Nuclear Innovation 2050

An NEA initiative to accelerate R&D and market deployment of innovative nuclear fission technologies to contribute to a sustainable energy future

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NUCLEAR INNOVATION 2050

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"Nuclear technology has not reflected the innovation that would be expected of a high technology industry over the years...

... if you had the operations and maintenance crews of a nuclear power plant who retired 30 years ago come back today, they would pretty much pick up where they left off. There's not a lot that has changed...

There's virtually no other current technology industry you can say that about. The truth is, we simply haven't innovated and that is beginning to now bite."

William D. Magwood, IV,
Director-General, OECD Nuclear Energy Agency

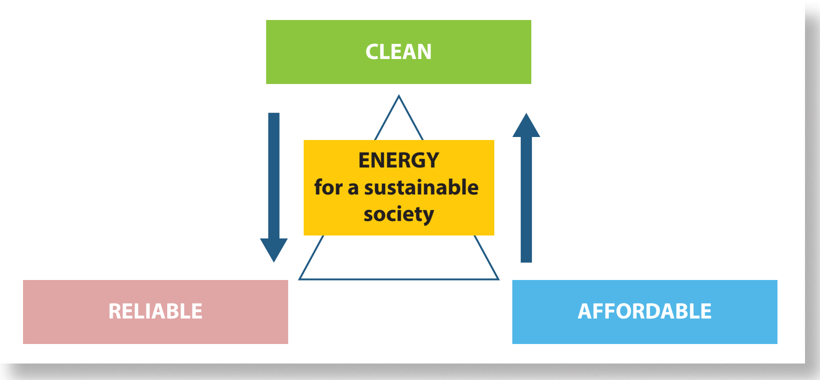
Speaking at the Virginia Nuclear Energy Consortium Authority Board Meeting, 7 June 2018

Why innovate - Why NI2050

The development and deployment of nuclear power has led to the most successful and fast "energy transition" in the last century, leading to the installation of 340 GWe over 40 years, accounting for around 18% of the global electricity generation at its peak in 1996. The historical growth of nuclear in the global energy generation was even faster than for hydropower and natural gas, helped by the high density of nuclear power plants.

Today, climate change is a central societal issue that has resulted in the need to deeply decarbonise the economy, and the energy sector in particular. The concept of the "energy transition" is high on many policy making agendas. It will be critical to ensure the right balance in the energy mix of the future, based on an energy policy delivering sustainable development through: i) global environmental protection; ii) affordability and competitiveness; and iii) security and reliability of energy supply.

Figure 1:
Sound and sustainable energy policy: Clean, affordable and reliable



Nuclear energy, as confirmed by the recent United Nations Intergovernmental Panel on Climate Change (IPCC) Report issued in October 2018, could play a role in the necessary energy transition towards a very low carbon energy mix. However, the total nuclear generation capacity has fallen by nearly 10% since 2006, resulting in a share of global electricity generation of only around 11% today. This is primarily due to the post Fukushima temporary shutdown of a number of plants in Japan, but also due to permanent closures in Japan, the United States and Europe. In some cases, they are the result of a political nuclear phase out decision; in others, the result of a lack of competitiveness of nuclear power plants in evolving electricity markets, due to low natural gas prices and/or subsidised renewables. Finally, while a number of reactors are under construction mainly in China and Russia, most of the new build projects in the United States and Western Europe have suffered schedule delays and budget overruns, making investors reluctant to further engage.

Innovation is therefore necessary to develop and bring to the market new nuclear technologies that will be able to compete in the global energy markets of the future, being cheaper, more flexible and faster to deploy than the nuclear technologies of yesterday, while continuing to meet high levels of safety. This applies to the traditional nuclear reactor systems per se, but also to the numerous necessary enabling technologies, both nuclear and non-nuclear specific, including those from other industrial domains where breakthroughs have been continuously matured and implemented.

For this reason, in 2015, the Nuclear Energy Agency (NEA) launched a broad initiative on nuclear innovation, potentially covering a wide scope of technology areas, addressing reactor systems design and operation, fuels and fuel cycle technologies, waste management and decommissioning, and applications beyond electricity generation, in particular to tackle the potential of the heat market and the corresponding increased flexibility in operation.

As a start, a survey of nationally funded nuclear R&D programmes showed that the overall nuclear public research budgets had stayed rather stable on a yearly basis over the last two decades. The lack of innovation appeared not to be directly related to a drastic decrease in financial support from the public authorities for their national laboratories.

It seemed that the root cause was the lack of ability to focus and streamline the objectives of these R&D programmes, and even more, to foster the effective transfer of the results of R&D towards market deployment. Very quickly, the NI2050 dialogue moved to the need to involve both the industry and the safety authorities early on and then throughout the innovation process, to enable the effective transformation from R&D to market readiness within a reasonable timeframe. This led also to embracing the full range of technology readiness levels (TRLs), from the early R&D steps up to industrial-scale demonstration for market readiness, classically linked with the well-known concept of the "valley of death" of evolving risk profiles as costs and investment needs are escalating.

Early in the NI2050 process it was necessary to focus the scope on areas and topics where the NEA, as an intergovernmental organisation, could make a real contribution to boost innovation. This was strongly reinforced by the rather diversified nuclear developments taking place in different parts of the world, at a different pace, in particular in terms of new reactor concepts and designs. As a result, NI2050 did not look at reactor designs per se, but focused more on cross-cutting issues, either from an enabling technology point of view (such as the application of heat uses and cogeneration, advanced materials and big data), or from an innovation process point of view. A prime example of the latter is engaging with the safety authorities early enough to ensure that innovative technologies are effectively integrated in terms of their licensing.

Overcoming headwinds to nuclear innovation

In order to further refine the activities under the NI2050 heading, a deeper analysis of the issues at stake in terms of the process of innovation led to the identification of three major barriers to be overcome. Each one of them is as important as any of the others.

The first is the complexity of financing increasing costs over the extended duration of innovation in the nuclear sector. Compared to most other sectors, the timeline for innovation is usually much longer than the policy making and investment timelines. National budgets are not expected to fully support the entire innovation process. Industry and the private investors need to come on board. Uncertainties associated with policy changes and extended financing periods often render the risk of nuclear innovation too high. Shortening the time to market is therefore critical.

The second, connected with the first, is the evolution of the regulatory framework. Since it is widely accepted that regulators, as independent bodies, are not promoters of nuclear technology innovation per se in most countries, they do not actively take part in the technology development process. In some cases, this is reinforced by the increased workloads associated with license renewals and extensions when fleets are reaching the end of their design lifetimes. Waiting until a new technology reaches high maturity before regulatory engagement leads to delays due to ineffective information exchanges, increasing uncertainties and costs. As a result, the regulatory process is often perceived as a barrier to innovation.

Another aspect to consider is the very national dimension of the regulatory processes, making the wide market penetration of innovative technologies more time consuming, more costly and more risky. Fostering the collaborative involvement of regulators early in the innovation process at an international level would help reduce the risk of innovation.

The third is the infrastructure necessary to support nuclear innovation. Nuclear technology development requires the availability of specific facilities, and in particular research reactors, test loops and special instrumentation, hot cells and manipulators, and special transportation means. It also requires a ready-for-purpose supply chain. All the equipment and, globally speaking, the supply chain, needs to be qualified and licensed. Beyond these hard infrastructures, soft infrastructures such as huge, validated information databases as well as trained, skilled and licensed personnel are also necessary.

Much of the existing infrastructure was built more than 40 (and even 60 for some important ones) years ago and is shrinking steadily, going out of service having reached its end of life or due to the lack of well organised, optimised usage. Supply chains can also wither and die if there is not a reasonable prospect for a sustainable business.

This analysis of the barriers to innovation allows a better definition of where the NI2050 should help to boost innovation: the main focus is on improving the innovation process through a better control of the costs and timelines. Innovation can be boosted through a more effective and timely involvement of all the stakeholders, and an optimised use of the necessary infrastructure. The NI2050 Advisory Panel has selected some technology areas and topics, where a collaborative approach might foster the innovation process. These are:

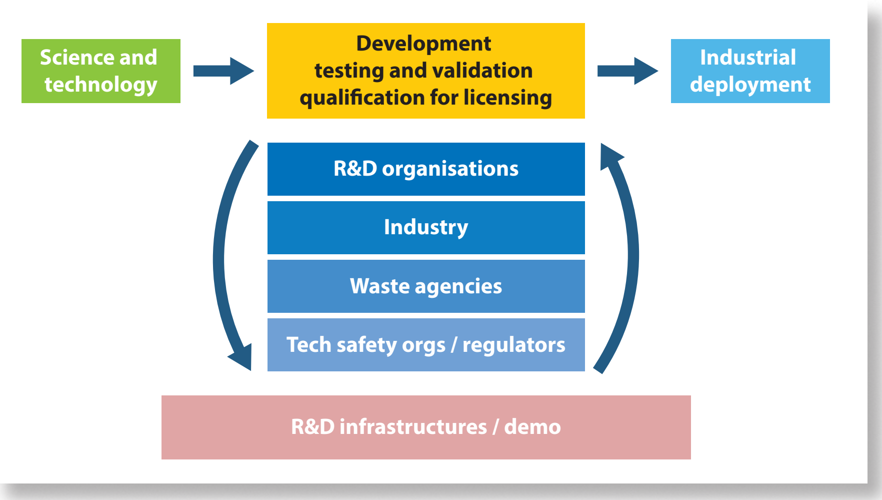
- passive safety systems and improved accident management;
- ageing management;
- advanced fuels and materials;
- advanced fuel cycles;
- decommissioning techniques;
- heat and cogeneration.

For each of these areas a roadmap was developed, using a standard template, describing a way forward to accelerate innovation: beginning with the state of play and progressing on to what can be done to reduce the costs and time to market.

The timely involvement of all stakeholders

The central concept for NI2050 was derived from the above considerations: accelerating the innovation process by a more effective and timely interaction between all the stakeholders to bring the results of science and technology research to deployment readiness. This means integrating licensing and economic aspects early on in the process of innovation by involving industry and regulatory authorities in the development, testing, validation and qualification phases of a technology.

Figure 2: **Going from science to market deployment: All stakeholders need to be on board**



If Figure 2 principles are implemented at an international level, involving a number of engaged parties that agree to build adequate testing, validation and qualification pipelines for the chosen technologies, it would lead to increased harmonisation, opening larger potential markets for additional products based on these technologies. This optimised paradigm would be appealing for industry and it would attract it to proactively engage in the process from the beginning.

Involving the regulatory authorities from the early stages of the innovation process was also necessary. Through the NI2050 dialogue, and relying upon the two key NEA standing technical committees, respectively in charge of regulatory (Committee on Nuclear Regulatory Activities, CNRA) and research/expertise (Committee on the Safety of Nuclear Installations, CSNI) activities, nuclear safety regulators confirmed that any new technology introduction should be seen, amongst other objectives, as a way to maintain, and even improve, the safety of installations. Indeed, working proactively on innovative technologies and processes in a conducive international environment was perceived as more effective than at the national level, where the necessary independence of the regulators makes early interaction with research and industry more sensitive.

In addition, a collaborative approach among the regulators, ensures an effective and successful licensing process in different countries, thus increasing the confidence of the technology providers and users and broadening the potential market base.

Last but not least, developing testing, validation and qualification pipelines at the international level, would naturally lead to a more effective use of research infrastructures, both hard and soft, at a time of global limited availability of resources.

Another way to present the same concept is to think in terms of a better alignment between technology readiness levels (TRL) and licensing readiness levels (LRL) (Figure 3).

There are plenty of cases where time, and consequently money, has been lost due to the lack of such alignment. Sometimes research and industry develop a new technology up to a TRL of around 6 or 7, only to need to go back to the drawing board (i.e. a lower TRL) when faced with numerous questions from the regulator, who is seeing the technology for the first time. Involving the regulator earlier in the process should help reducing the risk of having to go back and forth along the TRL scale.

Figure 3: **A key to success: Better aligning technology and licensing readiness**

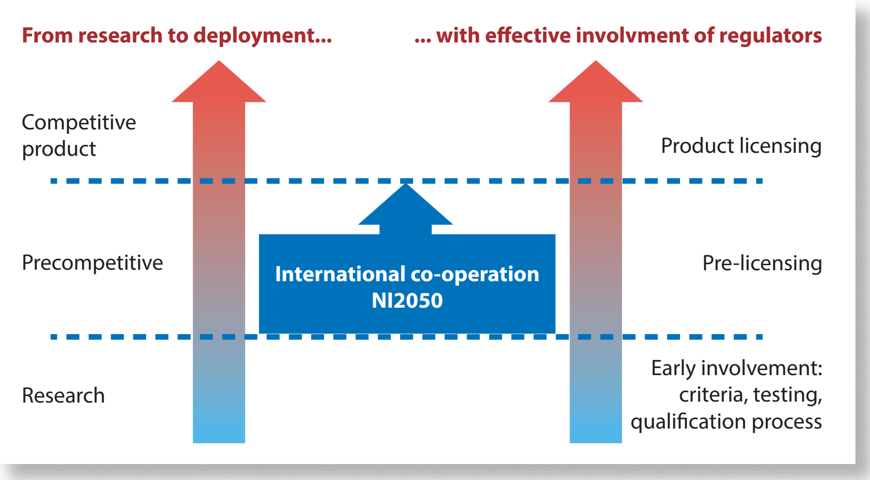


Figure 3 also shows that there are limits to the effectiveness, or even the feasibility, of international co-operation to help align TRLs and LRLs. The domain in which international co-operation is most effective is the area of precompetitive (TRLs)/pre-licensing (LRLs) phases. And here again, collaborating on the innovation process, such as the testing, validation and qualification pipelines, instead of the technology per se, offers the greatest potential for effectiveness and success, as it was demonstrated through the application of the NI2050 concept described herein to concrete cases.

The central concept of NI2050, beyond technology development aspects, consists of building together, among truly interested parties, pipelines for testing, validation and qualification of technologies before these technologies become industrial products, ensuring that all stakeholders, in particular regulators, are involved from an early stage of the process. These pipelines have to be set up and themselves validated using a sample of the technology, selected together by all stakeholders. Once a pipeline is operational for a technology, industry may then use it for qualifying industry products, in a much more effective way than having to redo the full qualification process from scratch for each new product and for each separate country or market.

Concrete outcomes from NI2050

NI2050 was launched in July 2015 and first operated for three and a half years under the umbrella of a dedicated Advisory Panel. A number of "innovation roadmaps" were developed for some selected technological areas and topics, proposing programmes of actions to accelerate innovation, while integrating the state of the art in these fields. This approach, in particular, allows benefit from activities and outcomes of existing working groups and parties within the NEA framework, while fostering a better horizontal interaction. This applies in particular to a number of working groups and parties operating under the umbrella of the NEA Nuclear Science Committee.

These "innovation roadmaps", all following the same template, constitute the main outcome of NI2050 to date. Three such roadmaps are described below; the full roadmaps can be found on the NI2050 dedicated website at www.oecd-nea.org/ndd/ni2050/. Once finalised and approved by the Advisory Panel, the roadmaps are channelled to appropriate ad hoc groups of interested parties or experts, mostly within the NEA framework, where they can be further developed into very detailed action plans for implementation.

1) *Improving the qualification process to accelerate the industrial deployment of advanced fuels*

Advanced fuel technologies are available at diverse levels of maturity in laboratories and fuel vendors. This reduces the potential for a wide co-operative process for a common development of advanced fuels technologies. The question of a collaborative process for validation and qualification of such advanced fuels, including in the licensing perspective, was therefore at the centre of the discussions at the NEA, in line with the NI2050 concept. The aim of the roadmap is to develop a more efficient qualification process to shorten the timeline and reduce costs. In recent history, new fuel development and qualification could take over two decades. The aim of the proposed paradigm shift is to reduce this by 50%, in particular by working more effectively in parallel rather than in sequence. The new paradigm involves the collective identification of phenomena to be quantified in support of the licensing process, the design and implementation of an optimised combination of experimental phases supported by state-of-the-art modelling and simulation and including the use of improved experimental instrumentation and measurements.

Figure 4: **A new paradigm for accelerating the qualification of nuclear fuels**

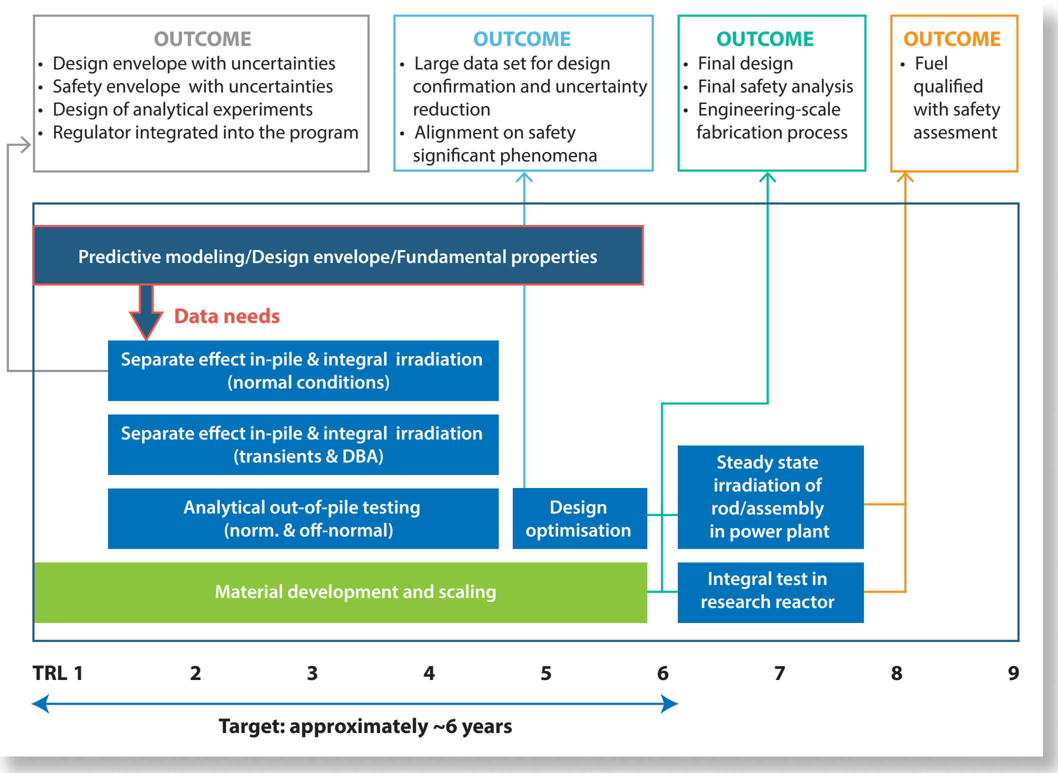


Figure 4 illustrates the principle of an optimised validation and qualification process, leading to increased efficiency and thus minimising lost time. This diagram has been developed by the technology holder side and is therefore scaled on the basis of the TRLs (instead of years). A similar complementary diagram has to be developed by the regulator, based on the LRLs. Putting the two diagrams together would allow a fruitful dialogue among all stakeholders to improve the synergies between TRLs and LRLs, and foster the development of a common validation/qualification process, with licensing in perspective. This specific activity is proposed as the very first concrete action in the NI2050 roadmap.

The roadmap has allowed constructive discussion on the necessary infrastructures basis to support the experimental phases, at a time when a number of facilities are going out of service, with the Halden Boiling Water Reactor as a prominent example, as the host of the NEA Halden Joint Project.

2) *Advanced structural materials for Generation IV systems*

The proposed roadmap flags two objectives:

1. Develop design rules for existing industrial materials, enabling reactor design for 60 years lifetime already in the case of Generation IV prototypes.
2. Develop industrially manufactured innovative materials with superior resistance to temperature, corrosion and irradiation, for use in future Generation IV commercial reactors.

The gaps addressed by the roadmap are:

- Creating a sufficiently large and consistent data set for the full codification of existing materials now selected for Generation IV prototypes.
- Selecting and optimising the most suitable advanced materials solutions to guarantee the optimal performance level of Generation IV commercial power reactors.
- Creating solid bases for physical and engineering model development and application, in support of design rules and materials development.

To close the gaps, proper international co-operation is needed, with the support of the NEA, in three specific areas:

- data sharing;
- harmonised materials testing and characterisation procedures;
- shared infrastructures and facilities and agreement on model development.

In addition, the involvement of TSOs and regulators for an early transfer of information on materials and to receive guidelines, is suggested as a way to accelerate the licensing of advanced nuclear systems.

This roadmap might be complemented in the future by another focussing on the development of the qualification of advanced manufacturing of components based on advanced materials.

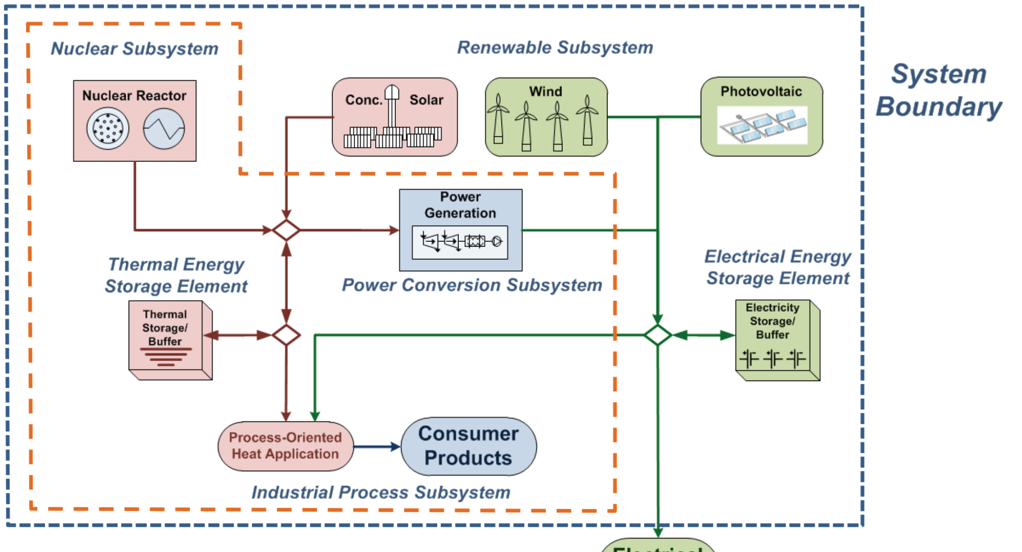
3) *Nuclear energy for cogeneration*

This roadmap focuses on high temperature reactors and aims at supporting the demonstration of the coupling of such a reactor with process heat application. The roadmap is based on the high-temperature gas-cooled reactor (HTGR) concept, a technology that has already been developed and demonstrated in the past and is now being revived with some improvements – in particular in the area of fuels, and in the future with higher temperature resistant materials. The primary objective of the roadmap is not on the reactor side per se, but is to support the possible construction of a demonstration of the coupling between such a high temperature reactor and an industrial heat user process.

This roadmap therefore can be seen as cross-cutting, in that it covers diverse high temperature reactor technologies. It might also help developing the concept of a hybrid system, helping the better integration of nuclear systems with intermittent renewable sources.

The first priority actions, best performed within an international framework such as the NEA, are focused on the safety demonstration, fitting into a much longer term vision of using nuclear energy for heat production or cogeneration.

Figure 5: **Hybrid systems for a very low carbon future**



Source: Rabiti, C. et al. (2015), "Status on the Development of a Modeling and Simulation Framework for the Economic Assessment of Nuclear Hybrid Energy Systems", INL/EXT-15-36451, revision 0.

The first set of priority actions aims to develop a licensing framework addressing not only the nuclear reactor, but also its coupling with process heat applications:

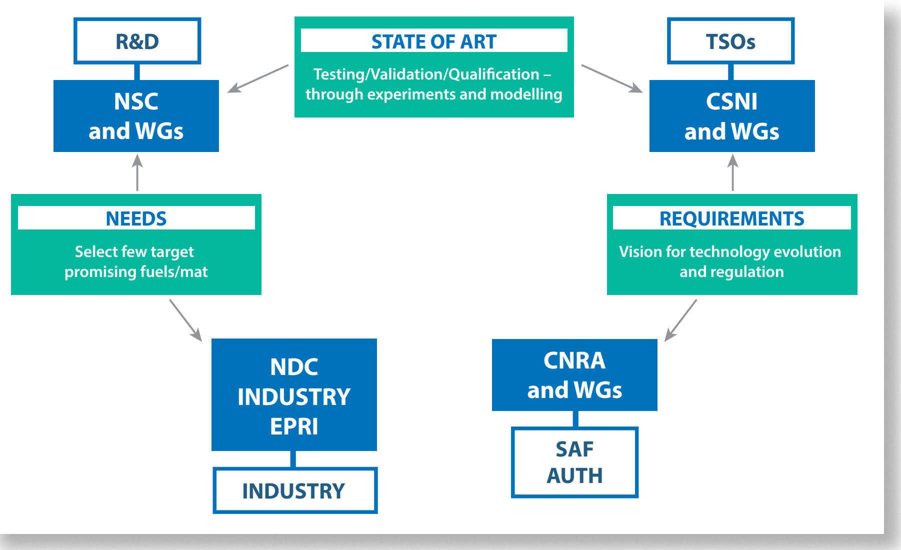
- Identifying possible R&D actions required to support the safety case of the demonstration plant through the production of any missing data and defining a plan for its creation.
- Developing advanced high temperature instrumentation needed for the demonstration plan.
- Developing solutions for HTGR decommissioning, used fuel and waste management.
- Developing an international network of test facilities accessible to the demonstration programme for its qualification needs.
- Initiating co-operation with process heat user industries to develop favourable technical and non-technical conditions for the deployment of nuclear cogeneration in these industries.
- Developing a plan for knowledge management and training for supporting the demonstration project and preserving the knowledge to underpin longer-term developments.

Implementing the NI2050 Concept and Roadmaps: A test case

Innovation roadmaps (vision documents describing what should be done to accelerate innovation in a given area or topic), once developed, have to be further discussed by groups of interested parties that are ready to engage in their implementation. Such groups need to include all the necessary stakeholders: industry as users of the technology, regulators and their technical safety organisations, and waste agencies (when relevant). The dynamic is topic dependant and such groups can be established on an ad hoc basis, specifically for each roadmap. Existing NEA working parties or expert groups, actively working on subjects linked to the topic of a roadmap, have been duly informed and involved as appropriate, to ensure coherence and the best use of available resources. NI2050 roadmaps can be seen as top-down strategic documents proposing broad programmes for action, which now need to better integrate a number of bottom-up activities already under way – in particular by NEA working parties or expert groups.

In the course of 2018, a specific effort has been made to test the implementation of one of the NI2050 roadmaps: improving the qualification process for advanced fuels. A number of activities already ongoing in the NEA framework on advanced fuels and materials were analysed and integrated in the design of the test case. This principle is illustrated by Figure 6.

Figure 6:
Making best use of expertise to foster innovation: The case of nuclear fuels and materials qualification



According to the central concept of NI2050, the better alignment of Technology Readiness Levels and Licensing Readiness Levels were at the core of the test case. Experts from the research community, industry and technical safety organisations/regulators came together to further discuss the programme of actions proposed in the roadmap, set top priorities and define what could best be done co-operatively.

These discussions focussed mainly on the need to optimise the identification of phenomena important for safety and performance, and the interaction between the experimental phases with modelling and simulation, while considering the inputs from industry in terms of their motivation and from the safety authorities in terms of the safety requirements for advanced fuels.

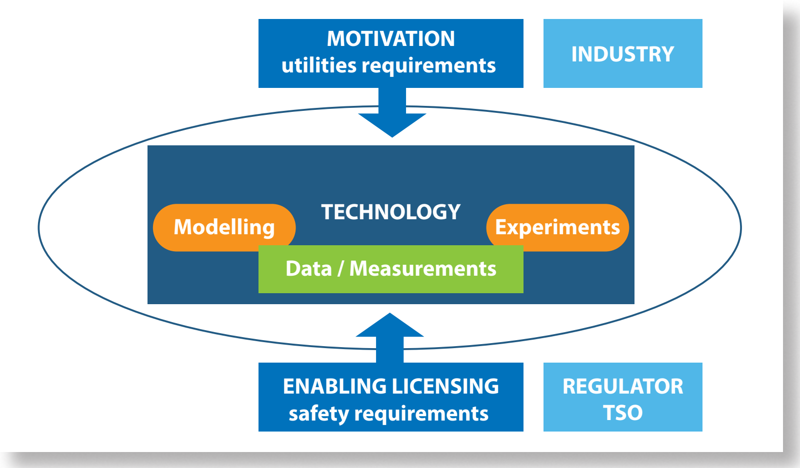
Such optimisation needs to consider the desired timelines for obtaining results versus the state of the art and capabilities of experiments, on one side, and modelling, on the other. This timeline needs to take into account the technology readiness level of the individual advanced fuel, be it evolutionary or revolutionary.

From an organisational perspective, optimisation is strongly connected to the effective communication between the research community (creating the knowledge by mobilising experimental and modelling capacities), industry (providing the requirements for new technologies), and the regulators (anticipating the questions to answer to ensure the safety). The NEA, through the mechanism of the NI2050 initiative, has organised diverse opportunities for in-depth discussion between all these stakeholders.

From a technical perspective, optimisation depends on the improved integration of state-of-the-art modelling capacities with experimental programmes. This integration spans from the design of these programmes right up to the interpretation of their results. It also includes the urgent need to invest in improved on-line instrumentation and measurement techniques to generate the necessary data points.

More generally, a critical element for the implementation of this roadmap is the availability of the experimental infrastructure, including the above mentioned optimisation of the instrumentation and measurements of parameters, associated with data for modelling. Given that a number of the key research infrastructures have been shut down, the latest and most critical example being the Halden Boiling Water Reactor, the NEA launched a dedicated initiative: the Multilateral Framework for Fuel and Material Testing, overseen by the Nuclear Science Committee and the Committee on the Safety of Nuclear Installations.

Figure 7: **No silos: Optimise all stakeholder contributions and the best infrastructure use**



The goal is to open access to experimental facilities for fuel and material testing for the organisations being parties of the Framework, thus providing highly valuable data for the qualification of existing and new fuel and material technologies, and for the validation of the supporting modelling. Within the context of the Framework itself, where all parties participate in setting general priorities, ad hoc Joint Experimental Programmes will then be designed and implemented to generate the necessary data.

The stakeholders concerned – including technical safety organisations, the industry, and research organisations – are currently discussing the Framework.

Towards a vision for the future

The vision is to keep NI2050 as a NEA-wide innovation incubator, along two tracks:

The first track will continue to focus on accelerating innovation on nuclear-specific technologies, such as nuclear fuels and materials, fuel cycle specific technologies, or new reactor designs.

This could embrace a range of TRLs/LRLs, from the development phase, towards readiness for deployment, through qualification and demonstration. A critical step, in the course of this process is the paring down of options identified during the development phase, before engaging in qualification and demonstration at large scale.

The second track will address accelerating the integration into the nuclear enterprise of advanced technologies already developed, and perhaps already in use in other industrial sectors: finding technical solutions to overcome integration barriers – in particular through qualification and demonstration for nuclear use. Particular attention will have to be given to the effective involvement of the regulators in this process. A first set of topics that may deserve attention, includes:

- Advanced Manufacture and Assembly, reducing time, costs and risks for building new plants and for the maintenance and refursbishment of existing units.
- Innovative Concrete, to benefit from advanced techniques already in use in civil engineering.
- Digitalisation and Data Management, to optimise operation and maintenance, as well as work processes, by improving data collection, management and use taking advantage of the latest big data, deep learning and artificial intelligence technologies.

NI2050 will become an NEA-wide innovation incubator, prioritising and selecting topics, and fostering their implementation. For each topic, an ad hoc implementation mechanism, with the necessary means and resources, will have to be set up by the participating stakeholders. Some NEA instruments that might be useful to consider in this reflection include the Joint Project mechanism.

Lessons learnt and recommendations for policy makers

Launched in July 2015 as a broad NEA initiative to accelerate R&D and market deployment of innovative technologies, NI2050 has succeeded in analysing the barriers to innovation and propose ways to overcome them. Innovation roadmaps have been developed for some areas and topics and their implementation has been tested on a case-by-case basis.

Three main takeaways from the work of NI2050 to date are:

1. It is crucial to involve all key stakeholders in the innovation process in a timely manner, with their roles and responsibilities made clear, and by fostering stronger synergies between technology development and licensing. This early engagement is an important way to increase its effectiveness, reducing the time, project risks and thereby the cost of bringing a technology to the market, from the early development phases to licensing, via testing, validation and qualification. This can be done through multinational frameworks, involving committed researchers, safety organisations and the industry, leading to a harmonisation of the testing, validation and qualification process. It will create a shared confidence in new technologies, both from the safety and performance perspective, and help broaden the market for industrial products based on this process.
2. While nuclear R&D public budgets have been rather stable over the last two decades, reflecting a business-as-usual situation with a globally stable fleet of power plants, this is unlikely to continue. Studies by the United Nations Intergovernmental Panel on Climate Change, the International Energy Agency and others, indicate the need for an increased contribution of nuclear energy in the low carbon economy of the future. At the same time, nuclear technologies are challenged in many aspects by the current situation in the electricity market. The pressure coming from both increasing needs and the challenges to be faced will require a significant boost in nuclear innovation. Public authorities, but also industry and investors need to come on board. A critical necessary condition for this is to have a long-term vision, with some degree of stability. In societies much more sensitive to risk management, it is necessary to be efficient and demonstrate value for money. Reducing the time to market, by a more effective innovation process, can help bring a better alignment of the innovation timelines with policy making and financing timelines. Synergies and collaboration at international level, to improve this innovation process, before technologies become industrial products, can also help.
3. A particular area where the nuclear community is reaching a critical juncture is in the infrastructure necessary to support R&D and innovation. This applies to the "hard" infrastructure, such as research reactors, hot laboratories, related fuel cycle facilities, but also "soft" infrastructures, such as databases of experimental results. It also includes human infrastructure: these have been ageing over the last decades and, if not properly renewed, may fast pass a point of no return. Here, once more, effective international collaboration may help.

The question of human capital is also central. If the next generation of researchers are to be engaged in the maturing of innovative nuclear technologies, then they have to be recruited, trained and retained. These links between innovation, education and knowledge management deserve the full attention of the nuclear community at large. The NEA Nuclear Education, Skills and Technology (NEST) Framework initiative in this domain directly addresses this need.

Based on the lessons learnt from the three years of operation of NI2050, the NEA is keen to further support the international nuclear community to make the innovation process more effective, and thereby help nuclear fission to contribute further to the sustainability of our societies.

Internet resources

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NEA member countries

(as of 1 April 2019)

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