European Commission

JRC SCIENCE FOR POLICY REPORT

Horizon Scanning for Nuclear Safety and security Yearly Report - 2021

Creating an anticipatory capacity within the JRC

Tanarro Colodron, J., Simola, K., Gerbelova, H., Cihlar, M., Liessens, A., Joanny, G., Renda, G., Colle, J-Y., Griveau, J.-Chr., Vigier, S., Vanleeuw, D., Cambriani, A.

2022

Joint Research Centre

EUR 30987 EN

Contact information
Name: F. Wastin
Address: Westerduinweg 3, 1755 LE Petten
Email: Franck.Wastin@ec.europa.eu
Tel.: +31-224 56 5066

EU Science Hub
https://ec.europa.eu/jrc

JRC128002

EUR 30987 EN

PDF ISBN 978-92-76-47243-8 ISSN 1831-9424 doi:10.2760/645368

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Tanarro Colodron, J., Simola, K., Gerbelova, H., Cihlar, M., Liessens, A., Joanny, G., Renda, G., Colle, J-Y., Griveau, J.-Chr., Vigier, S., Vanleeuw, D., Cambriani, A., *Horizon Scanning for Nuclear Safety and Security, Yearly report - 2021*, EUR 30987, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47243-8, doi:10.2760/645368, JRC128002.

Contents

Abstract

Horizon Scanning (HS) is a systematic outlook to detect early signs of potentially important developments. JRC.I.2 unit introduced the methodology in 2016 and, in collaboration with partner JRC Knowledge Management Units, tested it for a horizon scanning process at JRC level. JRC.G.9 benefited from this support and followed the methodology in subsequent years. Throughout 2021 JRC has collected a number of ideas related to nuclear technology, that were later on pre-filtered and finally clustered in a so-called 'sense-making workshop'. This report presents the outcome of this yearly exercise.

Executive summary

The JRC has adopted an approach to **strengthen its anticipatory capacity** with the aim to better support the policy-making within the Commission. In this context and within Dir G, the horizon scanning is used as a tool to detect and analyse early signs in order to identify important emerging issues in the field of nuclear safety, security and safeguards.

The scanning of relevant news items, then the filtering of these items followed by a sense-making workshop resulted in the following **foresight stories**:

- **Circular economy of nuclear material for increased sustainability**

A reliable fuel supply and a sustainable fuel cycle are of crucial importance for successful nuclear energy production in the future. Recent technological development in both ends of the fuel cycle (fuel production and waste management) are promising, but the integration of those individual concepts in a coherent and sustainable fuel cycle may be challenging in terms of safety, security, safeguard and technology. In addition, economic and legal constraints are slowing down progress. The adaptation of a better licensing framework, a more open fuel and waste market and the consideration of the fuel cycle as a whole would speed up the closing of the fuel cycle.

- **Need for a consistent and inclusive nuclear EU policy**

The highly polemical approach to nuclear energy at European political level has a significant impact on public acceptance in the Member States. The nonalignment between EU leaders creates uncertainty about the future deployment of nuclear and persistent differences between the Member States cause difficulties in maintaining the role of nuclear energy in the EU.

- **A surge of transportable nuclear reactors shaped by space exploration**

Pressurized water reactors (PWRs) were initially developed for propulsion of military submarines. Currently, almost 70% of all nuclear reactors producing electricity are PWRs. As nuclear industry gets ready to evolve and even revolve the most advanced reactor designs to make them mobile and small enough to compete with diesel generators, the driving initiatives to bring them to the market at a competitive price start to take shape.

In parallel to this Horizon Scanning exercise, a **bibliographic data analysis** was performed to add insights about the following technological developments:

- <u>3D printing</u>

In this year's exercise two emerging technologies related to 3D printing were identified: 3D printing nuclear fuel and 3D printing cemented carbide. Cemented carbide is mostly used as cutting tool material but it is also relevant for the nuclear industry regarding the fabrication of the pump pistons for high-performance pumps.

- <u>Autonomous operation</u>

The references captured by the "autonomous operation" query do not refer to full autonomous operation replacing the nuclear power plant human operator but rather the application of artificial intelligence algorithms such as neural networks and deep learning over very specific processes such as the control of the pressurizer, the power level control or the start-up of the reactor.

- <u>Microbiological protection against radiation</u>

The subject refers to the research dedicated to study the relation between gut microbiota and radiation injuries. Mainly targeting to improve the wellbeing of patients of

radiotherapy, the findings could also mitigate the related risks for those exposed to radiation in their professional environment.

The annexes of this report contain a list of staff involved in the process, an explanation about the bibliographic analysis tool and a detailed explanation about the horizon scanning methodology.

Follow-up actions may include in-depth studies and deep-dive discussions carried out on request of stakeholders and other parties, depending on their interest in any of these subjects.

1 Introduction

The JRC Strategy 2030[1] specifically stresses the need for the JRC to develop anticipation by stating the following in its chapter 8 ("*A stronger anticipation culture*"):

"There are many reasons why the Commission's anticipatory capacity needs to be strengthened. First, it would enable it to identify its knowledge needs very early on. This would give it time to amass the evidence it needs to launch well prepared policies and proposals in a timely fashion. It would be able to future-proof its impact assessments and its REFIT evaluations. Anticipating social changes and public opinion movements would contribute to shaping public debates and proposing new narratives, instead of being on the defensive."

In this context, the *horizon scanning* has been identified as one of the necessary tools *"which strives to identify and make sense of weak and diffuse indications of still hazy emerging trends or paradigm shifts"*.

The *Horizon Scanning for Nuclear Safety and Security* exercise is an initiative that attempts to build on this capacity and to provide anticipatory support by:

- Embedding a culture of anticipation throughout Dir G.
- Developing expertise in the use of the *horizon scanning* to detect and analyse early signs in order to identify important emerging issues.

In order to detect these early signs of potentially important developments, three different actions led by groups of experts were carried out in the exercise:

- Continuous scanning of nuclear technology sources by *Scanners* from across the JRC Dir G who picked up single ideas that were recorded in CONNECTED. The list of Horizon Scanners from Dir G can be found in Annex 1.
- Pre-filtering sessions led by *Aggregators* who collected the relevant scanned ideas and organised the discussions for the scanners, to involve them in the selection of ideas and to take the time to discuss and share views and ideas. The list of Scanners and Aggregators contributing to the Horizon Scanning for Nuclear Safety and Security can also be found in Annex 1.
- A sense-making workshop led by *Aggregators* who compiled the ideas selected in the pre-filtering sessions, selected sets of relevant items, and organised the discussions. The list of Aggregators contributing to the Horizon Scanning for Nuclear Safety and Security can also be found in Annex 1.
- Bibliographic data analysis exercises by analysts who performed a quantitative study of the scientific literature addressing the research topics underlying the clusters of ideas identified during the workshops. The data analysts involved are amongst the authors of this report.

The chapter dedicated to the *Nuclear Technology Observatory* summarises the results obtained after studying, with the JRC *Tools for Innovation Monitoring* (TIM), the technologies referenced by the ideas identified during the continuous scanning, thus enabling an assessment and better understanding of their potential importance and implications.

[1] https://ec.europa.eu/jrc/sites/jrcsh/files/jrc-strategy-2030_en.pdf

2 Foresight stories

The foresight stories aim to capture the possible impact in ten years and beyond of the weak signals considered most interesting today. They are the main outcome of the sense-making workshop, a creative process in which the group reflects jointly about the further-reaching consequences of on-going and emerging trends. Foresight reflections looking up to ten and more years in the future were developed, identifying the capacities and vulnerabilities related to three selected clusters of ideas, which are developed in the paragraphs below.

2.1 Circular economy of nuclear material for increased sustainability

A reliable fuel supply and a sustainable fuel cycle are of crucial importance for a successful and efficient production of nuclear energy in the future. Recent developments in innovative reactor concepts may lead to a diversification of nuclear fuels. At the other end of the fuel cycle, we have progress in partitioning and transmutation (such as the MYRRHA reactor as actinide burner), or a more recent design for further utilisation of spent nuclear fuel for district heating. These concepts can potentially support the development of a more sustainable fuel cycle and nuclear energy production.

To achieve sustainability, those new concepts may need the development of an entire new fuel cycle – mining, reprocessing, fabrication, irradiation, waste management and final disposal – different from the present ones. This may be challenging in terms of safety, security, safeguard and technology.

While we see advances in technological development in both ends of the fuel cycle, political, economical, legal and technological constraints and challenges are slowing down the progress. On the other hand, reprocessing of nuclear fuel could gain momentum due to limitations of waste storage and increased pressure on uranium demand. The closing of the fuel cycle could be accelerated by adapting the legal framework to better cope with the evolution of the technology, with the global markets for energy production, fuel and waste and by considering the duel cycle as a whole.

Further, the legislation needs to be prepared for an increase in nuclear material transportation due to the geographical spreading of nuclear technology, including mobile micro nuclear reactors. A sustainable circular economy of nuclear materials, including operational final disposal when needed, could improve the public acceptance of nuclear.

2.1.1 Time horizons

At present, there is not much diversity in nuclear fuel types used in the EU. The fuel in the majority of EU nuclear power plants consists of UO_2 ceramic fuel, with uranium enriched up to about 4.8% U-235. The Romanian CANDU reactors are designed for the use of natural or low enriched uranium, and about 10% of the nuclear fuel in France is mixed uranium oxide and plutonium oxide (MOX) fuel. There is however a lot of development of new fuel types going on due to e.g. several Gen IV reactor designs, or small and micro reactor concepts. At present, the nuclear fuel cycle is either an open cycle, where the once used fuel is not treated further, or a twice-through cycle in which Pu is recycled once in MOX fuel in current reactors. Fuel reprocessing, recycling of fissile material and final disposal techniques exist, although still not economically attractive and thus not fully exploited. The opposition to nuclear energy, especially due to concerns of nuclear waste, is still strong in many countries. This affects the political decisions, especially if the public does not trust the nuclear waste disposal solutions.

In the **mid-term**, with the emerging development of new reactor concepts, we can see more variety in nuclear fuels. Advances have been made in the development of accident tolerant fuels (ATF), many SMR designs rely on high-assay low-enriched uranium (HALEU) fuel, with 5% and 20% U-235 enrichment levels, and some of the new reactor concepts have e.g. fuel dissolved in molten salt. Although there is still an abundance of uranium, geopolitical tensions might affect the market, leading to restriction on fuel supply. Such tensions might boost the interest in diversification of fuel sources, and the use of thorium as a nuclear fuel might be accelerated in the mid-term. The rigidity of the actual licensing framework may cause delays in the approval of new reactor concepts with non-conventional nuclear fuel solutions. The new fuel developments call for new spent fuel management concepts. Increased sustainability demands will lead to the consideration of closing the fuel cycle for plutonium and further actinides management.

In the longer term, a larger variety of evolutionary nuclear fuels and their associated waste can be expected. Further, an increase in geographical dispersion of reactors, including floating nuclear power generation or nuclear propulsion in transport, might be seen. These call for an appropriate legal framework for managing the fuel and waste markets.

New technologies are being developed for the production of fuel and for the reprocessing of nuclear waste in order to valorise the fission products, e.g. by extracting rare elements from waste. In an optimistic scenario, a sustainable circular economy for nuclear materials might be in sight, where nuclear waste is considered as a valuable resource. In case of a failure in timely preparation for the deployment of evolutionary fuels, a proper waste management strategy might be lacking, causing the accumulation of nuclear waste in countries in the absence of a solution for radioactive waste management.

2.1.2 Relevant news

New fuels:

- 30/07/2020 - Gryphon to help develop HALEU-fuelled cislunar rocket 🌐
- 23/02/2012 - Ten years after Fukushima: could new fuels make nuclear power safer? 🌐
- 14/06/2021 - South Korea's KAERI And Samsung To Develop Molten Salt Reactor For Maritime Use 🌐
- 01/09/2021 - European and American companies are about to produce nuclear fuel for space rocket propulsion 🌐
- 09/07/2021 - CNL to create the world's first "finned" CANDU fuel 🌐

Increasing fuel demand:

- 13/05/2021 - Can the ocean fuel China's nuclear boom? 🌐
- 24/09/2021 Uranium prices are skyrocketing 🌐
- 04/11/2021 - China to supercharge uranium race with 150 new nuclear reactors 🌐

Valorisation of nuclear waste:

- 13/06/2021 - Nuclear waste recycling is a critical path towards energy innovation 🌐
- 16/03/2021 - Scientists gain insight into recycling processes for nuclear and electronic waste 🌐
- 09/01/2021 - Promising research to address nuclear waste and get more benefits 🌐
- 30/03/2021 - A unique Czech nuclear "Teplátor" using spent nuclear fuel can replace coal-fired heating plants 🌐
- 17/09/2020 - Bacterial enzyme extracts rare elements in an environmentally friendly way 🌐

Geopolitics:

- 06/10/2020 - Moscow sees nuclear as more than just an energy source 🌐

2.2 Need for a consistent and inclusive nuclear EU policy

Nuclear energy currently contributes significantly to CO2 emissions reductions from the power sector. Several energy/climate reports state that to meet the Paris Agreement target of not exceeding a 2°C rise in temperature, global nuclear capacity would play a crucial role. The highly polemical approach to nuclear energy at European political level has a significant impact on its public acceptance in the Member States. The nonalignment between EU leaders creates uncertainty about the future deployment of nuclear and persistent differences between the Member States cause difficulties in maintaining the role of nuclear energy in the EU.

The current lack of consistent policy context contributes to uncertainty in public perception, creates obstacles to technology development and causes difficulties in maintaining the knowledge and personnel qualification. The plans of some EU countries to phase out nuclear power in the relatively near future also raise questions about reaching EU's carbon emission goals, low carbon energy security and energy independence. By contrast, Russia and China are gaining momentum and becoming dominant players in the global nuclear industry with clear intentions of using nuclear export to gain geopolitical influence.

2.2.1 Time horizons

At present, the EU has 106 nuclear power reactors generating nuclear electricity in 13 of the 27 EU Member States. Nuclear energy contributes to approximately a quarter of the energy mix while ensuring the EU's climate objectives through its low carbon electricity production. Moreover, the long history of the nuclear sector has created great value in terms of experienced personnel, skills and vocational training. The progressive development of safety regulations and measures in the EU has contributed to making nuclear a safe and reliable source of energy. However, a significant part of Europe's nuclear power plants will soon reach the end of their operational lifetime. Extending the operational lifetime of an existing fleet emerges as the most feasible option to maintain the share of nuclear energy in the EU energy mix in **the short-term**.

Several EU Member States like Germany, Belgium or Spain have planned a gradual phasing-out of nuclear energy. Some others, such as France, the Czech Republic, Slovakia and Poland and 6 others, foresee nuclear energy as the main source of low-carbon energy and solicit a supporting policy framework for its future deployment. To reach an informed political consensus on nuclear energy programmes, it is essential to focus on enhancing the general knowledge of nuclear energy and non-power applications among European citizens and to improve its public perception. Recent public opinion data on nuclear energy acceptance combined with behavioural insights approaches could help in guiding campaigns aimed at rebalancing risk and risk perceptions related to nuclear power.

Trends show that younger generations seem to be more sensitive to climate issues, leading to higher acceptance of nuclear energy. Furthermore, the demonstrations of nuclear power plants in integrated systems with non-electrical applications (such as heat or hydrogen production) and for non-energy purposes (such as medical and space applications) may show the importance and multipurpose use of the nuclear energy. This way it can inform a greater number of consumers about potential benefits of nuclear energy. A global stronger public acceptance could lead policy makers to reconsider the opportunities and risks of nuclear energy and their applications.

A continuous decline of nuclear industry may pose a risk to the EU's energy dependence on non-European countries as well as to the loss of nuclear know-how **in the long-term**. The EU would not only lose its global position in the nuclear sector but could also experience increased EU internal political tensions due to the different approaches to nuclear energy in the individual Member States and potential safety issues. A clearer vision of the role of nuclear energy for Europe can support the development of advanced technologies, attract new talent and raise public awareness of nuclear power opportunities. These opportunities would sustain existing valuable capacities, thus maintaining the important role for the EU nuclear industry worldwide, strengthening the EU strategic energy autonomy and preserving the EU recognition within international organisations in contributing to global nuclear safety and security.

2.2.2 Relevant news

Improving public acceptance of nuclear energy:

- 15/09/2020 - Investors in the nuclear industry are acting based on public confidence.
- 31/08/2020 - Policies related to speed transitioning to a low-carbon economy and society might cause unintended consequences and reduce expected positive results.
- 27/05/2021 - Focusing behavioral insights studies and practice on nuclear energy acceptance could help in creating consensus and facilitate future steps on energy and climate policies.
- 30/07/2021 - A national public opinion survey conducted in the US found that support for nuclear energy grows with climate change concerns when analyzing trends over the last 38 years.

Unclear EU strategy for the future deployment of nuclear energy:

- 25/11/2020 - Czech nuclear expansion faces delay amid concerns of opposition, secret services.
- 08/10/2020 - Slovakia's Prime Minister Igor Matovič intends to set up an alliance of countries using nuclear energy in the EU.
- 26/02/2021 – Sweden must reconsider its nuclear policy due to the shortage of electricity supply after closure one of its nuclear power plant.
- 25/03/2021 - The leaders of seven European countries have issued a joint letter to the European commission to ensure that EU energy and climate policy accommodates nuclear in the EU climate and energy policies and incentives.
- 26/05/2021 – The IEA report suggests reconsidering phasing-out nuclear energy in Spain and maintaining the high level of nuclear technology infrastructure and skilled professionals for developing and implementing long-term energy strategies including nuclear.
- 15/06/2021 – Germany's Court of Auditors asks for scrutinizing the government's measures and goals during the energy transition and warns about the security of energy supply after shutting down nuclear and coal at the same time.
- 23/08/2021 - The Horizon 238 think-tank urges Belgian's Prime Minister Alexander De Croo to reconsider 'counterproductive' nuclear phase-out plans and asks to implement a long-term policy with review of possible 10 years life extension for the newest NPPs.
- 10/11/2021 - President Emmanuel Macron commits to restarting nuclear power development in France in order to better meet growing energy and environmental challenges

Russia and China becoming dominant players in the global nuclear market:

- 06/10/2020 - Moscow sees nuclear as more than just an energy source.
- 06/11/2020 - China would require an estimated quadrupling of nuclear power achieving carbon-neutrality before 2060.

2.3 A surge of transportable nuclear reactors driven from space

Pressurized water reactors (PWRs) were initially developed for propulsion of military submarines. Currently, almost 70% of all nuclear reactors producing electricity are PWRs. As nuclear industry gets ready to evolve and even revolve the most advanced reactor designs to make them mobile and small enough to compete with diesel generators, the driving initiatives to bring them to the market at a competitive price start to take shape.

While Russia seems to be investing heavily in the RITM-200 reactor, designed for powering up icebreakers, nuclear technology innovators in the United States bring their attention to the applications of nuclear reactors for space exploration, already anticipating the profitable advantages for those running ahead in the space race.

The European Union is still to decide whether to focus on enforcing a demanding regulation within its borders as premium client or to become a relevant actor in shaping the revolution of this strategic technology even beyond the planet.

2.3.1 Time horizons

At present the European Union has solid frameworks supporting aerospace and nuclear technological development and innovative research such as the European Space Agency and the Euratom treaty. There are also excellent academic institutions addressing these fields of study and mature industries employing a significant knowledgeable workforce. However, the still strong divergences within the European Union with respect to the use of nuclear technologies lead to uncertainties in future market potential and investments and create strong inertias resisting change and fearing the disruptive consequences of a technological revolution. A more integrated nuclear regulatory framework within Europe would sustain the economies of scale deriving from the possibility of deploying factory-ready microreactors in a potential market of 400 million consumers.

In the midterm, as the interest of developing countries in acquiring small nuclear power plants grow due to the lower cost of capital, limited grid size, stronger safety case and the related geopolitical prestige, the business case for transportable nuclear power such as floating nuclear reactors might gain momentum and attract further private investment. Once profitable businesses such as digital services, space tourism or asteroid mining start operating effectively from space, public investment would find even greater incentives to continue supporting space exploration through clear and concrete milestones such as sending crewed missions to the Moon and even Mars. These ambitious common endeavours could transform the political and social perception of enabling technologies such as transportable nuclear reactors, attracting the attention and interest of the most talented engineers and scientists.

Following this trend, **the longer-term** might see how those research and development efforts find practical applications and markets here on Earth even before their original purpose is accomplished. Transportable nuclear reactors built for space exploration might become a clean competitive alternative to diesel generators. A compact and reliable energy source able to propel merchant ships, to speed up progress in developing countries, to guarantee the power supply of critical infrastructure in all circumstances or to be deployed within hours as emergency power supply in areas devastated by natural disasters. Nuclear regulatory authorities would have to become highly agile and innovative to adjust to the new safety and security challenges when dealing with a much more distributed and mobile nuclear fleet subject to ever evolving digital vulnerabilities brought by increased connectivity and autonomy.

2.3.2 Relevant news

Transportable nuclear reactors for space exploration:

- 12/02/2021 - NASA concluded that in order to send humans to Mars repeatedly and in a sustainable way, nuclear space propulsion is needed.
- 13/07/2021 - NASA working with the Department of Energy (DOE) selected three reactor design concept proposals for a nuclear thermal propulsion system which would utilize high-assay low-enriched uranium fuel.
- 23/10/2021 - Investing more in nuclear space propulsion would help the United States to be competitive with China.
- 30/10/2021 - Former SpaceX engineers founded a company to build 'climate-friendly, cost-effective' portable nuclear reactors.

The space business case:

- 11/10/2021 - A space manufacturing startup expects to launch its first spacecraft in early 2023 to demonstrate the production of a wide range of materials in microgravity.
- 15/10/2021 - The company Space Adventures is ready to send Japanese online retail tycoon Yusaku Maezawa to the International Space Station (ISS) in December.
- 26/10/2021 - China launched the NEO-1 in April, the first commercial spacecraft dedicated to asteroid mining.
- 01/11/2021 - Amazon plans to launch its first prototype broadband satellites in late 2022 to compete with the Starlink satellites.

Floating nuclear reactors:

- 02/11/2020 - Terrapower, a company owned by Bill Gates, is planning to develop a marine Molten Salt Reactor to power large ships.
- 17/12/2020 - Seaborg has raised about €20m from private investors to bring to the market their 'nuclear barges'.
- 09/08/2021 - Rusatom Overseas has received a license to build a small nuclear plant with a RITM-200 reactor, originally designed to power icebreaker ships, at a site in Ust-Kuyga, in the Republic of Sakha (Yakutia).
- 17/09/2021 - Atomflot and Atomenergomash, both Russian companies, have reached an agreement to deploy four floating nuclear plants, each one with two RITM-200 reactors, to a copper and gold mining project in Chukotka.

3 Nuclear Technology Observatory

In parallel to the Horizon Scanning exercise, a bibliographic data analysis was performed with the aim to complement the Horizon Scanning conclusions with additional valuable insights about technologic developments such as:

- The relations amongst technologies, visualising how often they appear together in the same document.
- The maturity of the related research by observing the amount of scientific literature available on the technology as well as its evolution through time.
- Their *"activeness"*, as defined in the TIM tool, considering the number of publications on the technology released over the last three years in relation to the total number of scientific publications for the technology.
- The countries with more scientific activity on the topic.

For a more extended explanation of the terms and parameters used for this analysis, please consult *Annex 2. Bibliographic analysis tool and approach*.

As explained in the referenced annex, the graph visualisations (figure 1) presented in the following subchapters consist of:

- A **label** or dataset title that summarises the meaning of the search query.
- A **node** or circle, corresponding to each label, with an area equivalent to the number of documents retrieved by the search query.
- Several **edges** or relations corresponding to the number of documents retrieved simultaneously by two different searches that correspond to two different nodes.
- A **colour** code identifying the groups of nodes, or clusters, that tend to have more documents in common among each other according to the so-called Louvain Modularity algorithm.

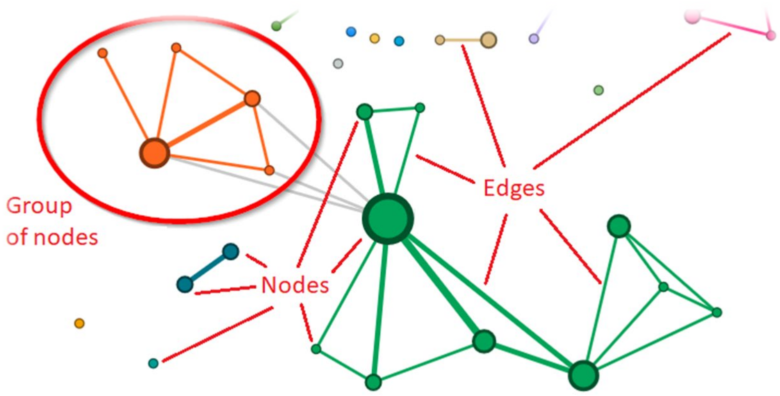
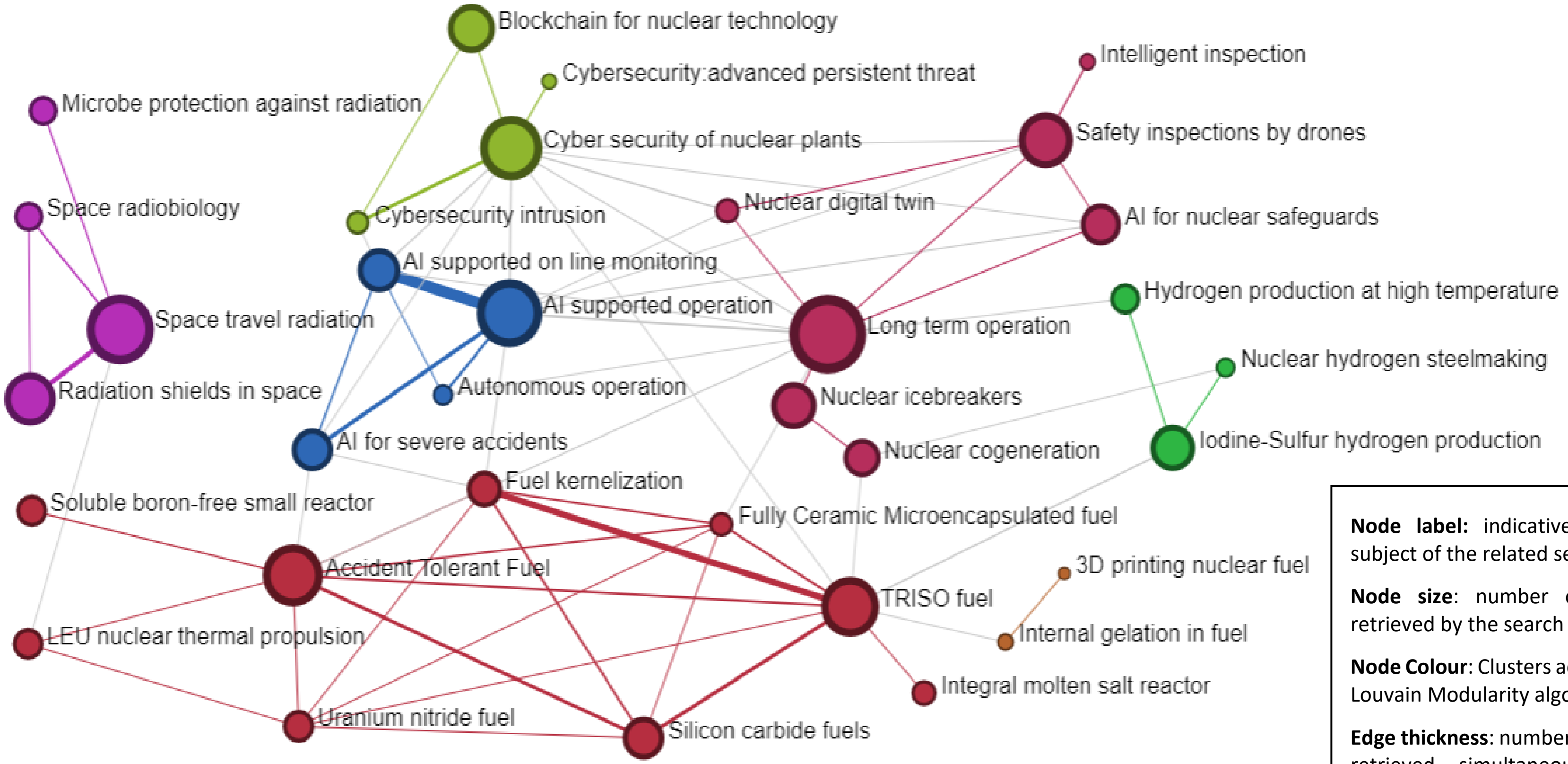


Figure 1. Network graph legend

The figure below (figure 2) shows the nuclear technologies recorded during the year and studied for this analysis that are connected in the main cluster.



Node label: indicative title of the subject of the related search query.

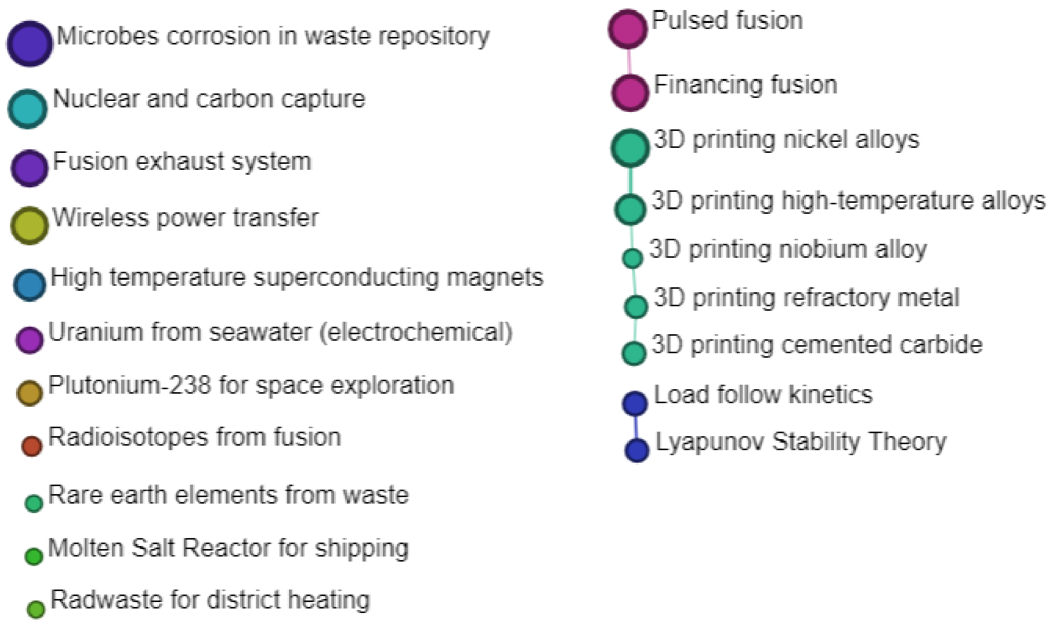
Node size: number of documents retrieved by the search query.

Node Colour: Clusters according to the Louvain Modularity algorithm.

Edge thickness: number of documents retrieved simultaneously by two different search queries.

Figure 2. TIM nuclear technologies 2021 datasetgram: Main cluster

The figure below (figure 3) shows the nuclear technologies recorded during the year and studied for this analysis that are **not** connected to the main cluster.



Node label: indicative title of the subject of the related search query.

Node size: number of documents retrieved by the search query.

Node Colour: Clusters according to the Louvain Modularity algorithm.

Edge thickness: number of documents retrieved simultaneously by two different search queries.

Figure 3. TIM nuclear technologies 2021 datasetgram: disconnected

The focus lies on the technologies with an "*activeness*" indicator higher than 50, meaning that the majority of their related documents were published in the last three years, which is considered to be an indication of emerging technologies, i.e. rapidly growing in time.

The technologies are the following:

Technology	Activeness (2019 - 2021)	Foresight reference
3D printing nuclear fuel	100	**New emerging trend**
Nuclear digital twin	94	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report - 2020
Uranium from seawater	76	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report - 2020
Blockchain for nuclear technology	73	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report - 2018
Cybersecurity intrusion	71	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report - 2018
3D printing cemented carbide	66	**New emerging trend**
Autonomous operation	66	**New emerging trend**
Soluble boron-free small reactor	53	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report - 2020
Microbe protection against radiation	51	**New emerging trend**
Accident Tolerant Fuel	51	Horizon Scanning for Nuclear Safety, Security & Safeguards Yearly Report – 2018

Some of these technologies had already been identified in previous Horizon Scanning exercises and the fact that they still have an activeness indicator above 50 indicates that they continued growing in the last year.

Below is a presentation of the new emerging trends detected.

3.1 3D printing

3D printing is the additive manufacturing of digital three-dimensional models referring to the different processes in which the material is added to the physical product under computer control.

In this year's exercise we identified two emerging technologies related to 3D printing: 3D printing nuclear fuel and 3D printing cemented carbide. Cemented carbide is mostly used as cutting tool material but it is also relevant for the nuclear industry regarding the fabrication of the pump pistons for high-performance pumps.

The following query was used to extract from TIM the information about patents, conference proceedings and scientific articles related to 3D printing of nuclear fuel:

topic:("3D printing" AND ("nuclear reactor" OR "nuclear power") AND fuel)

The query retrieved just four articles from Switzerland, China, South Korea and of Brazil in collaboration with the United States. Most of the references relate to the 3D printing of zirconium alloy. The historic distribution of those publications is shown in the figure below (figure 4).

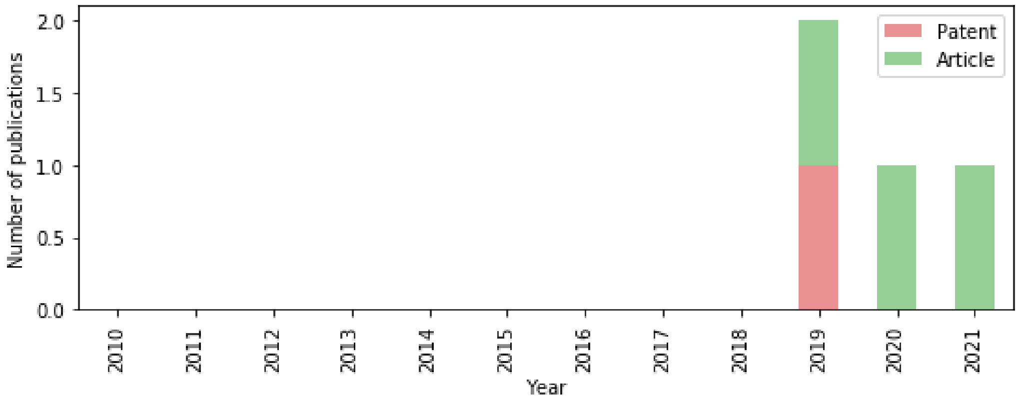


Figure 4. '3D printing nuclear fuel' dataset document type distribution

To extract from TIM the information about patents, conference proceedings and scientific articles related to 3D printing cemented carbide, the following query was used:

topic:("3D printing" AND "cemented carbide")

This query generated a dataset of 18 documents. The historic distribution of those publications is shown in the figure below (figure 5).

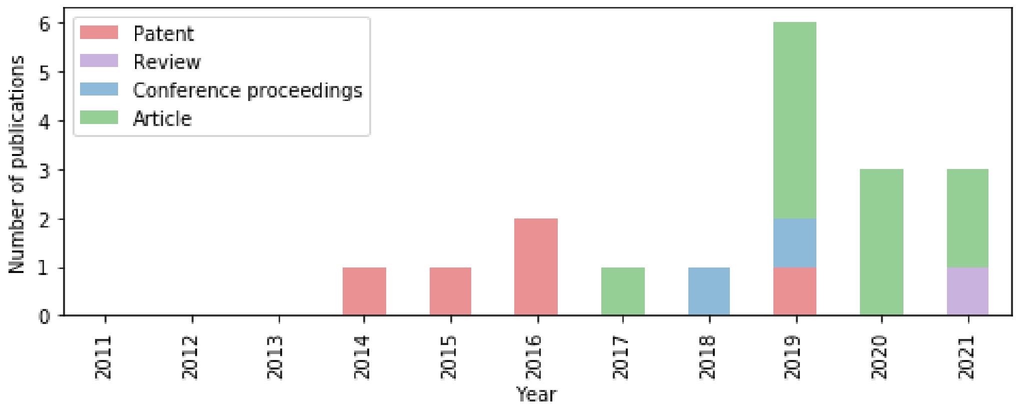


Figure 5. '3D printing cemented carbide' dataset document type distribution

According to the figure below (figure 6) the European Union seems to be relatively well positioned on the related research.

Figure 6. TIM network graph on '3D printing cemented carbide' world publications distribution.

Looking instead at [EMM Finder] to retrieve the pieces of news published in the press and use its dedicated algorithm to estimate the *'sentiment'* (the subjective information reflected in the text), we observe the trend displayed in the figure below (figure 7) for the query used for 3D printing of nuclear fuel.

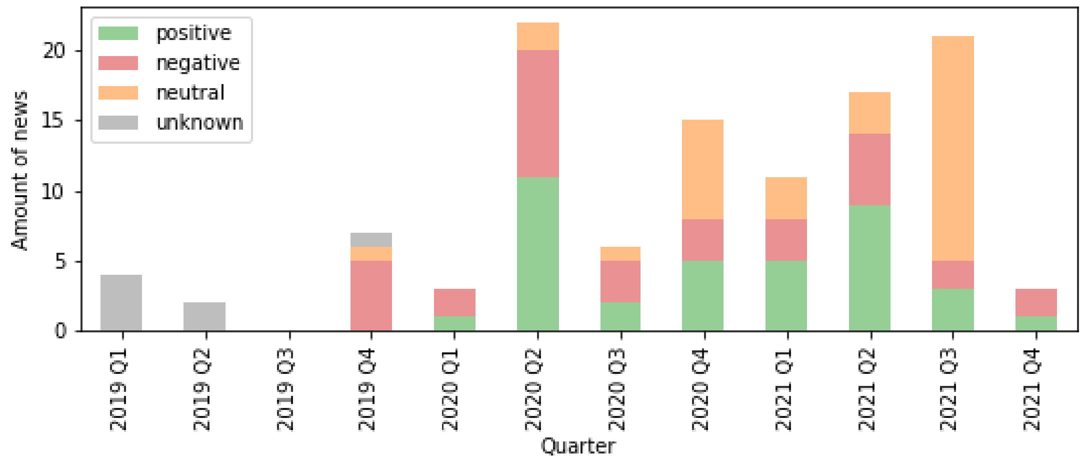


Figure 7. EMM Finder data on '3D printing nuclear fuel' news distribution.

For 3D printing cemented carbide the trend is presented in the figure below (figure 8).

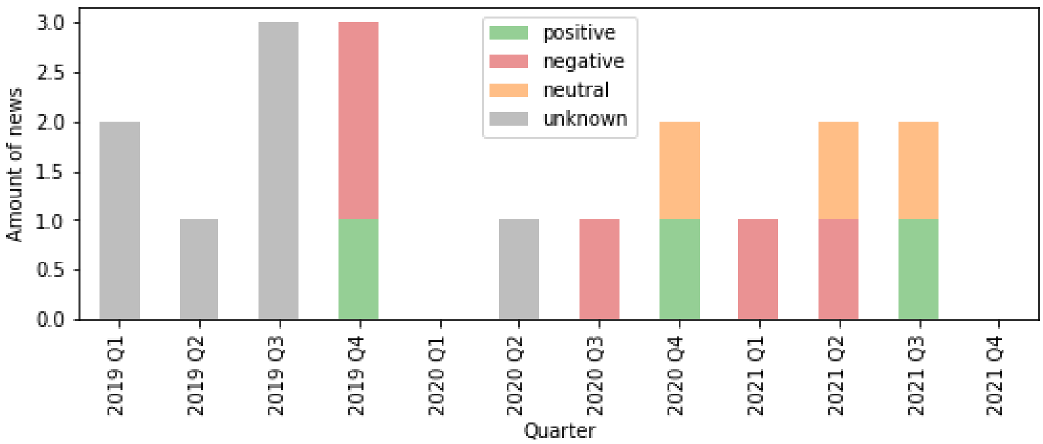


Figure 8. EMM Finder data on '3D printing cemented carbide' news distribution.

3.2 Autonomous operation

The references captured by the "autonomous operation" query do not refer to full autonomous operation replacing the nuclear power plant human operator but rather the application of artificial intelligence algorithms such as neural networks and deep learning over very specific processes such as the control of the pressurizer, the power level control or the start-up of the reactor.

The following query was used to extract from TIM the data about patents, conference proceedings and scientific articles related to autonomous operation:

topic:(("nuclear reactor" OR "nuclear power") AND "autonomous operation" AND ("artificial intelligence" OR "deep learning" OR "machine learning" OR "neural network") NOT (agriculture OR food))

This query generated a dataset of 9 documents. The historic distribution of those publications is shown in the figure below (figure 9).

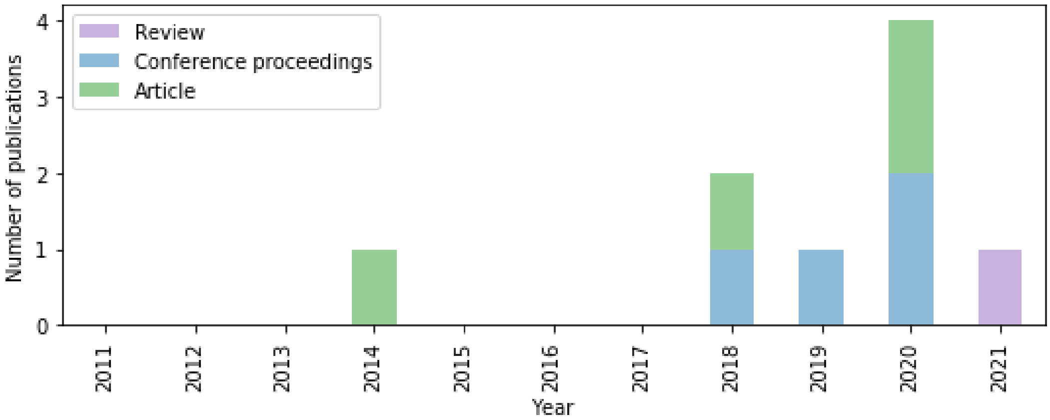


Figure 9. 'Autonomous operation' dataset document type distribution

According to the figure below (figure 10) no country within the European Union seems to have produced relevant related research.

Node label: country of origin of the documents retrieved by the search query.

Node size: number of documents retrieved by the search query.

Edge thickness: number of documents with origin on two different countries.

Figure 10. TIM network graph on 'autonomous operation' world publications distribution

Applying instead the same query in [EMM Finder] to retrieve the pieces of news published in the press and use its dedicated algorithm to estimate the *'sentiment'* (the subjective information reflected in the text), we observe the trend displayed in the figure below (figure 11).

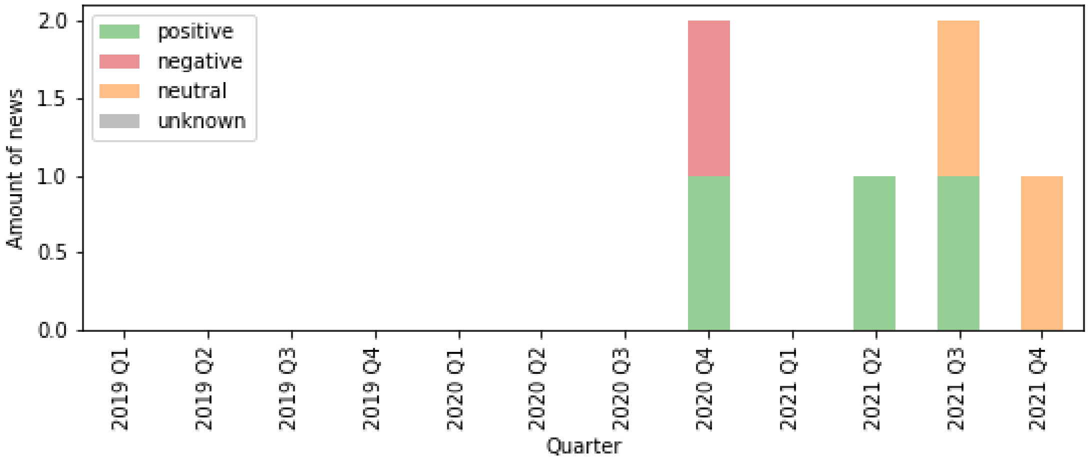


Figure 11. EMM Finder data on 'autonomous operation' news distribution.

In this case, the system retrieved very few pieces of news that considered several different examples of artificial intelligence applications, being the operation of nuclear reactors just one of them.

3.3 Microbe protection against radiation

The subject refers to the research dedicated to study the relation between gut microbiota and radiation injuries. Mainly targeting to improve the wellbeing of patients of radiotherapy, the findings could also mitigate the related risks for those exposed to radiation in their professional environment.

The following query was used to extract the information about patents, conference proceedings and academic articles related to microbe protection against radiation from TIM:

topic: ("radiation exposure" AND (bacteria OR microbes OR microbiota) AND (gut OR intestine OR gastrointestinal))

This query generated a dataset of 31 documents. The historic distribution of those publications is shown in the figure below (figure 12).

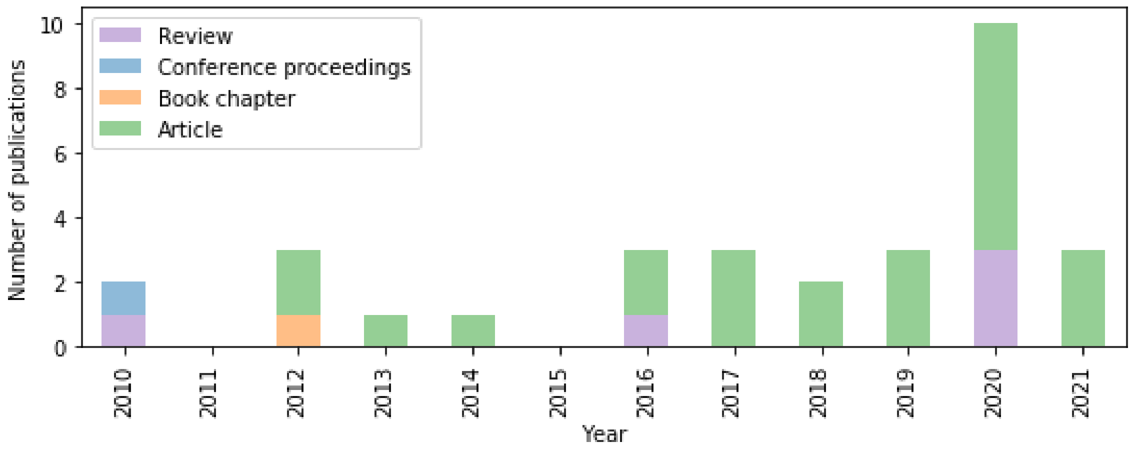
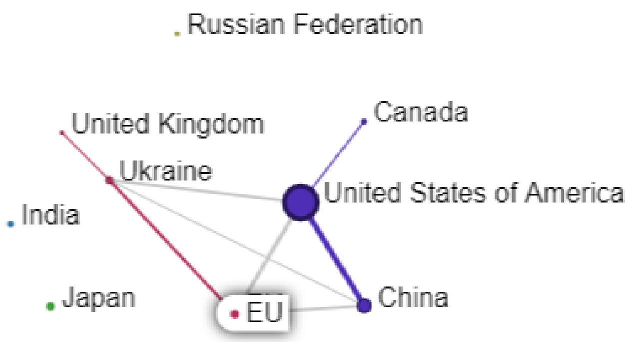


Figure 12. 'Microbe protection against radiation' dataset document type distribution

In this case the United States seem to be the most prolific followed by China. The contribution of the European Union seems more modest although well connected with those two leading countries (figure 13).



Node label: country of origin of the documents retrieved by the search query.

Node size: number of documents retrieved by the search query.

Edge thickness: number of documents with origin on two different countries.

Figure 13. TIM network graph on 'microbe protection against radiation' world publications distribution

Applying instead the same query in [EMM Finder]() to retrieve the pieces of news published in the press and use its dedicated algorithm to estimate the *'sentiment'* (the subjective information reflected in the text), we observe the trend displayed in the figure below (figure 14).

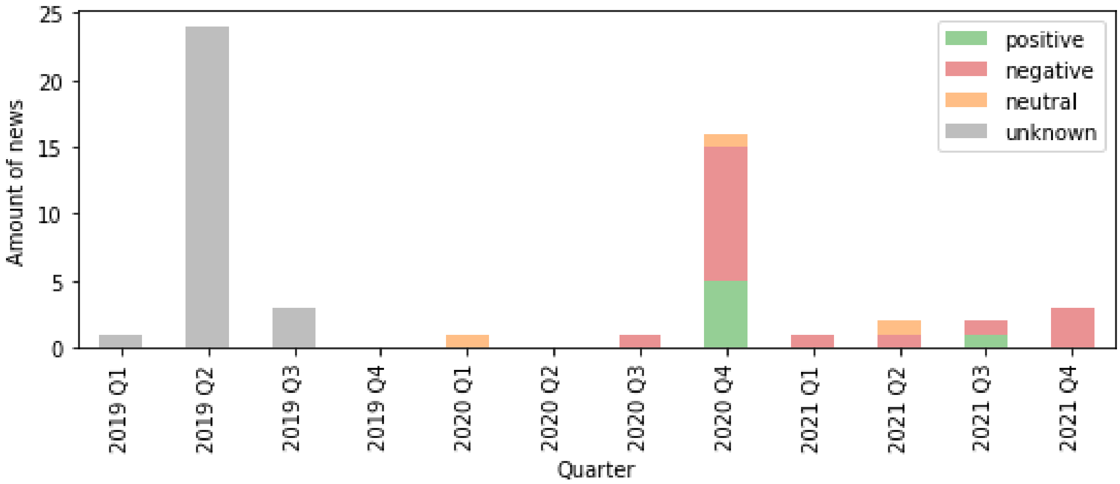


Figure 14. EMM Finder data on 'microbe protection against radiation' news distribution.

The predominant negative sentiment of the sample might be related to the connotation of medical applications often accompanied by concepts such as 'injury', 'sickness' or 'pain'.

4 Conclusions

During 2021, twenty *Horizon Scanners* from Dir G identified and recorded in *Connected* about 300 ideas with an impact in the development of nuclear technology that were first discussed during the pre-filtering sessions, and eventually during the sense-making workshop organised remotely using *Microsoft Teams* and *Miro*. In the process, the following JRC tools were used:

- *Connected* for the registration and voting of the new ideas as well as for the organisation of the sense-making workshops.
- The *European Media Monitor* (EMM) to automatically retrieve news about new ideas and developments concerning nuclear technology.
- The *Tools for Innovation Monitoring* (TIM) to explore the characteristics and relations between the identified technologies analysing the related scientific literature, patent data and data from R&D projects funded by the EU.

The topics that occupied most of the discussion time during the workshop and that focused the attention of the participating experts were:

- *Circular economy of nuclear material for increased sustainability*
- *Need for a consistent and inclusive nuclear EU policy*
- *A surge of transportable nuclear reactors shaped by space exploration*

Additionally, the bibliographic data analysis has been made in TIM. It has identified the following emerging technologies:

1. *3D printing*
2. *Autonomous operation*
3. *Microbiological protection against radiation*

This report contains a brief overview of these subjects as they were identified during the oversight activities carried out during the year. Follow-up actions may include in-depth studies and deep-dive discussions carried out on request of stakeholders and other parties, depending on their interest in any of these subjects.

5 Annexes

5.1 Annex 1. Horizon Scanning participants

5.1.1 List of appointed Horizon Scanners from Dir G

- HEYSE, Jan – JRC.G.2 (Geel)
- VANLEEUW, David – JRC.G.2 (Geel)
- CAMBRIANI, Andrea – JRC.G.I.3 (Karlsruhe)
- COLLE, Jean-Yves – JRC.G.I.3 (Karlsruhe)
- ROSENGARD, Ulf– JRC.G.I.4 (Petten)
- DE LA ROSA BLUL, Juan Carlos– JRC.G.I.4 (Petten)
- GRIVEAU Jean-Christophe – JRC.G.I.5 (Karlsruhe)
- ALVAREZ SARANDES LAVANDERA, Rafael – JRC.G.I.6 (Karlsruhe)
- FONGARO, Lorenzo – JRC.G.I.6 (Karlsruhe)
- VERSINO, Cristina – JRC.G.II.7 (Ispra)
- RENDA, Guido – JRC.G.II.7 (Ispra)
- RAUFF-NISTHAR, Nadya – JRC.G.II.8 (Karlsruhe)
- VIGIER, Sandrine – JRC.G.II.8 (Karlsruhe)
- HUBERT, Philippe – JRC.J (Ispra)
- CIHLAR, Milan – JRC.G.9 (Petten)
- GERBELOVA, Hana – JRC.G.9 (Petten)
- SIMIC, Zdenko – JRC.G.9 (Petten)
- SIMOLA, Kaisa – JRC.G.9 (Petten)

5.1.2 List of Aggregators contributing to the Horizon Scanning for Nuclear Safety and security

- LIESSENS, Ariane – JRC.G.9 (Petten)
- TANARRO COLODRON, Jorge – JRC.G.9 (Petten)

5.2 Annex 2. Bibliographic analysis tool and approach

5.2.1 JRC Tools for Innovation Monitoring (TIM)

The JRC *Tools for Innovation Monitoring* (TIM) are used to explore the characteristics and relations between the observed technologies analysing the related scientific literature, patent data and data from R&D projects funded by the EU.

TIM produces visualisations of the data with edges and nodes (i.e., network graphs). A graph that represents all the datasets defined and their documents in common is created(see figure 2). These datasets are defined using a search query that should contain the intended keywords connected by Boolean operators for each of the technologies corresponding to the identified cluster. The graph visualisation of all the resulting dataset consists on:

- A **label** or dataset title that summarises the meaning of the search query.
- A **node** or circle, corresponding to each label, with an area equivalent to the number of documents retrieved by the search query.
- Several **edges** or relations corresponding to the number of documents retrieved simultaneously by two different searches that correspond to two different nodes.
- A **colour** code identifying the groups of nodes that tend to have more documents in common among each other according to the so-called Louvain Modularity algorithm.

Datasets referring to the different technologies can be compared and their relations identified by analysing the resulting graph. This means that in order to study one specific technology in TIM, it is necessary to create first its related dataset, one for every technology. This collection of datasets can be then visualised as a graph called '*datasetgram*' in the TIM software.

In this type of visualisation, each node represents a dataset related to each of the technologies. The colours identify the groups of nodes that tend to have more documents in common among each other. These groups are detected using the so-called Louvain Modularity algorithm described by Blondel et al in https://arxiv.org/abs/0803.0476

In addition, TIM computes the so-called '*activeness*' score for each of the datasets. The *Activeness indicator* returns the number of documents of a dataset in the three last years, divided by the total number of documents of the dataset. Thus, nodes with most of their hits falling in the last three years of the time range will get a score closer to 100 and nodes with almost no hit in the last three years will get a score closer to 0.

5.2.2 Approach

Each dataset was studied separately using the insights acquired from TIM in order to identify promising technologies that are non-obvious or just recently identified but likely to gain significant weight in the future.

Promising new technologies can be found in small nodes linked with another couple of nodes. We selected the ones that have an 'activeness' TIM indicator of above 50%.

The proposed query strings for the datasets were reviewed and, when necessary, corrected by experts from JRC.I.3. Their expert assessment and advice on the use of the JRC *Tools for Innovation Monitoring* (TIM) and the interpretation of its results was also taken into account for the preparation of the conclusions of this report.

TIM provided us with the following information:

- The "*activeness*" TIM index.
- The number of connecting edges for each dataset.
- The total number of documents retrieved for each dataset.

- The charts visualising the document type total distribution and their yearly distribution.
- The countries where the documents were produced.

It is also important to notice that TIM contains references up to August 2021, meaning that when comparing the number of documents retrieved for 2021 with previous years there might be a drop to be interpreted just as a drop in data coverage.

5.3 Annex 3. Methodology

The *Horizon Scanning for Nuclear Safety and Security* as implemented at the JRC consists now of the following stages:

5.3.1 Scanning

Within the scanning phase, the scanners capture items/factual information coming from a large variety of sources. The items should be "raw" information (not necessarily analysed by someone else), reports on single developments, facts based and objective, concise, new developments and from many apparently unrelated domains. Just "opinions" or "advices" are not considered relevant for the exercise. We are looking for what "*can be"* or "*will be"* not for what "*should be"* or "*must be"*.

The sources are the materials or media providing well identified "raw" information on novelties. They may include journals providing concise news reports, scientific publications, reports, professional journals, conference proceedings, trade and business publications, magazines and newspaper, social media, blogs etc. The sources may also include already existing specialised scanning systems. For example, the Europe Media Monitor or shortly "EMM" is being used for finding relevant items about innovative developments on nuclear technology.

The items found within the scanning process are stored on the dedicated site of *Connected,* called *Horizon scanning – submit*. Once stored on *Connected*, the items become "ideas". The ideas are established according the following principles:

- An idea is created by choosing *Create an Idea* on the "Actions" menu or the box on the left of the screen.
- The new idea describing the item must have a clear title, a brief summary (maximum ½ page), a short explanation about its importance, the date of publication and the link to the source or attachment.
- The idea can be classified under one or more categories available in the edition screen, ticking at least the "*nuclear"* category.
- The idea is registered after clicking the button "Publish" at the bottom of the edition screen.

Before every workshop, which takes place several times a year, the aggregators check and if necessary improve the format of the ideas captured in Connected and provide the participants with instructions on how to prepare the workshop at least a week in advance of the sense-making workshop.

5.3.2 Pre-filtering

5.3.2.1 Purpose

The methodology updated in 2020 to better suit the needs of the Horizon Scanning within Dir G was continued in 2021. The number of ideas submitted on Connected even increased in such way that not two but three pre-filtering sessions were needed during the year. These sessions not only improve the quality of the input of the sense-making session but also allow to involve the scanners in the selection of ideas and to take the time to discuss and share views and ideas.

5.3.2.2 Preparation

When a reasonable number (80-100) of ideas related to nuclear are published on the dedicated site of *Connected*, a pre-filtering session is planned, to which all scanners are invited.

The aggregator responsible for managing the session (the facilitator) checks the ideas collected on *Connected* and formats them in a way that is user-friendly for the scanners.

The instructions for preparing the session are sent to the participating scanners about a week in advance of the pre-filtering session.

Before the session, the participants must go through the list of ideas and select their top 5-10 ideas that are the most interesting. They are asked to vote for their selected ideas through the dedicated feature on Connected. They should also write down why they think the chosen ideas are important, preferably by using the comment feature under the idea in *Connected*.

5.3.2.3 Participation

During the session, the participants put forward their selected ideas, explaining why they are important. This key aspect of the selection is the basis for discussions.

The aggregator(s) write down the selected ideas and harvest the essence of the discussions.

5.3.2.4 Reporting

The outcomes of each pre-filtering session are recorded in a document, which is complemented with each following pre-filtering session. The colleagues from the G.9 HS team contribute to this reporting.
In 2021, pre-filtering sessions were held in March, June and September, whereas the sense-making workshop took place in October.

5.3.3 Sense-making workshop

5.3.3.1 Preparation

About a week before the workshop, the document containing the outcome of the pre-filtering sessions aggregator is sent to the scanners together with the instructions for the preparation of the workshop.

Before the workshop, the participants must go through the list of ideas and think about how some of them would fit together suggesting an emerging trend or phenomena and gather those fitting together into clusters. They should write down the names and numbers of the ideas clustered and give the cluster a title to be presented during the workshop session.

The workshop is not a classification exercise, so there is no need to include all ideas in clusters. The aim of the workshop session is neither to criticise the abstracts nor to cover everything, but rather to collect the concepts which indicate new trends and emerging issues. Each participant is expected to present around three clusters.

5.3.3.2 Participation

In the sense-making workshop, participants try to cluster different ideas together to see what emerging issues can be found.

A cluster is a group of two or more ideas that can be linked in some way as a potential evidence for an emerging issue. Emerging issues may be new trends, weak signals, drivers of change, or discontinuities. They may also include outlier behaviour, unconventional wisdom or new technologies that could indicate future changes with potential significant impact on society and policy. Usually, the emerging issues are developments at an early stage that had not been seriously considered yet.

The participants usually tend to find clusters that confirm their previous ideas, which may not be a problem. However, as the workshop is meant to be an open and creative exercise, the participants should not hold back, even if they may feel that the cluster is "unthinkable".

The structure of the workshop is the following:

1. *Clustering of ideas*: Participants write down individually their own clusters (title, premise, and the numbers of the related ideas) on yellow post-its. When the workshop is held online, the organiser fulfilling the role of harvester creates the post-its on a digital whiteboard that is visible to all participants.
2. *Presentation of clusters*: Participants take turns to present their clusters and put them on a board or wall. When the workshop is held online, participants will write their clusters in digital tool allowing the harvester to put it on the whiteboard.
3. *Grouping the clusters*: The participants discuss the clusters to validate their different titles and group the ones strongly related into wider or more accurate narratives recorded (title and numbers) on pink post-its. When the workshop is held online, this is coordinated by the harvester on the whiteboard.
4. *Grouping the participants*: The participants separate the groups of clusters on the wall into three sections. Each section will be further developed by the participants in small groups. The participants can in principle choose the section that they would like to work on, but an equal distribution of participants between the smaller groups is preferred. The organisers provide one facilitator for each group to ensure the necessary structure, explanation and moderation of the discussions.
5. *Development of foresight stories in small groups*: Each small group shall develop one foresight story related to the clusters available in their section. For this purpose a methodology is proposed by the organisers, involving a PowerPoint containing the clusters for each small group and followed by suggestions for the discussions and questions to answer.
6. *Presentation of each foresight story*: a representative of each small group presents and explains the group's foresight story in the plenary meeting. Participants can ask questions and make comments to make sure the story is well understood.
7. *Forward-looking questions*: after each presentation in the plenary, participants are asked to come up with questions related to the future development of the story. The purpose is not to answer these questions, but to raise awareness about critical issues.
8. *Final capture*: The results of the session obtained are recorded in pictures, either from the physical wall of from the Miro digital board. The PowerPoint slides are also saved, giving special attention to the codes of the ideas related to each of them.

Teamwork and collaboration among the participants are especially relevant for refining and merging the clusters (stage 3) and for the development of foresight stories (stage 5).

5.3.4 All activities held online in 2021

In 2021, all Horizon Scanning activities were held online due to the restrictions on physical meetings related to the COVID-19 pandemic.

The pre-filtering sessions were held in a virtual meeting room. For the sense-making workshops, the virtual meeting room was complemented with the use of breakout rooms for parallel discussions in smaller groups. Also, special software allowing to work with all participants together on a virtual whiteboard was used.

Holding the activities online also generated the need to attribute tasks more clearly within the organising team. One person took the role of host, moderator and time-keeper; another acted as harvester and (virtual white)board manager. Additionally three persons from the organising team held the role of moderators during the work in smaller groups.

5.3.5 Reporting

The outcomes of the first pre-filtering session are recorded in a document which will contain the ideas (from Connected) that were picked out in the collective exercise, as well as the topics detected from the batch of selected ideas. After each subsequent pre-filtering session, the document is complemented with news topics and new ideas (from Connected), which can be related to new topics, or to those already identified. This document serves as a basis for the sense-making workshop which takes place every year around October.

The outcomes of the sense-making workshop are recorded in the present yearly report, which explains the three foresight stories developed by the smaller groups during the workshop, identifying the related possible risks and opportunities.

The nature of the exercise entails that these signs are neither predictions nor research conclusions; they are only indications or intuitive guesses made using a creative process of connecting the potential consequences of different recent developments.

List of abbreviations and definitions

3D	3-dimensional
ATF	Accident Tolerant Fuel
CANDU	Canada Deuterium Uranium
COVID	COronaVIrus Disease
Dir G	Nuclear Safety and Security Directorate
EMM	European Media Monitor
EU	European Union
HALEU	High-Assay Low-Enriched Uranium
HS	Horizon Scanning
JRC	Joint Research Centre
JRC.G.9	Knowledge for Nuclear Safety and Decommissioning unit
JRC.I.2	Foresight, Behavioural Insights & Design for Policy unit
JRC.I.3	Text and Data Mining unit
MOX	Mixed Oxyde
PWR	Pressurised Water Reactor
REFIT	The regulatory fitness and performance programme
RITM-200	Generation 3 pressurised water reactor
SMR	Small Modular Reactor
TIM	JRC Tools for Innovation Monitoring

List of figures

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
- at the following standard number: +32 22999696, or
- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-30987-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office
of the European Union

doi:10.2760/645368

ISBN 978-92-76-47243-8