Towards Optimized Use of Research Reactors in Europe
Project Number: 945 269

DELIVERABLE D 3.1

Strategy for optimized use of research reactors in Europe

Lead Beneficiary: ENEN

Due date: 31/01/2023 Released on: 29/06/2023

Authors:	Roberta Cirillo (ENEN), Renata Mikolajczak (NCBJ), Anže Pungerčič (JSI), Luka Snoj (JSI), László Szentmiklósi (EK), Jörg Starflinger (USTUTT), Markus Hofer (USTUTT), Tom Clarijs (SCK CEN), Vicente Becares Palacios (CIEMAT), , Evzen Novak (CVR), Gabriel Pavel (ENEN)

For the Lead Beneficiary	Reviewed by Work package Leader	Approved by Coordinator
Roberta CIRILLO	**Roberta CIRILLO**	**Gabriel PAVEL**
Roberta Cirillo	Roberta Cirillo	G. Pavel

Start date of project: **01/10/20** Duration: **36 Months**

Project Coordinator: Gabriel Pavel

Project Coordinator Organization: ENEN Version: 1.7

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Programme

Dissemination Level		
PU	Public	**X**
RE	Restricted to a group specified by the Beneficiaries of the TOURR project	
CO	Confidential, only for Beneficiaries of the TOURR project	

Version control table

Version number	Date of issue	Author(s)	Brief description of changes made
0.1	12.12.2022	Roberta CIRILLO	1st draft
0.2	30.01.2023	Roberta CIRILLO	Partners input integrated
1.0	31.01.2023	Michaela Velčková	Reviewed by MST
1.1	06.02.2023	Roberta CIRILLO	Final comments from the consortium integrated
1.2	09.02.2023	Gabriel PAVEL	Coordinator review
1.3	20.02.2023	Roberta CIRILLO	Final version prepared
1.4	05/05/2023	Roberta CIRILLO	Document updated
1.5	20/06/2023	Consortium	Document updated
1.6	20/06/2023	Roberta CIRILLO	Document content harmonized
1.7	29/06/2023	Gabriel PAVEL	Coordinator review and approval

Project information

Project full title:	Towards Optimized Used of Research Reactors in Europe
Acronym:	TOURR
Funding scheme:	Coordination Action
ECGA number:	945 269
Programme and call	H2020 EURATOM, Euratom Fission NFRP-2019-2020
Coordinator:	Gabriel Pavel
EC Project Officer:	Renata Bachorczyk-Nagy
Start date – End date:	01/10/20 – 30/09/23 i.e. 36 months
Coordinator contact:	+32 483 24 03 30, gabriel.pavel@enen.eu
Administrative contact:	+420 245 008 599, petr.koran@evalion.cz
Online contacts (website):	www.tourr.eu

"This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945 269."

EXECUTIVE SUMMARY

This report combines the major findings of the TOURR project in the first 2 years of its implementation.

After circulating a tailor-made questionnaire among Research Reactors (RR) in Europe - Figure 1 shows an overview of countries whose RR have responded to our questionnaire - which resulted in a response rate of 84%, three gap analyses have been drafted – to interpret the collected data – assessing the gaps and opportunities along the 3 axes of the TOURR project:

1. Science and technology
2. Medical applications
3. Education and training

As a further step, a SWOT (strengths, weaknesses, opportunities, and threats) analysis has been drafted and used as a basis by the consortium to write this report in a more descriptive form and in a way that makes it accessible to the largest possible public.

In parallel with the whole process, two events have been organised:

- Match-making workshop (held online due to active COVID restrictions in April 2021)
- Mid-term workshop (held in person, as a side event to the European Radiation Protection Week 2022 in October 2022)

The first event was mainly intended to make the TOURR project known to relevant audiences.
The second workshop targeted a particular segment of end-users: medical physicists and more in general professionals close to the medical applications of RRs.
This decision was made, since it was apparent after analysing the questionnaire responses, that data related to medical applications are not only among the most sensitive but also the most complex to handle when it comes to a European-wide view of the RR fleet.
Useful feedback has been gathered from both events, which will be taken into consideration in this report in the relevant chapters.

To support the findings and in line with the TOURR project target namely “to secure access and availability of RRs as a vital part of the European Research Area and to support stable supply of medical radioisotopes” an online platform is planned to be deployed. That will allow RR to better communicate and interact among themselves. It will also allow better internal and external communication. One **major goal is to provide a communication interface** that facilitates easier contact between potential users and RR operators.

It is worth specifying as general comments that:

- Given the fact that this report is public, and being the TOURR committed to guaranteeing the confidentiality of data shared with us, we will avoid making any references to specific facilities.
- All our considerations are based on the data collected which has been gathered voluntarily (no question was mandatory to answer) and also they reflect the perspective of the facility given by the particular respondent to the questionnaire.

The TOURR project is indicated as one of the outcomes of SAMIRA (Strategic Agenda for Medical Ionising Radiation Applications[1]) adopted by the European Commission to seek the energy sector contribution in beating cancer.

[1] https://energy.ec.europa.eu/topics/nuclear-energy/radiological-and-nuclear-technology-health/samira-action-plan_en

The TOURR project results are intended to contribute to the SAMIRA pillar on 'Securing the supply of medical radioisotopes' under ERVI (European Radioisotope Valley Initiative) [2].

The scope of this document is to provide the reader with a strategy to optimize the use of research reactors in Europe. The steps to implement the strategy have been inferred from all the analysis tools which have been put in place by the consortium.

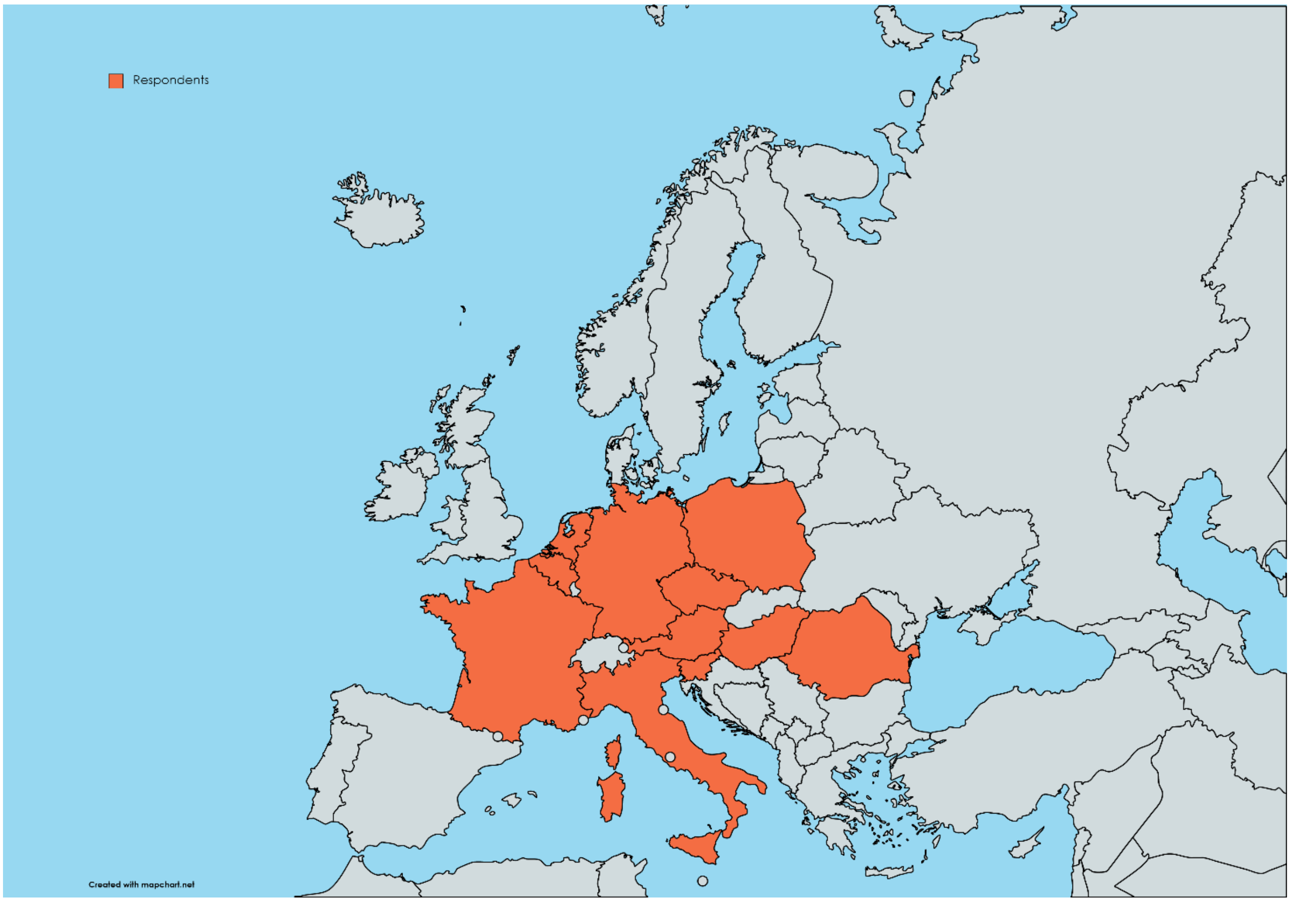


Figure 1 European countries represented in the analysis

[2] https://energy.ec.europa.eu/system/files/2023-01/Consultation%20results%20report%20Rev%20C.pdf

CONTENT

1 INTRODUCTION

This report summarizes the main findings of the TOURR Project after almost two years of analysis of the data received from RR across Europe.

The scope of this document is to present a strategy to optimize the use of research reactors in Europe. The steps to implement the strategy have been inferred from all the analysis tools which have been put in place by the consortium.
Specifically, it will rely on the following assets:

- Data collection from RR
- Gap analysis performed on three different axis
    - Science and technology
    - Medical applications
    - Education and training
- SWOT analysis
- Workshops feedback

It will be articulated into 'main findings', declined over the three axes of the TOURR project, and later 'recommendations' declined according to the time frame they apply to (immediate, near, and further future).

1.1 AIM

The TOURR project is a Euratom-funded collaborative action aiming at tackling the challenge of the decreasing number of RRs in Europe and the consequent loss of research capacity.

The European RR fleet is ageing and there are only two new RRs under construction at the time this report is drafted. The Jules-Horowitz reactor, in France, and the PALLAS reactor in the Netherlands[3]

This scenario describes a negative trend.

The TOURR consortium proposes a strategy, articulated in several steps to implement in different time frames, to tackle the challenges posed by such a scenario.

[3] https://www.pallasreactor.com/en/news/first-concrete-pour-construction-pit-pallas-reactor-a-fact/
AND https://jhrreactor.com/en/home/

2 MAIN FINDINGS

2.1 Science and Technology

This section is the most diverse of the whole analysis, as it addresses all other science and technology applications besides medical and education. In a research reactor (RR), several different technological applications are possible, many of them at the same time. Based on the information collected and the analyzed data the traditional and future RR possible applications are presented in the following chapters.

The degree of exploitation in different RR applications was determined using the questionnaire. Initial data acquired from the questionnaire is available in D1.1 – “Database of the European RR fleet”. This is a public report published on the webpage, under the ENEN website, devoted to the TOURR project: https://enen.eu/index.php/portfolio/tourr-project/ and on the TOURR website: https://www.tourr.eu/documents). Gaps and opportunities have been identified via statistical analysis and interpretation of the data obtained from the questionnaire. Detailed analysis is available in a confidential deliverable D1.2 – “Assessment of gaps and opportunities between capabilities of RRs and R&D and related scientific and technological fields”. The main findings and conclusions are presented in this report.

Regarding the overall RR utilization in science and technology (S&T), a statistical analysis for all RR applications in S&T was performed. Regarding the question on the level of exploitation, the majority 43 % of RRs answered that the degree of exploitation of their RR is low, 31 % indicated medium exploitation, and 27 % answered that exploitation is high. Results are presented in Figure 2. From this, a conclusion can be made that the overall level of exploitation of the EU RR fleet is between low and medium for technological applications other than medical and educational. An opportunity to further exploit the current RR can be observed.

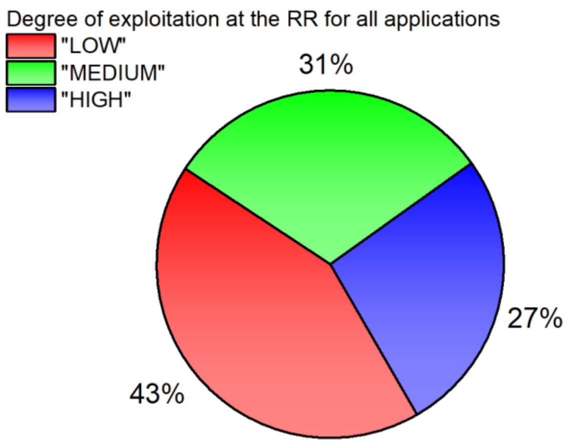


Figure 2 Relative representation of the degree of exploitation of RRs in applications connected to Science & Tecnhology. Number of total answers was N=162.

The statistical analysis showed that the need for expansion is present as 78 % answered that their institute would like to expand on the utilization of their RR and thus indicating that opportunity for expansion is possible. Results are presented in Figure 3.

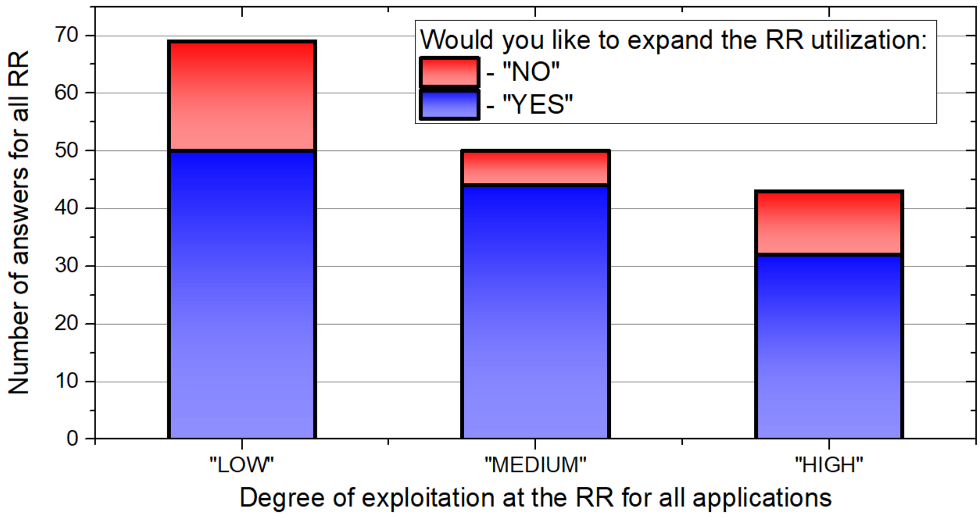


Figure 3 Statistical analysis of the degree of exploitation of RRs and their desire to expand the utilization.

Furthermore, we analyzed the average or major reason why their institute wouldn't want the expansion of their RR for individual applications and found that the reactor is already 100 % utilized in that application, and no further expansion is required. Another frequent answer was that the expansion is not possible as it is limited by the reactor properties (not high enough flux, a limited number of neutron ports, etc.).

A large portion of conclusions can be obtained from the analysis of research reactors who answered "yes" to the question: **"Would your institute like to expand the utilization of your RR for this application"**, where a follow-up question was asked: **"If yes, what obstacles are preventing your institute to do so"**. Multiple answers were possible, such as "Lack of manpower", "Lack of customers", etc. The results of the average answer for all applications combined are presented in Figure 4.

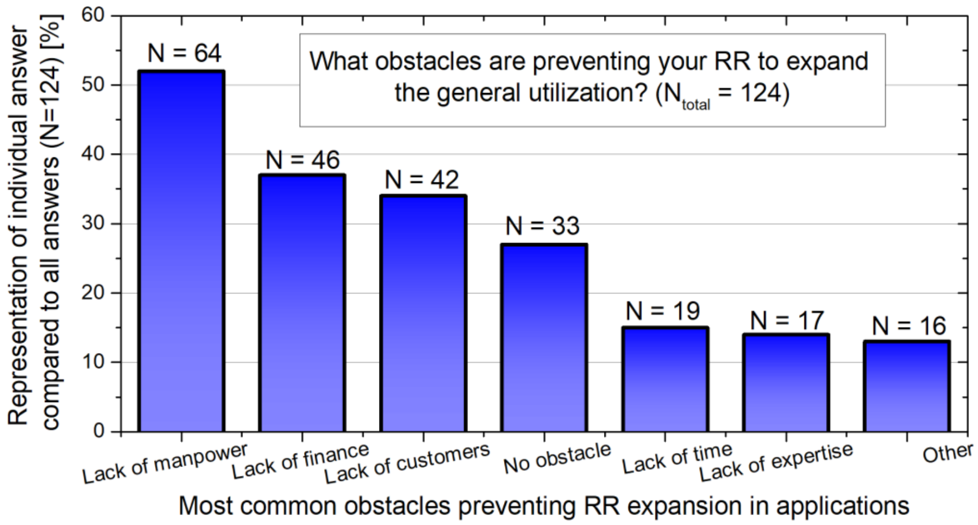


Figure 4 Relative representation of answers to what is the reason preventing your RR to expand the utilization of all applications together. The columns within one application do not sum to 100 %, since the multiple-option answer was possible.

It was determined that the expansion of utilization of RR is obstructed mainly by the **lack of funding and manpower**, which are correlated, and the **lack of customers.** Based on the former a strategy for increasing funding and manpower can be constructed.

The analysis further showed that there is definitely a high level of expertise in the nuclear sector in Europe and the available RRs in the EU RR fleet are quite diverse (TRIGA, SUR-100, tank-in-pool, VVR, critical assembly...) offering a potential for a variety of different possible applications. Having reached this point is important to remark that research reactors are not homogeneous and they can be classed into several groups, encompassing a large range of neutron fluxes, power levels, and applications. A possible classification can be:

1) Research reactors **dedicated to neutron beam production for neutron scattering research**. This class includes both the highest-flux (up to ~10^{15} n/cm^2/s) research reactors available (ILL and FRM-II in Europe) as well as several medium-flux reactors. After the recent closure of several of these medium-flux facilities (BER, Orphée, JEEP-II) only two such facilities remain in operation in Europe (BRR, HOR).

   High-flux research reactors are also involved in medical isotope production. For example, W-188, parent radionuclide of Re-188 can only be produced at the neutron flux 1 x 10^{15} n/cm2/s.

2) **Large medium flux** reactors (~10^{14} n/cm^2/s). These reactors are **mostly used for material irradiation and testing, silicon transmutation doping, and isotope production**. European research reactors in this class include BR2, HFR, MARIA, LVR-15, and TRIGA-Pitesti. The European research reactor fleet in this category has been reduced in recent years by the closures of the OSIRIS (2015) and Halden (2018) reactors, coupled with the delays in the construction of the JHR reactor.

3) **Low and very-low power reactors**. These reactors have too low power levels and neutron fluxes for the uses listed in the two previous points. While some designs (e.g SUR-100) have too low fluxes for applications other than education and training, other designs (most notably TRIGA reactors) offer fluxes high enough for a number of scientific and technical applications: neutron activation analysis (NAA), neutron radiography/tomography, geochronology, gemstone coloration, gamma irradiation, positron sources, Boron Neutron Capture Therapy (BNCT), instrument development and testing… In Europe, there still exists a large network of such facilities, although some closures have also taken place recently, namely the TRIGA reactors at VTT (Finland) in 2015 and ITN (Portugal) in 2016.

4) **Zero-power facilities for nuclear data validation**. After the closure of the Eole, Minerve (2017) and MASURCA (2018) facilities at CEA-Cadarache, the only remaining facilities in this class in Europe are the VENUS-F reactor at SCK CEN and the LVR-0 at CVR.

At the same time, the study shows that the expertise is much focused meaning the personnel is very highly specialised and for this reason very hard to replace. For several applications, there is a real threat that the knowledge and competencies will be lost once the current generation of experts will retire, for example in applications like **NAA (**Neutron Activation Analysis**) or PGNAA** (Prompt Gamma Neutron Activation Analysis) and more in general in **nuclear data measurements** or general research connected to **Nuclear data**.

A possible solution is represented by attracting new people to the field and investing in them over time with adequate training and opportunities to gain relevant experience. This approach will address the 'lack of personnel' issue but at the same time will allow for potential expansion of current domains of use.

In some other cases, **radiochemistry** for example, there are dedicated Euratom-funded actions to attract young people to the field. They are quite successful if we look at the manifestation of interest towards the proposed activities of the CINCH project series[4] for instance (website visits, number of applications to take part in Hands-on Training sessions…). But if the overall amount of RR around Europe is decreasing, as a direct consequence there will be fewer opportunities in this field as well, unless their usage is significantly intensified.

[4] https://www.cinch-project.eu/

Applications like **silicon transmutation doping or actinide transmutation studies** suffer from a lack of financing since they require quite a long-time investment in terms of partnerships to establish and development of the activity at the RR. Furthermore, transmutation requires high reactor power (and usually a fast neutron spectrum) so not all RR can develop this field. New installations like Myrrha may bring new strength and opportunities. It should be noted that with the increase of renewable energy and quickly expanding production of hybrid electric vehicles, the need for silicon doping will increase and a new RR with long-term investment strategy will be needed in the future.

A similar situation applies to **material irradiation and testing** since not all RRs have a high enough neutron intensity to carry on this activity. On the bright side, this knowledge is transferrable among RR so, once more, this proves that **better communication and interconnection** within the EU RR fleet can be beneficial.

A high neutron flux is required as well for **nuclear fuel irradiation and testing**; hence the same limitation applies. The demand for this service is increasing though, hence it can be seen as an opportunity for expansion and involvement of young new professionals. Such applications do not have the same level of threat of RR closures in the long run, as the Jules Horowitz material test reactor (JHR) is under construction, ensuring future capabilities.

It is also worth mentioning that for the long-term operation of nuclear power plants (NPP), especially in the case of assessing the lifetime of pressure vessels (PWR type reactors), **testing structural materials in RR** in well-defined radiation and temperature conditions is mandatory (surveillance program).

Other, more uncommon applications like **geochronology** or **gemstone coloration** although appealing since being open to cross-disciplinary interactions (e.g., with the geology community), require shipping and handling of neutron-activated material. Such actions require extensive paperwork and so it is seen as a discouraging activity. Furthermore, it was determined that such applications suffer from a lack of customers/demand. The less activity is performed by the RR, the higher the risk of losing this competence over time.

The same 'threat' of losing customers applies to **gamma irradiation** because there is no specific need for a RR to perform it (the ultimate goal being radiation hardness test) but it is also possible to use other intense gamma-ray sources, like accelerators. The advantage of using RR for gamma irradiations is the higher gamma flux, from which an opportunity can be derived as RRs could increase their involvement in the gamma field characterization, making the irradiations possible and with that attract the customers since irradiation can be performed also when the reactor is shut down.

In the field of **neutron scattering** and **neutron radiography/tomography,** which are among the most common applications of RRs and one in large demand[5], there is definitely room for expansion in its utilization. The main problem is that the installed equipment has to be renewed while at the same time, modernizing the installation (new digital imaging technique) could attract young specialists resulting in a good opportunity for bridging the generational gap in the EU RR fleet.

Instrument development, testing, and calibration is a field that all RR operators would like to further analyse, moreover with new RR designs (small modular reactors – SMR and Generation IV). It can definitely be seen as an opportunity to increase the field of RR utilisation. The diversity of facilities (intended as a type of RR) present in the EU RR fleet is a strong point since it enables to testing of state-of-the-art equipment and the need to test and calibrate instrumentation is likely to increase in the future. However, a threat of not building the new RR designs is present, as the instrument development would stall if no future reactor systems are present for the equipment to be tested on.

Positron sources production and **boron neutron capture therapy** have a high potential for expansion but they require a specific core configuration and ad hoc operation of the RR which makes

[5] https://europeanspallationsource.se/sites/default/files/files/document/2018-06/NEUTRON%20USERS%20IN%20EUROPE %20-%20Facility-Based%20Insights%20and%20Scientific%20Trends.pdf

it a limited field. However, it is necessary to state that interest in BNCT has lowered today due to the development of new treatment methods (e.g. proton therapy).

Finally, when it comes to the **support of nuclear power reactors programs** the analysis showed that this requires intensive collaboration between the different departments in the same RR as well as **better communication among different RRs in the fleet.** As of today, RRs are at full capacity having only some small margins and the aging of the fleet may lead to a loss of expertise.

An expansion of the fleet is advisable, not to lose this opportunity and to preserve the diversity among the facilities needed to enable to study and support of all future nuclear designs (SMR, Generation IV). It is important to mention that the type of RRs required for this purpose (zero-power mock-ups and prototypes, in particular with fast spectrum) are rather different (in design and utilization) from the kind of RRs (essentially pool type reactors) that are required for all the other applications discussed in this document.

Our research showed that besides the current RR applications, there are also opportunities in new and exciting fields in which a RR could be utilized. One is the **Nuclear-driven production and processing of chemicals**[6], where renewable fuel additives can be produced from waste organics, indicating a promising research field with a circular economy and waste treatment where research reactors would play a major role. Possible new opportunities for research reactors, connected to **Fusion,** are water activation studies, radiation hardness studies with high energy gamma rays, gamma and neutron shielding studies, materials activation studies, etc.

In the light of European energy transition **research in the field of fuel cells, hydrogen storage, and batteries** can be also depicted as an opportunity, as the hydrogen economy (e.g. fuel cells, hydrogen storage), electromobility (batteries, electromotors, efficient energy conversion) and circular economy are focal points of the EU policy on climate change. Neutron beamline techniques, including PGAA for element analysis, diffraction for structure analysis, and imaging for macroscale structure visualization, all offer non-destructive, contactless, and real-time measurement opportunities at RRs. This novel research field might bring fresh money to the neutron centers and allow them to demonstrate their usefulness to the general public.

To summarize the main findings in the field of science & technology, a short list of current and future Strengths, Weaknesses, Opportunities and Threats (SWOT) of the European RR situation is presented.

STRENGTHS:

- High level of expertise in the European research reactor sector.
- A diverse fleet of EU RR (from critical assemblies to high neutron flux and material testing reactors).
- The flexibility of certain RRs to be utilized within new and exciting fields (Chemical processing, Fuel cells, hydrogen storage, small modular reactors, circular economy, transition to zero carbon society, etc.).

WEAKNESSES:

- Lack of communication between different RR operators.
- **Uneven utilisation among various RRs**
- Relatively low average utilization.
- With the expansion of renewable energy sources, the need for silicon doping and high flux reactor will increase.

[6] Plant, A.G., Kos, B., Jazbec, A. *et al.* Nuclear-driven production of renewable fuel additives from waste organics. *Commun Chem* **4**, 132 (2021). https://doi.org/10.1038/s42004-021-00572-5

OPPORTUNITIES:

- Expand the utilization of the current RR with increased funding and manpower.
- Increase the communication among RRs (RR with lack of time is complementary to a RR with lack of customers).
- Research in new fields (chemical processing, fuel cells, hydrogen storage, etc.).

THREATS:

- The threat of losing knowledge and competence as current highly skilled and educated personnel is aging (NAA, PGNAA, Nuclear Data Measurements and Theory, benchmark experiments, etc.).
- Aging of current RR fleet, as the average age of RRs is 56. The threat of losing current capabilities and new opportunities.
- The threat of losing knowledge and competence as an application is not being performed (gemstone coloration, geochronology, gamma irradiation).
- The threat of not building new RR (no RR services available in the future)

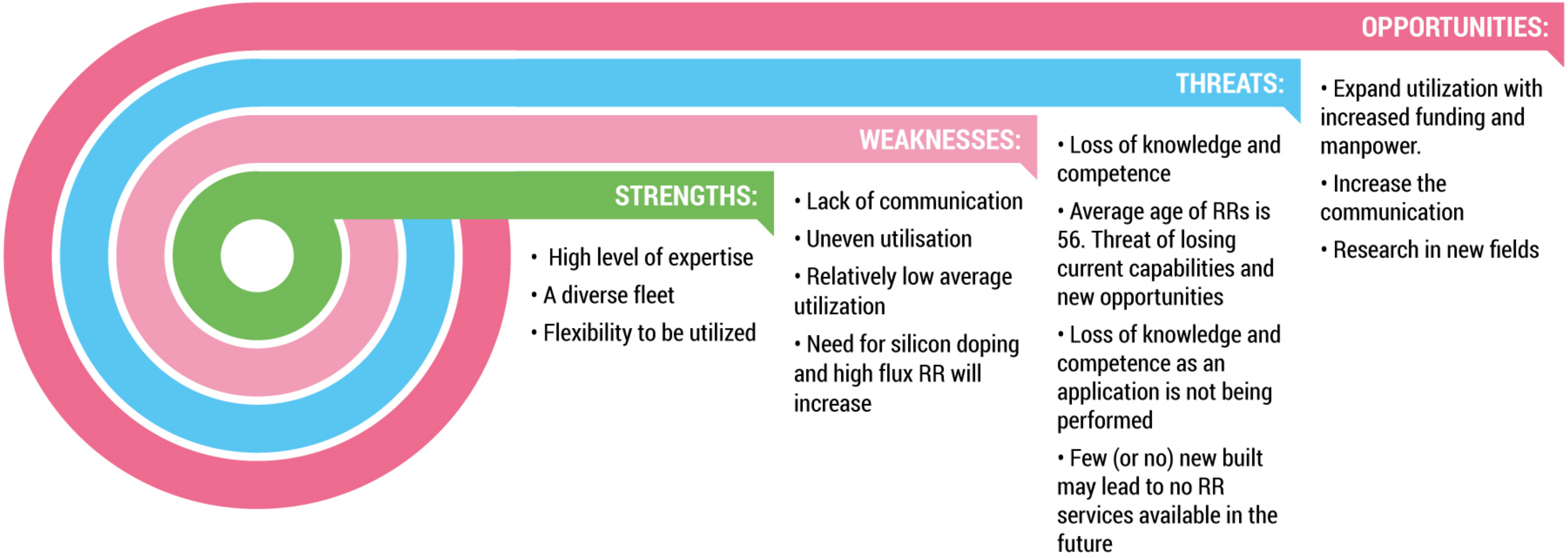


Figure 2 SWOT analyses presented in a graphic form (and with reduced text)

2.2 Medical Applications

The majority of facilities are quite reluctant to share data related to the medical applications that are in place at their RR. This is easily understandable since this type of data is deeply entangled with commercial interests and most of the time unique for the facility.

As a consequence, data collection for this section of the study has been more difficult. This is the main reason behind the decision to have the mid-term workshop targeting this specific end-user segment.

The population related to the medical applications of RR is composed of facilities operators but also end users of RR products. Reaching out to them allowed us to have a more rounded vision of the issue.

Since the implementation of medical applications is dependent on radioisotope production and dispatch of the radioisotopes to end-users, we will provide our main findings per each of the main elements.

TOURR will not, however, consider Molybdenum (Mo-99) since the primary goal of the Nuclear Energy Agency (NEA) group of the Organisation for Economic Co-operation and Development (OECD) and their initiative of the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR) as well as Nuclear Medicine Europe (former AIPES) is the sustainable supply chain of molybdenum-99 (Mo-99) and its daughter radionuclide technetium-99m (Tc-99m).

Furthermore, Mo-99 is studied by the European Observatory on the Supply of Medical Radioisotopes monitoring of the supply, optimized use of research reactors and appropriate planning of production (The Observatory is composed of members from the Euratom Supply Agency, the European Commission, the European Association of Nuclear Medicine (EANM) and various industry stakeholders most of which grouped within the industry association Nuclear Medicine Europe (NMEu)).

For these reasons, the TOURR project in the analysis of the RR fleet capacities focuses on radionuclides other than molybdenum-99 (a parent radionuclide for technetium-99m).

It's worth mentioning, that trends in medical isotopes applications were analysed in TOURR Deliverable 2.1. "Comparison of current and forecasted needs and production capabilities with conclusions from existing reports on supply of medical radioisotopes and trends in their uses". Herein only few exemplary RR produced radionuclides are discussed emphasizing their role in health care system.

Iodine (I-131 / I-125 / I-124)

There is a high demand for Iodine-131 (^{131}I) in Europe and globally. For decades it was and still remains the most widely used radionuclide and it has a very well-established role in the nuclear medicine field. Due to the affinity of iodine to the thyroid tissue, it's indicated for the imaging and therapy of thyroid disorders, including thyroid cancer. Iodine-131 is approved for medical use either as such (in the form of sodium iodide-^{131}I solution for injection or for oral administration) or in the form of gelatin capsules containing sodium iodide-^{131}I for oral administration, both for diagnostic and therapeutic use depending on the administered radioactivity dose. Another application of ^{131}I is for the radiolabeling of molecules, an example of that being radiopharmaceutical metaiodobenzylguanidine (^{131}I-MIBG) which localizes to adrenergic tissue and thus can be used to identify the location of tumors such as pheochromocytomas and neuroblastomas as well as for therapy of these tumors, especially in pediatric patients. More recent developments include ^{131}I labelled prostate cancer inhibitor MIP-1095 for diagnostic imaging and therapy in patients with prostate cancer or ^{131}I IPA(I-iodo-phenylalanine) for therapy in recurrent glioblastoma multiforme.

Iodine-131 is produced in research reactors using two different production routes. One of them is the isolation from ^{235}U fission products in the process parallel to the separation of molybdenum-99, hence its production is very much dependent on the production of ^{99}Mo and is limited to the few nuclear reactors worldwide. This limitation does not apply to the production of ^{131}I in medium flux reactors via the neutron irradiation of tellurium targets, but due to the high number of irradiation positions needed to satisfy the high demand for ^{131}I, its production limits the access of these positions for the production of other radioisotopes. The use of ^{131}I for therapy generates liquid biological and radioactive waste, this is usually well taken care of in dedicated therapy wards in hospitals.

Another reactor-produced radioisotope of iodine interesting for the medical community is iodine-125, which is used in the form of sealed sources in radiation therapy (brachytherapy) to treat a number of conditions, including prostate cancer, ocular cancers, or brain tumors. Its half-life is 59.49 days and decays by gamma decay with a maximum energy of 35 keV. Hence, it is an excellent isotope to administer low-dose rate (LDR) brachytherapy.

Iodine has also a positron-emitting radioisotope, ^{124}I, which is produced in cyclotrons and allows diagnostic imaging using the positron emission tomography (PET) technique. Some new applications are under investigation, for instance, the use of ^{124}I for prostate-specific membrane antigen (PSMA) PET imaging.

In the last decades and at present, there is **high demand for ^{131}I** globally. In the long history of medical applications, ^{131}I had played an important role in the management of patients and the demand for ^{131}I and other matching iodine radioisotopes is on the rise. In the fall of 2022, when the BR2 reactor in Belgium was out of operation and could not contribute to the irradiations of ^{131}I, the issue of a sustainable supply chain for ^{131}I became critical.

Lutetium (Lu-177)

When looking at the number of published papers, lutetium-177 (^{177}Lu) became the most effective and demanded radioisotope for therapeutic use in patients with neuroendocrine tumours. The ^{177}Lu belongs to the radiolanthanides and is ideally suited for therapeutic use due to its attractive physical characteristics. It decays by β^- emission with energies of 177 keV and 498 keV. Furthermore, the emitted γ photons of 113 keV and 208 keV can be used for imaging the in-vivo localization of the administered ^{177}Lu targeting agent using SPECT scanners. The emitted photons facilitate dosimetry calculations.

The benefit of using ^{177}Lu in the therapy of neuroendocrine tumours has been demonstrated in a number of clinical trials which lead to the first ^{177}Lu-labelled radiopharmaceutical with marketing authorisation – ^{177}Lu-DOTATATE (Lutathera). **In the last decade, the demand for ^{177}Lu increased dramatically** after the success in the therapy of disseminated metastases of prostate cancer using ^{177}Lu-labelled PSMA inhibitors.

One major limitation in the production of ^{177}Lu is the access to highly enriched target materials. It can be produced in research reactors using two different nuclear reactions, one of them leading to the carrier-added ^{177}Lu and the other one leading to the non-carrier-added ^{177}Lu. In both cases, highly enriched target materials are needed (either in ^{176}Lu or in ^{176}Yb). In Europe, there is a number of facilities capable to process ^{177}Lu and they would be able to cover larger needs. However, at present, the shortage in the supply of enriched target materials seems to be the bottleneck in the access to ^{177}Lu. New methods for the separation of stable isotopes ^{176}Lu and/or ^{176}Yb as well as new facilities for their production are needed in order to satisfy the growing demand for ^{177}Lu.

Terbium (Tb-161)

After the success of ^{177}Lu in the therapy of various cancers nowadays the focus of investigators is on terbium-161 (^{161}Tb) which decays by β^- emission with a half-life of 6.89 d. It is a low-energy β^- emitter. These physical properties make it similar to ^{177}Lu, but ^{161}Tb emits also a significant amount of conversion and Auger electrons, which are expected to provide a better therapeutic effect compared to ^{177}Lu. This radionuclide is particularly interesting because together with other terbium isotopes such as ^{149}Tb (alpha emitter), ^{152}Tb (positron emitter), and ^{155}Tb (gamma emitter) it can form a series of theranostic pairs. Compared to ^{177}Lu, the use of ^{161}Tb in the therapy of neuroendocrine tumors and in prostate cancer patients is expected to result in a better therapeutic effect. Currently, the first promising pre-clinical and clinical results have been published and there is a number of ongoing clinical trials. The demand for ^{161}Tb is growing rapidly. This was also reflected by the high demand for target material – enriched ^{160}Gd.

Terbium-161 can be produced in a nuclear reactor by irradiation of ^{160}Gd with thermal neutrons. Needless to say that i**n the last few years, the potential of ^{161}Tb for therapy dominated the research and the debate** on new medical radioisotopes.

Radium (Ra-223)

Ra-223 has an 11.4-day half-life. Radium-223 dichloride is an alpha particle-emitting radiotherapy drug that mimics calcium and forms complexes with hydroxyapatite at areas of increased bone turnover. The principal use of radium-223, as a radiopharmaceutical to treat metastatic cancers in bone, takes advantage of its chemical similarity to calcium, and the short range of the alpha radiation it emits. Notably, radium-223 (Xofigo) was the first radiopharmaceutical with an alpha-emitting radionuclide that has been granted marketing authorization. That paved the way for the use of other alpha emitters in medical applications, such as ^{225}Ac.

TOURR consortium recommends further research in the field of alpha-emitters. The SECURE[7] project (detailed in the following pages) has among its objectives to push research on alpha emitters and it is very beneficial that some of TOURR partners are involved in SECURE as well.

Actinium (Ac-225)

The decay properties of actinium-225 are favorable for usage in targeted alpha therapy (TAT); clinical trials have demonstrated the applicability of radiopharmaceuticals containing ^{225}Ac to treat various types of cancer. Its efficiency in clinical treatment still needs to be proved by further tests. However, the scarcity of this isotope resulting from its necessary synthesis in nuclear reactors or cyclotrons limits its potential applications. **For this reason, at present, there are several initiatives aiming at the increased availability of ^{225}Ac.** One should remember, that either for the nuclear reactor or cyclotron route the starting material for the production of ^{225}Ac is radium-226, and access to this target material is a challenge. In both routes, there is a **need for specialized processing facilities.**

Copper (Cu-67)

Copper-67 (^{67}Cu) is a β^- emitter useful for therapeutic treatments. Its half-life of 2.7 days is long enough to match the pharmacokinetics of slowly circulating large molecules, such as monoclonal antibodies. ^{67}Cu can also be paired with the cyclotron-produced β^+emitters ^{64}Cu, ^{61}Cu, and ^{60}Cu to perform pretherapy biodistribution determinations and dosimetry using positron emission tomography (PET). ^{67}Cu can be produced in a nuclear reactor, however, requires a high flux of fast neutrons exceeding 10^{14} n cm^{-2}s^{-1}. Alternatively, it can be produced in cyclotrons. While the production of ^{67}Cu in nuclear RR is currently limited, there are several reports on the feasibility of ^{67}Cu production in cyclotrons, giving a promise of its wider availability. Currently, the use of ^{64}Cu of high-specific-activities in medical applications is very well established, and there are medicinal products with marketing authorisation on the market. It can be produced in a cyclotron using expensive nickel (Ni-64) targets which need to be recycled. Although ^{64}Cu can be used for both diagnostics and therapy, it is expected that the combination of ^{64}Cu for diagnostic imaging and ^{67}Cu for therapy is more effective. In the USA, the DOE provides ^{67}Cu for research and early clinical trials. Such services are not available in Europe, hence, reliable sources of ^{67}Cu are needed.

Cobalt (Co-60)

[7] https://enen.eu/index.php/portfolio/secure-project/

Its long half-life (more than 5 years) makes it highly suitable for brachytherapy. On the downside, **it can be produced only by a very limited amount of RR** and it requires strong shielding and hot cells to be handled. An opportunity is represented by producing ‘gamma knives’. It’s worth mentioning that ^{60}Co is broadly used in industry for industrial process control, in non-destructive testing, and also in sterilization by gamma radiation, which is employed in medicine. These applications are using large volumes of RR-produced ^{60}Co in the form of sealed sources.

Iridium (Ir -192)

The production of this isotope **production is a standardized procedure**, which constitutes a great advantage. Ir-192 is used industrially for non-destructive tests (NDT). It can also be used in patient brachytherapy but in that case, **hospitals are required to have a dedicated ward** for patients treated with this isotope, because the dose received is quite high. This also implied that the personnel needs to observe strict radiation protection measures. Due to the short half-life of the source (74 days), it needs to be replaced four (4) times a year.
There are 23 medical centers only in Poland performing brachytherapy using ^{192}Ir sources. Globally, the demand for brachytherapy shows an upward trend.

The few examples discussed above clearly demonstrate that RR-produced radioisotopes play a very important role in the healthcare system in Europe. A number of new developments were recently translated into the clinics, and the forecasted demands for RR-produced isotopes are much larger than in the last years. Actions towards upgrading and expanding the existing RR fleet are mandatory.

2.3 Education and Training

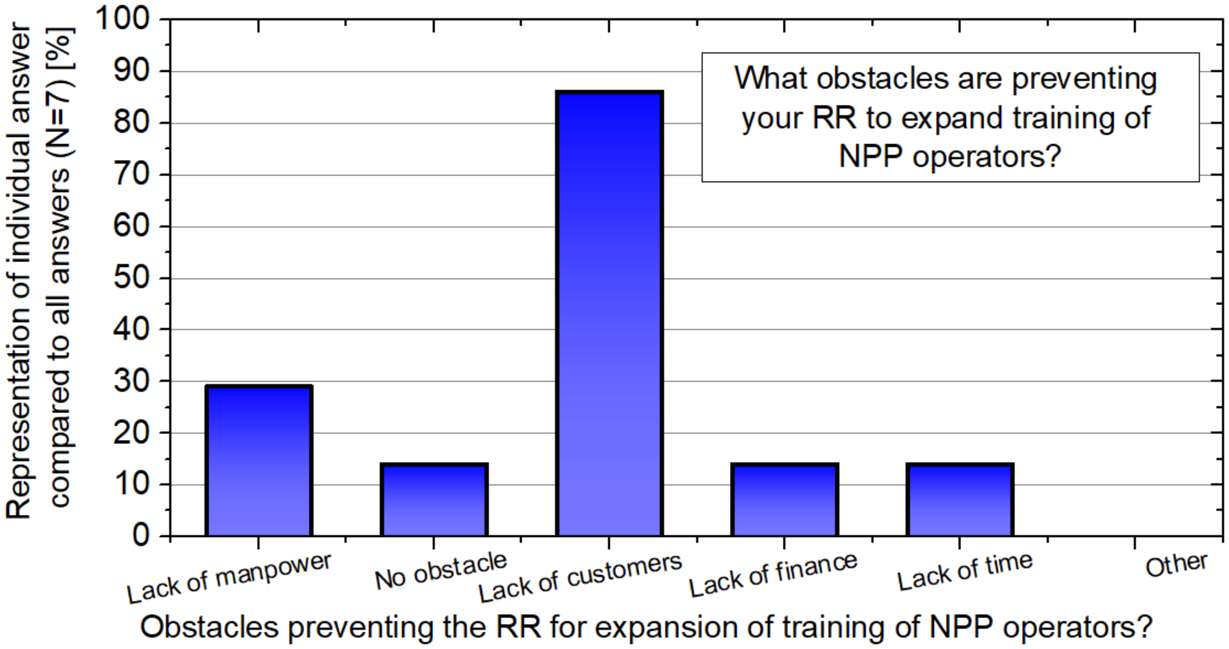
This section gathered quite complete feedback from the surveyed facilities since the need for E&T is well recognized and acknowledged.

The use of RR by researchers, students, and fellow partners from other facilities is a great contributor to the increase in highly skilled human capacity. This highly skilled human resource is needed both by the facilities themselves and also by the users of the RRs products.

Table 1 summarizes the findings regarding gaps and opportunities in the E&T sector. In general, there is a strong will (80 % positive answers) across the RRs community to expand E&T activities. Nevertheless, since in some cases, “lack of manpower” was mentioned, it can be seen as an opportunity to look for more personnel. In the following, the different activities are discussed in more detail.

Training represents one fundamental pillar activity. The level of delivered training is very high thanks to the wide expertise. However, advanced training which goes beyond basic reactor physics is reactor technology specific and long in time (requires several months to be completed). For example, each NPP has its own “certified” training centre and is normally not dependent on the training offers of RRs, which quite often do not have their training course certified e.g. by regulators (country dependent). The training is not exploitable outside the specific RR in which it was undertaken, even in the case of similar RR technologies (RR in which the training was undertaken and RR in which the operator wishes to be employed), country-specific regulations will limit the operator to be recognised as ‘ready to work and be employed’.

Therefore, a lack of customers prevents the RRs to expand their training activities. Regarding other aspects, the scenario is similar to teaching, e.g. the lack of manpower may become critical, especially in the future.



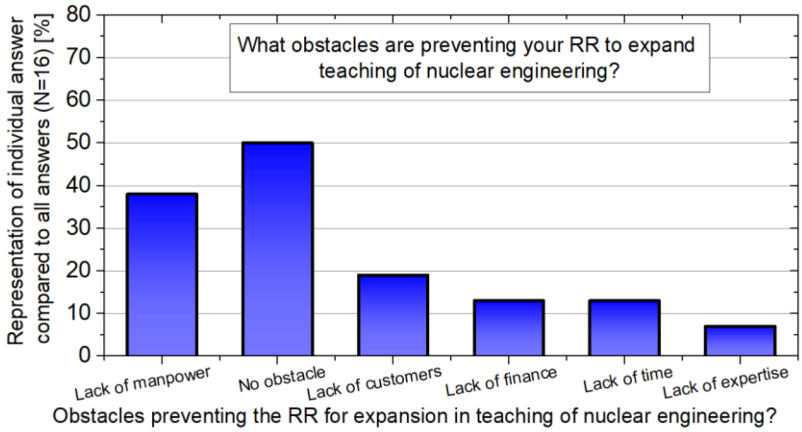
Another important aspect of educational activities is represented by **teaching**: radiation protection, nuclear engineering, biological science, etc. This aspect is already implemented on a medium or high level in two-thirds of the RRs and there is a strong will to further expand it.

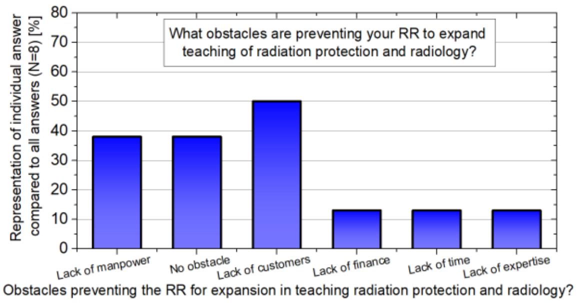
In this field, teachers are very experienced professionals because they deliver a very high level of knowledge. Most of the time teaching often provides an extra workload for the RR employee. This explains the "lack of manpower" found in the questionnaire, since to have time devoted to teaching the RR employee must take it from their other duties. This shift of tasks is not always in agreement with the RR priorities.

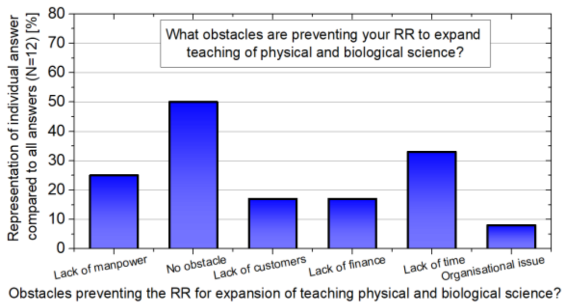
With the nuclear phase-out and the ageing of the EU RR fleet, it is hard to allow professional development for skilled employees and even harder to keep competent teachers. This will result in a drain of well-trained scientific personnel from RRs.

An approach to overcome a possible future lack of scientific personnel is to foster the synergy, and efficient use of resources of as many EU RR facilities as possible. RR should communicate intensively – on the same platform – in order to overcome difficulties and go from an approach that takes into account RR as single facilities to an integrated and structured approach that considers the whole 'EU RR fleet'.

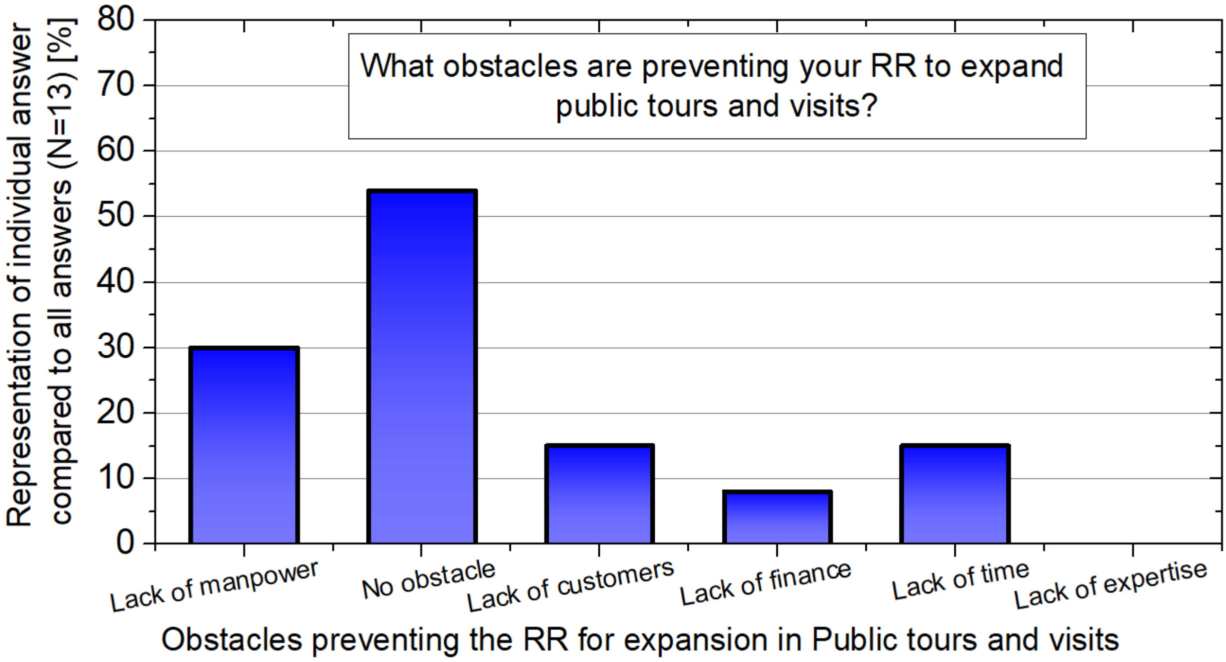
In the field of radiation protection and radiology, besides the lack of manpower, also a lack of customers was observed. This may be related to the fact that these topics are already covered by the nuclear engineering programs or depending on the specific content, these topics may rather be taught in other set-ups. (Some subjects, perceived as very close to the 'medical' field may be taught in hospitals for instance)







Activities like **public tours and visits** are very useful to raise public awareness around nuclear installations. They are a way to open the dialogue with participants to the visits and maybe to attract some of them to the field. The weak point is represented by the fact that sometimes allowing visits to nuclear facilities requires extensive paperwork and personnel acting as 'guides' will need to make time for this extra workload for which normally there are no structural fundings. The strong point on the other hand is provided by the unique character of the visit experience: each facility is one-of-a-kind in some sense and given that the guides are also technical professionals they can answer not only general but also technical-scientific questions. Altogether, most RRs can handle the extra workload to offer tours and visits and mostly there are no obstacles to expanding these activities. Thus, there is no real gap between the current scenario and the ideal one in this case.



Although access to RRs especially for researchers and for educational purposes is open, good coordination in terms of time and use of isotopes is required. It has been identified that sharing this type of information between providers (RRs) and end users (researchers, educators, etc.) would be in the benefit of all involved parties and it will help to better plan the use of the facilities.

Table 1: Summarized gaps and opportunities in E&T including major obstacles

Activity	Status	Plan	Major obstacles
Training or retraining	Relatively low exploitation	Further expansion (except for some RRs)	Lack of customers,
Teaching science	Medium exploitation	Further expansion	No major obstacle, in some cases, lack of manpower
Public tours and visits	Relatively high exploitation	Generally further expansion	No major obstacle, sometimes lack of manpower

3 RECOMMENDATIONS

Based on the collected data, the TOURR consortium recommends the following set of actions:

3.1 Actions to implement in the immediate future

There is a clear need to attract more workforce to the nuclear sector.

There is definitely the need to attract new talents to the nuclear field, to educate more engineers, scientists, technical staff, etc. to cope with the lack of personnel or lack of time for the existing personnel. Opportunities can be found in higher education programs or training for professionals. To be able to offer access to these opportunities, close collaboration with other networks, and projects, is encouraged.

In many cases, facilities indicated 'lack of personnel' or 'lack of time' response as the main obstacle to expanding their applications. This latter can be interpreted as given the actual workforce in the facility, they cannot devote their time to specific applications (regardless of the 'type' of application).

To proceed in this direction, the consortium recommends fostering collaboration with and across other projects. The more this issue is manifested in the 'outer word' the higher the chances to find interested talents to be attracted to the field.

A strong connection is provided already with the ENEN2plus project[8], whose aim is exactly to build European nuclear competencies.

Having a pool of nuclear-educated people larger than today will represent a resource for the RRs community, in need of a larger workforce to expand their activities in all the sectors (and in particular in education and training - E&T).

If there was a system that allows planning among all RRs connecting all facilities, it would allow a broad view of the opportunities offered by the existing technology for students, PhDs, or general research collaborators. This may lead to producing scientific results (publications and articles are just an example). If RR E&T activities were centralized, it would be easier to keep track of them and tackle possible problems.

A common platform, where RRs could inventory their activities, look for a target audience and cooperate with other RRs to offer a better program of activities would be highly beneficial for the RR community. The response of the TOURR project is to provide a website to ease the path toward reaching this goal. Deliverable 3.2 – "Model for utilisation and coordination of RR activities" and Deliverable 3.3 – "Online platform for optimized use of research reactors in Europe" (both public) will provide further insights on this topic.

One of the aims of the TOURR project is indeed to build a platform and put it online for beta testing among the partners first and, for a wider community afterwards. This can represent the first step towards a centralised online reference for all EU RR facilities.

There are already actions in place which are complementary to TOURR, for instance: the SECURE[9] project that has just recently (October 2022) kicked off and has a lot of RR in its consortium. SECURE will investigate advanced techniques to produce and ensure the long-term production of radio-isotopes, and the RR involved could represent a valid pool of users of the TOURR platform.

For the sake of completeness, it is worth mentioning the third project indicated as outcome of SAMIRA[10] along TOURR and SECURE. That is PRISMAP project.[11]

[8] https://enen.eu/index.php/portfolio/enen2plus-project/
[9] https://enen.eu/index.php/portfolio/secure-project/
[10] https://energy.ec.europa.eu/topics/nuclear-energy/radiological-and-nuclear-technology-health/samira-action-plan_en
[11] https://www.prismap.eu/

A common “place” to discuss E&T opportunities available all across EU RRs would be of great interest also for:

- Students looking for practical experience (e.g. in their thesis work or internship)
- Students and/or professionals who need reactor time for the validation of their work
- Specialized and/or general public who wish to visit a nuclear facility.

This latter point may also help in the way of “public perception” of nuclear technology and applications since visits would be open to the general public and the non-expert segment of the population would feel more engaged in a reality otherwise very far from them.

Table 2 summarizes and prioritises the main actions to be implemented in the immediate future.

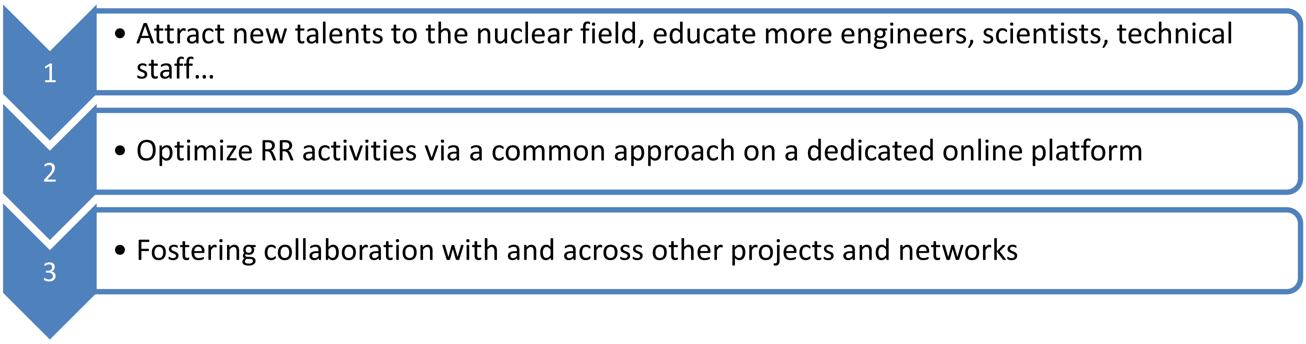


Table 2: Actions to be implemented in the immediate future

3.2 Actions to implement in the near future

It is advisable to train the personnel to make them ready to be good mentors and or teachers on top of being good technical experts.

In general, not all research reactors in Europe are primarily designed for both education and training. This is related to the history of their origin and the subsequent focus on nuclear energy (development of new types of reactors) and materials research or production of radiopharmaceuticals.

This is usually related to the expertise of the personnel, mostly lacking a specific pedagogical education and without experience with E&T. Experience shows that in some countries it is often difficult for students of nuclear disciplines (at all levels) to find "suitable" tutors who, in addition to their work or projects, are able to lead and pedagogically guide those interested in the field.

Besides special pedagogical programmes of research reactor personnel, setting up cooperation with technical universities or academic institutions plays an important role.

At the same time, collaboration with hospitals (or in general medical-related set-ups) is advisable to achieve a more complete education in the field of non-power nuclear applications.

In particular, ensuring the "non-competitive" position of both parties (RR and universities) and creating communication platforms for mutually beneficial sharing of research experience and results, and building a healthy competitive environment for science and research.

Table 2 summarizes and prioritises the main actions to be implemented in the near future.

1. Integrated technical and pedagogical training for RR personnel
2. Enhance cooperation with academia and medical-related realities (e.g. hospitals)
3. Decision regarding new European Multipurpose Research Reactor

Table 3: Actions to be implemented in the near future

3.3 Actions to implement in the long term

One of the conclusions of our analysis is that: it can be inferred that RRs are a great resource in terms of 'teaching' and allowing students and young professionals to get first-hand experience. This is in contrast with the fact that the number of RRs in the EU is decreasing.

Having fewer RRs means losing opportunities for the E&T sector including a high risk for human capacity in terms of qualified RR operators and/or employees. The RR fleet should be kept numerous and equipped with state-of-art installations to be attractive for the new generation of nuclear workforce.

This leads to the conclusion that having a larger pool of nuclear-educated people will represent a resource for the RRs community in need of a larger workforce to expand their E&T activities.

The following actions summarized in the table are encouraged to fill the gap between the current scenario and the ideal one.

Table 2 summarizes and prioritises the main actions to be implemented in the long-term scenario.

1. Continuous promotion of nuclear education
2. Retention of nuclear-educated people in the nuclear field
3. Retention and attraction of nuclear-educated people specifically **in Europe** and to EU RRs
4. Continuous exchange with other nuclear networks and nuclear projects
5. Modernize the EU RR fleet
6. New RR for testing new technologies (electricity generation with high % of renewables)

Table 4: Actions to be implemented in the long-term scenario

In order for the EU RR fleet to be attractive for the young generations it is advisable to take into account the option of building new RRs, more modern and more accessible, focusing on cutting-edge research and being an E&T opportunity in the same research fields. A new research reactor could serve as well to test new technologies for future electricity generation using nuclear energy, together with a higher percentage of renewables. This reactor could be a micro-reactor (or SMR) in development by several companies around the world, the concepts of which have not yet been tested in real experiments (e.g. being built and operated).

This aspect will be analysed in more detail in D3.4 - Recommendations for planning refurbishment of existing research reactors or construction of new ones.

The TOURR consortium recommends that new Research Reactor focused projects should be started under the coordination of the European Union level, where all EU states will have access to a vast number of RR applications. We recommend supporting national initiatives regarding the building of new reactors (e.g. PALLAS or projects in central Europe countries).

These recommendations aim at recovering and enlarging the capacity to cover a large number of applications mentioned and discussed in this report. A good example is a medium-power research reactor flexible for almost all domestic applications of Science and Technology (S&T) (e.g. NAA, nuclear data measurements, neutron, and gamma irradiation,) and education & training (E&T) by being capable of performing unique experiments for future European nuclear engineers. Another is a zero-power RR, dedicated mainly to the research of reactor physics and benchmark experiments but that can also be employed for E&T.

4 CONCLUSIONS

This report summarizes the main finding of the TOURR consortium about how to optimize the use of research reactors in Europe.

The TOURR project is articulated on three axes and the analysis has followed the same structure:

1. Science and technology
2. Medical applications
3. Education and training

A synthesis of the implemented analytical process has been presented and recommendations have been issued. Recommendations are suggested according to different time frames:

- To apply in the immediate future
- To apply in the near future
- To apply on the long run

As a general conclusion regarding the production of medical radioisotopes, Europe occupies a privileged position hosting several of the largest radioisotopes producers (BR2, MARIA, LVR-15, and HFR-PALLAS). No closure is envisaged during this decade, but they all will reach the end of their currently expected operational lives rather simultaneously during the 2030s, which can create a massive problem. A mitigation strategy to address this issue will be presented in D3.4 – Recommendations for planning the refurbishment of existing research reactors or the construction of new ones.

Regarding large neutron sources, Europe has traditionally been the leader in this area and retains some large facilities (ILL, FRM-II, BRR, HOR) despite some recent closures (BER-II, Orphée, JEEP-II). No more closures are foreseen until after 2030 and new accelerator-based neutron sources (most notably, the European Spallation Source (ESS)) can enter into service in the coming years. Hence, in this area, the near future perspectives are relatively good.

Europe can also show a large number of facilities devoted to Education and Training (SUR-100, TRIGA). No closure is foreseen for any of them in the near future. Furthermore, these reactors (TRIGA in particular) can be also used for many of the S&T applications listed in section 2.1 of this report. Initiatives like SNETP’s OFFERR platform can be very useful to boost their usage, enabling users’ access to these facilities while at the same time generating income for the facilities.

Although other types of facilities like simulators or neutron generators can be used for some Education and Training purposes also, they can’t replace research reactors for some others (the most obvious, teaching reactor physics).

The consortium recommends taking action to attract new people to the nuclear field, to train the personnel of the RR to be pedagogically prepared on top of their technical knowledge and to keep strong connections with academia and other project networks.

Specifically, a strong connection is advisable to be kept with the ENEN2plus consortium. This project, among the outcomes, shall outline nuclear competencies and show E&T needs under different axis (research, academia, and industry). Some reports are already publicly available D1.2- Report on Human Resources needs in Research, Safety and Waste Management[12] and D1.3 - Report on HR needs in non-power nuclear sector applications[13].

The ENEN Association is the largest network for E&T in Europe and is coordinating both the TOURR and the ENEN2plus projects. This leadership will ensure synergies between the outcomes of the projects.

[12] https://www.enen2plus.eu/fileadmin/user_upload/ENEN2plus_D1_2_20230531.pdf
[13] https://www.enen2plus.eu/fileadmin/user_upload/ENEN2plus_D1_3_20230531.pdf

Furthermore, a digital platform will soon be put in place within the TOURR project to facilitate achieving the optimization of resources.

Here follows a synthetic view of the SWOT analysis major findings and a match-making between the Strengths/Weaknesses with the Opportunities / Threats.

TOURR nuclear research reactors **SWOT Analysis**	**Strengths** S1: High level of expertise S2: Diverse fleet of EU RR S3: Flexibility of RR	**Weaknesses** W1: Lack of communication between RR W2: Uneven utilization among RR W3: Lack of education of non -power nuclear applications
Opportunities O1: Expand utilization with funding O2: Increase communication between RR O3: Research in new fields O4: Use of new medical isotopes	**Strategy S-O** S3O3: Using RR flexibility for research in new fields S1O1: Using expertise to construct new RR for testing new nuclear technologies S1O1: **Foster collaboration across other projects and networks**	**Strategy W-O** W1O2: **Create a platform to increase communication between RR** W3O4: Enhance cooperation between academia and medical sector (hospitals) W2O3: Increase RR utilization by promoting research in new fields
Threats T1: Losing knowledge – personnel aging T2: Aging of RR fleet – RR closures T3: Not building new RR – losing RR services in the future	**Strategy S-T** S1T1: **Promote educational platforms to transfer expertise to younger generations** S2T2,3: New European Multipurpose Research Reactor S1T2: Modernization of the EU RR fleet	**Strategy W-T** W1T3: Build new RR accessible to all EU states W3T1: **Retention and attraction of nuclear-educated people**

Figure 3 SWOT Analysis and match-making matrix