from the U-238 isotope. Reminder: fast neutrons are more efficient in transmuting non-fissionable U-238 to fissionable Pu-239. The sodium-, lead- and gas (helium)-cooled fast reactors (SFR, LFR, and GFR) are designed to burn plutonium and minor actinides. The actinides are separated from the spent fuel and returned to the fission reactors. One may consider fuel cycle closure also in two other reactor systems: the Molten Salt Fast Reactor (MSR) and the Supercritical Water-Cooled Reactor (SCWR) which both can be built as fast reactor systems with full actinide recycle.

The bulk of the GIF international R&D effort is on power sizes ranging from 1000 to 1500 MWe. All the above systems operate at higher temperatures than the Generation-II and III reactors currently in operation – this is a 21st century industry requirement. The new systems range from a supercritical-water-cooled reactor (SCWR, the only one cooled by water), which operates above 500 °C, to a helium-cooled very-high-temperature gas reactor (VHTR), which has an operating temperature of up to 1000 °C - compared with less than 330 °C for today's light water reactors. In particular, four GIF systems are designed to generate electricity and also to operate at sufficiently high temperatures, e.g., to produce hydrogen by thermo-chemical water cracking (without CO_2). Namely: the very high temperature reactor (VHTR - max coolant temperature 1000 °C), the gas- and lead-cooled fast reactors (GFR, LFR – max 550 °C), and the molten salt reactor (MSR – max 1000 °C).

GEN IV systems take into account, in particular, lessons learnt from the Fukushima Daiichi accident (March 2011) by reinforcing the defence-in-depth approach against external events and promoting the robustness of safety demonstration, as it is reported in the GIF website and in the GIF Annual Reports [29] as well as in other articles of this handbook.

*** GIF Technology Roadmap (viability, performance, demonstration) - towards industrial deployment by 2045**

The *2002 GIF Technology Roadmap* [30] defines three phases for each GIF system:

- <u>viability phase</u>: basic concepts for reactor technologies, fuel cycle and energy conversion processes, established through testing on an appropriate scale under

[29] GIF Annual Report (in particular, 2020) - https://www.gen-4.org/gif/jcms/c_44720/annual-reports

[30] Technology Roadmap for Generation IV Nuclear Energy Systems, issued by OECD/NEA for the GIF - www.gen-4.org/gif/jcms/c_40473/a-technology-roadmap-for-generation-iv-nuclear-energysystems

* GIF Roadmap 2002 / "A Technology Roadmap for Generation-IV Nuclear Energy Systems" (Dec. 2002): https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/genivroadmap2002.pdf

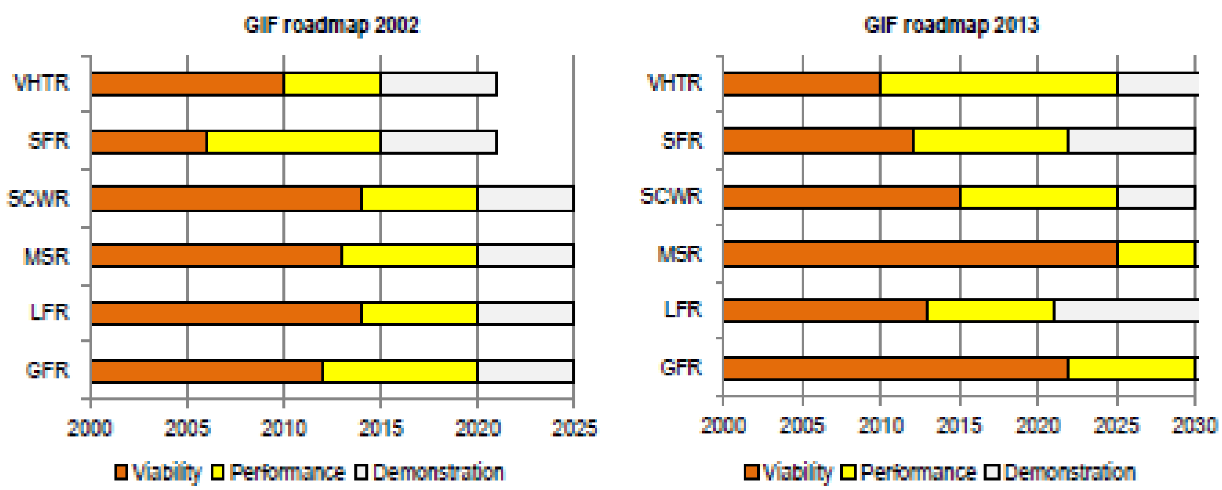
* GIF Roadmap 2013 / "Technology Roadmap Update for Generation-IV Nuclear Energy Systems - https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

relevant conditions, with all potential obstacles identified and resolved, at least in theory; very preliminary cost analysis - conceptual design / 5-15 years needed

- performance phase: assessment of the entire system, sufficient for procurement specifications for construction of a demonstration plant; validation of waste management strategy; materials capabilities are optimized under prototypical conditions; detailed cost evaluation - preliminary design / 5-15 years needed

- demonstration phase: demonstration of safety features through large scale testing; environmental impact assessment; safeguards and physical protection strategy for the system; application meetings with regulatory agency; detailed design – in view of the engineering design for the industrial phase / at least 15 years needed.

According to the updated *2013 GIF Roadmap*, the most advanced GIF systems are as follows: SFR and LFR (performance phase due to finish in the early 2020s), followed by VHTR and SCWR (2025) and GFR and MSR (after 2030) - see Figure below.



GIF Roadmaps 2002 and 2013 - viability, performance and demonstration phases

It should be noted that only the above phases 1 (viability) and 2 (performance) are covered by the GIF collaboration agreements. In other words, the multilateral collaborative effort covers the following design phases:

- viability - pre-conceptual and conceptual design: a "Viability Report" is produced, involving mainly fundamental research institutions (mainly public funding)
- performance - preliminary design: a "Performance Report" is produced, involving mainly applied research organisations and industrial experts (public and private funding).

The implementation of phase 3 (demonstration) is left to specific arrangements among GIF members, because it is considered too close to commercial exploitation. At the time being, half of the GIF systems are well advanced in their performance phases (preliminary design) whereas the other half are still in the viability phase (pre-conceptual design).

The general strategy of the GIF member countries is to continue to build Generation-III reactors between now and 2045 when the first commercial Generation-IV reactors will be built, i.e., when the demonstration phase has been implemented. Expenditure so far is in line with the initial estimate of approximately USD 6 billion relating to all six systems over 20 years - about 80% of the cost being met at the onset by the USA, Japan and France.

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

In millennium year 2000, the IAEA in Vienna launched an important initiative: the INPRO programme (*International Project on Innovative Nuclear Reactors and Fuel Cycles*) [31]. Its aim was to foster availability of nuclear energy, thereby contributing to the energy needs of the 21st century in a sustainable manner. This project was proposed at the *United Nations Millennium Summit* and confirmed by the UN General Assembly in 2001. To achieve this, INPRO brings together nuclear technology users (as opposed to developers who are the main target in GIF) to consider international and national actions to promote innovation in nuclear reactors, fuel cycles and institutional approaches.

As of June 2021, INPRO's membership consists of 42 Members (41 IAEA Member States, plus the European Commission represented by Euratom), namely:
Algeria, Argentina, Armenia, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Egypt, France, Germany, India, Indonesia, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Republic of Korea, Malaysia, Mexico, Morocco, Netherlands, Pakistan, Poland, Romania, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Thailand, Turkey, Ukraine, United States of America, Vietnam and the EU. Several other countries participate at a working level or as observers in meetings.

In the early 2000s, INPRO produced a methodology to assess the sustainability of *Innovative Nuclear energy Systems* (INS). In 2005, INPRO was requested to provide guidance in using the proposed methodology in the form of an INPRO assessment manual. The resulting INPRO manual [32] comprises an overview volume (no 1), and eight additional volumes covering the areas of economics (Volume 2), infrastructure (Volume 3), waste management (Volume 4), proliferation resistance (Volume 5), physical protection (Volume 6), environment (Volume 7), safety of reactors (Volume 8), and safety of nuclear fuel cycle facilities (Volume 9).

In summary, INPRO focuses on the needs of the "end-users" of innovative systems (i.e., focus on the demand side), including in emerging countries, while GIF is more concerned

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[31] IAEA - INPRO collaborative platform – "International Project on Innovative Nuclear Reactors and Fuel Cycles" - "Enhancing Global Nuclear Energy Sustainability", 2012 - https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro
[32] INPRO manual (128 pages) - http://www-pub.iaea.org/MTCD/publications/PDF/TE_1575_web.pdf

with the “suppliers” mostly concerned with innovative Research – Development & Demonstration – Deployment /RD&DD/ (i.e., international collaboration of the GIF type involving industrialised countries). As a result of the GIF and INPRO programmes, a framework exists world-wide for all stakeholders interested in research and innovation in nuclear fission. The aim is to solve not only scientific and technological but also political, socio-economic and environmental challenges related to nuclear fission systems.

GIF interaction with industry: the “Senior Industrial Advisory Panel” (SIAP)

Of particular importance in the GIF governance is the feedback provided by SIAP. It is composed of executives from the nuclear industries. It was established in 2003 to provide recommendations on long-term strategic issues, including regulatory, commercial and technical aspects. In particular, the SIAP provides guidance on investor-risk reduction and incorporating the associated challenges in system design at an early stage of development.

The SIAP agreed on three main attributes necessary for Gen IV to compete in the “market”:
- to be economic,
- to be publicly accepted,
- and to be able to be integrated in the energy mix.

For example, the SIAP was asked to advise the GIF on the following:
- how to ensure the supply chain for Gen-IV systems, including identification of gaps in the supply of non-Light-Water-Reactor (LWR) components (e.g., emphasis on availability of materials and industrial practices as well as international standards)
- how to enhance knowledge management in advanced reactor R&D, given the history of knowledge management in the LWR industry (e.g., emphasis on capture of expert knowledge in a manner that “survives” changes in personnel).

According to the SIAP, the time perspective is a *readiness for commercial fleet deployment by around 2045* (for the first systems). Industry is expecting to have viable and performing “options” available in this time frame. Timely R&D and further industrial-type demonstration phases should make this possible.

GIF decided recently to improve their communication of results not only to industry but also to citizens, policy makers and regulators (e.g., through education and training initiatives including the above-mentioned 54 webinars, newsletters and visual branding).

GIF interaction with regulators: NRC (USA), IRSN (FR) and MDEP (OECD/NEA)

Looking to the future, GIF expects to continue its work on safety and regulatory frameworks. Engagement with regulators and technical support organisations (TSOs) will also continue, and the regulators are expected to begin providing guidance to Gen IV system developers on regulatory requirements in the not-too-distant future. Two recent initiatives should be mentioned: (1) the development of system specific Safety Design

Criteria (SDC) and Guidelines, e.g. in association with NRC and (2) an increased interaction in the frame of the OECD/NEA Working Group on Safety of Advanced Reactors (WGSAR). Continuing this dialogue with the regulators will benefit not only GIF system developers, but also the regulators and their technical support organisations.

It is worth recalling that the US Nuclear Regulatory Commission (NRC) issued in 2018 a draft "Regulatory Guide /RG/ on the General Design Criteria for non-water-cooled reactors" [33]. In this report NRC proposes guidance on how the general design criteria (GDC) in Appendix A, "General Design Criteria for Nuclear Power Plants," of Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities", may be adapted for non-light-water reactor designs. Appendix A of this RG is quite general and covers Advanced Reactor Design Criteria related to the following six types of non-light-water reactor: SFR, LFR, GFR, VHTR, fluoride high-temperature reactors, and MSR.

An interesting study by the French Technical Safety Organisation IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*) should also be mentioned: "*An overview of the "safety potential" of Generation-IV Nuclear Energy Systems*" [34], December 2014. The IRSN carried out a review of all six Generation-IV systems from the point of view of safety and radiation protection. Their conclusion reads:
"It should be borne in mind that any industrial deployment of a Generation-IV reactor system in France will be linked to its advantages, not only regarding reactor fleet operation and safety, but also in terms of the coherence and performance of the associated fuel cycle. This concerns all aspects relating to safety, radiation protection, material management and efforts made to minimise the quantities of radioactive waste generated, without overlooking the overall economic competitiveness of the nuclear system. Ultimately, the choice of system must be made as part of an integrated approach, based on studies that cover multiple criteria and all the aspects mentioned above."

Finally, it is worth mentioning that a number of national regulatory authorities world-wide agreed to develop innovative approaches to leveraging the resources and knowledge accumulated during their assessment of Generation-III reactor designs. As a result, the *Multinational Design Evaluation Programme* (MDEP) was established in 2006 - the technical secretariat is within the OECD/NEA [35]. The nuclear regulatory authorities of 15 countries participate in the multinational initiative MDEP, which includes 5 design-specific working groups dedicated to Generation-III reactors: EPR (1600 MWe, EU), AP-1000 (USA), APR-1400 (South-Korea), VVER-1200 (Russia) and HPR-1000 (China).

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[33] NRC Regulatory Guide 1.232 Rev.0, April 2018 - https://www.nrc.gov/docs/ML1732/ML17325A611.pdf
[34] IRSN 2014 Report "*Review of Generation-IV Nuclear Energy Systems*" https://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Report-GenIV_04-2015.pdf
[35] *Multinational Design Evaluation Program* (OECD/NEA) - https://www.oecd-nea.org/mdep/index.html
As of June 2021, the MDEP members include national regulators from 15 countries world-wide:
Argentina (ARN), Canada (CNSC); People's Republic of China (NNSA); Finland (STUK); France (ASN); Hungary (OAH); India (AERB); Japan (NRA); Republic of Korea (NSSC); Russian Federation (Rostechnadzor); Republic of South Africa (NNR); Turkey (NDK); United Arab Emirates (FANR); United Kingdom (ONR); United States of America (NRC). IAEA also participates in some activities.

MDEP's main objectives can be defined as follows:

- to enhance multilateral co-operation within existing regulatory frameworks
- to encourage multinational convergence of codes, standards and safety goals
- to implement MDEP products in order to facilitate the licensing of new reactors, including those being developed by the Generation IV International Forum.

Particular attention is devoted in MDEP to "common regulatory practices and regulations that enhance safety", e.g., in the areas of design basis accidents and emergency core cooling system performance, severe accident requirements, digital *Instrumentation & Control* (I&C). There are also 3 issue-specific working groups: the Vendor Inspection Co-operation Working Group (VICWG); the Codes and Standards Working Group (CSWG); the Digital Instrumentation and Controls Working Group (DICWG).

4. Eight high-level goals for Generation-IV nuclear energy systems and associated world-wide GIF R&D collaborative effort

In order to prepare the first Generation-IV Technology Roadmap (2002), it was necessary to establish goals for these innovative nuclear energy systems. The goals had three purposes:

- they served as the basis for developing criteria to assess and compare the systems in the technology roadmap
- they were challenging and stimulated the search for innovative nuclear energy systems (both fuel cycles and reactor technologies)
- they also served to guide the R&D on Generation-IV systems as collaborative efforts got underway.

Broad R&D areas were defined in connection with the four GIF objectives (details about major achievements and current outlook in synthesis document "GIF R&D Outlook" [36]):

1. sustainability (in particular, optimal utilization of natural resources and waste minimization) including decarbonisation of the economy and security of supply
2. safety and reliability (through design, technology, regulation and culture)
3. economics (industrial competitiveness, integration in low-carbon energy mix) together with social aspects (in particular, easy access to affordable energy for all)
4. proliferation resistance and physical protection (aligned with the Non-Proliferation Treaty, IAEA 1970).

Eight high-level "*Goals for Generation-IV Nuclear Energy Systems*" were announced in the original GIF Charter of 2001 pertaining to the four above GIF objectives (sustainability;

[36] GIF R&D Outlook for Generation IV Nuclear Energy Systems: 2018 Update", 2019 - https://www.gen-4.org/gif/upload/docs/application/pdf/2019-06/7411_gif_r_and_d_outlook_update_web.pdf

safety; economics; proliferation resistance and physical protection). These challenges are key concerns of the public with regard to "nuclear." Gen IV systems need to demonstrate real progress in those areas. It may become more of a communication issue (related to social acceptance) than a technical issue, but it deserves a lot of attention.

Sustainability (efficient resource utilisation and minimization of radioactive waste)

Two GIF high-level goals (nos. 1 and 2) are defined in connection with *Sustainability*:

- 1. Generate energy sustainably and promote long-term availability of nuclear fuel
- 2. Minimize radioactive waste and reduce the long-term stewardship burden.

Consensus was reached, in particular, on the following items:

- the needs of improved waste management, minimal environmental impact, effective fuel utilization (e.g., by converting non-fissile U-238 to new fissile fuel)
- development of new energy products that can expand nuclear energy's benefits beyond electrical generation.

More generally, this GIF goal of sustainability aims at guaranteeing a very low full-lifecycle environmental footprint (CO_2, SOx, NOx, water and land usage and pollution) during normal functioning of the system (plant and associated fuel cycle). For example, by minimising land impacts, cooling requirements (water reliance) and waste generation during operation and decommissioning.

Part of GIF R&D efforts are concentrated on the back-end of the nuclear fuel cycle, that is: reduce the amount and lifetime of the ultimate high-level radioactive waste, e.g., by developing, demonstrating and quantifying improvements in high-level waste (HLW) management and by addressing the potential for partitioning and transmutation of transuranic elements. Diverse routes to be investigated include multi-recycling in a fleet of fast neutron reactors, or with dedicated transuranic burners.

Like all industries, the generation of electricity produces waste. Whatever fuel is used (fossil or nuclear), this waste must be managed in ways which safeguard human health and minimise the environmental impact. Unlike other industrial toxic wastes, however the principal hazard associated with HLW (i.e.: radioactivity) diminishes with time.

<u>GIF high-level Goal no 1</u> above, "*Generate energy sustainably and promote long-term availability of nuclear fuel*" leads to considering plutonium (in particular, Pu-239) as fuel for fast neutron spectrum reactors (i.e., plutonium is a valuable asset - not a liability)

In this type of reactor, a chain reaction takes place in which the neutrons are not thermalized (there is no moderator) but instead produce fission at relatively high energies (in the order of 1.0 MeV). With uranium fuel, Pu-239 is produced by the capture of neutrons in U-238. As a result of this physical process (based on breeding of fissile Pu-239 fuel from non-fissionable but fertile U-238), fissile material is produced and consumed in the reactor before the fuel is removed, supplementing the original U-235 in the fresh fuel. To avoid thermalization of the neutrons, fast breeder reactors use coolants with a high mass number to reduce moderation, such as liquid metals (e.g., sodium Na-23 or lead Pb or eutectic lead-bismuth Pb-Bi). The fuel of fast breeder reactors consists of pellets of mixed Pu and U oxides (MOX): PuO_2 (about 20 %) and UO_2 (about 80 %). Uranium depleted in U-235 (residue from earlier enrichment) is commonly used in fast reactors – non-conventional (usually more expensive) uranium ores could also be used.

An alternate breeding cycle is based on thorium (Th); this implies conversion of fertile Th-232 to fissile U-233 which is being investigated in some countries (e.g., India, Canada). We should remember that Th is about three times more abundant than U in the earth's crust. Basic development work has been conducted in Germany, India, Canada, Japan, China, Netherlands, Belgium, Norway, Russia, Brazil, the UK & the USA.

According to the GIF strategy, fast neutron reactors can also be used to consume unwanted Pu (rather than to produce Pu as a fuel) and to destroy other heavy elements in weapon stockpiles or radioactive waste: in this case they act as burners instead of breeders.

GIF high-level Goal no 2 above, "*Minimise radioactive waste and reduce the long-term stewardship burden"* implies consideration of recycling, i.e., minimising the volume, heat and toxicity of ultimate radioactive waste while separating and conserving everything that is potentially recyclable (namely U and Pu).

As regards Generation-II and –III, recycling U and Pu is rather exceptional. Worldwide, only 44 nuclear reactors have used Mixed Oxide fuel since 1972 (*NB: MOX consists of about 7-11% Pu mixed with depleted U*), including 22 in France, 10 in Germany, 5 in Japan, 3 in Switzerland, 2 in Belgium, 1 in the Netherlands and 1 in the United States.

Recycling (or reprocessing) of civilian fuel in view of MOX fuel fabrication is performed in only a few countries (current reprocessing capacity is about 2000 tonnes per year):

- in Europe - LWR fuel at the Cap de la Hague site /CEA-Orano/ in France
  NB: operations at the Sellafield reprocessing site THORP in the UK ended in 2018
- in the Russian Federation - LWR fuel at the Ozersk site (Mayak Chemical Combine), situated in the province of Chelyabinsk in the southern Ural Mountains
- in Japan - LWR fuel at the long-delayed reprocessing plant at Rokkasho – Pu-U co-extraction technology - Japan Nuclear Fuel Ltd (scheduled in 2022).

A reminder about natural U and composition of spent nuclear fuel (SNF) may be necessary [37]. The core of a standard LWR of 1000 MWe contains about 72 tonnes of low-enriched U (LEU) - the SNF usually contains 94 % U-238. In a yearly operating cycle (refuelling annually with one third replaced, i.e., 24 tonnes of LEU per year), the SNF contains about 23 tonnes of U (including 240 kg U-235), 240 kg Pu-239 and about 1 tonne of fission products and trans-uranium elements other than Pu. There are about 36 kg minor actinides (neptunium /Np/, americium /Am/, and curium /Cm/, equivalent to 0.15 % of

[37] "The Nuclear Fuel Cycle - Material balance for the annual operation of a 1000 MWe NPP", World Nuclear Association – including "Material balance in the nuclear fuel cycle" (Fuel removed from a reactor, after it has reached the end of its useful life, can be reprocessed so that most is recycled for new fuel) - http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Nuclear-Fuel-Cycle-Overview/

total SNF). Despite their relatively small mass in SNF, transuranic elements such as Pu, Np, Am, and Cm, are the primary contributors to long term radiotoxicity and long-term heat generation in SNF.

According to the GIF strategy, partitioning and transmutation techniques are fostered in GEN-IV to further improve the desired recycling process. Application of these techniques to Pu and other heavy radionuclides, such as the minor actinides Np, Am and Cm, aims at reducing the volume, heat and toxicity of ultimate radioactive waste for disposal. Much of the calculated long-term waste hazard actually comes from a limited set of minor actinides (about 0.15 % of the SNF, as explained above), with half-lives ranging from tens to millions of years such as Cm-244 and Np-237, respectively. Exposure of these radio-nuclides to high neutron fluxes can transmute them into much less hazardous nuclides. In such cases, chemical separations are necessary to allow partitioning of selected groups of radio-nuclides into different waste streams.

Generation-IV reactor systems of the fast neutron spectrum type include high level waste destruction as an integral part of the fuel cycle, rather than as a separate process. In a still more ambitious project such as the international fission research reactor project MYRRHA (an accelerator-driven system /ADS/, discussed below), the main purpose is to demonstrate that it is technically feasible to process the most radiotoxic elements (neptunium, americium and curium) by transmutation. The fission of these long-lived elements into products that are radiotoxic for a considerably shorter period of time ensures further reduction of the quantity and life span of the waste. As a consequence, fast neutron reactors do not obviate the need for deep geological repositories but the required storage time is drastically reduced, from hundreds of thousands of years to a few hundred.

Concluding this Section on sustainability, GEN-IV systems of the fast neutron type will manage to enhance fuel utilisation (by recycling U and Pu), while minimising the volume, heat and toxicity of ultimate radioactive waste (by partitioning and transmutation). As a consequence, in GEN-IV systems, SNF is not waste but could become a source of power for the future, since the current NPPs burn only a very small amount of the U resource.

In other words, a very large amount of energy is still to be found in what has erroneously come to be known as “waste”. In fact, up to 96 % (U-238, U-235, and Pu) could be recycled in Generation-IV reactor systems with a fast neutron spectrum. Thus, Pu is not a liability but a "valuable asset". There will be adequate fuel once the U-238 resource can be optimally exploited, i.e., when fast neutron spectrum reactors of the Generation-IV type with actinide burning capacities come into service.

Safety (maximum safety performance through design, technology, regulation and culture) & Reliability

Three GIF high-level Goals (nos. 3, 4 and 5) are defined in connection with *Safety*:

- 3. Excel in safety and reliability
- 4. Have a very low likelihood and degree of reactor core damage
- 5. Eliminate the need for offsite emergency response.

Consensus was reached, in particular, on the following items:

- simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences, thereby enhancing public confidence in nuclear
- systematic consideration of human performance as a major contributor to plant availability, reliability, inspectability and maintainability.

More generally, this GIF goal of safety aims at excluding severe accident/core melt or ensure no off-site radioactive release in case of severe accident/core melt, through reactor concept-dependent prevention measures, e.g., low power density fuel, accident-tolerant fuel and systems, high core thermal inertia, resistance to black out, smaller power ratings (Small and Medium Reactors - also called "Modular"- SMRs), etc. and through mitigation measures, e.g., in-vessel/ex-vessel corium cooling, in-containment management, etc.

Gen IV systems need to demonstrate real progress in safety. In addition, the "residual nuclear accident risk" needs to be put into perspective in comparison to other accident risks in the energy domain.

GIF high-level Goal no 3 above, *"Excel in safety and reliability"* refers, for example, to the need to provide robust safety cases describing safety practices. In fact, there is a good convergence of safety practices in the Member States, notably in the following domains:

- defence in depth and integrity of the successive barriers between radioactive products and the environment (including active and passive safety systems)
- radiological consequences of postulated accidents (see above 2013 BSS Directive)
- deterministic analysis => identification of postulated or design basis accidents
- probabilistic safety analysis (PSA) => evaluation of the overall risk from the plant, including severe accidents analysis and management (e.g., mitigation measures for high-consequence low-frequency events)
- ALARA (*As Low As Reasonably Achievable*) policy to reduce doses affecting personnel and the public.

GIF high-level Goal no 4 above, "*Have a very low likelihood and degree of reactor core damage*" requires a reminder of the Reactor Safety Study WASH-1400 [38] in the USA which was in 1975 amongst the first to examine the phenomenology of severe accidents. They used methodologies developed by the US Department of Defence (DoD) and the National Aeronautics and Space Administration (NASA) such as event trees and fault trees. They were then able to compare the likelihood of nuclear and non-nuclear accidents (man-caused events as well as natural events) having similar consequences (expressed in terms of fatalities and property damage in US Dollars). The main risk issues in NPPs of the LWR

[38] N.C. Rasmussen, "Reactor Safety Study: An assessment of accident risk in US commercial nuclear power plants", AEC Report, WASH-1400-MR (NUREG-75/014), United States NRC, Washington, DC, October 1975 - http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/35/053/35053391.pdf

type were identified in the WASH-1400 report, namely: molten corium behaviour, fission product release and hydrogen combustion. The total risk is the expected loss: it is the sum of the products of the consequences multiplied by their probabilities. A number of containment failure modes or challenges were identified as follows: 1. Overpressure; 2. Dynamic pressure (shock waves); 3. Internal missiles; 4. External missiles (not applicable to core melt accidents); 5. Melt-through; and 6. Bypass. As a consequence of WASH-1400 and of the introduction of PSA after the TMI accident in 1979, a number of regulatory authorities world-wide introduced nuclear safety objectives of the probabilistic type.

Of particular interest are the probabilistic safety criteria proposed by IAEA: *Core Damage Frequency* (CDF) and *Large Early Release Frequency* (LERF – a large release is typically 100 TBq Cs-137) calculated in Level 1 and Level 2 PSA, respectively. In 75-INSAG-3 (IAEA 1988, Basic Safety Principles for Nuclear Power Plants), the following safety goals of a quantitative probabilistic type are proposed: the LERF value should be 10 times smaller than the CDF value. For existing NPPs, a safety target of < 10E-4 / reactor-year was proposed as the likelihood of CDF. Accident management and mitigation measures should reduce the probability of large off-site releases (requiring short term off-site response) to < 10E-5 / reactor-year. Implementation at future plants should lead to safety improvements by a further factor of 10 for all events (75-INSAG-3 Rev. 1, INSAG-12, IAEA 1999). The threshold value < 10E-6 / reactor-year for unacceptable consequences is already required for existing NPPs in many OECD countries. For radiological definition of off-site release limits during normal operation and incidents, and for off-site release targets for accidents, other internationally recognised standards are usually taken, such as the specific IAEA recommendations and/or the above EU Basic Safety Standards ("BSS").

GIF high-level Goal no 5 above, "*Eliminate the need for offsite emergency response*" is embedded in the revised 2014 Euratom Safety Directive. It is also at the heart of the *European Utility Requirement* (EUR) [39] organisation. The EUR initiative was launched in December 1991 by several European utilities interested in Generation-III reactors. The main objective of EUR was to produce a common set of utility requirements (so-called "EUR standards"), endorsed by major European utilities for the next generation of LWRs. Seven GEN-III reactors were considered, some of which with passive safety features, namely: EP-1000 – European Passive LWR (based on AP-600, Westinghouse-Ansaldo); EPR - Evolutionary Pressurized Reactor (EDF-Framatome); BWR90/90+ - Evolutionary Boiling Water Reactor (ABB Atom); ABWR - Advanced Boiling Water Reactor (GE-Hitachi); SWR 1000 – Boiling Water Reactor (Siemens); AP-1000 – Advanced Passive PWR (Westinghouse); and VVER-1200 - Pressurized Water Reactor (OKB Gidropress).

[39] "European Utility Requirement" (EUR): https://www.europeanutilityrequirements.eu/Welcome.aspx Started by five partners in 1991, the EUR Organisation nowadays brings together thirteen Utilities which represent the major European electricity producers.: CEZ - EDF - EDF Energy - ENERGOATOM – Fortum - GDF SUEZ/Tractebel Engineering (now Engie) - GEN energija (Slovenia) - IBERDROLA - Paks II (Hungary) – NRG (Netherlands) - ROSENERGOATOM - TVO - VGB Power Tech (Germany)

As far as safety requirements are concerned, the EUR organisation dedicated special attention to severe accident management. Situations and phenomena which could lead to early failure of the containment system and subsequent uncontrolled large releases of fission products into the environment should be *practically eliminated by design*. For example, for EPR, the main safety objectives are to *further reduce the core melt probability and, in the hypothetical case of a severe core melt accident, to improve the containment of fission products by excluding in a "deterministic" way any major off-site damage*, i.e., by design, to "practically eliminate" accident situations and phenomena that could lead to large early releases.

To better understand the safety challenge, an integral assessment approach is needed. This is provided by the GIF via their *Risk and Safety Working Group* (RSWG). This group produced a methodology called the "*Integrated Safety Assessment Methodology*" (ISAM - GIF/RSWG) [40] for use throughout the Gen-IV technology development cycle. ISAM allows evaluation of a particular Gen-IV concept relative to various potentially applicable safety metrics or "figures of merit". ISAM is particularly efficient for assessing active versus passive safety components and systems.

The ISAM is a tool that can be used throughout, from concept development to design and to licensing. It combines probabilistic and deterministic perspectives. It improves understanding of safety related design vulnerabilities and the contribution to risk. It also helps identify areas for additional research and data collection. The ISAM consists of five steps: (1) Qualitative Safety Features Review; (2) Phenomena Identification and Ranking Table; (3) Objective Provision Tree; (4) Deterministic and Phenomenological Analyses; (5) Probabilistic Safety Analysis.

As far as practical applications of the ISAM are concerned, it is worth mentioning two trial applications to a realistic advanced reactor development effort: one for a Japanese Sodium Fast Reactor (JSFR) concept, and one for a French Sodium Fast Reactor concept.

Other applications of the ISAM were conducted in Euratom RTD projects such as:

- LEADER ("*Lead-cooled European Advanced DEmonstration Reactor" /* 2010 – 2013), coordinated by Ansaldo in Italy, connected to the ALFRED design
- EVOL ("*Evaluation and Viability Of Liquid fuel fast reactor systems*"/ 2010 – 2013), associated with the Rosatom MARS project ("Minor Actinides Recycling in molten Salt"), connected to Th-U MSFR (Molten Salt Fast Reactor)
- SARGEN-IV ("*Proposal for a harmonized European methodology for the safety assessment of innovative reactors with fast neutron spectrum planned to be built in Europe*"/ 2012 – 2013), coordinated by IRSN in France.

[40] "Guidance Document for Integrated Safety Assessment Methodology (ISAM) - (GDI): EC JRC report prepared for GIF Risk and Safety Working Group", JRC 2014 - ("science for policy" report no 92779) –- https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/guidance-document-integrated-safety-assessment-methodology-isam-gdi-ec-jrc-report-prepared

Moreover, considerable effort has been dedicated to cross-cutting issues in Generation-IV reactors, such as major safety issues. For example, the above-mentioned Euratom project SARGEN-IV identified phenomena and issues able to affect the safety of more than one Generation-IV concept, i.e.:

- for the coolant: sensitivity to impurities, coolant activity, retention of fission products, toxicity, opacity,
- for the structural materials: corrosion, erosion, irradiation behavior, ageing effects
- management of the three safety functions (reactivity control, decay heat removal, containment),
- passive safety systems, including capability to cool the core by natural circulation,
- considerations relating to the Fukushima-Daiichi events (extreme flooding, extreme earthquakes, total loss of electricity supply, accident management),
- categorization of initiating events organized by challenges: challenge to clad integrity, challenge to reactor boundary, containment challenge
- advanced modelling simulation (advanced computational techniques for multi-physics, multi-scale, and multi-phase problems where the time and length scales of the individual processes involved often differ by orders of magnitude)
- specific issues in relation to fast reactors: sensitivity to blockage, power density, core compaction, reactivity void effects, handling hazards, failure of core supporting structures.

To conclude this Section on safety and to answer the question "*how safe is safe enough?*", attention is drawn to *managerial and human factors* and, in particular, to their impact on safety performance. This concern is at the heart of the development of a common *nuclear safety culture* in nuclear fission installations, and, in particular after the Chernobyl accident, in NPPs and in the fuel cycle industry. In medical, industrial and scientific applications of ionizing radiation, the focus is on *radiation protection safety culture.*

Economics (competitiveness w.r.t. other energy sources) and social aspects (e.g., public engagement in decision making)

Two high-level GIF goals (nos. 6 and 7) are defined in connection with *Economics*:

- 6. Have a life cycle cost advantage over other energy sources
- 7. Have a level of financial risk comparable to other energy projects.

Consensus was reached, in particular, on the following items:

- accommodation of future nuclear energy systems to the worldwide transition from regulated to deregulated energy markets (including integration in smart grids)
- anticipate needs for a broader range of energy products beyond electricity (including smaller units), such as process heat, district heating, potable water and hydrogen.

More generally, this GIF goal of economics aims at reducing the costs of investment (overnight capital cost), reducing and mastering the duration of construction (financing cost), optimising the costs of licensing, operation and maintenance (O&M), the fuel cycle and waste management, as well as optimising the decommissioning costs as early as at the design stage in order to be competitive in the market with other sources of energy. It should be noted, however, that the unknowns and uncertainties in electricity (and possible future energy) market design and operation make it difficult to go beyond the pure cost dimension. The maximum therefore has to be done to reduce all elements of Gen IV costs, including the cost of licensing in each country.

More generally, to assess socio-economics, the collaboration of experts is needed, in particular those with skills in finance and accounting, in the hard sciences (e.g., energy, environment, new technologies, life sciences), as well as the soft sciences (e.g., sociology, psychology, risk perception). This issue is particularly complex due to various technological and socio-economic uncertainties and because of the long-time horizon involved (remember: “A successful nuclear power programme requires broad political and popular support and a national commitment of at least 100 years”, IAEA 2018).

GIF high-level Goal no 6 above, "*Have a life cycle cost advantage over other energy sources*" means in fact minimising *Levelized Unit Energy Costs* (LUEC): this favours large units with economies of scale. The LUEC methodology is an economic assessment of the cost of building and operating a power-generating asset over its lifetime (usually several decades) divided by the total power output of the asset over that lifetime; typically, the unit of LUEC is euro/MWh or US$/MWh. In this accounting system, no benefit is drawn from the avoided CO_2 emissions.

A good understanding of nuclear economics is provided, in particular, by an authoritative cost study conducted by OECD/NEA in 2019 [41]. This study assesses the costs of alternative low-carbon electricity systems capable of achieving strict carbon emission reductions consistent with the fifth report of the “Intergovernmental Panel on Climate Change” in 2014 (UN IPCC - 195 members) and with the aims of the 2015 Paris Agreement (COP-21). It analyses several deep decarbonisation scenarios designed to reach the same stringent carbon emission target but characterised by different shares of the variable renewable technologies, hydroelectric power and nuclear energy.

The conclusion of the study reads: “*Nevertheless, this study shows how nuclear power still remains the economically optimal choice to satisfy stringent carbon constraints despite the economic challenges it faces during the changeover between different reactor generations. The reason for nuclear power’s cost advantage is not in its plant-level costs. Instead, it resides in its overall costs to the electricity system. Variable renewables have reduced quite impressively their plant-level costs, but their overall costs to the system are not accounted for as their output is clustered in a limited number of high-level hours. All of these factors will come to play in the ultimate choices of each country.”*

Realistic cost estimates for electricity production are provided by the nuclear market. For example, in Turkey, the discussion with Rosatom in 2015 focused on a 15-year fixed price *Power Purchase Agreement* (PPA) within a *Build-Own-Operate-Transfer* (BOOT)

[41] “The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables”, OECD NEA, June 2019 (W. D’haeseleer et al.) - https://www.oecd-nea.org/ndd/pubs/2019/7299-system-costs.pdf

scheme: the weighted average cost is USD 123.5 per MWh (i.e., 111 euro in 2015 prices) and the quantity of electricity is fixed. In the UK, in 2015, EDF has been offered an investment contract for Hinkley Point C (i.e. the first construction of a nuclear plant in the UK after 1995, when the last one constructed, Sizewell B, had begun operating) with a "strike price" for its electricity output of GBP 92.50 (i.e. 132 euro in 2015 prices) per MWh which will be adjusted (linked to inflation) during the construction period and over the subsequent 35 years tariff period; this "strike price" for electricity from Hinkley Point C is roughly twice the current wholesale price of power.

GIF high-level Goal no 7 above, "*Have a level of financial risk comparable to other energy projects*" means minimizing Capital-at-Risk (i.e., investment before commercial operation): this Goal rewards smaller units that require less capital. Capital investment costs should be seen in the context of total social costs (= private + external costs) and the nuclear sector should be compared to the renewable and fossil energy sectors.

Private and external costs (i.e., the total social costs) can be described as follows:

- Private costs: (i) capital investment cost (60 - 85 %); (ii) O&M cost (10 - 25 %); (iii) Fuel-cycle cost (7 - 15 %) including natural uranium (circa 5 %)
- External Costs: (i) Radioactive emissions; (ii) Long-term waste disposal (often already internalized); (iii) Accidents – liability; (iv) Proliferation; (v) Avoided CO_2 emissions; (vi) System effects (in particular, on electrical grid stability).

Nuclear power plants are expensive to build but relatively cheap to run. In many countries, nuclear energy is competitive with fossil fuels as a means of electricity generation. External costs, such as waste disposal and decommissioning costs, are usually fully included in the operating costs. If the societal, health and environmental costs of fossil fuels are taken into account, the competitiveness of nuclear power is enhanced. A large part of the external costs is indeed included in the price of nuclear electricity production. Some external costs, however, are difficult to estimate, such as insurance to cover nuclear accident damage (e.g., what reasonable measures should be implemented? what is the causal link between an accident and disease occurring many years after the event?).

The uncertainty is greater when it comes to estimating the "*capital expenditures*" (CAPEX) for new build reactors, be it Generation-III or -IV. Construction costs have been estimated by scaling from known cost distributions and adaptation by expert judgement. Besides scaling to power level, other considerations may lead to increases or decreases in certain accounts with respect to the accounts of the reference design, such as: the reactor vessel and other reactor plant equipment; space requirements; containment size; application of passive safety systems; need for an intermediate circuit; complex fuel handling in all GIF systems; use of complex fluids or gases as coolants (e.g. chemically highly reactive sodium in SFR); use of Rankine vs. Brayton cycle.

The *Economics Modelling Working Group* (EMWG) [42] of GIF prepared "*Cost Estimating Guidelines for Generation-IV Nuclear Energy Systems*" (GIF/EMWG) for economic

[42] Economic Modelling Working Group, also focusing on the deployment of Gen-IV systems in future low-carbon energy markets, including flexibility requirements for integration in grids with significant renewable

optimization during the viability and performance phases of the Generation-IV projects. This Group has upgraded existing nuclear-economic sub-models, and developed new ones where needed, addressing each of the following five economic areas: Capital and Production Cost Models, Nuclear Fuel Cycle Model, Optimal Scale Model, and Energy Products Model. These five models have been brought together in an *integrated nuclear energy economic model* (INEEM).

The GIF Cost Estimating tool G4-Econs has been applied to provide an overall economic assessment and to assess the plant design characteristics of future nuclear reactors and their associated fuel cycles. All six GEN-IV designs have been investigated and compared to a reference GEN-III design. Fuel cycle costs were divided into front-end and back-end costs. When estimating costs for GEN-IV reactor fuel cycles, non-conventional fuels (e.g. MOX, nitride ceramics, carbides and metallic fuels) should be taken into account.

Evaluating the wider aspects of competitiveness in a full-cost approach, in comparison with the cost of renewable energy sources (RES) and other low-carbon dispatchable sources and taking into account CCS/U (carbon capture and storage/usage) and large-scale storage, would be useful. It would require making necessary assumptions linked to the evolution of the market design and operation, which have, in particular, an impact on the system costs. In addition, applications beyond pure electricity production have to be considered, such as district heating and industrial heat applications.

Moreover, it is important to ensure that Gen IV nuclear systems are sufficiently flexible, at minimal cost, to be integrated in electricity systems with increasing shares of variable/intermittent renewable energy sources, using diverse possible options: load following, remote control, modularity (SMRs), cogeneration and hybrid systems. A highly flexible hybrid electricity system with 50% variable (or intermittent, non-dispatchable) RES might be considered as challenging but realistic.

To conclude this Section on socio-economics, one should stress the following question: *How to improve public information and engagement in energy policy issues, notably in connection with nuclear decision making?* Breakthrough technologies in the nuclear sector are under development world-wide: they are under discussion not only amongst scientists and engineers but also by national regulators and civil society (see *Science based policies and legislation* in Topic 8 of above "*2012 Interdisciplinary Study*").

Proliferation resistance and physical protection (Non-Proliferation Treaty, IAEA 1970)

One GIF high-level Goal (no. 8), the last one in the general GIF strategy, is defined in connection with *"Proliferation resistance and physical protection"*:

- 8. Be a very unattractive route for diversion or theft of weapon-usable materials, and provide increased physical protection against acts of terrorism.

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resources - https://www.gen-4.org/gif/jcms/c_40407/economic-modelling-working-group-emwg and 2013 GIF EMWG "*Cost Estimating Guidelines for Generation-IV Nuclear Energy Systems*" - https://www.gen-4.org/gif/jcms/c_40408/cost-estimating-guidelines-for-generation-iv-nuclear-energy-systems

Consensus was reached, in particular, on the following items:

- further improvement of the safeguards in all nuclear material inventories involved in enrichment, conversion, fabrication, power production, recycling, waste disposal
- design of advanced systems from the start with improved physical protection against acts of terrorism, thereby increasing public confidence in nuclear facilities.

Remember the “Atoms for Peace” conference (speech delivered by U.S. President Dwight D. Eisenhower to the UN General Assembly in New York City on December 8, 1953). This event created the ideological background for the creation of the IAEA and the “Treaty on the Non-Proliferation of Nuclear Weapons” (NPT). The NPT is an international treaty whose objective is (1) to prevent the spread of nuclear weapons and weapons technology, (2) to promote cooperation in the peaceful uses of nuclear energy, and (3) to further the goal of achieving nuclear disarmament and general and complete disarmament. Opened for signature in 1968, the NPT entered into force in 1970. The Treaty defines nuclear-weapon states as those that have built and tested a nuclear explosive device before 1 January 1967: these are the USA, Russia, the UK, France, and China. As of today, 191 states have adhered to the NPT (NB: 5 states are non-parties).

The fear of so-called "rogue nations" acquiring nuclear weapons, or terrorist organisations carrying out malevolent actions by misuse of nuclear materials, clearly remains intense. As a consequence, a great number of political and technological experts are working on reducing the risk of dissemination and proliferation of nuclear weapons. It should be recalled, however, that during the Cold War, the objective risk of proliferation was high, with more than twenty countries attempting to develop nuclear weapons, nine of which eventually did so. In contrast, since the end of the Cold War, less than a handful of countries have attempted proliferation and only one – North Korea – has succeeded [43].

The long-term safe, secure and sustainable use of nuclear energy must be ensured by a consistent approach to the “3S” nexus, namely: safety (implementation of appropriate and commensurate common principles, rules and standards); security (prevention, detection and response), as well as international acceptance and mutual trust (transparency); and safeguards (verification, reporting and non-proliferation commitments such as export controls). This can only be achieved based on sound scientific evidence, reliable nuclear measurements and appropriate control tools, as well as on public involvement, which at the same time can only be guaranteed if competence and technology leadership are maintained world-wide (research, education, training and knowledge management).

In this context, it is worth recalling the JRC activities in the field of “3S”. Their focus is in four areas: effective and efficient safeguards (through research in, e.g. nuclear material measurements, containment and surveillance, process monitoring and on-site laboratories); verification of absence of undeclared activities (through e.g. trace and particle analysis, and development of in-field tools); nuclear non-proliferation (through

[43] “*Nothing to Fear but Fear Itself ? Nuclear Proliferation and Preventive War*”, by Debs and Monteiro, Pol. Science, Yale Univ, 2010 - http://www.nunomonteiro.org/wp-content/uploads/DebsMonteiro2010.pdf

e.g. export control, trade analysis, and studies); and combating illicit trafficking (through, e.g. equipment development and validation, nuclear forensics, preparedness plans).

Some experts claim that recycling plutonium in the form of MOX fuel helps to combat nuclear proliferation by "burning" it in the reactor, while other experts claim that handling and storing plutonium should be prohibited, due to the risk of diversion by terrorists.

The ambitions of Generation-IV in this domain focus on two breakthrough technologies:

(1) new reprocessing (partitioning) techniques where U and Pu are no longer separated, as is the case in the traditional PUREX process, and

(2) new fuel fabrication techniques for fast neutron flux reactor (transmutation) systems aiming to use (fertile) U-238 to breed (fissionable) Pu-239, while burning the minor actinides Np, Am and Cm (thereby preventing the use of the isotopes Np-237 and Am-241, Am-242m, and Am-243 in a nuclear explosive).

The *Proliferation Resistance and Physical Protection* (PR&PP) Working Group of GIF issued a document: "*Evaluation methodology for PR&PP of Generation-IV nuclear energy systems*" [44]. For a proposed design, the methodology defines a set of challenges, analyses system response to these challenges, and assesses outcomes. Uncertainty of results is recognized and incorporated into the evaluation. The results are intended for three types of users: system designers, policy makers, and external stakeholders.

The PR&PP methodology can be applied to the entire fuel cycle or to portions of a design. It was developed, demonstrated, and illustrated by use of a hypothetical "example sodium fast reactor" (ESFR), by members of the PR&PP WG. The ESFR case study was the first opportunity to test the full methodology on a complete system, and many insights were gained from the process. Others, in national programmes, have adapted the PR&PP methodology to their specific needs and interests, such as:

- in the USA, where the methodology has been used to evaluate alternative spent fuel separations technologies
- in Belgium, where the PR&PP methodology was used in the analysis of the MYRRHA accelerator-driven system (fast spectrum Pb-Bi irradiation facility).

To conclude this section on proliferation resistance, on could expand the discussion towards cyber-terrorism, e.g., an attack causing serious damage to a critical infrastructure. Until the 2010s, only hackers targeting industrial systems have been involved in cyber-terrorism actions. In the nuclear sector, however, there are strong defences. In principle, a cyber-attack cannot prevent critical systems in a nuclear energy facility from performing their safety functions (i.e., reactivity control, decay heat removal, containment), Nuclear power plants are designed to shut down safely, if necessary, even if there is a breach of cyber-security. They are also designed to automatically disconnect from the power grid if there is a disturbance caused by a cyber-attack. Nevertheless, other types of cyber-attacks could destroy, for example, vulnerable physical components of the electricity grid.

[44] GIF – "*Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems - Rev 6" – GIF PR&PP-WG 2011-* https://www.gen-4.org/gif/jcms/c_9365/prpp

5. EURATOM RESEARCH AND TRAINING ACTIONS IN INNOVATIVE REACTOR SYSTEMS AND EU "SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM"

EURATOM actions that are considered as contributing to the six GIF reactor systems

While the fast reactor systems of Generation-IV type produce substantially more energy (up to 50 times) from the original uranium than conventional reactors, they are expensive to build and still need to demonstrate that they can offer, in particular, a significantly improved level of safety compared with Generation-III reactors. As a consequence, additional R&D is necessary in areas, such as: instrumentation & control; human machine interface; reactor physics and thermal-hydraulics; risk management; operation and maintenance. Further research is required, in particular regarding the behaviour of these systems under severe accident conditions. Each Generation-IV system requires challenging R&D common to all systems, whereas others are system-specific. The list of Generation-IV crosscut items in the domain of safety comprises, for example, system optimization and safety assessment methodology; emergency planning methods; a licensing and regulatory framework; radionuclide transport and dose assessment; human factors (see above mentioned "GIF R&D Outlook for Generation IV Nuclear Energy Systems" 2019).

Detailed information on Euratom research in Generation II, III and IV is available in the proceedings of the 2019 conference FISA and EURADWASTE.[45]. This conference was co-organised by the EC with the Ministry of Research and Innovation of Romania and the Institute for Nuclear Research (RATEN ICN) under the auspices of the Romanian Presidency of the Council of the European Union in 2019. The event took place on 4 – 7 June 2019, in Pitesti, Romania. A lot of information is also available in the previous FISA-2013 conference in Safety of Reactor Systems (Vilnius, Lithuania, 14 - 17 October 2013).

The aim of FISA-2019 was to present progress and key achievements of the most relevant Euratom projects – both indirect actions [46] and direct actions [47] - carried out since 2013.

Focussing on GEN-IV, an extensive investigation over the ten-year period 2010-2020, going through all the existing Euratom Fission Projects of FP5, FP6, FP7 and Horizon 2020 (RTD indirect and JRC direct actions), produced the following list of Euratom actions that are considered as contributing to the six GIF systems. These Euratom actions are cross-

[45] FISA 2019 and EURADWASTE '19 (ninth) EU conference - http://fisa-euradwaste2019.nuclear.ro/ and proceedings in Publications Office of the EU https://op.europa.eu/en/publication-detail/-/publication/9cfc43f8-cbc7-11ea-adf7-01aa75ed71a1/language-en/format-PDF/source-140481060

[46] Summary of indirect actions (RTD) in "Euratom Research and Training in 2019: challenges, achievements and future perspectives", by Roger Garbil, Christophe Davies, Daniela Diaconu, in EPJ Nuclear Sci. Technol. 6, E2 (2020) - https://epjn.epj.org/articles/epjn/abs/2020/01/epjn190056/epjn190056.html

[47] Summary of direct actions (JRC) in "JRC Euratom Research and Training Programme − 2014–2020", by Said Abousahl, Andrea Bucalossi, Victor Esteban Gran, Manuel Martin Ramos, EPJ Nuclear Sci. Technol. 6, 45 (2020) - https://epjn.epj.org/articles/epjn/abs/2020/01/epjn190067/epjn190067.html

cutting: safety of NPPs, fuel developments, thermal hydraulics, materials research, numerical simulation and design activities, partitioning and transmutation, as well as support to infrastructures, education, training and knowledge management, international cooperation. It is worth mentioning that many of these Euratom projects were conducted in the wake of the above-mentioned EU "stress tests" (i.e., 131 NPP units in 2011) and produced results that are applicable to current GEN-II and -III as well as to GEN-IV.

Some RTD indirect actions in the Generation-IV domain during the ten-year period 2010-2020 were 'concept oriented' such as: *CP-ESFR (2009–2013)* Collaborative Project on European Sodium Fast Reactor; *LEADER (2010–2013)* Lead-cooled European Advanced Demonstration Reactor; *HELIMNET (2010–2012)* Heavy liquid metal network; *GOFASTR (2010–2013)* European Gas Cooled Fast Reactor; *VINCO (2015–2018)* Visegrad Initiative for Nuclear Cooperation (Advanced GFR Safety Allegro); *ESNII+ (2013–2017)* Preparing ESNII for HORIZON 2020; *EVOL (2010–2013)* Evaluation and Viability of Liquid Fuel Fast Reactor System; *SAMOFAR (2015–2019)* A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor; *MYRTE (2015–2019)* MYRRHA Research and Transmutation Endeavour; and *ESFR-SMART (2017–2021)* European Sodium Fast Reactor Safety Measures Assessment and Research Tools.

Other RTD indirect actions addressed cross-cutting research and innovation areas such as: *GETMAT (2008–2013)* Gen-IV and Transmutation MATerials; *MATTER (2011–2014)* MATerials TEsting and Rules; *MATISSE (2013–2017)* Materials' Innovations for a Safe and Sustainable nuclear in Europe; *FAIRFUELS (2009–2015)* FAbrication, Irradiation and Reprocessing of FUELS and targets for transmutation; *F BRIDGE (2008–2012)* Basic Research for Innovative Fuels Design for GEN IV systems; *THINS (2010–2015)* Thermal-hydraulics of Innovative Nuclear Systems; *SEARCH (2011–2015)* Safe ExploitAtion Related CHemistry for HLM reactors; *SESAME (2015–2019)* Thermal hydraulics Simulations and Experiments for the Safety Assessment of MEtal cooled reactors; *SACSESS (2013–2016)* Safety of ACtinide Separation processes; *GENIORS (2017–2021)* GEN IV Integrated Oxide fuels recycling strategies (FC Partitioning); *CINCH-II (2013-2016)* Cooperation in education and training In Nuclear Chemistry; *ASGARD (2012–2016)* Advanced fuelS for Generation IV reActors: Reprocessing and Dissolution; *TALISMAN (2013–2016)* Transnational Access to Large Infrastructure for a Safe Management of ActiNide; *ARCAS (2010–2013)* ADS and fast Reactor CompArison Study in support of Strategic Research Agenda of SNETP; *JASMIN (2012–2016)* Joint Advanced Severe accidents Modelling and Integration for Na-cooled fast neutron reactors; and *SARGEN-IV (2012–2013)* Towards a harmonized European methodology for the safety assessment of innovative reactors with fast neutron spectrum planned to be built in Europe.

Here are a series of more recent Horizon 2020 indirect actions related to Generation-IV: *PASCAL* (LFR - Advanced HLM - ALFRED - MYRRHA) ; *SafeG* (GFR - Advanced Safety - Allegro) ; *GEMINI+* (Advanced HTR – Cogeneration) ; *ECC - SMART* (SCWR - Advanced SMR safety features) ; *SAMOSAFER* (MSR - Advanced Molten Salt) ; *PUMMA* (FC Fuel Pu management) ; *INSPYRE* (FC - MOX fuel licensing) ; *PATRICIA* (FC - P&T MYRRHA) ; *MEET-(&A) CINCH* (FC - E&T RadioChemistry) ; *GEMMA* (Advanced Materials) ; *M4F* (Fu/Fi materials) ; *McSAFER* (Advanced Modeling SMR).

Under the current Euratom Research and Training Programme (2021-2025), the selected projects for 2019-2020 covering Generations II, III and IV amounted to a budget of 140 million euros. Five projects on advanced systems are funded on topics such as: fuel cycle Pu management, safety of Gas Fast Reactors, partitioning and transmutation, safety of SCWR SMR, and the high-performance computing safety evaluation of SMRs.

The main JRC direct actions in the Generation-IV domain during the ten-year period 2010-2020 under consideration are the following:

- *ANFC* - Alternative Nuclear Fuel Cycles (e.g., development of aqueous and pyrochemical processes for the separation of long-lived radionuclides and the conversion into shorter-lived or stable ones by irradiation in dedicated reactors)
- *ND-MINWASTE* - Nuclear data for radioactive waste management and safety of new reactor developments (e.g. contribution to the Joint Evaluated Fission and Fusion nuclear data file – JEFF –, and Evaluated Nuclear Data File, ENDF/B-VII).
- *FANGS* - Feasibility Assessment of Next Generation nuclear energy Systems (e.g., feasibility and performance investigations regarding fast reactor/transmutation fuel and high temperature reactor fuel, for which several successful irradiation tests in the High Flux Reactor (HFR) Petten, the Netherlands, were performed
- *MATTINO* - MATerials performance assessmenT for safety and Innovative Nuclear reactOrs (e.g., thermo-mechanical properties, corrosion resistance, and irradiation and environmental safety performance assessment of structural materials; input to material design codes and standards)
- *NURAM* - Nuclear Reactor Accident Analysis and Modelling (e.g., in the area of severe accident management)
- *SNF* - Safety of Nuclear Fuels and Fuel cycles (e.g., conventional and advanced fuels including minor actinide containing fuels, going from the traditional post-irradiation techniques providing information on microstructure and fission gas release to advanced techniques providing fundamental data on the thermo-physical and thermomechanical properties of nuclear fuel
- *CAPTURE* - Knowledge and Competence Management, Training and Education in Reactor design and Operation (e.g., evaluation of human resources trends in the energy sector; harmonization and standardization of nuclear skills recognition within the EU; open database taxonomy of commonly recognized nuclear skills and competences, implementation of the ECVET system in the nuclear energy sector).
  NB: ECVET = European Credit System for Vocational Education and Training

It is worth recalling that JRC owns nuclear research installations in four sites in the EU, some of them focussing on specific aspects of Generation-IV: JRC-Geel in Belgium, JRC-Karlsruhe in Germany, JRC-Petten in the Netherlands and JRC-Ispra in Italy:

- JRC-Geel research infrastructure mainly focuses on nuclear data, radioactivity metrology, and nuclear reference materials. It is one of the few laboratories in the world which is capable of producing the required accuracy for neutron data needed for the safety assessments of present-day and innovative nuclear energy systems.

- JRC-Karlsruhe mainly focuses on properties of irradiated and non-irradiated nuclear materials, as well as on research in fuel, fuel cycle, radioactive waste, security and safeguards. Their materials research laboratories contain unique, mostly home-built experimental installations dedicated to the study of thermodynamic and thermo-physical properties of actinides and nuclear materials.
- JRC-Petten hosts and operates laboratories for the assessment of materials and components performance under thermo-mechanical loading, corrosion, and neutron irradiation. Their Structural Materials Performance Assessment laboratories (SMPA) are used for the mechanical performance characterisation, life assessment and qualification of materials for present and next generation nuclear systems.
- JRC-Ispra carries out research in safeguards and security. Their Advanced safeguards, measurement, monitoring and modelling laboratory (AS3ML) is used for testing and developing innovative integrated solutions for the implementation of safeguards in the different types of nuclear installations.

Also, worth mentioning are the three direct actions conducted by JRC as major projects in the domain of Gen-IV: (1) The Safety of Advanced Nuclear Systems and Innovative Fuel cycles (SEAT-GEN-IV), (2) System Analysis of Emerging Technologies (SAITEC) and (3) Waste from Innovative fuel (WAIF). The topics covered are focussing on SFR, LFR, VHTR and MSR, such as: reactor safety of Gen-IV reactor designs, including modular reactors (severe accident modelling), materials R&D, safety of fuel, conditioning matrices for waste from innovative fuels, and safeguards. Activities in support of the GIF PR&PP-WG are carried out in the MEDAKNOW project (Methods, Data analysis and Knowledge management for Nuclear Non-Proliferation, Safeguards & Security).

Moreover, the Euratom RTD action “Research Infrastructures - Material Testing Reactors” includes two actions on the Jules Horowitz Reactor (JHR, CEA Cadarache) that will allow for innovative fuel and material testing:

• access rights for Euratom researchers (6% JHR irradiation time, 6 million euros from Euratom, leading today to about 40 million euros in collaborative projects);

• the JHR operation plan 2040 in the context of the optimized use of research reactors to plan European specific irradiations (2.6 million euros from Euratom).

Also worth mentioning is the adoption of the Supplementary Programme for HFR Petten, supported by about 30 million euros from the governments of the Netherlands and France.

As far as innovative materials and fuels are concerned, a number of promising technologies to further improve safety are being tested in national and Euratom laboratories, in particular, in the context of the “Joint Programme on Nuclear Materials” (JPNM) under the “European Energy Research Alliance” (EERA) [48]. As a result, development of innovative

[48] European Energy Research Alliance - more than 250 organisations from 30 countries - https://www.eera-set.eu/ and Joint Programme on Nuclear Materials - http://www.eera-jpnm.eu/ . The EERA-JPNM has currently 50 between full (18) and associate (32) members. Members are research centres, universities, umbrella organisations and industries. Altogether they represent 17 European countries.

materials and fuels benefits from advancements of EERA JPNM for fission and fusion.

Regarding above JPNM, it is worth mentioning that cross-thematic activities with non-Euratom programmes are quite successful. For example, many technologies and innovative approaches for fabrication, repair and joining (including surface modification of materials) are currently available in non-nuclear industries, but are not yet addressed in nuclear codes and standards or endorsed by regulatory bodies. Here is the list of Standards Development Organisations recognised by above MDEP of OECD/NEA: ASME (USA), AFCEN (France), CSA (Canada), JSME (Japan), KEA (Korea) and NIKIET (designated in Russia).

Regarding nuclear safety improvements, the development of Accident-Tolerant Fuel (ATF) and materials is of particular interest. Fuel and fuel elements in Gen-IV reactor systems will need to ensure that high burnups are reached, including the possibility of burning minor actinides. Fuels and materials will be exposed to high levels of temperature and irradiation, with some in contact with potentially aggressive non-aqueous coolants, targeting 60 years of reactor operation. As a consequence, ATFs are being developed, as a means of preventing the release of fission products. Surface modification on ATF cladding materials can result in significant enhancement on both oxidation resistance and cooling performances, which are essential to ensure the integrity of fuel claddings (under normal operations and accident conditions). For example, the Euratom project Il TROVATORE, 2017-2022 (30 beneficiaries across 3 continents, 5 million euros) focuses on innovative ATF cladding material concepts such as SiC/SiC composite clads, MAX phase-coated ceramic materials and oxide-dispersed-strengthened (ODS) FeCrAl alloy clads.

Additionally, the entire nuclear fuel cycle is studied. Innovative strategies and technologies, from front-end to back-end of the fuel cycle, including waste streams and high-level waste management (in particular, partitioning and transmutation), should help to meet the sustainable goals of minimisation of waste and better use of natural resources.

A number of Euratom research and innovation projects are also devoted to cross-cutting nuclear data activities to the level needed by simulation codes to fulfil present requirements for the safe and sustainable operation as well as development of future reactors. Close collaboration exists between Euratom research programmes and the Nuclear Data bank of OECD/NEA and IAEA (70 years of nuclear research, including about 2000 computer codes), which are the main repositories of data and standards for nuclear energy applications, thereby providing open access to the scientific community.

The Euratom technical contribution to the GIF systems consists not only of above-mentioned Euratom DG RTD indirect actions and JRC direct actions, but also of direct contributions from the EU Member States.

During this reporting period 2010-2020, EU Member States have indeed invested through their national research programmes in several GIF systems. France estimated its investment on Generation IV R&D at 102 MEUR on a yearly basis. Belgium and Italy have been investing mainly in Lead (Lead-bismuth) system: SCK-CEN (Belgium) has also obtained a grant from its government for MYRRHA R&D (Pb-Bi LFR and ADS – *NB: the Belgian federal government decided to invest 558 million euros during the 2019-2036 period*). Italy has dedicated a 30 MEUR to LFR ALFRED reactor systems. Romania has also allocated around 6 MEUR for the innovative systems with a focus on LFR during the ten-year reporting period. Germany has allocated 3-4 MEUR for each of the 3 fast reactors technologies and VHTR. Finland has invested 0.5-1 MEUR for each of the 3 fast reactors, VHTR and SCWR. The Czech Republic has focused on SCWR (3 MEUR) and LFR (1 MEUR). The Netherlands invested in VHTR, SCWR, MSR and LFR with budgets of 0.4-0.8 MEUR each. Hungary focussed on SCWR systems (0.6 MEUR) and on GFR (0.3 MEUR - ALLEGRO reactor system). Poland has invested 1.5 MEUR in the HTRPL project on VHTR. Spain has supported VHTR (0.5 MEUR), SFR (0.1 MEUR) and LFR (0.1 MEUR) R&D activities. Sweden has focussed on SFR (0.3 MEUR) and LFR (0.2 MEUR).

European Sustainable Nuclear Fission Industrial Initiative (ESNII) and Nuclear Cogeneration Industrial Initiative (NC2I)

As a consequence of Euratom accession to the GIF Framework Agreement in 2005, the EU is committed to international cooperation in Generation-IV development. This commitment has been entrusted to SNETP, the *"Sustainable Nuclear Energy Technology Platform"* (over 110 members) [49] . SNETP was set up in 2007 under the auspices of the European Commission: it is composed of three pillars (NUGENIA, ESNII and NC2I).). Of particular interest for Generation-IV are pillar no 2, the “European Sustainable Nuclear Fission Industrial Initiative” (ESNII) - somehow equivalent to the above SIAP - and pillar no 3, the “Nuclear Cogeneration Industrial Initiative” (NC2I). More precisely, ESNII focusses on the Fast Neutron Reactor systems that are considered as key for the deployment of sustainable nuclear fission energy, whereas nuclear fission applications beyond electricity production are favoured in NC2I. As a consequence, EU/Euratom contributions cover all six GIF Systems.

The three pillars of SNETP do cover all generations of NPPs and the most important applications of nuclear fission while being aligned with the EU policy for a more competitive resource-efficient economy (including circular economy):

1. *NUclear Generation-II & -III Association* /NUGENIA/ dedicated to Gen-II (e.g., long-term operation issues) and Gen-III (e.g., severe accident management)
2. *European Sustainable Nuclear energy Industrial Initiative* /ESNII/ dedicated to Gen-IV systems of fast neutron type and associated fuel cycle facilities

[49] List of *European Industrial Initiatives* of interest to research, innovation and education in reactor safety
* SNETP = "*Sustainable Nuclear Energy Technology Platform*" - http://www.snetp.eu/
  - NUGENIA = *NUclear Generation-II & III Association* - http://www.nugenia.org/
  - ESNII = *European Sustainable Nuclear energy Industrial Initiative* - http://www.snetp.eu/esnii/
  - NC2I = *Nuclear Cogeneration Industrial Initiative* - http://www.snetp.eu/nc2i/

3. *Nuclear Cogeneration Industrial Initiative* /NC2I/ dedicated to combined heat and power /CHP/ generation.

The role of SNETP should be stressed in the context of the ambitious 2008 EU Strategic Energy Technology /SET/ Plan ("Making the European energy system more sustainable and secure"), which has identified 10 actions for research and innovation at EU level: action no 10 is "nuclear safety". SNETP has evolved to form a "European Technology & Innovation Platform" and became an international non-profit legal association in 2019. It is now in the process of updating its Strategic Research and Innovation Agenda.

Originally, ESNII was a Task Force, comprising research organisations and industrial partners, addressing the need for demonstration of Generation-IV Fast Neutron Reactor technologies, together with the supporting research infrastructures, fuel facilities and R&D work. The focus was thus on Euratom and national actions aiming at improving sustainability (i.e. efficient resource utilisation and minimisation of volume, heat and radiotoxicity of waste) and safety & reliability, as well as proliferation resistance.

According to ESNII, the three types of fast reactors (using as coolant, respectively, sodium /SFR/, lead /LFR/ or gas /GFR/) have a comparable potential for making efficient use of uranium and minimising the production of high-level radioactive waste. When it comes to priorities, the experience accumulated in the EU in sodium technology gives this option a strong starting position. As an alternative to sodium, however, the lead and gas fast reactors also offer a number of interesting features. Lead, for example, is chosen as a coolant for being high-boiling, radiation-resistant, low-activated and at atmospheric pressure.

As a consequence, the different Generation-IV systems were prioritised as follows:

(1) the sodium-cooled fast neutron reactor technology (ASTRID-like SFR prototype sodium cooled fast reactor) as the reference solution;
(2) two alternatives ("ex aequo"): the lead-cooled fast reactor ALFRED supported by the lead-bismuth irradiation facility MYRRHA as a first alternative; the gas-cooled fast reactor ALLEGRO as a second alternative.

As far as ASTRID (*Advanced Sodium Technological Reactor for Industrial Demonstration*) is concerned, it should be noted, however, that on 30 August 2019, the CEA confirmed the abandonment of their plans to build this prototype fast neutron reactor. This French Gen-IV prototype is no longer "programmed in the short or medium term". Work on the sodium technology, however, is expected to be continued, but the construction of a potential demonstrator of this technology will be postponed until the second half of the 21st century. Education and training activities will be continued, in particular, in collaboration with the ESML ("Ecole du Sodium et des Métaux Liquides") and the EC ("Ecole des Combustibles"), both located at CEA Cadarache in France. Though some research may be continued in fast neutron technologies in France, many experts fear that it will not be enough to maintain industrial expertise in developing new reactor systems.

Besides the three above priorities of ESNII, the Molten Salt Fast Reactor (MSFR) is considered as a very attractive long-term option. Two other fast neutron Generation-IV technologies are also of interest for Euratom: the European Sodium Fast Reactor (ESFR) and the Swedish Advanced Lead Reactor (SEALER).

As a conclusion of this sub-section, through Euratom and national research effort coordinated by ESNII and NC2I, the EU supports R&D activities in all innovative reactor systems proposed by GIF. The Euratom obligations within the GIF Framework Agreement are thus covered (see comprehensive description in JRC 2017 report [50]).

Moreover, it should be stressed that, in the EU, public participation in the decision-making process is crucial in the development of energy policies, notably in the domain of nuclear fission (see *revised 2014 Euratom Safety Directive* and *2013 Euratom BSS Directive*). Worth noting in this context is the interest of an increasing number of citizens' associations for getting reliable information (facts and figures) regarding nuclear fission, including Generation-IV. For this purpose, a European association was created in February 2019: weCARE [51] ("Clean Affordable Reliable Energy for Societal Sustainability"). This is an Alliance pooling existing NGO type organizations that share and foster common objectives that can be best summarised using one of their mottos: *"Restore the facts; Change the tone; Refocus the debate on the contributions of nuclear energy, rather than on nuclear itself."*

6. EXPERIMENTAL RESEARCH REACTORS IN THE EU AND SMALL MODULAR REACTORS

Experimental research reactors (training, materials testing, isotope production)

As far as experimental research reactors in the world are concerned, the situation has recently evolved, with the shutdown of several Material Testing Reactors (MTR):

- the Osiris reactor (radioisotope productions, 70 MWth) in CEA, France in 2015
- the Japan Material Test Reactor (Japan Atomic Energy Agency, 50 MWth) in 2017
- the Halden Boiling Water Reactor in Norway (heavy water, 25 MWth) in 2018.

A quick look at some major remaining MTRs in operation today indicates that several of these are quite old: ATR (USA, 1967), MIR and SM3 (Russia, 1967 & 1961 resp.), BR2 (Belgium, 1962), HFR (the Netherlands, 1961), while LVR-15 (Czech Republic, 1995) and

[50] "Euratom Contribution to the Generation IV International Forum Systems in the period 2005-2014 and future outlook" - http://publications.jrc.ec.europa.eu/repository/bitstream/JRC104056/kjna28391enn.pdf

[51] The European weCARE Alliance groups together 10 members and 2 associates as of June 2021– it is listed in the EU Transparency Register under no 473723535459-78 - https://www.wecareeu.org

* 10 Member Organisations : 100 TWh (Belgium); Ekomodernist Finland, European Association for Energy Security (Slovak Republic); Institute for Sustainable Energy Poland; Jihocesti Tatkove (Czech Republic); Patrimoine Nucléaire et Climat (France); Sauvons Le Climat (France); Stichting Energietransitie & Kernenergie (the Netherlands) ; Terrapraxis (United Kingdom) ; 18for0 (Ireland) ;

* two Associated Organisations: European Physical Society (international); Les Voix du Nucléaire (FR).

the TRIGA in Pitesti (Romania, 1980) are younger. The probability of final shutdown in the next 10 to 20 years of facilities built in the 1960s appears very high. To cope with this situation, only a limited number of projects of new MTRs are under construction.

Moreover, high performance research reactors have to overcome the challenging conversion from highly enriched to low enriched uranium fuels, to fulfil a worldwide non-proliferation effort.

Major experimental facilities are needed to support Generation-IV systems (SFR, LFR, GFR, VHTR, MSR and SCWR) [52]. This enables progress to be made in the three above-mentioned phases of the GIF roadmap (viability, performance, demonstration), depending on the Technological Readiness Level (TRL) of each GIF reactor system.

In line with the priority assigned to fast neutron spectrum reactors, ESNII is supporting the design and construction of four demonstrators related to Generation IV in the EU, namely:

1. The ASTRID-like SFR demonstration reactor with sodium coolant, to be built in France in the second half of the century as a project led by French government /CEA/ (using originally a national loan of EUR 650 million) in association with a number of industrial national and international partners. ASTRID was originally designed to pursue R&D on sodium fast reactors and demonstrate the feasibility of transmutation of minor actinides. ASTRID's main technical choices (basic design phase) were originally : 1500 MWth - 600 MWe pool type reactor ; with an intermediate sodium circuit; CFV core (low sodium void worth); oxide fuel UO_2-PuO_2; preliminary strategy for severe accidents (internal core catcher); diversified decay heat removal systems; fuel handling in gas; internal storage; conical inner vessel ("redan") adopted; open design option : energy conversion system (classical Rankine water-steam cycle or Brayton gas cycle). It should be recalled, however, that CEA confirmed in August 2019 the abandonment of their plans to build ASTRID but work on the sodium technology is expected to be continued.

2. The MYRRHA fast spectrum irradiation facility [53] in a research reactor with lead-bismuth coolant, open to international collaboration ("*Multipurpose hYbrid Research Reactor for High-technology Applications*", 50-100 MWth). MYRRHA is led by and hosted at SCK-CEN Mol, Belgium: its aim is to replace the high thermal neutron flux research reactor BR2. It has featured in the roadmap of the "*European Strategy Forum on Research Infrastructures*" /ESFRI/ since 2010.
   The focus is on minor actinide burning (i.e., radioactive waste minimisation) via an accelerator driven system (ADS) using a sub-critical fast neutron spectrum core. With the subcritical concentration of fission material, the nuclear reaction is sustained by the particle accelerator only. Turning off the proton beam results in an immediate and safe halt of the nuclear reactions.

[52] "GIF R&D Infrastructure Task Force" (GIF RDTF – final report – 96 pages - January 2021) - https://www.gen-4.org/gif/upload/docs/application/pdf/2021-02/gif-rdtf_final_report_jan2021.pdf
[53] MYRRHA - Less (toxic) nuclear waste (testing of Partitioning &Transmutation); Production of medical radio-isotopes; New reactor concepts; Fundamental research - https://www.sckcen.be/en/projects/myrrha

The MYRRHA facility which is a Material and Fuel Testing Reactor, consists of four major components:

- the Linear Accelerator (linac injector) - the 4-mA proton beam is injected into the reactor, generating a flux of fast neutrons through spallation
- the lead-bismuth eutectic (LBE) cooled fast reactor will utilises U-235 and U-238 as well as MOX fuel; and may contain up to 30% of long-lived minor actinides, such as Np, Am and Cm (= > reduction of waste burden)
- the Proton Target Facility (= > production of radioisotopes and research into several fields)
- the Fusion Target Station (high constant fast flux level and large irradiation volume of 3000 cm^3 => irradiation conditions required for fusion materials).

MYRRHA will be implemented in three phases (2026; 2033; 2036). On 7 September 2018 the Belgian Federal Government decided to have the MYRRHA project built on the SCK-CEN site in Mol. Based on a total budget of 1.6 billion euros, the federal government decided to invest 558 million euros during the 2019-2036 period in phase 1 of MYRRHA including the construction of the MYRRHA accelerator up to 100 MeV and its proton target facilities as well as in the preparatory phases of design & R&D for extending the accelerator up to 600 MeV. The reactor is scheduled to be commissioned in 2036.

3. ALFRED demonstrator with lead coolant (*Advanced Lead Fast Reactor European Demonstrator*) [54], project to be hosted in the Nuclear Research Institute (ICN), Pitești, Romania, in collaboration with the FALCON consortium "Fostering ALFRED Construction". The partners are Romania's Nuclear Research Institute (RATEN-ICN) as well as Ansaldo Nucleare and Italy's National Agency ENEA. ALFRED is expected to produce 125 MWe; its design should as far as possible be based on available technology, in order to speed up the construction time; it will use structural materials compatible with the corrosive lead used as coolant (selected candidate: AISI 316LN, 15-15/Ti). Decay Heat Removal Systems will be based on passive technology to reach the expected high safety level (low primary system pressure drops to enhance natural circulation).

4. ALLEGRO (not an acronym), a *Gas Cooled Fast Reactor demonstrator* with helium coolant [55], resulting from regional collaboration in the V4G4 Centre of Excellence *(Visegrad 4* countries for *Gen-IV* reactors) composed of Hungary's Academy of Sciences Centre for Energy Research (MTA EK); the Czech Republic's ÚJV Rež; the Slovak engineering company VUJE Trnava; and Poland's National Centre for Nuclear Research (NCBJ Swierk). The project started in 2009 as a close collaboration with French CEA which provided a good technical base for

[54] ALFRED - "Research and Innovation in Romania", European Research Area and Innovation Committee, 21 March 2019 - https://era.gv.at/public/documents/3781/3_Research_and_Innovation_in_Romania.pdf and LFR related GIF webinars no 10 in 2017 by US Naval Graduate School and no 23 in 2018 by Ansaldo

[55] "The ALLEGRO experimental gas (helium) cooled fast reactor project ", GIF webinar no 27 (20 March 2019) by ÚJV ŘEŽ - https://www.gen-4.org/gif/upload/docs/application/pdf/201903/geniv_template-_dr._ladislav_belovsky_final_3-20-19.pdf and GFR related GIF webinar no 6 in 2017 by CEA

further development by V4G4. Short-term priorities in the development are as follows: improve level of safety using passive systems (where possible); design UOX-based driver core while maintaining interesting power density & irradiation characteristics. The short-term priorities in R&D are: coolability in protected transients using natural convection (core outlet T < 530 °C); feasibility of guard vessel for elevated pressure; optimization of Decay Heat Removal systems (valves, heat exchangers, pressure drop, etc); turbomachinery in secondary circuit; potentially alternative cladding material for the driver core.

An important achievement in the context of thermal neutron spectrum facilities under construction in the European Union is the *Jules Horowitz Reactor* (JHR) [56]. This is a research reactor (100 MWth, pool-type, JHR school added in 2019) under construction at CEA Cadarache. The JHR construction was recommended by ESFRI as a replacement for the EU's existing material testing reactors, which were all built in the 1960s, and which are expected to reach the end of their service lives in the 2020s. The JHR is funded and steered by an international consortium bringing together the following partners: CEA (France), EdF-Framatome (France), TechnicAtome (France), SCK-CEN (Belgium), UJV (Czech Republic), CIEMAT (Spain), Studsvik (Sweden), DAE (India), IAEC (Israel), NNL (United Kingdom) and the European Commission (Euratom) and its JRC (EU) as observer. The European Commission has secured 6 % of the guaranteed access to irradiation capacity. It makes the EC the larger non-French contributor to the JHR, seven bilateral foreign partners having taken 2 % each and India 3 %. When operating at full capacity, the JHR will produce, in the reflector surrounding the core area, a thermal neutron flux to study current and innovative nuclear fuels. In-core experiments will address typically material experiments with high fast flux capability up to 5.5x10E14 n/cm²/s fast neutron flux with energy larger than 1 MeV. The JHR is expected to achieve its first criticality in 2021.

As far as plans for construction of thermal neutron research reactors in the EU are concerned, the *PALLAS* reactor project should be mentioned. It is aimed at taking over from the 50-year-old HFR in Petten, the Netherlands, dedicated to medical isotope production and other applications of ionizing irradiation [57]. The Pallas design and construction contract was awarded in January 2018 by the “Foundation Preparation PALLAS Reactor” to a consortium led by the Argentinean company Invap (Argentine National Atomic Energy, Bariloche). The Pallas reactor is to be of the "tank-in-pool" type, with a thermal power of around 55 MWth. Basic design is completed, construction will begin in 2022. In 2025, a four-year transition period is planned to finish construction and commissioning of the reactor and transfer of all irradiation programmes from the HFR to the PALLAS reactor. The lifetime of the new reactor is expected to be at least 40 years.

[56] “SUPPORTING INFRASTRUCTURES AND RESEARCH REACTORS: STATUS, NEEDS AND INTERNATIONAL COOPERATION, with emphasis on JHR” by CEA France at FISA-2019 conference (Pitesti, Romania, 4-7 June 2019)- http://fisa-euradwaste2019.nuclear.ro/wp-content/uploads/2019/07/Jean-Yves-BLANC-presentation.pdf and CEA JHR website http://www-rjh.cea.fr/news.html

[57] ‘the Foundation Preparation Pallas-reactor’ - https://www.pallasreactor.com/en/pallas-organisation/ and “Green light for Pallas reactor”, NEI, 17 March 2020 - https://www.neimagazine.com/news/newsgreen-light-for-pallas-reactor-7830460 (NB - The costs for the new reactor are estimated at 700 million euros)

NB : Invap has a broad experience in the construction and operation of research reactors and has been exporting its technology to Peru, Algeria, Egypt, Australia and Brazil.

As far as the Nuclear Cogeneration Industrial Initiative (NC2I) is concerned, it should be recalled that, in Europe, about 89 GWth, i.e., 50% of the process heat market is found in the temperature range up to 550°C (today mainly in the chemical industry, in the future possibly in steelmaking, hydrogen production, etc.). NC2I thus strives to provide a non-electricity nuclear contribution to the decarbonisation of industrial energy. NC2I gives highest priority to HTR. The Polish government has shown interest in developing HTR technology for heat supply to its industry (reference: 2017 policy document), because:

- it is the most mature technology (750 reactor-years of operational experience), capable of industrial deployment before 2050
- it can fully address, without further development, the needs of a large class of processes receiving heat or steam as a reactant from steam networks (typically around 550˚C), as is the case in the chemical and petrochemical industries
- it has the potential to address, in the longer-term, other types of applications which are not connected at present to steam networks, in particular bulk hydrogen production and other applications at temperatures higher than 550˚C.

Commonalities between fusion and Generation IV fission reactors are also worth discussing. Because of the extreme conditions characteristic of these systems, several safety concerns and materials issues are relevant to both of them. A number of Euratom fast neutron experimental facilities and R&D projects are investigating shared solutions. We should remember that (1) the main wastes in fusion are activated structural materials (tritiated waste management is a common concern), and that (2) the main safety issue for fusion is represented by tritium management in terms of the need to reduce inventory and avoid release (tritium, as an isotope of hydrogen, is easily absorbed in any material).

SMR technology is a great opportunity for the nuclear industry and could lead to a nuclear renaissance

A special mention is needed regarding Small and Medium nuclear power Reactors (also called "Modular" – in short SMR) that are awaiting licensing and industrial deployment. The IAEA defines "small" as under 300 MWe, and "medium" as up to about 700 MWe [58]. SMRs (both evolutionary and innovative) are characterized by components and systems that can be shop fabricated and then transported as modules to the sites for installation as demand arises. Generally, SMRs are expected to have greater simplicity of design, and to benefit from economies of series production, largely in factories, with short construction times and reduced siting costs. As a result, capital costs are reduced and electric power (and/or heat in the case of cogeneration plants) is provided away from large grid systems.

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[58] "Advances in small modular reactor technology developments" IAEA, Sept 2020 – This IAEA report covers land based and marine based water-cooled reactors, high temperature gas cooled reactors, liquid metal (sodium and lead), gas-cooled fast neutron spectrum reactors, molten salt reactors, and the recent micro modular reactors (up to 10 MWe) - https://aris.iaea.org/Publications/SMR_Book_2020.pdf and IAEA website "small modular reactors" - https://www.iaea.org/topics/small-modular-reactors

As of 2020, there are about 50 SMR designs and concepts globally. Most of them are in various developmental stages and some are claimed as being near-term deployable. There are currently three SMRs in advanced stages of construction: one in Argentina (CAREM) and two in China (GEN-IV /HTR-PM/). One SMR began commercial operation in May 2020: it is the world's only floating NPP, the Akademik Lomonosov (KLT-40S) in the Russian Arctic region - the power capacity is 70MW, the heat capacity is 58 MW.

SMRs are also expected to have lower core damage frequencies and longer post-accident coping (so-called "grace") periods, due to a high level of passive or inherent safety. They are usually more resistant to natural phenomena and have potentially smaller emergency preparedness zones than currently licensed reactors. Implementation of DiD in SMRs is relatively simpler than in large power reactors, that is: the use of stringent access controls, physical barriers, redundant and diverse key safety functions (in particular, 1 - control of reactivity, 2 - cooling of fuel elements, and 3 - activity retention), and effective emergency response measures. Here are some objectives set by the SMR developers: having full understanding of cost-benefit (the first requirement); simplifying operations (e.g., by reducing reliance on human actions); harmonising safety and security; considering remotely operated defence systems; having as much containment as possible; building the nuclear island below ground; ensuring online refuelling; developing new (international) transport regulations if the SMR (e.g. floating NPP) is transported; apply integrated security and safety cost-benefit analysis to ensure affordability.

Within GIF, there is revival of interest in SMRs for generating process heat and/or electricity (combined heat and power or CHP), mainly in view of applications such as: (1) replacing aging fossil (in particular coal-fired) power plants; (2) integrating hybrid nuclear/renewables energy systems; (3) providing cogeneration for developing countries with small electricity grids, underdeveloped infrastructure and/or limited financial resources; (4) operating in remote settlements (off grid areas) or industrial facilities with insufficient cooling capacity for large NPPs; (5) technology process applications (e.g. water desalination, petro-chemistry, hydrogen production and others).

In addition, flexibility in electricity generation from nuclear can be enhanced by the development of SMRs. In recent years, with large new nuclear projects advancing slowly, as well as an increased presence of variable (intermittent, non-dispatchable) sources in the energy mix and progressive decentralization of the grid, opportunities in smaller scale nuclear power reactors have again become subject to analysis. In SMR design, attention is paid in particular to the capacity of the reactor to respond rapidly to changes in the required power output. It should be noted, however, that a switch from traditional base-load operations to load-following operations leads to increased temperature and pressure cycling, which may lead to a new type of material degradation (e.g., thermal fatigue).

A few SMRs of power under 300 MWe are considered amongst the GIF systems and are under construction in the world, notably in the areas of (V)HTR, LFR and SFR:

1 (V)HTR (High Temperature Reactor-Pebble-bed Modules /HTR-PM or HTR-200/) designed for commercial power generation, under construction in China:

It is the world's first modular high temperature helium gas-cooled reactor demonstration plant (composed of two modules of 250-MWth, jointly driving a steam turbine generating 200 MWe) has been installed at the Shidaowan plant, near the city of Rongcheng in Shandong Province. Design is by the *Institute of Nuclear Energy Tsinghua* University (INET) and development is by *China Nuclear Engineering Corporation* (CNEC) and Huaneng. Construction began at the end of 2012. Main component installation started with the first reactor pressure vessel in March 2016. CNEC said the high-temperature gas-cooled reactor demonstration project has completed cold tests and began hot testing in early January 2021. Fuel loading start operations are scheduled for late 2021. A further 18 such HTR-PM units are proposed for the Shidaowan site (2000 MWe in total).

2 LFR (pool type) planned in the EU (Belgium), in Russia and in the USA

2.1 – in the European Union, the above MYRRHA facility under construction at SCK-CEN Mol Belgium: fast spectrum irradiation, accelerator driven system of 50-100 MWth, focussing on minor actinide burning (commissioning planned by 2036)

2.2 - in the Russian Federation, a system of intermediate size (lead-cooled fast reactor BREST-300-OD of 700 MWth / 300 MWe) with high density U-Pu nitride fuel. The licence for construction in Seversk (near Tomsk) has been issued by Russian regulator Rostechnadzor in February 2021. According to the planned timeline, the BREST-OD-300 reactor should start first of a kind engineering demonstration in 2026.

2.3 - another challenging Russian design is the Lead-Bismuth Fast Reactor SVBR-100 of 280 MWth / 100 MWe, with a wide variety of fuels (refuelling interval of 8 years). This multi-purpose prototype reactor is under construction by OJSC OKB Gidropress at the Research Institute for Atomic Reactors /NIIAR/ in Dimitrovgrad. Last project milestone (planned): serial production and supply of packaged equipment in 2032.

2.4 - in the USA, a small size transportable system ("Small, sealed, transportable, autonomous reactor" /SSTAR/: 45 MWth / 20 MWe) with a very long core life (30 years). This lead-cooled nuclear reactor, primarily developed by the Lawrence Livermore National Laboratory, was meant for use in developing countries (which would use the reactor for several decades and then return the entire unit to the manufacturing country).

3 SFR (small modular SFR configuration /SMFR/) planned in the USA:

A small size (50 to 150 MWe) modular-type reactor is under discussion: uranium-plutonium-minor actinide-zirconium metal alloy fuel; fuel cycle based on pyro-metallurgical processing in facilities integrated with the reactor.

N.B.: Historical reminder regarding the "European Fast Reactor" project (1984 – 1993)

The bases for the "European Fast Reactor" (EFR) co-operation were laid in 1984 when the governments of Belgium, France, Germany, Italy and the UK signed a memorandum of understanding to harmonise their fast reactor development programmes and achieve more efficient pooling of their experiences and resources [59]. Utilities, design companies and R&D organisations were involved during a decade. The main funding was originally provided by national programmes and by utilities from the five EU countries concerned.

Three subsequent specific agreements were signed shortly after 1984:

- the "*R&D Agreement*", relating to research and development, which was signed by European R&D organisations
- the "*Industrial Agreement*", relating to co-operation in design, construction and marketing, which was signed by European design and construction companies
- the "*Intellectual Property Agreement*", setting out the terms and conditions controlling the use of existing and future know-how information at the disposal of the European partners.

More than 1000 specialists worked efficiently together, even though they were located in twenty or so offices and laboratories spread across Europe, and although they belonged to several companies with diverse backgrounds, terms of reference and management structures. The EFR approach was very similar to the above-mentioned three phases of the Generation-IV deployment strategy (viability – performance – demonstration).

One of the main activities of R&D management was to identify current research needs and avoid duplication (or even triplication) of efforts in existing research programmes (related to Phenix, SPX-1 and -2 in France; KNK-2, SNR-300 and SNR-2 in Germany, PFR and CDFR in the UK). For this purpose, EFR created a number of Working Groups called "AGT": AGT is a German-French acronym: ArbeitsGruppe - Groupe de Travail.

Here is the list of AGT Working Groups (each of them comprising tens of different tasks):

> *AGT1 Fuel Elements and Core Materials; AGT2A Sodium Chemistry; AGT2B Instrumentation; AGT3 Core Physics; AGT4 Safety Research; AGT5 Thermal Hydraulics and Core Mechanics; AGT6 Reactor Vessel, Handling, and Auxiliaries; AGT7 Thermal Transfer Systems and Components; AGT8 Reactor Operation; AGT9A Plant Structural Materials; and AGT9B Structural Integrity*.

The end of the EFR Project came almost unnoticed after the Concept Validation Phase, which expired at the end of 1993 (step 2 out of 3). Firstly, the governments, especially in the United Kingdom and in Germany, withdrew from financing the Research and Development Programme. Then the European utilities (European Fast Reactor Utilities Group /EFRUG/) stopped financing the design companies. It is nevertheless considered that the EFR collaboration was a very successful example of how an advanced technological development can be handled across nations, thereby sharing costs and reaping the benefits of international skills and expertise.

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[59] EFR – merge the on-going efforts for the national commercial projects (SuperPheniX-2 or SPX-2 in France, SNR-2 in Germany and CDFR in the United Kingdom) into a single European project (originally 3 step plan) - http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/25/028/25028985.pdf
"*The Story of the European Fast Reactor Cooperation*", Dr. Willy Marth, Kernforschungszentrum Karlsruhe KfK 5255, Dezember 1993 - http://bibliothek.fzk.de/zb/kfk-berichte/KFK5255.pdf

7. Conclusion: science for policy - Euratom leadership in nuclear fission R&D – challenge for the EU

Thanks to Euratom, the European Union will maintain world leadership in nuclear safety, radiation protection, radioactive waste management and decommissioning as well as in non-proliferation (safeguards and security) with the highest level of safety standards. Moreover, fission technologies will be transmitted to coming generations within the framework of a responsible strategy (science for policy). Sustainability comes as an additional challenge in our 21-st century, with requirements such as recycling of fissile and fertile nuclear materials, which are satisfied by GEN-IV reactors of the fast neutron type.

The Euratom research and training programme in nuclear fission naturally contributes to the achievement of the main objectives of the EU's energy and climate policy, namely:

- the EU Energy Union Package (2015) aligned with the ambitious 2008 EU SET Plan: towards secure, sustainable, competitive and affordable energy systems
- the EU Green Deal (2020): towards a European climate-neutral economy by 2050.

Regardless of the EU Member States decisions on continuing, phasing out or embarking in new build nuclear power plants, nuclear energy will continue for the next decades to be part of the energy mix in the EU and also world-wide, especially in a low-carbon economy. Efficient research, innovation and training under Euratom framework programmes are crucial to help achieve the above EU objectives (in particular, regarding the EU Green Deal 2020), which will also help reduce energy and technology dependence at EU level.

In this article, the last two decades of Euratom research, innovation and development in reactor systems and associated fuel manufacturing facilities regarding Generation II, III and IV are taken into consideration, focussing on safety and sustainability. Small and Medium Reactors (SMRs) also require a lot of attention: this technology is a great opportunity for the nuclear industry and could lead to a nuclear renaissance. A number of scientific-technological and socio-political challenges are discussed in connection with the three phases of Generation-IV deployment (viability – performance – demonstration).

The "Technology Roadmap" for the six GIF systems (updated in 2013) and the main Euratom achievements are presented in connection with the GIF objectives:

1. sustainability (in particular, optimal utilization of natural resources and waste minimization) including decarbonisation of the economy and security of supply
2. safety and reliability (through design, technology, regulation and culture)
3. economics (industrial competitiveness, integration in low-carbon energy mix) together with social aspects (in particular, easy access to affordable energy for all)

4. proliferation resistance and physical protection (aligned with the Non-Proliferation Treaty, IAEA 1970).

As a consequence of Euratom accession to the GIF Framework Agreement in 2005, the EU is committed to international cooperation in Generation-IV development. This commitment has been entrusted to the "European Sustainable Nuclear Fission Industrial Initiative" (ESNII) and to the "Nuclear Cogeneration Industrial Initiative" (NC2I). It has been shown that ESNII focusses on the Fast Neutron Reactor systems that are considered as key for the deployment of sustainable nuclear fission energy, that is: Sodium-cooled Fast Reactors (SFR); Lead-cooled Fast Reactors (LFR); Gas-cooled Fast Reactors (GFR); Molten Salt Reactors (MSR); and Super-Critical Water Reactors (SCWR). A fast neutron reactor deployment would extract far greater energy per tonne of uranium than is obtained from other reactors (gain factor of up to 50 as compared to LWR fleet). On the other hand, NC2I focusses on nuclear fission applications beyond electricity production – in particular, process heat supply (including chemicals refinement and hydrogen production). NC2I is concentrated on the Very High Temperature Reactors (VHTR), with thermal neutron spectrum. As a consequence, EU/Euratom contributions cover all six GIF reactor systems.

As regards the criterion of competitiveness, considerable effort is being put by both the research community and the industrial organisations concerned, into reducing the costs of installed capacity (euro/kWe) and of power generation (euro/MWh). Also worth noting is the challenge of integrating nuclear fission in a low-carbon energy mix: this is actually the main change compared to the start of GIF in 2000 when the question was focused on Gen IV versus Gen III, while still assuming reactors would operate in baseload.

As far as the future of Euratom research and training programmes is concerned, it should be noted that the Scientific and Technical Committee /STC/ (Euratom Treaty - Article 7) put the following questions to the Euratom community (i.e., a challenge for the EU):

- what should be the immediate research priorities to be considered at EU level?
- what are the key assumptions underpinning the development of these priorities?
- what is the output and impact that could be foreseen if the development of these priorities is successful?
- which are the bottlenecks, risks and uncertainties, and how could these be addressed?
- which science and technology gaps and potential game changers need to be taken into account?
- what are the perspectives for cross-thematic activities of Euratom research with other areas under Horizon Europe 2021-2027?
- what are the perspectives for supporting horizontal activities, notably international cooperation, education and training, social sciences and humanities?

Restoring the nuclear industry's lead in technology development is critical in the EU if it is to regain its attractiveness as a sector to work in. Transmission of knowledge, skills and competences to coming generations is at the heart of Euratom programmes (see Euratom Treaty, 1957). The central role of the "European Nuclear Education Network" (ENEN) in this regard has been illustrated. Results were presented of the close co-operation of organisations involved in the application and teaching of nuclear science and ionising radiation, including universities, research organisations, industry and regulatory bodies.

EU research and innovation programmes (in particular in the nuclear fission sector) are conducted in the context of a new governance structure, based on greater openness, participation, accountability, effectiveness and coherence. In the Euratom R&D programmes, participation of all stakeholders, for example, through SNETP ("Sustainable Nuclear Energy Technology Platform") helps to build the climate of confidence that is needed to continuously improve applications of nuclear fission science and technology, notably through the development of sustainable Generation-IV reactor systems.

More generally, effective interaction is maintained in the Euratom nuclear fission community thanks to the participation of all stakeholders concerned, i.e.:

- research organisations (e.g., public and private sectors)
- systems suppliers (e.g., nuclear vendors, engineering companies)
- energy providers (e.g., electrical utilities and associated fuel cycle industry)
- technical safety organizations (TSO) associated with nuclear regulatory authorities
- academia and higher education and training institutions dedicated to nuclear
- civil society (e.g., policy makers & opinion leaders), NGOs, citizens' associations).

In conclusion, a new way of "developing / teaching science" is emerging in the EU, closer to end-user needs of the 21st century (in particular, society and industry). A strong scientific foundation is being established to support decision making in regulatory and/or industrial organisations, based on confirmed facts and research findings stemming from "Best Available Science". For example, proper impact assessment methodologies are being developed in the EU energy policy decision process to compare the pros and cons of the primary energy sources (renewables, fossil and nuclear) in terms of sustainable development, security of supply and industrial competitiveness.

As a result of this "science for policy" approach, science is no longer confined to the laboratories: it is discussed in the public arena. A clear signal is sent to the young generations to undertake scientific studies in the field of energy - in particular, nuclear - which will contribute to optimize the energy mix in accordance with the expectations of the 21st century (towards secure, sustainable, competitive and affordable energy systems).

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GENERATION IV CONCEPTS: EURATOM

Breakthrough technologies to improve sustainability, safety & reliability, socio-economics and proliferation resistance

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