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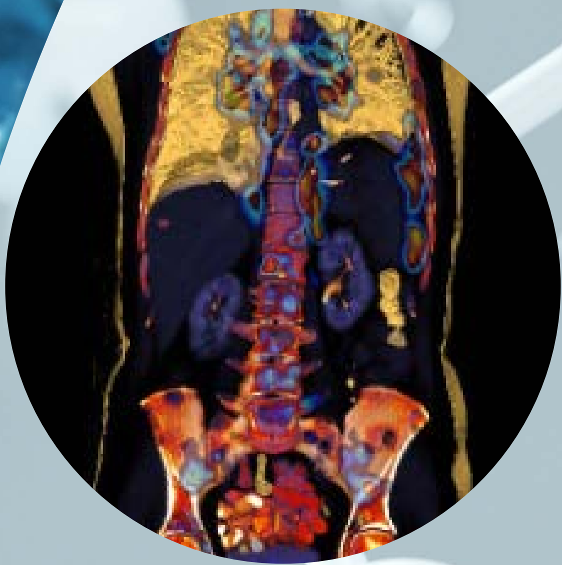

A Review of Research, Development and Innovation of Peaceful Uses of Nuclear Technologies in South Africa

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ASSAf
ACADEMY OF SCIENCE OF SOUTH AFRICA

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The Academy of Science of South Africa (ASSAf) was inaugurated in May 1996. It was formed in response to the need for an Academy of Science consonant with the dawn of democracy in South Africa: activist in its mission of using science and scholarship for the benefit of society, with a mandate encompassing all scholarly disciplines that use an openminded and evidence-based approach to build knowledge. ASSAf thus adopted in its name the term 'science' in the singular as reflecting a common way of enquiring rather than an aggregation of different disciplines. Its Members are elected on the basis of a combination of two principal criteria, academic excellence and significant February contributions to society. The Parliament of South Africa passed the Academy of Science of South Africa Act (No 67 of 2001), which came into force on 15 May 2002. This made ASSAf the only academy of science in South Africa officially recognised by government and representing the country in the international community of science academies and elsewhere.

https://www.assaf.org.za/

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LIST OF ACRONYMS

AFCONE	African Commission on Nuclear Energy
AFRA	African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology
APP	Annual Performance Plan
ARC	Agricultural Research Council
ASSAf	Academy of Science of South Africa
AU	African Union
CAN	Canadian Nuclear Association
CARST	Centre for Applied Radiation Science and Technology
CAT	Computerised axial tomography
CERN	European Organization for Nuclear Research
CGS	Council for Geosciences
CMJAH	Charlotte Maxeke Johannesburg Academic Hospital
CNSS	Centre of Excellence for Nuclear Safety and Security
COVID	Coronavirus disease
CPF	Country Programme Framework
CPPNM	Convention on the Physical Protection of Nuclear Material
CQMP	Clinically qualified medical physicist
CRP	Coordinated Research Project
CSIR	Council for Scientific and Industrial Research
CT	Computerised tomography
DALRRD	Department of Agriculture, Land Reform and Rural Development
DEAT	Department of Environmental Affairs and Tourism
DMRE	Department of Mineral Resources and Energy (formerly the Department of Energy [DoE])
DPE	Department of Public Enterprises
DPWI	Department of Public Works and Infrastructure
DSI	Department of Science and Innovation
ESRG	Energy Systems Research Group
FAO	Food and Agriculture Organization of the United Nations
FORATOM	European Atomic Forum
GHG	Greenhouse gas
HIV	Human immunodeficiency virus
IAEA	International Atomic Energy Agency
ICNDT	International Committee for NDT
ICRP	International Commission on Radiation Protection
IEC	International Electrotechnical Commission
INFCIRC	Information circular to IAEA member states
iPCIF	Interim Pre-clinical Imaging Facility

LIST OF ACRONYMS

IRMS	Isotope ratio mass spectrometry
IRP	Integrated Resource Plan
ISO	International Organization for Standardization
iThemba LABS	iThemba Laboratories for Accelerator Based Science
JAIF	Japan Atomic Industrial Forum
MHTR	Mozweli High Temperature Reactor
MLIS	Molecular Laser Isotope Separation
MPR	Multipurpose Reactor
NCCP	National Cancer Control Programme
NCD	Non-communicable diseases
NDP	National Development Plan
NDT	Non-destructive testing
Necsa	South African Nuclear Energy Corporation
NEI	Nuclear Energy Institute
NGO	Non-governmental organisation
NIA	Nuclear Industry Association
NIASA	Nuclear Industry Association of South Africa
NICD	National Institute for Communicable Diseases
NII	Node for Infection Imaging
NLO	National Liaison Office
NMISA	National Metrology Institute of South Africa
NNR	National Nuclear Regulator
NPP	Nuclear Power Plant
NQF	National Qualifications Framework
NRWDI	National Radioactive Waste Disposal Institute
NTeMBI	Nuclear Technologies for Medicine and Biosciences Initiative
NTP	NTP Radioisotopes SOC Ltd
NuMeRI	Nuclear Medicine Research Infrastructure
NWU	North-West University
OCGT	Open cycle gas turbine
OVI	Onderstepoort Veterinary Institute
OVR	Onderstepoort Veterinary Research
PACT	Programme of Action for Cancer Therapy
PACT	Programme of Action for Cancer Therapy
PBMR	Pebble Bed Modular Reactor
PET	Positron emission tomography
PGDip	Postgraduate Diploma
PSMA	Prostate-specific membrane antigen

LIST OF ACRONYMS

PUI	Peaceful Uses Initiative
QCTO	Quality Council for Trades and Occupations
R&D	Research and development
RAIS	Regulatory Authority Information System
RAL	Radiation Analytical Laboratory
RCF	Regional Country Framework
RDI	Research, development and innovation
RPB	Radiation Protection Board
RPM	Radiation protection monitoring
RPO	Radiation protection officer
RPTA	Radiation Protection Training Academy
RRT	Radiation and Reactor Theory
RSA	Republic of South Africa
RT	Radiotherapy
RT-PCR	Real-time polymerase chain reaction
SABS	South African Bureau of Standards
SACNASP	South African Council for Natural Scientific Professions
SADC	Southern African Development Community
SAHPRA	South African Health Products Regulatory Authority
SAIF	South African Isotope Facility
SAIW	Southern African Institute of Welding
SANEDI	South African National Energy Development Institute
SAQA	South African Qualifications Authority
SARIR	South African Research Infrastructure Roadmap
SARPA	Southern African Radiation Protection Association
SBAH	Steve Biko Academic Hospital

LIST OF ACRONYMS

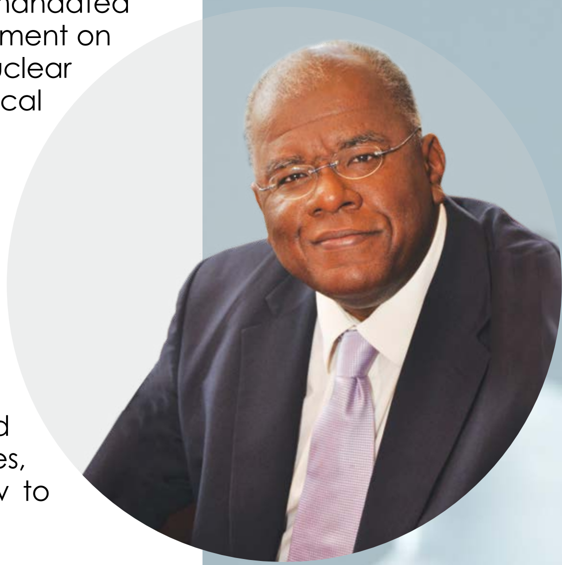
SDG	Sustainable Development Goal
SIT	Sterile insect technique
SMR	Small modular reactor
SMU	Sefako Makgatho Health Sciences University
SoE	State-owned enterprise
SPECT	Single photon emission computed tomography
STI	Science, technology and innovation
SU	Stellenbosch University
SWOT	Strengths, weaknesses, opportunities and threats
TCP	Technical Cooperation Project
TIA	Technology Innovation Agency
TUT	Tshwane University of Technology
UCT	University of Cape Town
UFS	University of the Free State
UK	United Kingdom
UP	University of Pretoria
USA	United States of America
UWC	University of the Western Cape
WHO	World Health Organization
Wits	University of the Witwatersrand
WNA	World Nuclear Association
WRC	Water Research Commission

UNITS OF MEASUREMENT

Ci	Curie *(defined as the radioactivity of one gram of pure radium-226; this is equivalent to 3.7 x 1010 decays per second)*
W	watt
GW	gigawatt
MW	megawatt
MWe	megawatt electrical
MWt	megawatt thermal
MeV	megaelectron volt
TWh	terawatt hour

FOREWORD

The Academy of Science of South Africa (ASSAf) is mandated to provide evidence-based science advice to government on matters of critical national importance. The role of nuclear technologies counts among those matters of critical importance to South Africa.



South Africa has a long history of nuclear technologies, starting with the establishment of the Atomic Energy Board through the Atomic Energy Act of 1948. Research, development and innovation (RDI) in nuclear technologies became firmly entrenched in 1961 with the establishment of a nuclear research centre at Pelindaba near Pretoria. Since then, the country has followed a path of progressive and ethical RDI in the peaceful use of nuclear technologies, responding to global developments but with a view to local developmental and strategic objectives.

The value of nuclear technologies is cross-sectoral, ranging from contributing to food security, energy security and water security, to improving healthcare and conservation efforts. Consequently, nuclear RDI can play a significant role in advancing South Africa's social and economic development.

South Africa holds an important position in the global and regional arenas, affording the country a regional advantage in terms of access to capacity, infrastructure and funding. However, local and global social, economic and political challenges and developments threaten this advantage. It is the Academy's stance that RDI in peaceful, ethical and sustainable uses of nuclear technologies must be promoted in a coordinated way, to make the most of what is available and to retain South Africa's global advantage in nuclear technologies.

The study followed the traditional Academy consensus study methodology, in which a panel of experts, guided by the panel chair, undertakes the study. The advantage of this multiple-perspective approach based on volunteerism is that it is free of partisan interest. As a result, the findings and recommendations are the best considered outcomes in the circumstances. As required by ASSAf for such studies, the report was reviewed by one local and two international experts.

I would like to thank the members of the panel for their time and effort applied during this study and to the drafting of this report. I would also like to acknowledge the staff of the Academy for their dedication and attention in undertaking their duties.

Professor Jonathan Jansen
President: Academy of Science of South Africa

ACKNOWLEDGEMENTS

Consensus studies are a team effort, with involvement not only of secretariat staff but people beyond the immediate project team. I would like to thank the following people and organisations for ensuring the success of the study:

- The Academy of Science of South Africa (ASSAf), the president of ASSAf, Professor Jonathan Jansen, and the council for their ongoing support throughout this project.
- The South African National Energy Development Institute (SANEDI), with the support of the Department of Science and Innovation (DSI), for commissioning and funding the project. In particular, Ms Tebogo Snyer of SANEDI and Ms Mandy Mlilo of the DSI.
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- Prof Gledhill (ASSAf council) for her constructive comments and editorial changes that were incorporated into the revised document.

Prof Mike Sathekge
Chair of the panel

EXECUTIVE SUMMARY

The Academy of Science of South Africa (ASSAf) was assigned to evaluate the state of research, development and innovation (RDI) with regard to peaceful uses of nuclear technologies in South Africa. The aim was to contribute to developing a strategic framework document to help identify priorities that will inform the Country Programme Frameworks of the International Atomic Energy Agency (IAEA). The Department of Science and Innovation (DSI) initiated the study and requested that it be administered by the South African National Energy Development Institute (SANEDI), an entity within the Department of Mineral Resources and Energy (DMRE) that hosts the National Liaison Office (NLO), the principal interface with the IAEA on technical cooperation.

The aim of the report is to support the high-level agreement between South Africa (through the DMRE) and the IAEA by providing a solid foundation upon which a national strategic framework on peaceful uses of nuclear technologies in South Africa can be built. The objectives of the study were to review relevant current and historical national policies, plans and strategies; review the national landscape of existing and emerging RDI roleplayers and activities in the country; develop baseline information around the nuclear technology landscape to assist with targets and indicators for monitoring and evaluation; review the Country Programme Framework (CPF) between South Africa and the IAEA and make recommendations on how the IAEA Technical Cooperation Programme could be leveraged to strengthen the nuclear technology sector in South Africa; and make proposals on how to define a South African nuclear technology RDI flagship programme.

A consensus study methodology was used for this study, led by a multidisciplinary panel of experts with the appropriate knowledge, from a variety of sectors, and supported by an ASSAf programme officer. A part-time independent researcher was appointed to assist with collating and documenting relevant and up-to-date information, including a workshop to verify with the relevant entities the information collected and to test high-level preliminary findings ahead of completing the final report. In order to address the objectives and themes, the panel carried out an analysis of strengths, weaknesses, opportunities and threats (SWOT), allowing the needs and gaps of each theme to be identified.

The characterisation of the needs and gaps contains the following elements: a brief explanation of the need setting out the context in terms of the severity and relevance; a strategic objective to be achieved; and an indicator, or indicators, for the proposed objective. The study was divided into six broad areas, namely agriculture and food security, human health, radiation protection, water and environment, energy and industry, and nuclear safety, security and safeguards.

The desktop study, sourcing and researching of background materials, as well as documentation of the deliberations of the panel and collegial interaction, have generated some significant findings.

Currently, nuclear RDI is very fragmented in South Africa, from both the execution as well the regulatory perspectives, with little or no coordination or strategic direction. The following strategies, plans and reports of the DMRE and DSI are linked to nuclear technology RDI, in line with the priorities of the National Development Plan (NDP) 2030, unlike the strategies and plans of the departments of Health; Higher Education and Training; Public Enterprises; Agriculture, Rural Development and Land Reform; and Water and Sanitation, which make almost no mention of nuclear technology. This leads to diminishing human capital development, as well as RDI in nuclear technologies with fewer master's and doctoral graduates, thus losing critical skills in this area.

The country has several international agreements and treaties in place and supports the role of nuclear technology in the progress of achieving the 2030 Agenda for Sustainable Development and the 17 Sustainable Development Goals (SDGs), while being informed by the Medium-Term Strategic Plan. Based on the strategic goals, objectives and performance indicators, South Africa formulates the Technical Cooperation Projects (TCPs) and Coordinated Research Projects (CRPs) of the IAEA. Currently, South Africa has low participation in the 2020–2021 Technical Cooperation

Programme budget by thematic area. For noting, Africa has the following levels of participation:

- Food and agriculture: 35%
- Health and nutrition: 28%
- Safety and security: 18%
- Nuclear knowledge development and management: 9%
- Water and environment: 6%
- Industrial applications: 4%.

South Africa has limited participation in the IAEA TCPs and CRPs on critical topics such as nuclear power plant lifecycle, nuclear infrastructure, land and water management (food and agriculture), nuclear fuel cycle and biodiversity loss.

A major finding of this report is that South Africa is in a position of suboptimal participation in, and benefit from, the IAEA TCPs and CRPs.

While the country has several global leaders among its infrastructures, including iThemba Laboratories for Accelerator Based Sciences (iThemba LABS) and the South African Nuclear Energy Corporation (Necsa), there are infrastructural challenges impeding nuclear technology development, RDI and the nuclear economy due to lack of integration of nuclear technology planning in the RDI infrastructure for agriculture, health, radiation protection, water and sanitation, and energy, and a failure to capitalise on the strength of the highly regarded nuclear programmes of several universities. Furthermore, there is little benefit from the potential contribution of the private sector, because public–private partnerships have not been fostered.

The following general recommendations should be monitored by the South African National Energy Development Institute (SANEDI):

1. Improve integration and interdepartmental approaches to nuclear RDI

Integration and interdepartmental approaches to RDI on nuclear technologies must be achieved, based on national priorities. Currently, the strategies and plans of the departments of Health; Higher Education and Training; Public Enterprises; Agriculture, Land Reform and Rural Development; and Water and Sanitation make almost no mention of nuclear technology. It is therefore recommended that a central coordinating desk should be placed under the control of ASSAf, tasked with addressing the poor record of collaboration and the present failure to integrate the results of nuclear technology research into a coherent body of knowledge that can contribute to the national economy.

2. Increase the number of institutions and RDI projects collaborating in the TCPs and AFRA

An integrated interdepartmental approach will be formulated, based on national priorities, which will lead to maximum benefits and input from IAEA.

3. Formulate a human capital development strategy for sustainable nuclear applications

The economic potential of nuclear technology infrastructure development and personnel qualification and certification within general industry is far from being realised in South Africa or elsewhere on the African continent. The potential of the available workforce therefore needs to be unlocked through infrastructure development and upskilling of local citizens.

A strategy will be developed for a holistic approach that acknowledges skills, experience, knowledge, concepts, and innovative ideas on transformation. The current state of human resource development in the nuclear field must be strengthened. Nuclear education at South Africa's universities and other training institutions should continue, and could be prioritised, in order to supply the South African nuclear industry with a steady stream of well-educated professionals. Practical solutions will be provided by using existing and new interdisciplinary centres of excellence to support the country's priorities and the safe and sustainable operation of nuclear power programmes. The development strategy and funding of these centres should be based on collaborative strength and high-level skills, leading to high productivity, advanced manufacturing capability and job creation in the nuclear field.

The following recommendations are related to specific themes:

4. Agriculture and food security

4.1 Improve routine practices for soil and water management with combinations of nuclear techniques through a dedicated RDI programme

This will provide direct benefits to farmers by fostering climate-smart agricultural practices to enhance and continuously improve agricultural productivity through various technologies, including novel uses of isotopes. Although nuclear techniques offer good prospects for improving routine practices for soil and water management, they are not routinely used by farmers. RDI activities focused on mutation induction to broaden the genetic base of crop germplasm in seed and vegetatively propagated crops could assist in removing certain production constraints, an initiative that is much needed in South Africa. Flagship RDI collaborative programmes should be included in the strategic planning of the Department of Agriculture, Land Reform and Rural Development (DALRRD).

4.2 Develop human capacity and RDI to increase the application of isotope ratio mass spectrometry (IRMS) to enable the monitoring of food fraud

Stable isotope analysis has become a powerful tool for food authentication and traceability due to its advantages of high precision and efficiency. There is a need to review the current limitations and improve future research directions of isotope analysis in food authentication and traceability. The monitoring of food fraud must be improved by increasing the number of laboratories using improved IRMS methods for food authentication and traceability.

4.3 Take an integrated approach to animal health and zoonotic infections

The complex links between human, animal and environmental health require coordinated multidisciplinary and multipronged collaboration to address the threats from zoonotic diseases. While the global public health community needs to act decisively now, South African institutions should take an integrated approach to collaboration and investment with regard to nuclear applications.

5. Human health

5.1 Introduce nuclear medicine departments in level II hospitals using human capacity development and RDI

Insufficient access to nuclear medicine and theranostic procedures leads to increased morbidity and mortality. Health technology assessments have demonstrated the benefit and cost-effectiveness of making nuclear medicine and theranostic procedures available outside central hospitals.

5.2 Develop a comprehensive national cancer control programme (NCCP) to address optimal usage of radiation medicine (radiotherapy, nuclear medicine, radiology, medical physics and radiobiology)

There is a need to develop a comprehensive NCCP with actions based on the mission of the IAEA Programme of Action for Cancer Therapy (PACT), and to make investments that would enhance access to imaging equipment, workforce capacity, digital technology, radiopharmaceuticals, and research and training programmes in South Africa. Such an initiative would have massive health and economic benefits and reduce the global burden of cancer. This would also enable better support the IAEA Ray of Hope Initiative, 'Cancer care for all'.

6. Radiation protection

6.1 Develop and implement a strategy including a public–private partnership model for education, training and research for radiation protection

A national strategy for a public–private partnership model for education, training and research with regard to radiation protection would maximise usage of the limited skills and infrastructure. This would also address (i) awareness of radiation protection and safety in veterinary medicine, (ii) establishment of a single radiation protection training body with subdivisions for various professions by 2024, and (iii) publication of radiation protection officer (RPO) training in the Government Gazette.

6.2 Harmonise the radiation protection regulatory functions of the National Nuclear Regulator (NNR) and the Department of Health

A framework needs to be designed to harmonise the functioning of the two independent national regulatory bodies, namely the NNR and the Directorate of Radiation Control under the South African Health Products Regulatory Authority (SAHPRA), an entity of the national Department of Health. This could be facilitated by SANEDI with the assistance of ASSAf, as stated in Recommendation 1, and would assist with the exchange of accurate data that could be used for RDI, increased participation in TCPs, help with planning, and improved regulatory control programmes in accordance with IAEA safety standards and guidelines, without compromising the legislative mandates of each body.

7. Water and environment

7.1 Improve integrated management of RDI on isotope hydrology of water resources

The management of RDI on the isotope hydrology of water resources is currently inadequate. Isotope hydrology is a very cost-effective means of assessing the vulnerability of groundwater sources to pollution. There is thus a need to support collaborative RDI projects on the use of isotope hydrology competences in South Africa in organisations such as Necsa, the CSIR and local universities, and to integrate them into a comprehensive water resource management programme for the country.

7.2 Develop new and more sustainable methods for water production by desalination

One of the methods of increasing water production is to apply proven technology that is economically viable and uses manageable levels of electricity for desalination by reverse osmosis. The use of nuclear power for water desalination should be considered. There is a need to leverage the envisioned 2 500 MW nuclear build programme, as articulated in the Integrated Resource Plan (IRP) of 2019 (RSA, 2019). This flagship investment and RDI are particularly urgent, taking into consideration the water scarcity in the country and the projections of a water deficit in the future.

8. Energy

8.1 Strengthen analytical capacity to develop energy supply and demand models and scenarios for the medium and long term

Given the uncertainty that still prevails, more detailed studies are needed using comprehensive models to analyse energy supply and demand. These studies will strengthen analytical capacity to justify the inclusion of nuclear energy based on evidence from databases, indicators, scenarios and sustainable development for energy. This approach will provide clarity on the future of nuclear energy and on whether South Africa can afford to build new nuclear energy capacity. Furthermore, this will demonstrate the need for a sustained and established nuclear fuel cycle and lower carbon footprint, thus justifying participation in IAEA TCPs and other international grand challenge RDI projects. These RDI projects could contribute to better understanding and planning for small nuclear units (i.e. small modular reactors), which are considered more manageable in terms of financial investment.

8.2 Improve communication and education on nuclear energy

There are negative perceptions of the nuclear energy industry in South Africa for various reasons, ranging from concerns about safety, technical understanding and radioactive waste, to political and economic miscommunication. Hence, there is a need to conduct an honest and transparent information programme that will increase the understanding and education of the public with regard to the benefits and risks associated with nuclear energy. Importantly, it is crucial to state that nuclear energy has a role to play in the development of South Africa based on a comprehensive scientific analysis.

9. Industry

9.1 Increase the competitiveness of nuclear technology in South African industries, and contribute to combating climate change

Several industries, such as mining and the processing, production, food and agriculture industries, face a number of problems, including relatively low competitiveness, the impact of their activities on climate change, and inefficient energy consumption. Increasing the competitiveness of nuclear technology in South African industries will help provide opportunities for employment and RDI. It is strategic to include uranium exploration, prospecting and final extractions in the planning and prioritisation, given that during exploration, many inexpensive research opportunities become available to assist in capacity building. Training and R&D in non-destructive testing (NDT) and related areas in industry must continue to be sustained and optimised.

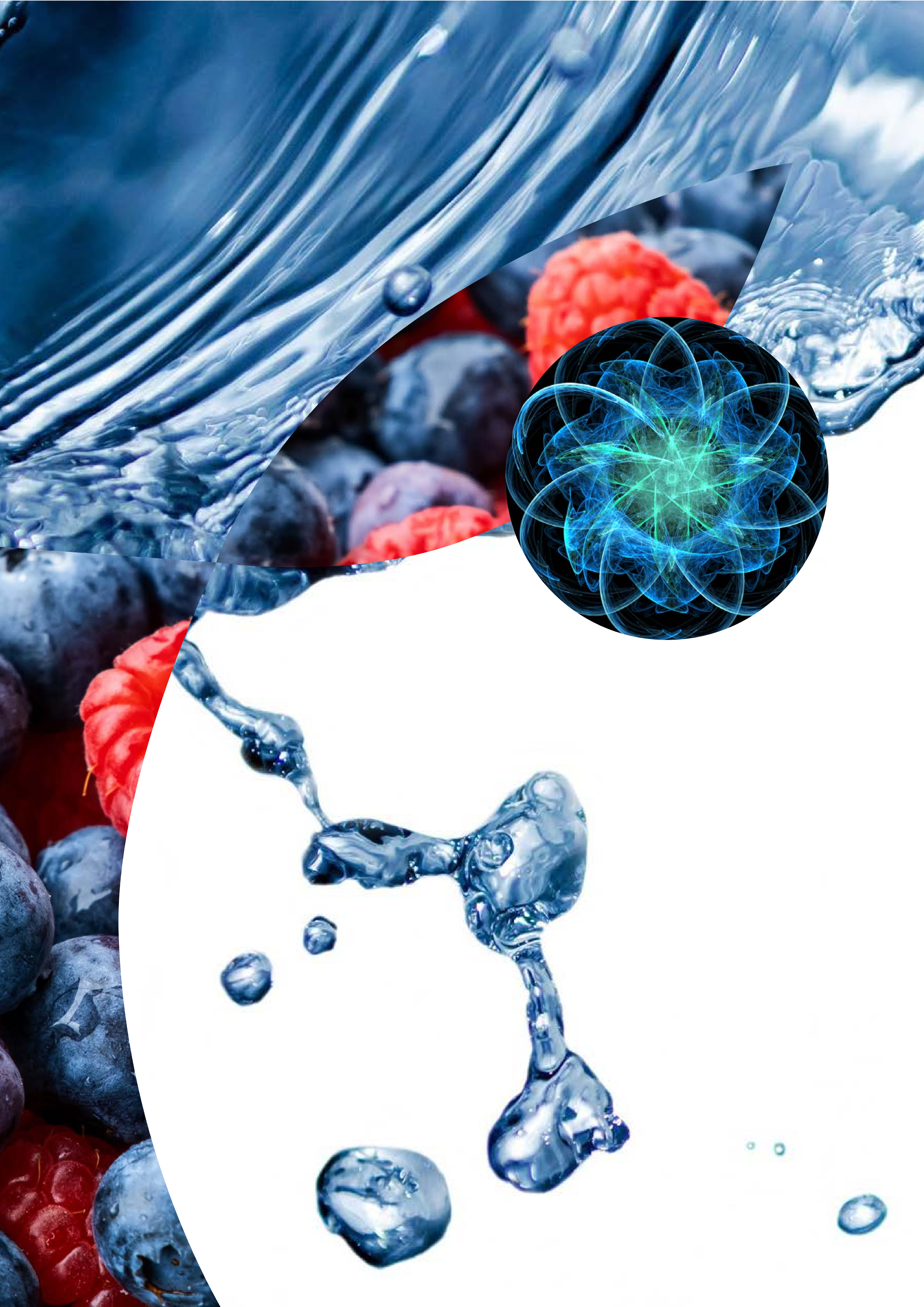
10. Nuclear safety, security and safeguards

10.1 Increase nuclear reactor RDI to promote high standards of safety, security and safeguards

Cabinet approval of the Multipurpose Reactor (MPR) proposal allows South Africa to retain its nuclear technology global footprint so that radioisotope production, RDI and related nuclear technology innovations can continue without interruption. This will provide an opportunity to increase the number of IAEA TCPs in the safety, security and safeguards space, as well as related human capacity development through projects concerning research reactor safety elements (nuclear safety, radiation safety, transportation safety, and radioactive waste safety related to spent fuel and use products). The signing of the Amendment to the Convention on the Physical Protection of Nuclear Material (CPPNM) is encouraged, as well as relevant government departments addressing the actions demanded by the Amendment.

While these recommendations are not exhaustive, they will help to develop a national strategy that articulates the strategic priorities of the country in line with existing policy documents, such as the NDP, and would inform consultations on the Country Programme Framework and proposals on how to define a South African nuclear technology RDI flagship programme.

The application of nuclear technologies, once integrated with existing local and international development initiatives, will result in the realisation of plans that support the identification of areas in which these technologies may be successfully deployed. These research focus areas will aim to contribute to both global and local arenas, identifying opportunities that could be considered to be low-hanging fruits, and providing avenues for building partnerships between institutions (both national and international) and individual researchers. The recommendations define a South African nuclear technology RDI flagship programme for the 2030 Agenda for Sustainable Development, thus informing the Country Programme Framework (CPF). Importantly, South Africa should leverage on the strong and healthy relationship with the IAEA to address national needs and priorities through the CPF and its individual projects.



1. INTRODUCTION

1.1 Background and orientation

South Africa is a founding member of the International Atomic Energy Agency (IAEA), which was initiated in 1957. The mandate of the IAEA is to promote safe, secure and peaceful nuclear technologies globally through its members, of which there are 175 (as at 2 March 2022).

The Agency's statutory objective is to "*… seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world*" and "*… ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose*."[1]

The IAEA is responsible for two main areas: the Regular Programme and the Technical Cooperation Programme. The IAEA's base income is through the Regular Budget Fund, the Technical Cooperation Fund and Extrabudgetary Programme Funds, for which Member States are the core funders while in some cases donors also contribute. The extrabudgetary funds and the Technical Cooperation Fund are largely dependent on voluntary contributions. In 2010, the IAEA launched its Peaceful Uses Initiative (PUI), which is an important means of raising extrabudgetary contributions for the Agency's activities in the peaceful uses of nuclear technology. The PUI enables the IAEA to implement additional unfunded projects for Member States in order to pursue the peaceful applications of nuclear technology.

The Agency's technical cooperation with Member States aims to promote tangible socioeconomic impacts, supporting the use of nuclear science and technology to address major sustainable development priorities at national, regional and interregional levels. Although all the IAEA technical departments (the Department of Nuclear Energy, Department of Nuclear Safety and Security, Department of Nuclear Sciences and Applications, and Department of Safeguards) have direct contact with, and provide support to, Member States, the Department of Technical Cooperation has the responsibility for formulating and delivering the IAEA's development mandate.

The Technical Cooperation Programme, implemented by the IAEA's Department of Technical Cooperation with the support of the IAEA technical departments, is the primary mechanism for transferring nuclear technology to Member States. IAEA technical cooperation projects provide expertise in fields where nuclear techniques offer advantages over other approaches, or where nuclear techniques can usefully supplement conventional means. All Member States are eligible for support through technical cooperation projects, although in practice these tend to focus on the needs and priorities of less-developed countries. Technical cooperation projects can be national, regional or interregional. In this regard, South Africa is one the countries that has benefited from several projects through the Country Programme Framework (CPF) in terms of research proposals, skills development and attitudes towards nuclear technologies.

The technical cooperation medium-term (4–6 years) frame of reference between a Member State and the IAEA is specified under the CPF, which is crucial to ensuring that a country's technical cooperation programme and its individual projects are focused on agreed national needs and priorities within the overall framework of that Member State's national plan for the use of nuclear-related technology. The technical cooperation is grounded on national priorities, reflecting national development plans, regional priorities and the country's development aims in specific sectors.[2]

1 https://www.iaea.org/about/statute
2 https://www.iaea.org/sites/default/files/documents/tc/LFA-ref.pdf

The National Liaison Office (NLO), currently located within South Africa's Department of Mineral Resources and Energy (DMRE), is tasked with liaising directly with the IAEA, as well as managing ongoing activities in the country supported by the IAEA. A key component of the NLO is to coordinate consultations on the CPF and facilitate the finalisation and ratification of the framework. Ideally, a national strategy that articulates the strategic priorities of the country in line with existing policy documents, such as the National Development Plan (NDP), would inform the consultations on the CPF, but in South Africa such a strategy does not exist.

The Department of Science and Innovation (DSI) has been paying the country membership fees to the IAEA on behalf of South Africa for almost two decades. Consequently, the responsibility for signing the CPF on behalf of South Africa lies with the Director-General of the DSI.

Given the absence of a national strategy to inform the CPF for South Africa, the Director-General of the DSI requested the development of a strategic framework document that would give an indication of the research, development and innovation (RDI) priorities of South Africa for a five-year timeframe.

The Academy of Science of South Africa (ASSAf) was commissioned to undertake an evaluation of RDI related to the peaceful uses of nuclear technologies in South Africa. The study was initiated by the DSI and administered by the South African National Energy Development Institute (SANEDI) as the Energy Secretariat established by the DSI. SANEDI is an entity within the DMRE which hosts the NLO. The purpose of this report is to support the high-level agreement between South Africa and the IAEA by providing a solid foundation upon which a national strategic framework on the peaceful uses of nuclear technologies in South Africa can be built.

1.2 Objectives

The objectives of this study were as follows:

1. To perform a review of relevant current and historical national policies, plans and strategies (e.g. National Development Plan, White Paper on Science, Technology and Innovation, Decadal Plan, current and future Medium-Term Strategic Framework, Nuclear Energy Policy) to understand how these interface with one another to provide sufficient strategic emphasis for the development and application of nuclear technology in South Africa.

2. To undertake a survey of the national landscape, reviewing the existing and emerging RDI roleplayers (funders, implementing agencies and key government departments) and activities in the country, including the flagship programmes of the DSI, related to the peaceful uses of nuclear technologies.

3. To develop baseline information around the nuclear technology landscape to assist with determining:

    i. Indicators for monitoring and evaluation
    ii. The setting of targets
    iii. The best approach to collecting information on a continual basis.

4. To assess relevant international agreements or collaborations, including the arrangements between South Africa and the IAEA.

5. With specific reference to the IAEA:

    i. To review the DSI's Strategic Framework document, and provide recommendations for possible improvements and how it should be positioned within the Nuclear Technology RDI Framework in South Africa.

ii. To review the CPFs between South Africa and the IAEA (first, second, third and fourth iterations) and assess the benefits to the South African national system of innovation relative to investment.
iii. To review the proposed process for the development of the fifth CPF and make recommendations for improvements to the process.
iv. To make recommendations on how the IAEA Technical Cooperation Programme, through a fifth and sixth iteration of the CPF, could be leveraged to strengthen the nuclear technology sector in South Africa.

6. To present proposals on how to define a South African nuclear technology RDI flagship programme, with recommendations on new RDI sub-programmes that will address emerging issues in South Africa (e.g. Agenda 2030).

The objectives are addressed in various sections of the report. For ease of reference, Table 1 contains a brief comment on where and how the various objectives are addressed in the report.

Table 1: Brief orientation of responses to the objectives

Objective	Comment
1. To perform a review of relevant current and historical national policies, plans and strategies (e.g. National Development Plan, White Paper on Science, Technology and Innovation, Decadal Plan, current and future Medium-Term Strategic Framework, Nuclear Energy Policy) to understand how these interface with one another to provide sufficient strategic emphasis for the development and application of nuclear technology in South Africa.	This objective is addressed for each theme mainly under the infrastructure and production, human capital and SWOT analyses in chapters 4–10.
2. To undertake a survey of the national landscape, reviewing the existing and emerging RDI roleplayers (funders, implementing agencies and key government departments) and activities in the country, including the flagship programmes of the DSI, related to the peaceful uses of nuclear technologies.	This objective is addressed for each theme mainly under the infrastructure and production, human capital and SWOT analyses in chapters 4–10.
3. To develop baseline information around the nuclear technology landscape to assist in determining: i. Indicators for monitoring and evaluation ii. The setting of targets iii. The best approach to collecting information on a continual basis.	This objective is addressed for each theme/field mainly under the infrastructure and production, human capital and SWOT analyses in chapters 4–10. Objective 3ii is addressed under the needs and gaps of each section, and objective 3iii is included under Recommendation 1.
4. To assess relevant international agreements or collaborations, including the arrangements between South Africa and the IAEA.	Chapter 2 responds to the relevant international agreements in general, including the IAEA.

Objective	Comment
5. With specific reference to the IAEA: i. To review the DSI's Strategic Framework document and provide recommendations for possible improvements and how it should be placed within the Nuclear Technology RDI Framework in South Africa.	This objective is addressed mainly in section 2.2 and under the needs and gaps of each section.
ii. To review the CPF between South Africa and the IAEA (first, second, third and fourth iterations) and assess the benefits to the South African national system of innovation relative to investment.	This objective is addressed mainly in section 1.1 and under the recommendations.
iii. To review the proposed process for the development of the fifth CPF and make recommendations for improvements to the process.	This objective is addressed mainly in section 1.1 and under the recommendations.
iv. To make recommendations on how the IAEA Technical Cooperation Programme, through a fifth and sixth iteration of the CPF, could be leveraged to strengthen the nuclear technology sector in South Africa.	This objective is addressed mainly under the needs and gaps, including the indicators.
6. To present proposals on how to define a South African nuclear technology RDI flagship programme, with recommendations on new RDI sub-programmes that will address emerging issues in South Africa (e.g. 2030 Agenda for Sustainable Development).	This objective is addressed mainly in the summary, concluding statement and recommendations.

1.3 Methodology

The Academy of Science of South Africa (ASSAf) used the methodology of a consensus study, led by a multidisciplinary panel of experts with the appropriate knowledge, from a variety of sectors. Members of the ASSAf consensus study panel are endorsed by the ASSAf council. Table 2 lists the members of the panel, which was chaired by Prof Machaba (Mike) Sathekge. Biographies of the panel members are provided in Appendix 1.

Table 2: Members of the multidisciplinary panel and their affiliations

Name	Affiliation
Prof Mike Sathekge	University of Pretoria (UP) and Nuclear Medicine Research Infra-structure (NuMeRI)
Dr Faïçal Azaiez	iThemba Laboratories for Accelerator Based Sciences (iThemba LABS)
Prof James Larkin	University of the Witwatersrand (Wits)
Dr Moses Modiselle	Drs Van Niekerk Ramjee Modiselle and Lengana Inc.
Ms Tebogo Motlhabane	National Radioactive Waste Disposal Institute (NRWDI)
Mr Gaopalelwe Santswere	South African Nuclear Energy Corporation (Necsa)
Prof Dawid Serfontein	North-West University (NWU)

Following approval by the ASSAf council in March 2021, the study was initiated and the inaugural meeting of the panel took place on 10 June 2021. During the study, the panel continued to meet to discuss progress, challenges, findings and overall report content.

The panel was supported in its work by an ASSAf programme officer, who was responsible for providing logistical and administrative assistance, liaising with SANEDI as the commissioning entity, sourcing and researching background material, as well as documenting the deliberations of the panel. With due recognition that the topic of nuclear technologies is transdisciplinary, and that the panel that was appointed would not comprehensively account for all fields of knowledge, multiple consultations were undertaken with additional subject-matter experts. A part-time independent researcher was appointed to assist the panel with collating and documenting relevant and up-to-date information.

As part of the information collation, a workshop with 76 relevant national stakeholders and key roleplayers was held on 3 May 2022. The purpose of the workshop was to verify with the relevant entities the information collected and to test high-level preliminary findings ahead of completion of the draft report. A list of the institutions represented at the workshop is provided in Appendix 3. The draft report then underwent peer review by three independent reviewers. In line with ASSAf policy, three experts were invited to review the report: one from South Africa, one from beyond South Africa's borders but on the African continent, and one from beyond African shores. The biographies of the reviewers are included in Appendix 2. Following feedback from peer reviewers, the report was revised ahead of submission to the ASSAf council for final approval, which was obtained in December 2022.

2. LEGISLATIVE ENVIRONMENT

2.1 National policy context

The nuclear sector in South Africa is governed mainly by the Nuclear Energy Act (No. 46 of 1999) as amended, the National Nuclear Regulator Act (No. 47 of 1999), the Non-Proliferation of Weapons of Mass Destruction Act (No. 87 of 1993) as amended, and the National Radioactive Waste Disposal Institute Act (No. 53 of 2008). These Acts are administered by the DMRE. In the following sections, these Acts are summarised together with several others relevant to nuclear technologies.

2.1.1 Nuclear Energy Act

The Nuclear Energy Act (No. 46 of 1999)[3] as amended provides for the establishment of the South African Nuclear Energy Corporation (Necsa) and outlines Necsa's functions, powers, financial and operational accountability, as well as the mode of governance.

The Act also provides the responsibilities for the implementation and application of the Safeguards Agreement and any additional protocols in support of the Nuclear Non-Proliferation Treaty.

The Act provides for the regulation, acquisition and possession, as well the importation and exportation, of nuclear fuel, related material and related equipment in order to comply with international obligations. Finally, the Act describes the measures towards discarding radioactive waste and the storage of irradiated nuclear fuel.

2.1.2 National Nuclear Regulator Act

The establishment of the National Nuclear Regulator (NNR) is provided for in the National Nuclear Regulator Act (No. 47 of 1999)[4]. In addition to governance and operations, the Act defines the responsibilities, which include:

…granting nuclear authorisations and exercising regulatory control related to safety over the siting, design, construction, operation, manufacture of component parts, and the decontamination, decommissioning and closure of nuclear installations; and vessels propelled by nuclear power or having radioactive material on board which is capable of causing nuclear damage.[5]

The facilities and activities regulated by the NNR include:
- Operation of nuclear power reactors, research reactors, nuclear technology applications, radioactive waste management and mining
- Processing of radioactive ores
- Users of small quantities of radioactive material
- Transport of radioactive materials
- Vessels propelled by nuclear power or having radioactive material on board
- Any other actions capable of causing nuclear damage to which the National Nuclear Regulator Act applies.

The Act also provides for safety standards and regulatory practices to protect against nuclear damage.

3 https://www.gov.za/documents/national-energy-act
4 https://www.gov.za/documents/national-nuclear-regulator-act
5 https://nnr.co.za/about-us/introduction-to-the-nnr/

2.1.3 National Radioactive Waste Disposal Institute Act

The National Radioactive Waste Disposal Institute Act (No. 53 of 2008)[6] provides for the establishment of the National Radioactive Waste Disposal Institute (NRWDI). The Act describes the functions of the institute as well as the modes of governance and operations thereof. According to the Act, the institute is to manage 'ownerless' radioactive waste disposal on a national basis. The institute is to conduct research and plan development for the disposal of radioactive waste, as well as develop, transfer or exploit technologies related to radioactive waste disposal. The Act includes provisions related to the responsibilities of generators of radioactive waste, and the application and requirements for radioactive waste disposal certificates.

2.1.4 Non-Proliferation of Weapons of Mass Destruction Act

The Non-Proliferation of Weapons of Mass Destruction Act (No. 87 of 1993)[7] as amended includes provisions related to the import, end use and export of controlled goods (goods that may contribute to the design, development, production, deployment, maintenance or use of weapons of mass destruction). Such controlled goods could include monitoring equipment, software or related technology, some of which may be needed for RDI in nuclear technologies.

2.1.5 Department of Health: Radiation Control

The Department of Health's Directorate of Radiation Control receives its regulatory mandate through the Hazardous Substances Act (No. 15 of 1973)[8], which classifies electronic generators of ionising radiation as group III hazardous substances, and radioactive sources as group IV hazardous substances.

- Section 3 of the Act controls the sale, letting, use, operation, application and installation of group III substances. These are further regulated by Regulation R1332 of 1973.
- Section 3A of the Act controls the production, acquisition, disposal, importation, exportation, possession, use and conveyance of group IV substances. These are further regulated by Regulations R246 and R247 of 1993.

Device control is mandated by the Schedule for Listed Electronic Products Regulation R1302 of 1991[9].

2.1.6 Nuclear Energy Policy for the Republic of South Africa

The Nuclear Energy Policy (DMRE, 2008) provides a policy framework for the prospecting, mining, milling and use of nuclear material (including uranium ore and any other ores), as well as the development and use of nuclear technology for the generation of energy for peaceful purposes in South Africa. (The policy is limited only to energy-related applications of nuclear technology.) It is guided by the White Paper on Energy Policy (DMRE, 1998), which includes nuclear energy as an option for electricity generation, given that nuclear energy is considered a low carbon emitting source of electricity. The Nuclear Energy Policy is South Africa's commitment to further develop and expand the country's existing nuclear energy sector and provides a national vision for promoting a national nuclear energy sector.

Some of the objectives are related to the management of radioactive waste,

6 https://www.gov.za/documents/national-radioactive-waste-disposal-institute-act
7 https://www.gov.za/documents/non-proliferation-weapons-mass-destruction-act-2-jul-1993-0000
8 https://www.gov.za/documents/hazardous-substances-act-16-apr-2015-1120
9 https://www.sahpra.org.za/radiation-control/

monitoring of a (safe) nuclear industry, and effective oversight and regulation of the nuclear energy sector. In addition to outlining South Africa's legislative environment for nuclear energy, the policy also identifies current roleplayers and key stakeholders in the industry and describes further functions necessary for coordinated expansion of the nuclear energy industry. In this regard, the policy identifies Necsa as the entity responsible for coordinating nuclear energy RDI in South Africa, including stimulating research at universities and in the private sector.

The focus areas of the policy include the nuclear fuel cycle, nuclear reactor construction and operation, security of uranium supply, employment, awareness creation, human resource development and environmental protection.

Phases and timelines for the development and expansion of the nuclear energy sector are indicated:

Phase 1: 2008–2010

1. Maintenance and enhancement of current national nuclear infrastructure
2. Preparatory work for expansion of the nuclear infrastructure across the nuclear fuel cycle, including funding and preparations for the construction of nuclear power plants
3. Continued research into advanced nuclear energy systems
4. Acceleration of skills development initiatives in line with expected expansion, including increased capacity at institutions of higher learning
5. Promotion of uranium exploration and mining
6. Roll out of aspects of the Radioactive Waste Management Policy
7. Implementation of public information programme.

Phase 2: 2011–2015

8. Construction of new nuclear infrastructure including nuclear power plants
9. Continued maintenance of existing nuclear infrastructure
10. Demonstration of advanced nuclear energy systems
11. Initiation of localisation of nuclear equipment and component manufacturing, including construction of heavy machinery infrastructure
12. Building of capacity for nuclear technology transfer.

Phase 3: 2016–2025

13. Operation of new power plants
14. Maintenance of existing nuclear infrastructure
15. Local manufacturing of nuclear equipment and components
16. Commercialisation of advanced nuclear energy systems
17. Accelerated research into further advanced nuclear energy systems.
18. The policy reiterates South Africa's commitment to cooperate and collaborate internationally when planning and promoting research, development and utilisation of nuclear energy (for peaceful purposes).

2.1.7 Integrated Resource Plan

The Integrated Resource Plan (IRP) is a scenario-based plan under the custodianship of the DMRE and is to be revised regularly (the initial suggestion was every two years) to reflect rapidly changing global and technological circumstances. The primary purpose of the IRP is to document the predicted long-term demand for electricity and to provide detail on how the demand will be met with regard to generation capacity, type of energy generation, cost and timing. The IRP "*aims to achieve a balance between an affordable price for electricity to support a globally competitive economy, a move to a more sustainable and efficient economy, a move to create local jobs, the demand on scarce resource such as water and the need to meet nationally appropriate* *emissions targets in line with global commitments*"[10]. The IRP also provides input into other planning processes such as economic development.

The first draft of the IRP, compiled by the DMRE (then the Department of Energy), was completed in January 2010 and covered a limited period (2010–2013). The intention was to follow an inclusive consultation process to develop an extended plan for the period 2010–2030.

The final version of the Integrated Resource Plan 2010–2030 (IRP2010) was subsequently released in March 2011, forecasting the energy demand for the 20-year period 2010–2030. The start of the forecast period moved on with each new release of the IRP; however, the duration of the forecast period did not always remain constant. For example, in October 2019 the IRP2019 was gazetted with updated energy forecasts for the period 2019–2030 (i.e. the forecast period shrank to 11 years). The intention of the IRP was to follow an inclusive consultation process to develop an extended plan for the period 2010–2030. The final version of the IRP2010 (DMRE, 2011) describes the process.

Each version of the IRP contains a substantial number of science-based forecasting scenarios (e.g. a low-growth, medium-growth and high-growth scenario). The high-growth scenario will then forecast that a large generation capacity of new power plants should be built, while the low-growth scenario forecasts that only a much smaller capacity will be required. It thus follows that companies and other special interest groups with a stake in power plant construction would lobby government to implement the high-growth scenarios. However, the scenario in each IRP that was intended for implementation was always the Policy Adjusted Scenario where government selected one of the science-based scenarios of the IRP as a point of departure and then modified it to fit government policy. For example, several versions of the IRP did not recommend the construction of any nuclear power plants, at least not in the Least-Cost Scenarios. However, government then overruled this by inserting certain capacities of nuclear power plants into the Policy Adjusted Scenario. Similarly, the Policy Adjusted Scenario always contained more new coal plants than suggested in the science-based scenarios. Consequently, the Policy Adjusted Scenarios were normally more expensive than the Least-Cost Scenario and also less effective at reducing CO_2 emissions, at least as estimated by the model. The reasons for the country's load-shedding are partly driven by the declining plant performance of the coal fleet and over-reliance on open cycle gas turbines (OCGTs), hence the revised scenarios. Figure 1 shows the new generation capacity in the Revised Balanced Scenario, in which the allocation to (new) nuclear energy was 9 600 MW.

10 https://www.gov.za/sites/default/files/gcis_document/201409/executivesummarydraftirp20102final201010070.pdf

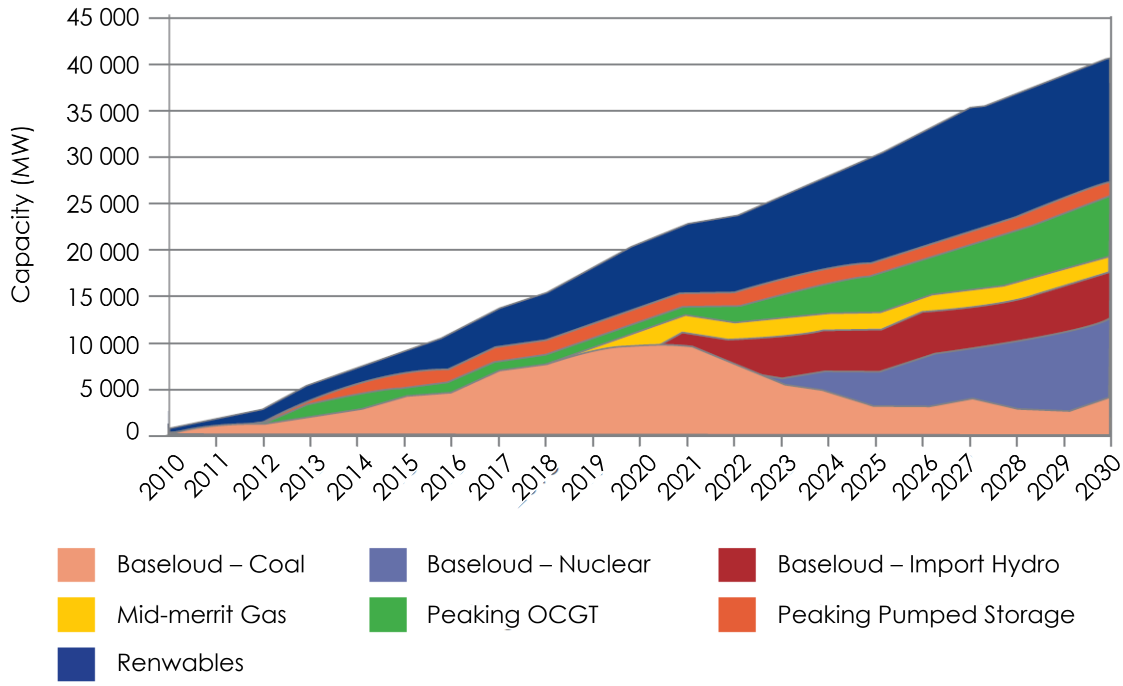


Figure 1: Revised balanced scenario for new generation capacity (DMRE, 2011)

The latest release of the IRP, IRP2019 (RSA, 2019), includes the installed nuclear capacity of 1 860 MW of the Koeberg Nuclear Power Plant (NPP) and the extension of its design life by a further 20 years beyond 2024. Furthermore, IRP2019 states the decision to "*commence preparations for a nuclear build programme to the extent of 2 500 MW, at a pace and scale that the country can afford*". The new nuclear power capacity is most likely to be in the form of small nuclear units (i.e. small modular reactors), which are considered more manageable in terms of financial investment.

2.2 South African government departmental strategies and plans

The following strategies, plans and reports of various South African government departments were reviewed for their links to nuclear technology RDI, in line with the priorities of the NDP 2030 (National Planning Commission, 2011).

2.2.1 White Paper on Science, Technology and Innovation

The 2019 White Paper on Science, Technology and Innovation (DSI, 2019), approved by Cabinet in March 2019, provides a long-term policy view to grow the role of science, technology and innovation (STI). The White Paper aims to promote the use of STI in assisting South Africa's economic and societal development by employing the best and latest technological developments in the face of rapid global challenges and changes.

The White Paper has the following objectives:
- To improve coherence and coordination
- To increase the partnering of the national system of innovation (NSI) between business, academia, government and civil society
- To strengthen and transform NSI institutions
- To increase human capabilities
- To expand the research enterprise
- To enhance an enabling environment for innovation
- To improve funding across the NSI.

Policy intents and actions directly applicable to nuclear technology RDI include:

- Revitalising the role of state-owned enterprises (SoEs) in innovation
- Exploiting new sources of growth (including the low carbon economy)
- Revitalising existing sectors through innovation (including the mining industry).

In terms of human capabilities and expanding the knowledge enterprise, the following relate to nuclear RDI:

- With respect to high-end infrastructure, a multipurpose fluorochemical pilot plant, a titanium pilot plant and several technology demonstrators are in operation.
- International collaborations involving, iThemba LABS among others, train many more South African master's and doctoral students than the European Organization for Nuclear Research (CERN).
- South Africa has gained access to cutting-edge research infrastructure through partnerships with international research facilities (e.g. CERN, the European Synchrotron Radiation Facility and Russia's Joint Institute for Nuclear Research).

The proposed policy actions will be implemented according to decadal plans currently under development.

2.2.2 Department of Science and Innovation Strategic Plan 2020–2025

The DSI's Strategic Plan 2020–2025 identifies the following outcomes, which support the pillars of the NDP in terms of a strong and inclusive economy, capabilities of South Africans and a capable and developmental state:

Outcome 1: A transformed, inclusive, responsive and coherent national system of innovation
Outcome 2: Human capabilities and skills for the economy and for development
Outcome 3: Increased knowledge generation and innovation output
Outcome 4: Knowledge utilisation for economic development in (a) revitalising existing industries and (b) stimulating R&D-led industrial development
Outcome 5: Knowledge utilisation for inclusive development
Outcome 6: Innovation in support of a capable and developmental state.

The only reference to nuclear technologies in the Strategic Plan is:

The Department enjoys respect among its peers in the science diplomacy arena, with South Africa known for producing world-class research outputs, with quality in many disciplines above the world averages, participation in large/global research institutions and projects like CERN (the European Organization for Nuclear Research), and the European Synchrotron Radiation Facility.[11]

Through the Strategic Plan, the DSI will contribute to national priorities outlined in the 2019–2024 Medium-Term Strategic Framework (MTSF). The following DSI initiatives have potential links to nuclear technology:

Priority 2: Economic transformation and job creation
- Integration of R&D targets and commitments in appropriate sector masterplans
- Development of a decadal plan outlining national priorities for science, technology and innovation.

Priority 3: Education, skills and health
- Support development of health innovations.

11 p 26

Priority 4: Consolidating the social wage through reliable and quality basic services

- Innovative technology approaches for the delivery of basic services (energy, water).

Priority 5: Spatial integration, human settlements and local government

- Provision of information, applications and products for precision agriculture and water bodies.

Priority 7: A better Africa and world

- Provision of support for implementation of the Science, Technology and Innovation Strategy for Africa (STISA 2024)[12] in accordance with South Africa's national interests
- Approved African Union (AU) or Southern African Development Community (SADC) STI initiatives, including programmes, projects or governance frameworks endorsed or supported at AU or SADC ministerial levels.
- Participation in global efforts to strengthen transformative innovation policy and STI policy in support of the Sustainable Development Goals (SDGs) adopted by the United Nations.

2.2.3 Department of Science and Innovation Annual Performance Plan 2021–2022

Much of the information in the DSI's Annual Performance Plan (DSI, 2021) is contained in the Department's Strategic Plan (section 2.2.2). Nuclear technologies are mentioned under 'International Cooperation'[13].

2.2.4 South African Research Infrastructure Roadmap

The South African Research Infrastructure Roadmap (SARIR), released by the DSI in 2016 (DSI, 2016), provides a strategic, medium- to long-term framework for planning, implementing, monitoring and evaluating research infrastructures in South Africa. The roadmap is intended to promote a competitive and sustainable national system of innovation within the global context.

The development of SARIR involved a broad consultation process between researchers and research managers from the private and public sectors, and a selection process by a committee of 15 experts from a range of sectors. Of the 17 research infrastructures that emerged from the consultation process, 13 were put forward in the SARIR framework. The research infrastructures are clustered around six scientific domains:

1. Humans and society
2. Health, biological and food security
3. Earth and environment
4. Materials and manufacturing
5. Energy
6. Physical sciences and engineering.

The potential for the application of nuclear technology exists in most of these domains.

Two research infrastructures related directly to nuclear technology were selected for inclusion in the SARIR framework: (i) a nuclear medicine research facility (the Nuclear Medicine Research Infrastructure [NuMeRI] approved for establishment in 2016/2017) and (ii) a materials characterisation facility (due to be implemented during 2023). A third infrastructure related to nuclear technology (a materials research reactor – SAFARI-2) was included in the initial list of 17 infrastructures but not in the final SARIR framework. The South African Isotope Facility (SAIF), which is worth more than 600 million Rand, raised between National Treasury and iThemba LABS radioisotope income, is unique in the southern hemisphere and could also have been a good fit for SARIR.

12 https://au.int/en/documents/20200625/science-technology-and-innovation-strategy-africa-2024
13 pp 24

2.2.5 Department of Mineral Resources and Energy Strategic Plan 2020–2025

The vision of the Department of Mineral Resources and Energy (DMRE) is to facilitate the transformation of the country's economic growth through sustainable development of the mining and energy industries. The DMRE's 2020–2025 strategy (DMRE, 2020a) recognises the contribution of energy to national development and growth. Growth in energy supply and energy security thus underpins the strategy in line with IRP2019 (RSA, 2019), as discussed in section 2.1.7.

In terms of reference to nuclear technologies, the nuclear build programme is to be emphasised (adding 2 500 MW to the national generation capacity). This approach is aligned with Decision 8 of IRP2019. Small modular reactors (SMRs) are highlighted in the strategy as a possible technology to be used to achieve the desired pace of nuclear energy development, scale and affordability.

In parallel with the initiation of the nuclear build programme, the necessary technical and regulatory work to extend the design life of Koeberg NPP by a further 20 years (the Koeberg Life Extension Programme) is to be undertaken immediately. This is aligned with Decision 2 of IRP2019 (RSA, 2019).

A further activity envisaged in the strategy, the replacement of the SAFARI-1 Research Reactor with a new Multipurpose Reactor (MPR), was listed as an outcome indicator. Research reactors are recognised in the strategy as strategic infrastructure in terms of reactor-based isotope production and nuclear medicine, with the demand for radioisotopes and other applications increasing.

In terms of sustainable nuclear waste management, a Centralised Interim Radioactive Waste Storage Facility is to be procured by 2024, for operational use in 2025. In the long term, a Deep Geological Repository is being planned for 2065.

The strategic plan does not mention uranium exploration or extraction, which is a significant oversight that needs to be corrected. Exploration, prospecting and final extractions go hand in hand. During exploration, many inexpensive research opportunities become available, assisting in capacity building. At the exploration stage, the pilot plants that offer proof of concept generate many innovations, while extraction, if done in a transparent manner, has the potential to lift people's lives by providing employment opportunities at all levels.

2.2.6 Department of Mineral Resources and Energy Annual Performance Plan 2021–2022

The performance targets of the DMRE's Annual Performance Plan (APP) for 2021–2022 (DMRE, 2020b) are based on the department's strategic plan 2020–2025. While considering the direct and indirect impacts of the COVID-19 pandemic, the APP includes the following performance indicators related to nuclear technologies:

- Implementation of a framework to procure 2 500 MW of new nuclear power, the nuclear build programme
- Support for the extension of the operational lifespan of the Koeberg NPP
- Submission of a pre-feasibility report on the proposed Centralised Interim Storage Facility
- Submission of a pre-feasibility report on the proposed MPR to replace the SAFARI-1 Research Reactor
- In terms of the National Liaison Office (NLO), finalisation of the process of acceding to the African Regional Cooperative Agreement for Research, Development and Training related to nuclear science and technology.
  From a regulatory perspective, the National Nuclear Regulator Amendment Bill and the Radioactive Waste Management Fund Bill are to be submitted to Cabinet for tabling in Parliament for promulgation.

2.3 Other government department strategies and plans

The strategies and plans of the departments of Health; Higher Education and Training; Public Enterprises; Agriculture, Land Reform and Rural Development; and Water and Sanitation make almost no mention of nuclear technology.

2.4 International agreements and treaties

2.4.1 Sustainable Development Goals

The 2030 Agenda for Sustainable Development and the 17 SDGs were adopted by the United Nations Member States in 2015. The purpose of the Agenda is to provide a universal set of goals, targets and indicators that nations, globally, are expected to achieve.

A report published in 2021[14] highlighted the role of nuclear technology in the process of achieving the SDGs. The report was published by a number of nuclear organisations around the world, including the Canadian Nuclear Association (CNA), European Atomic Forum (FORATOM), Japan Atomic Industrial Forum (JAIF), Nuclear Energy Institute (NEI), Nuclear Industry Association (NIA) and World Nuclear Association (WNA) (CNA, FORATOM, JAIF, NEI, NIA & WNA, 2021). For each goal, the contribution of nuclear technology towards the achievement of targets is stated, with examples as justification.

High-level categories for the contribution of nuclear technology to the SDGs include:

- Provision of electricity (reliable, affordable and low carbon emitting) and fuel
- Economic contributions by way of foreign investment, job creation and energy security
- Applications of nuclear technology, including, among others, food security, agriculture, health, water treatment and water provision, environmental safeguarding and peace
- Creation of skills and jobs through education.
  Nuclear technology is a cross-cutting element of the SDGs, like water, energy and technology.

2.4.2 Agreement between the Government of the Republic of South Africa and the International Atomic Energy Agency for the Application of Safeguards in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons

The agreement between the South African government and the IAEA for the application of safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons was signed in Vienna on 16 September 1991. According to the Treaty:

The Safeguards provided for in this Agreement shall be implemented in a manner designed:

- *to avoid hampering the economic and technological development of South Africa or international cooperation in the field of peaceful nuclear activities, including international exchange of nuclear materials;*
- *to avoid undue interference in South Africa's peaceful nuclear activities, and in particular in the operation of nuclear facilities; and*
- *to be consistent with the prudent management required for the economic and safe conduct of nuclear activities.*
  A 'Protocol Additional' to the Safeguards Agreement was signed by South Africa and the IAEA on 13 September 2002. This additional protocol aimed to:

14 https://www.world-nuclear-news.org/Articles/Report-highlights-nuclear-s-contribution-to-SDGs

- Further enhance nuclear non-proliferation by strengthening the effectiveness and improving the efficiency of the IAEA's safeguards system
- Emphasise the need to avoid hampering the economic and technological development of South Africa or international cooperation in the field of peaceful nuclear activities.

2.4.3 African Nuclear Weapon-Free-Zone Treaty and its Protocols

The African Nuclear Weapon-Free-Zone Treaty, known as the 'Pelindaba Treaty', was approved by African Heads of State on 23 June 1995 and came into force on 15 July 2009. Of the African continent's 53 states, 47 have signed the treaty.
Each party to the Treaty undertakes[15] not to conduct research on, develop, manufacture, stockpile or otherwise acquire, possess or have control over any nuclear explosive device by any means anywhere; not to seek or receive any assistance in the research on, development, manufacture, stockpiling or acquisition, or possession of any nuclear explosive device; and, not to take any action to assist or encourage research on, development, manufacture, stockpiling or acquisition, or possession of any nuclear explosive device.

However, the Treaty acknowledges the right of a state to conduct RDI in terms of nuclear science and technology for peaceful purposes. The Treaty promotes bilateral, subregional and regional cooperation mechanisms in the endeavours to support economic and social development. In this regard, participation in the IAEA's programme of assistance is encouraged, as well as strengthening cooperation under the African Regional Cooperative Agreement for Research, Training and Development related to Nuclear Science and Technology (AFRA).

Furthermore, for the purposes of compliance, the Treaty makes provision for the establishment of the African Commission on Nuclear Energy (AFCONE).

2.4.4 African Commission on Nuclear Energy

The African Commission on Nuclear Energy (AFCONE) was established in November 2010 in response to the Pelindaba Treaty. AFCONE serves to advance the peaceful application of nuclear science and technology in Africa and to facilitate support for state parties to comprehensively benefit from the application of nuclear science and technology. Furthermore, AFCONE engages in regional and global efforts of disarmament and the non-proliferation of nuclear weapons.
The responsibilities of AFCONE include, among others:

- Collating national reports and exchange of information
- Arranging consultations as well as convening Conferences of the Parties on any matter arising from the implementation of the Treaty
- Reviewing the application to peaceful nuclear activities of safeguards by the IAEA
- Bringing into effect the complaints procedure
- Encouraging regional and sub-regional programmes of cooperation in the peaceful uses of nuclear science and technology
- Promoting international cooperation with extra-zonal States for the peaceful uses of nuclear science and technology. [16]

Members of AFCONE are represented by 12 commissioners (who serve a three-year term) representing State Parties, selected by the Conference of State Parties, based on considerations of geography, as well as nuclear science and technology development activities. The commission meets in ordinary session once per year, with ad hoc sessions as required.

15 https://www.iaea.org/publications/documents/treaties/african-nuclear-weapon-free-zone-treaty-pelindaba-treaty
16 https://www.afcone.org/

In 2021, AFCONE released its Mid-Term Strategic Plan 2021–2025 (African Commission on Nuclear Energy, 2021). The plan was developed to strengthen AFCONE's capability and to widen the scope of activities of the commission, and identifies high-priority activities for the commission:

The medium-term Strategic Plan takes into account the progress achieved so far in the field of NS&T [Nuclear Science and Technology] as well as the persistent challenges that are still slowing down the growth of the African nuclear capacity. The medium-term SP [strategic plan] establishes strategic goals, specific objectives, and performance indicators for progress measurement and calibration. It has been conceived and formulated with the aim to enable the AFCONE Secretariat to take full charge of the responsibilities assigned to AFCONE by the Treaty, while broadening its partnership base to further gain in relevance and visibility.

The plan consolidates the regional context in terms of nuclear science and technology on the African continent as well as the relevant stakeholders, and provides the strategic goals and objectives of the commission within that context. The AFCONE Secretariat, being housed in South Africa, places local RDI in a vantage position. The establishment of a Regional Collaborating Centre in Nuclear Safeguards for Anglophone Countries, again located in South Africa, ensures that South Africa plays a leading role in RDI in this unique area.

2.5 AEA Technical Cooperation Programme

The DMRE, together with the DSI, contributes funding for the financial obligations towards the IAEA. During the National Liaison Officers meeting held in March 2020, the IAEA reported the distribution of the 2020–2021 Technical Cooperation Programme budget to Africa according to thematic areas as follows:

i. Food and agriculture: 35%
ii. Health and nutrition: 28%
iii. Safety and security: 18%
iv. Nuclear knowledge development and Management: 9%
v. Water and environment: 6%
vi. Industrial applications: 4%.

Table 3 provides an analysis of the current active Technical Cooperation Projects (TCPs) and Coordinated Research Projects (CRPs), based on information from the IAEA website.

Table 3: An analysis of South Africa's involvement in IAEA technical cooperation projects (TCPs) and coordinated research projects (CRPs)

IAEA topics	Total IAEA TCPs and CRPs (number)	Total South African involvement in TCPs and CRPs (number)	IAEA projects per topic (percentage)	South African involvement per topic (percentage)
Cancer	108	6	8.8%	8.7%
Nuclear power plant lifecycle	99	0	8.1%	0.0%
Government, legal and regulatory framework	92	7	7.5%	10.1%
Nuclear Infrastructure	92	0	7.5%	0.0%
Radiation and quality assurance (health)	83	2	6.8%	2.9%
Radiation protection	59	3	4.8%	4.3%
Management in nuclear	58	9	4.7%	13.0%

IAEA topics	Total IAEA TCPs and CRPs (number)	Total South African involvement in TCPs and CRPs (number)	IAEA projects per topic (percentage)	South African involvement per topic (percentage)
Land and water management (food and agriculture)	56	0	4.6%	0.0%
Food safety and quality	55	6	4.5%	8.7%
Pollution	55	2	4.5%	2.9%
Livestock	51		4.2%	4.3%
Nuclear fuel cycle	47	0	3.8%	0.0%
Nuclear installation safety	46	0	3.7%	0.0%
Water resource management (water)	42	1	3.4%	1.4%
Insect pest control	41	8	3.3%	11.6%
Research reactors	40	1	3.3%	1.4%
Diagnostics	36	2	2.9%	2.9%
Radiation waste and spent fuel management	35	2	2.9%	2.9%
Nuclear power reactors	35	1	2.9%	1.4%
Isotopes	28	5	2.3%	7.2%
Nutrition	21	3	1.7%	4.3%
Nuclear research (science)	16	4	1.3%	5.8%
Plant breeding	16	2	1.3%	2.9%
Emergency preparedness and response	16	2	1.3%	2.9%
Biodiversity loss	15	0	1.2%	0.0%

South Africa had six active national projects (in the areas of human health/medicine, nuclear safety, radiation safety and food and agriculture) during the 2020/2021 Technical Cooperation Programme (Table 4). Three of these projects were expected to end in December 2021. Four new project proposals (Table 5) have been submitted for IAEA approval and are expected to commence during the 2022–2023 cycle.

Table 4: National projects in progress

Organisation and project counterparts	Project title	Expected completion date
Agricultural Research Council (ARC)	Supporting the control of nagana in South Africa using an area-wide integrated pest management approach with a sterile insect technique component – Phase I (SAF5015)	December 2021
National Nuclear Regulator (NNR)	Implementing a regulatory review improvement plan (integrated regulatory review service) and preparation of regulatory aspects for the Nuclear Build Programme (SAF9007)	December 2021

Organisation and project counterparts	Project title	Expected completion date
Agricultural Research Council (ARC)	Promoting mutation breeding of vegetables to improve rural livelihoods – Phase I (SAF5016)	December 2023
National Institute of Communicable Diseases (NICD)	Assessing the sterile insect technique for malaria mosquitoes – Phase III (SAF5017)	December 2023
National Nuclear Regulator (NNR)	Minimising radiological exposure of the public resulting from existing exposure conditions (SAF9008)	December 2022
National Metrology Institute of South Africa (NMISA)	Establishing national diagnostic reference levels (SAF9009)	December 2021

Table 5: New projects expected to start during the 2022–2023 cycle

Organisation and project counterparts	Project title	Expected completion date
South African Nuclear Energy Corporation (Necsa)	Strengthening industry, infrastructure and innovation through the utilisation of national research reactors (SAF1007)	December 2025
Agricultural Research Council (ARC)	Establishing national capacities for monitoring and control of pesticide residues in agricultural produce (SAF 2018)	December 2024
South African Medical Research Council (SAMRC) North-West University, Faculty of Health Sciences	Improving nutritional status and health of children through the use of isotopic techniques (SAF 6022)	December 2023
NuMeRI Steve Biko Academic Hospital	Enabling support for healthcare research, imaging, therapy and drug development (SAF 6023)	December 2024
iThemba LABS	Designation of iThemba LABS as IAEA collaborating centre in accelerator based sciences since 2022	December 2027 (review)

2.6 African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology

The African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology (AFRA) programme was established in February 1990 with the aim of promoting cooperation in the peaceful uses of nuclear science and technology applications among IAEA Member States in the African region and with the IAEA. The programme is commended for the establishment of a successful, sustainable network of scientists, engineers and technologists trained in the peaceful use of nuclear science and technology applications for the socioeconomic development of the African continent.

The Regional Country Framework (RCF) serves as a strategic planning tool for the implementation of the AFRA programme by government parties. It further sets the programmatic objectives and expected outcomes to be achieved through the implementation of the planned cooperative activities.

South Africa, as a member of AFRA, plays a critical role through its advanced nuclear science and technology knowledge and infrastructure, and provides assistance with the allocation of resources and expertise in areas of specific needs. To this end, numerous AFRA projects have been undertaken depending on the needs (Table 6). The blank cells in the table indicate instances where South Africa was not a participant in the project. The contributions include the provision of project scientific consultants, who are scientists recognised as experts and regional leaders in their respective fields. At the time of compiling the report, the AFRA Secretariat was in the process of finalising new projects for the 2022–2023 cycle.

Table 6: AFRA projects involving South African institutions

Project number	Project title	Year commenced	Participating organisations
RAF0047	Promoting the sustainability and networking of national nuclear institutions for development, Phase II	2016	Necsa
RAF0050	Promoting institutional capacity building through triangular partnerships	2018	
RAF0052	Supporting human resource development in nuclear science and technology	2018	
RAF0054	Supporting programme development and review including pre-project assistance		
RAF0055	Promoting the sustainability and networking of national nuclear institutions for development – Phase III	2020	
RAF0056	Enhancing nuclear science and technology capacity building through technical cooperation among developing countries	2020	SU
RAF0057	Establishing and enhancing national legal frameworks	2020	
RAF0058	Enhancing the management and ownership of the programme	2020	
RAF0059	Supporting the establishment of the nuclear education science and technology network	2020	NWU
RAF0060	Educating secondary school students and science teachers on nuclear science and technology	2020	NRWDI
RAF1007	Strengthening the capacities of research reactors for safety and utilisation	2018	Necsa
RAF1008	Supporting radiation technologies in industrial applications and preventive maintenance of nuclear and medical equipment	2018	
RAF2012	Enhancing regional capabilities for a sustainable uranium mining industry	2018	CGS
RAF5074	Enhancing capacity for detection, surveillance and suppression of exotic and established fruit fly species through integration of sterile insect technique with other suppression methods	2016	
RAF5078	Establishing a food safety network through the application of nuclear and related technologies – Phase II	2016	NMISA; ARC; OVI

Project number	Project title	Year commenced	Participating organisations
RAF5079	Enhancing crop nutrition and soil and water management and technology transfer in irrigated systems for increased food production and income generation	2018	
RAF5080	Supporting area-wide tsetse and trypanosomosis management to improve livestock productivity – Phase IV	2018	UP; ARC; OVI
RAF5081	Enhancing productivity and climate resilience in cassava-based systems through improved nutrient, water and soil management	2018	
RAF5082	Enhancing veterinary diagnostic laboratory biosafety and biosecurity capacities to address threats from zoonotic and transboundary animal diseases	2020	ARC; OVI; UP; SBAH
RAF5083	Enhancing crop productivity through climate smart crop varieties with improved resource use efficiency	2020	
RAF5084	Strengthening food contaminant monitoring and control systems and enhancing competitiveness of agricultural exports using nuclear and isotopic techniques	2020	NMISA
RAF6050	Improving access to quality cancer management through sustainable capacity building	2016	SU; Tygerberg Hospital; UP; SBAH
RAF6051	Strengthening education and human resources development for expansion and sustainability of nuclear medicine services in Africa	2016	Tygerberg Hospital; UP; SBAH
RAF6053	Enhancing capacity building of medical physicists to improve safety and effectiveness of medical imaging	2018	Tygerberg Hospital
RAF6054	Strengthening and improving radiopharmacy services	2018	Tygerberg Hospital; SMU
RAF6055	Improving the quality of radiotherapy in the treatment of frequently occurring cancers	2018	UP; SBAH
RAF6056	Supporting human resources development in radiation medicine	2020	UP; SBAH; CMJAH; Wits
RAF6057	Strengthening the quality of nuclear medicine services	2020	UP; SBAH
RAF7014	Applying nuclear analytical techniques to support harmful algal bloom management in the context of climate and environmental change – Phase II	2016	DEAT
RAF7017	Promoting technical cooperation among radio-analytical laboratories for the measurement of environmental radioactivity	2016	NNR; Necsa
RAF7018	Applying radiation technologies to assess sediment transport for the management of coastal infrastructures	2016	
RAF7019	Adding the groundwater dimension to the understanding and management of shared water resources in the Sahel region	2018	

Project number	Project title	Year commenced	Participating organisations
RAF9057	Strengthening national capabilities on occupational radiation protection in compliance with requirements of the new international basic safety standards	2016	SABS
RAF9058	Improving the regulatory framework for the control of radiation sources in Member States	2016	
RAF9059	Strengthening Member State technical capabilities in medical radiation protection in compliance with requirements of the new International Basic Safety Standards (BSS)	2016	NMISA
RAF9060	Building competent authority effectiveness on regulating the transport of radioactive material	2016	NNR
RAF9061	Enhancing the capacities of national regulatory bodies for safety in AFRA Member States	2018	NNR
RAF9062	Strengthening radioactive waste management	2018	NRWDI; Necsa
RAF9063	Strengthening competent authorities for the safe transport of radioactive material	2020	NNR
RAF9064	Improving the capabilities of states in radiation protection of patients	2020	NMISA; SAHPRA
RAF9065	Establishing regulatory infrastructure for control of radiation sources	2020	
RAF9066	Strengthening regional infrastructures for effective preparedness and response to radiological emergencies	2020	NNR
RAF9067	Sustaining the establishment of education and training in radiation safety and human resource development and nuclear knowledge management – Phase II	2020	
RAF9068	Enhancing regional capabilities on occupational radiation protection	2020	SABS

The topics in Table 5 cut across all themes as set out in this study. Given South Africa's limited participation in some of the themes, this study will assist in addressing the agenda for topics prioritised by AFRA and thus improve South Africa's participation.

3. HISTORICAL OVERVIEW OF NUCLEAR TECHNOLOGY RDI ACTIVITIES IN SOUTH AFRICA

The first legislation regarding nuclear technology that was promulgated in South Africa was the 'Wet op Atoomenergie' (Atomic Energy Act), which was adopted by Parliament on 7 September 1948 and followed by the establishment of the Atomic Energy Board. Research activities were accelerated from 1959 after a decision by Cabinet to establish a domestic nuclear industry. The milestones characterising South Africa's R&D programme in the field of nuclear technology are provided in Table 7 and supplemented by Figure 2.

Table 7: Milestones in South Africa's nuclear technology R&D

Year	Milestone
1961	A nuclear research centre was established on the Pelindaba site near Pretoria.
1965	The 20 MWt SAFARI-1 research reactor achieved its first criticality.
1970	The Uranium Enrichment Corporation was established. This led to the commencement of an extensive nuclear fuel cycle programme.
1971–1975	A pilot uranium enrichment plant (the 'Y-plant', based on a unique aerodynamic vortex tube process developed in South Africa) was constructed at Valindaba, adjacent to the Pelindaba site.
1979	The pilot plant started producing 45% enriched uranium.
1981	The first fuel assemblies for SAFARI-1 were fabricated at Valindaba.
1990	Pilot plant operations ceased and the plant was dismantled under IAEA supervision.
1983–1997	Intensive nuclear fuel production and uranium enrichment programmes were supported.
1983	A Molecular Laser Isotope Separation (MLIS) programme commenced at Valindaba. The MLIS programme was cancelled in 1997 due to funding constraints and technical challenges.
1984	A commercial uranium enrichment plant (the 'Z-plant', utilising the aerodynamic vortex tube process) was commissioned.
1984–1985	Two 900 MWe French-built nuclear power reactors were commissioned at Koeberg NPP.
1988	The commercial uranium enrichment plant went into full production, with a capacity of 300 000 separative work units per year (SWU/yr). Fuel elements with 3.25% enrichment were supplied to the Koeberg NPP.
1999	Necsa was established.
1999–2009	The South African government, Eskom, Westinghouse and the Industrial Development Corporation (IDC) invested in the Pebble Bed Modular Reactor (PBMR) project.
2007	The draft nuclear energy policy was released. This included an ambitious programme to develop all aspects of the nuclear fuel cycle (including conversion, enrichment, fuel fabrication, as well as reprocessing of used fuel).
2007	The R&D division of Necsa was established to consolidate the research and technology development activities within Necsa.
2009	NRWDI was established to achieve excellence in the safe management and disposal of radioactive waste in a manner that protects the environment for both current and future generations.

Year	Milestone
2010	The PBMR project (in which South Africa was considered to be a world leader) was terminated. The reasons given included the economic climate, public opinion, positioning of the PBMR within the Department of Public Enterprises (while the project was still in an R&D phase), unrealistic cost estimates, a change in technical focus, licensing issues, lack of international support, lack of an interested customer, and political factors (such as the changing nature of the project, unrealistic expectations and a lack of inter-departmental coordination and planning).
2017	NuMeRI, as part of the DSI's South African Research Infrastructure Roadmap (SARIR), was dedicated for drug development, and thus for human capacity development.
2019	iThemba LABS expanded its infrastructure to enhance the production of radioisotopes with the acquisition of the new 70 MeV cyclotron.
2020	The DMRE proceeded with a new nuclear build power procurement programme.
2021	The application to extend the operational lifespan of the Koeberg was submitted by Eskom on 10 May 2021 and accepted for further processing on 17 August. The decision of the NNR will be communicated in 2024.
2021	Necsa and Cabinet approved a new Multipurpose Reactor (MPR), which is intended to succeed the SAFARI-1 Research Reactor when it reaches its end of life.

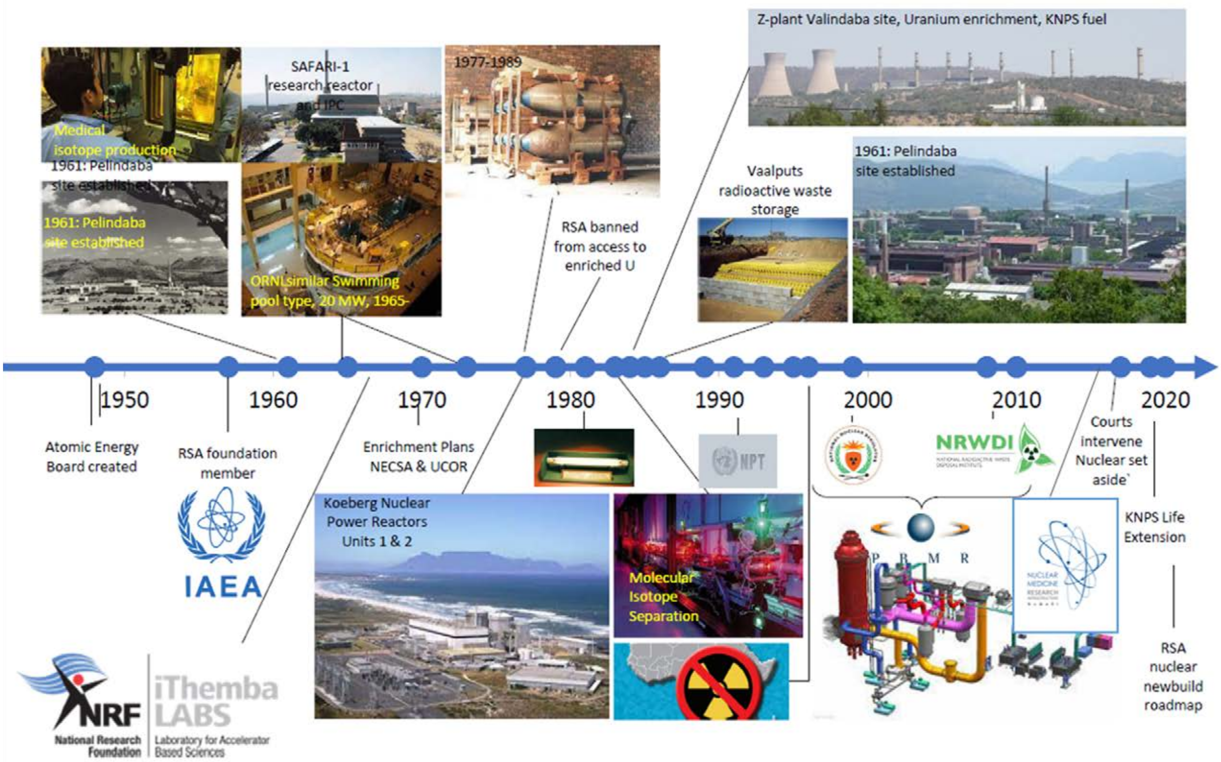


Figure 2: History of nuclear technology in South Africa[17]

Necsa's mandate, as derived from the Nuclear Energy Act (No. 46 of 1999), is to undertake and promote research on nuclear energy, radiation sciences and technology; to process source material, special material and restricted nuclear material, including uranium enrichment; and to collaborate with other entities in these and related fields.

The Act also provides for the delegation of specific responsibilities to the corporation, including the operation of the SAFARI-1 reactor; applying radiation technology for medical

17 Van Niekerk, F. 2022. Presentation on 'Establishing a nuclear capability in South Africa: the role of the public, private and higher education institutions" to the IAEA, July 2022.

and scientific purposes; decontamination and decommissioning of nuclear facilities from historical strategic programmes; and implementing and executing national safeguards and other international obligations.

The adoption of the Nuclear Energy Policy in June 2008 (DMRE, 2008) reconfirmed Necsa's mandate, and designated the organisation as the anchor for nuclear energy RDI in South Africa. The policy also highlighted the need for the corporation to develop viable nuclear fuel cycle options to support South Africa's envisaged nuclear energy expansion programme.

Over the years, several activities or departments of Pelindaba were 'spun off' to new or existing organisations, for example:

- Uranium exploration and mining to the Council for Geoscience and Mintek
- Issuing of nuclear licences to the Council for Nuclear Safety (CNS), now the NNR
- Nuclear safeguards to Necsa and the DMRE
- Nuclear energy research to Eskom / PBMR
- Nuclear waste management to NRWDI.

Over time, the research activities at Pelindaba became focused on various aspects of the nuclear fuel cycle and radioisotope production. State funding for Necsa declined sharply in the post-apartheid era, and research activities were further curtailed.

Currently, nuclear RDI is very fragmented in South Africa (from an execution as well as regulatory perspective) with little or no coordination or strategic direction.

As can be seen from the following sections, nuclear technologies find application in almost every sector of the economy. It is imperative that the limited resources available for nuclear RDI are optimally utilised to achieve national goals and benefit all the people of South Africa. Some of the lessons learned from South Africa's history of nuclear technologies include:

- One of the most important lessons from South Africa is that proliferation can be prevented and nuclear disarmament achieved with valuable experience for both the county and the IAEA (Albright & Stricker, 2016).
- It is beneficial for all nuclear technology practices to be compliant with IAEA safeguards.
- Full access, openness and transparency were vital to ensuring the credibility of the dismantlement effort and reaping the sought-after international engagement, and thus achieving compliance with the Treaty on the Non-Proliferation of Nuclear Weapons.
- Encouragement increases compliance with the legislation as well supporting collaboration among nuclear technology institutions.

4. AGRICULTURE AND FOOD SECURITY

4.1 Background

Food insecurity and poor nutrition have contributed to mental and physical stunting in South Africa and Africa (Govender, Pillay, Siwela, Modi, & Mabhaudhi, 2016). Hence, there is an urgent need to encourage more sustainable methods of addressing food security challenges, such as the use of nuclear technologies.

South Africa aims to produce 30% of local nutritional needs by 2030[18]. To reach this goal, the country will have to increase the development of agricultural technologies in the following five areas:

1. Food safety and control
2. Insect pest management
3. Improved soil and water management
4. Plant breeding and genetics
5. Animal health.

Each of these is discussed in the following sections.

4.2 Food safety and control

Ionising radiation is applied as a mechanism for the sterilisation of agricultural products and foodstuffs, and the control of agricultural pests of economic significance. Ionising radiation sterilisation is a process that employs highly penetrating gamma rays and X-rays from high-activity compound sources or 'bremsstrahlung' generators to expose products in bulk[19].

Although bulk irradiation facilities play an important role in the sterilisation of regulated imported and exported agricultural products (such as certain fruits, spices and honey) to rid these of foodborne pests, very little R&D is currently being undertaken in this area. Fortunately, there is a South African register of all irradiation facilities, which is maintained by the SAHPRA Directorate of Radiation Control under the national Department of Health.

Following the establishment of the African Continental Free Trade Agreement in 2018, sound food contaminant monitoring programmes are critical. The application of nuclear technologies and reliable, harmonised analytical techniques is playing an increasing role in enabling proficient food safety testing. The programmes are driven by a network of analytical laboratories (mandated monitoring and inspection laboratories) across the African continent. The nuclear techniques used include radio receptor assays for screening of contaminants (such as mycotoxins), pesticides and veterinary drug residues of antimicrobials in water and various food products. The use of isotope ratio mass spectrometric techniques to combat food fraud and adulteration is also expected to increase.

The most common source of energy used for food irradiation, including in South Africa, is cobalt-60 (a radioactive form of cobalt). The energy applied to irradiate food is extremely low and does not induce radioactivity. Good manufacturing and irradiation practices ensure that all irradiated foodstuffs are divided into different classes according to the reason for the irradiation of foodstuffs. For example, class 2 refers to fresh fruits and vegetables, which are irradiated for the purpose of delaying ripening or extending shelf-life.[20] This is an important technology that, if deployed in most regional countries, would alleviate poverty and enhance the quality of life of

18 https://www.nda.agric.za/docs/media/national%20policyon%20food%20and%20nutrirition%20security.pdf
19 https://www-pub.iaea.org/MTCD/publications/PDF/Pub1313_web.pdf
20 https://members.wto.org/crnattachments/2012/sps/ZAF/12_3138_01_e.pdf

citizens, as food wastage would be minimised, more varieties would be available on market shelves, and employment opportunities would be created in the associated irradiation facilities and logistic networks.

In terms of control, the Foodstuffs, Cosmetics and Disinfectants Act (No. 54 of 1972)[21] makes provision for control of the safety and quality aspects of the sale, manufacture and importation of foodstuffs, as well as of aspects such as labelling. Regulation R.1600 of 1983 of this Act governs the irradiation of food. The Hazardous Substances Act (No. 15 of 1973)[22] requires the licensing of irradiation facilities, as well as the training experience and qualification of the operators, and prescribes the requirements for radiological safety. Furthermore, there is cooperation between the national Department of Health, provincial departments of health, local authorities and the Department of Agriculture, Land Reform and Rural Development (DALRRD).

4.3 Insect pest management

The sterile insect technique (SIT) has since the mid-1990s evolved as an eco-friendly, alternative method to chemical pest control, especially in geographically isolated crop production regions. SIT programmes are currently active and effective in deciduous fruit, table grape, citrus and sugarcane producing areas (Barnes, Hofmeyr, Groenewald, & Conlon, 2015). The necessity to export fruit from pest-free areas to minimise crop losses of commercial and small-scale farmers in the importing countries has contributed to the growth of this application of nuclear technology. The South African IAEA technical cooperation programme on expanding the sterile insect technique has shown economic and environmental achievements through public–private partnerships with the fruit industry, with encouraging signs of the sustainability of activities in the future.

The National Institute for Communicable Diseases (NICD) has been able to determine the amount of radiation required to sterilise mosquitoes without killing them or compromising their sexual competitiveness. This project is successful and is still ongoing. Deployment of the SIT in both managing and eliminating mosquitoes across the continent would be a game changer for livelihoods – both mortalities and lost working hours for adults who fall sick and survive.

Having witnessed the positive effects of SIT on the citrus industry, the South African Sugarcane Research Institute (SASRI) used the technique to address a similar problem with Eldana moths[23], whose larvae penetrate and feed on the soft tissue inside sugarcane, destroying the crop, and decimating the sugarcane industry in South Africa since the 1970s[24].

4.4 Improved soil and water management

Isotopes are employed to track and monitor soil quality and soil erosion. Combinations of nuclear techniques have been developed to distinguish and apportion the impacts of climate variability and agricultural management on soil erosion (Figure 3). Compound-specific stable isotope (CSSI) techniques, based on the measurement of the natural abundance signatures of Carbon-13 (^{13}C) in specific organic compounds (i.e. fatty acids), and cosmic ray soil moisture neutron probes (CRNP) are very useful in this regard (Balesdent, Mariotti, & Guillet, 1987).

It remains important that climate-smart agricultural practices for enhancing agricultural productivity are continuously improved. It is essential to minimise gaseous nitrogen

21 https://www.gov.za/documents/foodstuffs-cosmetics-and-disinfectants-act-2-jun-1972-0000#:~:text=The%20Foodstuffs%2C%20Cosmetics%20and%20Disinfectants,to%20provide%20for%20incidental%20matters.

22 https://www.gov.za/documents/hazardous-substances-act-16-apr-2015-1120

23 https://www.iaea.org/newscenter/news/south-african-experts-advance-in-researching-nuclear-technique-to-fight-malaria-sugarcane-pest

24 https://www.iaea.org/newscenter/news/south-african-experts-advance-in-researching-nuclear-technique-to-fight-malaria-sugarcane-pest

losses (NH_3, N_2). This can be done by quantifying N_2O and N_2 emissions using the ^{15}N technique to validate agricultural system-specific emission factors (Wang, Amon, Schulz, & Mehdi, 2021).

Carbon sequestration in soil is increased by determining C budgets based on the quantification of C fluxes (CO_2, CH_4) using nuclear and related techniques. These processes are crucial because agriculture contributes 25% to greenhouse gas (GHG) emissions. It is thus important to mitigate the emission of GHGs (nitrous oxide, methane and carbon dioxide) from agriculture under different agroecosystems, and to optimise capturing atmospheric CO_2 through carbon sequestration[25]. In South Africa, there has been a positive effect on soil properties, although crop yield site-specific research involving farmer participation is needed due to diverse agroecological zones and the risks of lower yields for the first two to five years of transition from plough-based farming to a conservation agriculture system (Swanepoel, Swanepoel, & Smith, 2018).

Nitrogen-15 (^{15}N), a stable isotope of nitrogen (an essential plant nutrient), is used to determine the fertiliser use efficiency of crops. It is also used to quantify the amount of nitrogen that crops can acquire from the atmosphere through a process known as biological nitrogen fixation. This helps to reduce the application of purchased nitrogen for crop and livestock production and can result in very significant cost savings in agriculture. Nitrogen-15 is also used to assess integrated soil–water management practices to optimise crop productivity[26]. This method can be applied to various vital crops, including rice and sugar cane, and may be a project to consider for initiation in South Africa. A research study has demonstrated that the government supply of free N fertilisers to resource-poor farmers in South Africa increased bean yields for food and nutritional security (Habinshuti, Maseko, & Dakora, 2021). The low soil fertility status of South African marginal soils threatens the sustainable production of biofuel feedstock by smallholder farmers, and the ongoing R&D on the usage of N-15 should be encouraged (Malobane, Nciizah, Mudau, & Wakindiki, 2020).

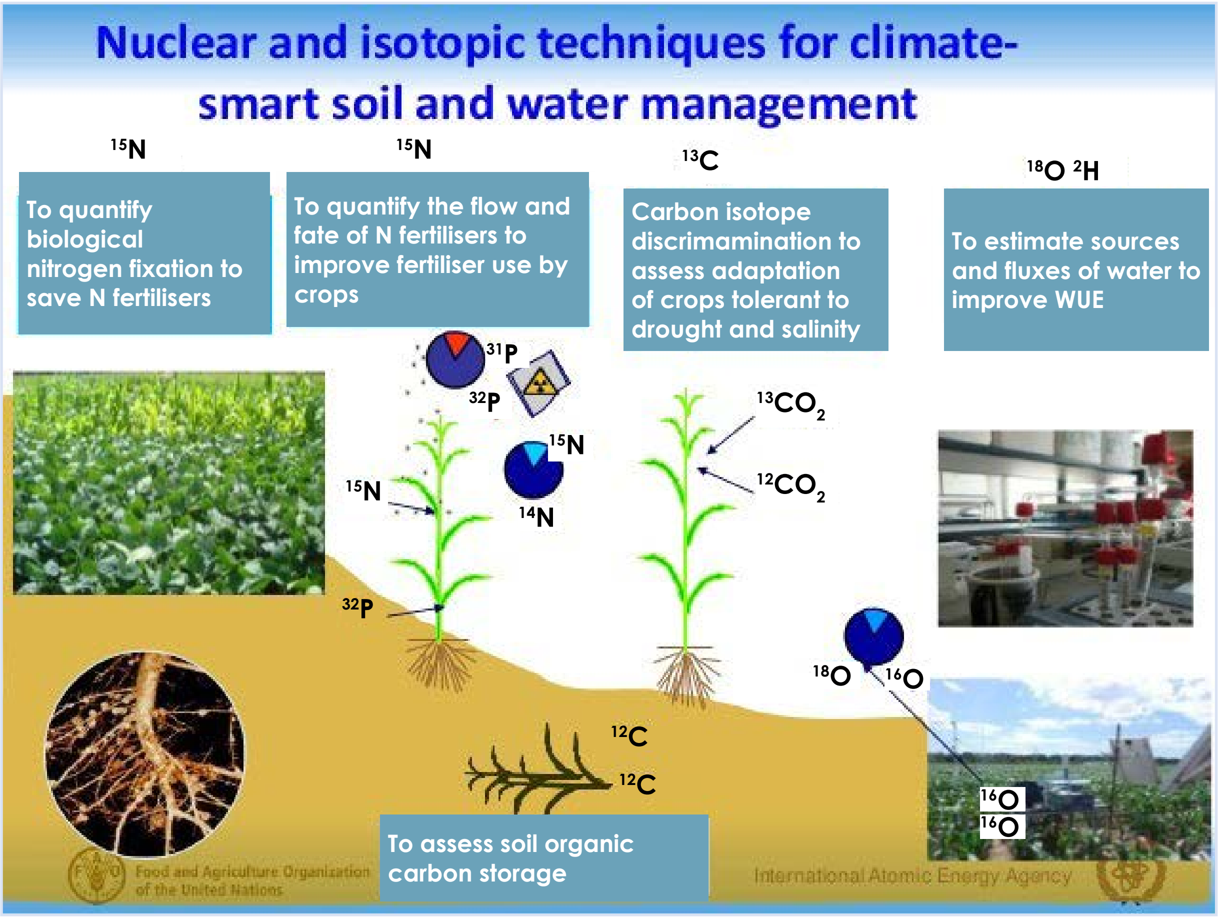


Figure 3: Uses of nuclear energy in food and agriculture (IAEA & FAO)

4.5 Plant breeding and genetics

Nuclear technologies are used to improve crop yields and quality; tolerance to drought, heat or flooding; and resistance to pests[27].

Future food security will require the reduction of crop losses due to environmental factors, including climate change, as well as transformative advances that provide major gains in yields. Mutation-induced plants irradiated with the cobalt-60 source, together with genomic technologies, can expedite breeding and trait development for increased environmental resilience and productivity. This is especially important since the current trajectory for crop yields will be insufficient to nourish the world population by 2050 (Ray, Mueller, West, & Foley, 2013). In South Africa, the limited mutation breeding R&D using irradiation has been successful, as shown by the effectiveness of gamma irradiation on papaya selections that developed dwarfed and/or disease-resistant selections (Husselman, Daneel, Sippel, & Severn-Ellis, 2016).

Furthermore, the provision of DNA fingerprinting services for crop mutants with promising agronomic traits provides diagnostic molecular markers for use in marker-assisted breeding. R&D activities focused on mutation induction for broadening the genetic base of crop germplasm in seed and vegetatively propagated crops are much needed in South Africa and can assist in removing certain production constraints.

4.6 Animal health

Nuclear technologies are essential in the detection, control and prevention of transboundary animal and zoonotic diseases. Isotope spectrometry, stable isotope

27 https://www.iaea.org/topics/plant-breeding/laboratory

analysis and molecular characterisation can be used in the typing of strains of microorganisms, providing information on environmental parameters and the genetic makeup of the organisms. Stable isotopes can also be used to monitor animal movements. By tracking the movements of wild birds, outbreaks of transboundary diseases, which have arisen from the movement of livestock or incursions of infected wildlife into livestock-rearing areas, can be traced. It is essential that the research outcomes are translated to farmers, thereby contributing to food security (Viljoen & Luckins, 2012).

Real-time polymerase chain reaction (RT-PCR) is a nuclear-derived method for detecting the presence of specific genetic material in any pathogen, including a virus. The original method used radioactive isotope markers to detect targeted genetic materials, but subsequent refining has led to the replacement of isotopic labelling with special markers, most frequently fluorescent dyes. RT-PCR is one of the most widely used laboratory methods for detecting the COVID-19 virus. While many countries have used RT-PCR for diagnosing other diseases, such as the Ebola and Zika viruses, several countries need support in adapting this method for the COVID-19 virus and for increasing national testing capacities[28].

4.6.1 Veterinary diagnostics

The veterinary profession makes use of diagnostic scintigraphy, especially in the equine racing industry, to diagnose lameness. It is also important to comment that nuclear radiation detectors and sensors are critical. The University of Pretoria's Veterinary Academic Hospital at Onderstepoort has scintigraphy capacity, as does a private equine hospital in Johannesburg.

4.6.2 Biomedical research

While biomedical research will probably be considered as medical research, it does involve the use of animals in research and in some cases also for quality control (toxicity testing).The biomedical research using radioisotopes in the preclinical imaging set-up using animal models has helped to study the physiological and metabolic process that helps to evaluate benefits and risks of the pharmaceuticals.

4.6.3 Cancer radiation therapy

Previously, veterinarians made use of a dedicated veterinary cobalt therapy unit in Johannesburg. Since that unit closed, veterinary radiation treatment is now done at medical facilities when there is spare capacity.

4.6.4 Radio tagged molecules

Radio tagged molecules are used internationally to set food safety standards for withholding periods following the use of veterinary medicines. These studies are essentially tissue distribution studies for non-diagnostic purposes, but are invaluable for human food safety. Currently, no work is being done in South Africa in this field and there is scope for such research.

4.7 Infrastructure and production

South Africa's limited global competitiveness with regard to agriculture and food security is among other reasons due to lower levels of investment in agriculture and lack of infrastructure. Infrastructure enables production, consumption, distribution and trade, as well as food security, especially in the rural economy.

There are several approaches to categorising agricultural infrastructure. One of

28 https://www.iaea.org/newscenter/news/how-is-the-covid-19-virus-detected-using-real-time-rt-pcr

the most comprehensive approaches is to group agricultural infrastructure under four broad categories, namely: (i) input-based infrastructure such as seeds, fertiliser, pesticides, farm equipment and machinery; (ii) resource-based infrastructure such as water/irrigation and farm power/energy; (iii) physical infrastructure such as road connectivity, transport, storage, processing and preservation; and (iv) institutional infrastructure such as agricultural research, extension and education technology, information and communication services, financial services and marketing (Mtombeni, et al., 2019; Patel, 2010).

The details of each group are beyond the scope of this report; however, access to land and water for agriculture remain contiguous issues and major challenges for emerging farmers in South Africa. Emerging farmers do not have title deeds, which makes it difficult for them to access land and water rights. Lack of provision and maintenance of basic infrastructure such as road networks, rail, silos, irrigation systems, water and electricity have contributed to low agricultural productivity and poor linkages to markets for farmers (Mazibuko, Antwi, & Rubhara, 2020).

Thus, it is important to assess the infrastructural challenges obstructing agricultural development in South Africa. While nuclear technology contributes to all four broad categories of agricultural infrastructure (input-based infrastructure, resource-based infrastructure, physical infrastructure and institutional infrastructure), it has unfortunately not been integrated into the infrastructural matters for agricultural development. DALRRD should therefore consider the inclusion of nuclear technology RDI in the revitalisation of essential agricultural infrastructure through the implementation of the Agriculture and Agro-processing Master Plan (AAMP).

4.7.1 Gamma sterilisation facilities

There are currently few private companies engaged in gamma sterilisation. The existing companies include:

- Gamwave Gauteng (NTP Group owns 40%)
- Gamwave, Durban
- STERIS AST - Synergy Sterilization South Africa (Pty) Ltd, Gauteng
- HEPRO Cape (Pty) Ltd.

More initiatives are needed, possibly through public–private partnerships.

4.7.2 Insect pest management: sterile insect technique facilities (Co-60)

The facilities involved in insect pest management using the sterile insect technique include:

- X Sterile Insect Technique (Pty) Ltd, Citrusdal, Western Cape
- ARC Infruitec, Stellenbosch
- FruitFly Africa, Stellenbosch
- A new SIT facility at NICD in Johannesburg. The facility took delivery of an X-ray generator in May 2022 to replace their Cs-137 blood irradiator. Their focus will be on malaria mosquitoes.

Only one company is embarking on replacing its ^{60}Co source with a more modern and safer electron accelerator.

4.8 Human capacity

South Africa has formal education in agriculture, which is offered by 12 colleges of agriculture, including six universities of technology and 11 universities that offer various nationally accredited tertiary agricultural education and training programmes (Raidimi & Kabiti, 2019; DALRRD, 2008). Furthermore, non-formal agricultural education is offered by a range of providers, including public agricultural extension and training services, providers in non-governmental organisations and the private sector, as well as universities, colleges and some agricultural high schools (DALRRD, 2008). There is also a dedicated unit in DALRRD for the promotion of appropriate agricultural skills, known as Education, Training and Extension Services. This directorate generally runs ad hoc in-service training programmes that do not prepare extension staff adequately to deal with complex agricultural problems.

The knowledge transfer role in agricultural extension has gained traction in the face of increased climatic variability, with unpredictable weather and rapidly changing environmental conditions (Zwane & Montmasson-Clair, 2016).

4.9 SWOT analysis (inclusive of infrastructure, education and research)

4.9.1 Strengths

- Programmes to respond to foodborne illnesses and disease outbreaks, and an effective food-monitoring and surveillance record.
- Strong collaborations with the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture via the NLO and NMISA, resulting in the transfer of mechanisms for relevant technology addressing current and emerging food safety and trade issues.
- Environmental-neutral targeted pest control mechanisms, endeavouring to minimise negative implications for farmer livelihoods, biodiversity conservation and the human right to food.
- Control of livestock diseases through a variety of factors, including legislation, the strength and capacity of the veterinary services, cross-border efforts for disease surveillance, political will, diagnostic facilities and financial support. Several measures are used, including movement control and quarantine, vaccination, treatment and mass slaughtering.

4.9.2 Weaknesses

- Applications being limited to certain pests and focused on some more than others, so that any crop is a dynamic system, constantly changing within a season due to the natural growth stages of the crop.
- Insufficient investment to establish facilities. Furthermore, the current scientific and technological infrastructures often work in isolation.
- Reluctance among some consumers to accept irradiated foods, mostly due to lack of access to science-based knowledge, which impedes the commercial success of irradiated foods that are safe and nutritious.
- Inadequate inclusion of nuclear agriculture in strategic planning. This could be due partly to limited and reduced total agricultural R&D spending, which has also resulted in a loss of scientific personnel in recent decades.

4.9.3 Opportunities

- Modern electron accelerator/high-flux bremsstrahlung devices able to dramatically increase throughput, negate security risks and serve as multipurpose science research platforms.
- The integration of digital technology such as mobile phones coupled with internet-based solutions for agriculture. This is a major opportunity that could significantly boost access to financing for agricultural inputs across the value chain.
- Climate diversity, which enables South Africa to produce a huge range of agricultural commodities and to grow diverse crops.

4.9.4 Threats

- Ongoing civil unrest and cyber-attack on ports and transportation, which will cause long-lasting damage to the economy and agricultural sector.

- Knowledge generation being limited to the public sphere and intellectual property, resulting in limited evaluation of data that would form a deeper, more inclusive evidence base to update new investments, as well as ongoing policy assessment.
- Climate changes, which negatively impact the availability, access, utilisation and stability of food security.
- Potential emergence of new or endemic diseases that are highly lethal to fruits and crops, resulting in excessive use of pesticides for maintaining control.

4.10 Needs and gaps

The needs and gaps identified in this section relate to nuclear technology applications and not the entire agricultural sector. The priorities are based on the findings and interpretation of the background, SWOT analysis and relevance to the development of the country.

Improvement of routine practices for soil and water management with combinations of nuclear techniques

The distribution of the 2020–2021 TCP budget to Africa by thematic areas for food and agriculture is 35% of the total allocations for the continent and slightly less for South Africa. The direct benefits to farmers using climate-smart agricultural practices to enhance agricultural productivity are continually increasing due to several technologies, including isotopes. For example, almost all foods are based on carbon-based organisms. The potential for the development of carbon isotope technology is thus boundless, and stable carbon isotope ratio analysis (SCIRA) presents an effective tool for detecting food adulteration and for food traceability control. Although nuclear techniques offer good prospects for improving routine practices for soil and water management, they are not routinely used by farmers.

Objective: To improve routine practices for soil and water management with combinations of nuclear techniques.

Indicator/s:

i. Number of institutions collaborating in the TCP.
ii. Number of TCP/R&D projects translated into practice by communities.
iii. Number of relevant recommendations included in the DALRRD strategic plan/ annual reports.

Application of isotope ratio mass spectrometry to enable the monitoring of food fraud in South Africa and the region

Stable isotope analysis has become a powerful tool for food authentication and traceability due to its advantages of high precision and efficiency. The progress of isotope analysis use in food authentication and traceability is concentrated on three aspects: the food adulteration (e.g. juice, honey), the geographic origin traceability of food (e.g. olive oil, dairy products) and the authenticity of organic food (e.g. beef, potatoes) (Zhang, 2015). With the development of the regional and global food market, food authenticity has become a major concern for South African consumers. Hence there is a need to review and improve on the limitations and future research directions of isotope analysis in food authenticity and traceability.

Objective: To increase the application of isotope ratio mass spectrometry so as to enable the monitoring of food fraud.

Indicator/s: Number of laboratories using improved isotope ratio mass spectrometry methods for food authentication and traceability.

Integrated approach to animal health and zoonotic infections

The One Health approach is critical to addressing zoonotic public health threats and environmental issues. The complex links between human, animal and environmental health require coordinated multidisciplinary and multipronged collaboration to address the threats from zoonotic diseases, and the global public health community needs to act decisively now[29].

This can be done through One Health, an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals and ecosystems, which is key to addressing zoonotic public health threats, environmental issues and neglected tropical diseases. Fortunately, nuclear technology has already proved itself in this regard. For instance, RT-PCR is one of the most widely used laboratory methods for detecting the COVID-19 virus. Furthermore, stable isotope analysis and molecular characterisation can be used in the typing of strains of microorganisms, providing information on environmental parameters and the genetic makeup of organisms. Stable isotopes can also be used to monitor animal movements. One Health should therefore be involved in collaborations with nuclear applications to benefit the overall health of the nation.

Objective: To improve preparation for and response to zoonotic infections.
Indicator/s:

i. Increasing the number of harmonised protocols that will include nuclear technologies in One Health.
ii. Reducing the number of transboundary animal diseases using validated nuclear technologies.

Improvement of food preservation using radiation

Import rules to other countries, delayed transportation and riots require that fruits be preserved.

Objective: To increase the application of radiation for food preservation.
Indicator/s:

i. Number of laboratories using improved isotope methods for food preservation.
ii. Number of institutions collaborating in the TCP.

29 https://www.who.int/news/item/21-03-2022-one-health-is-critical-to-addressing-zoonotic-public-health-threats-and-environmental-issues

5. HUMAN HEALTH

5.1 Background

The recent poor health prognosis for South Africa has been associated with 'colliding epidemics' and the 'quadruple burden of disease'; the latter comprises communicable diseases, non-communicable diseases (NCDs), maternal and child health, as well as injury-related disorders (Mayosi, et al., 2012; Achoki, et al., 2022). Furthermore, South Africa is significantly affected by the big five NCDs, namely cardiovascular diseases (CVDs), cancer, type 2 diabetes mellitus, respiratory illnesses (such as chronic obstructive pulmonary disease) and mental health disorders (Samodien, Abrahams, Muller, Louw, & Chellan, 2021). The challenges experienced in South Africa are exacerbated by being one of the most unequal societies in the world. Among the strategies aimed at addressing the quadruple burden of disease, imaging is essential. Imaging in the medical context refers to different technologies using ionising (plain X-rays, computed tomography, nuclear medicine) and non-ionising radiation (ultrasound, magnetic resonance imaging) to diagnose, monitor or treat medical conditions. Imaging is an integral part of healthcare. However, a recent study highlighted a huge shortage of imaging equipment in low- and middle-income countries (LMICs), including South Africa. This shortage of equipment is accompanied by a substantial workforce shortage of radiologists, nuclear physicians, radiographers and medical physicists (Hricak, et al., 2021). A microsimulation model of 11 cancers showed that the scale-up of imaging would avert 32% (246 million) of the 760 million deaths caused by the modelled cancers worldwide between 2020 and 2030, saving 5 492 million life years. A comprehensive scale-up of imaging, treatment and care quality would avert 955 million (12.5%) of all cancer deaths caused by the modelled cancers worldwide, saving 230 million life years (Figure 4).

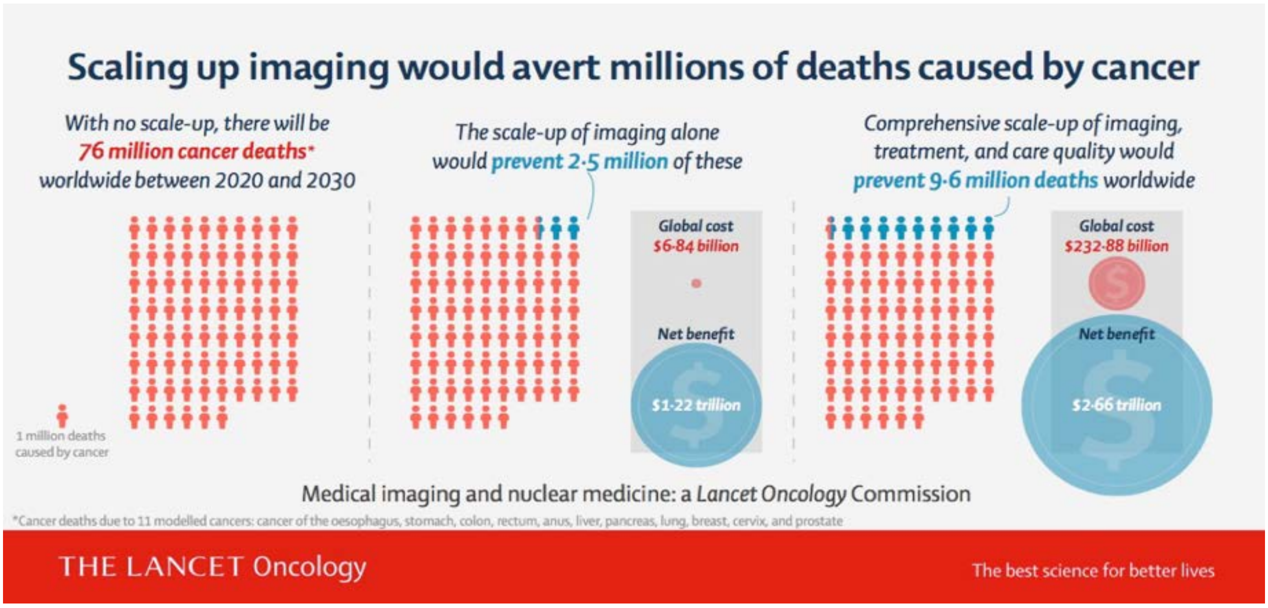


Figure 4: Impact of scaling-up imaging (Hricak et al., 2021)

The report focuses primarily on nuclear medicine. To this effect, the recent evolution and growth of nuclear medicine contributed largely to improved effort in the clinical testing of innovative radiopharmaceuticals through a multidisciplinary approach (Sathekge, 2013). This is especially critical given the current chaotic state of cancer care in South Africa and the predicted increased incidence of new cancer cases, which are expected to rise to 138 000 by 2030 and 175 000 by 2040 (Cairncross, Parkes, Craig, & Are, 2021). Progress and innovation in radiotheranostics require a careful and coordinated approach to help address cancer-management needs.

Nuclear medicine in South Africa can be traced back to the importation of the first radioisotopes for medical use in 1948. The Pretoria General Hospital bought a sodium iodide counter in 1952. The first rectilinear scanner was installed in 1964 on the premises of the CSIR in Pretoria, and the first gamma camera was installed at the Pretoria General Hospital in 1969. Nuclear medicine grew to become a subspecialty under Radiology in 1980, and then a separate specialty in 1987[30]. The origins and early use of radiology in South Africa date back to 1896 when the Port Elizabeth Amateur Photographic Society invited a representative of the Port Elizabeth Telegraph to attend a demonstration of their apparatus. South Africa has a proud history in that Allan Cormack (a physicist born in South Africa), together with Godfrey Hounsfield, was awarded the 1979 Nobel Prize for Physiology or Medicine for his work in developing the powerful new diagnostic technique of computerised axial tomography (CAT) by providing the mathematical technique for the CAT scan. Radiology (X-ray and CT scan) continues to be well established in South Africa and is the main imaging modality used in managing several diseases, including cancer.

Clinically qualified medical physicists (CQMP) are required in an imaging facility, including diagnostic radiology and nuclear medicine. For South Africa, only one of the five centres is adequately staffed. Assuming that 27.3 full-time equivalent CQMPs service 10% of the current imaging and nuclear medicine needs, then approximately 270 imaging and nuclear medicine CQMPs are required to cover existing services in South Africa (Trauernicht, et al., 2022).

Some of the important impacts of nuclear physics and technology are the discovery of radioactivity, the exploration of radioactive isotopes for use in medical diagnostics, and the development of particle accelerators for medical therapy. Advances in the study of the properties of radioactive isotopes for the initial purpose of understanding how elements are produced in the universe offered a unique opportunity to use some of the so-called 'theranostics' for both medical diagnostics and therapy.

5.2 Nuclear medicine and molecular imaging

Radioactive isotopes labelled with biomolecules can provide physiologically different molecular targets for the diagnosis of several conditions. This trace approach provides longitudinal sets of volumetric and quantitative images that can be used to diagnose a wide range of diseases and/or assess responses to disease-specific treatments.

The possibility of external detection offers a non-invasive way to follow changes in the distribution of tagged radioactive isotopes, to observe anomalies of metabolism (changes in blood flow, oxygen utilisation, glucose metabolism) or detect tumours. These radioisotopes can be followed in the human body using a dedicated system, such as a single photon emission computed tomography (SPECT) system or a positron emission tomography (PET) system (Hacker, et al., 2015). Some of the advantages of nuclear medicine and molecular imaging include:

1. Effectiveness and safety in diagnosis, staging, prognostication and follow-up of many clinical indications
2. Avoiding unnecessary treatments, and reducing patient discomfort and side effects
3. Individualisation of patient treatment
4. Contribution towards the reduction of healthcare costs
5. The use of theranostics to first diagnose and then treat diseases.

5.3 Radiotherapy and radiopharmaceutical therapy

It is estimated that 25–30% of the populations of industrial countries will contract cancer in their lifetime and that about half of these will receive some form of radiation therapy. The aim of radiotherapy is to destroy malignant cells without damaging healthy tissues.

30 https://sasnm.com/about-sasnm/history

Unfortunately, radiation travels through the body in straight lines and destroys cells in the entrance region between the surface and the tumour, and most kinds of radiation also have effects downstream before exiting the body. Unwanted damage to normal tissues is minimised by delivering the radiation from different directions, crossing at the location of the tumour.

The treatment of cancer continues to depend largely on three major modalities: surgery, radiotherapy and systemic therapies, including chemotherapy. Recently targeted radiopharmaceutical therapy is rapidly growing to become an essential part of cancer management. Other approaches include immunotherapy and gene therapy (IAEA, 2017).

Radiotherapy is currently an essential component in the management of cancer patients, either alone or in combination with surgery or chemotherapy, both for cure and for palliative care. The role of radiotherapy (RT) in cancer care is well described, with clear correlation between access to radiotherapy and overall survival. Yet there is a shortage of access to linear accelerators (LINACs) for this kind of treatment, especially in rural and semi-urban areas.

Radiotherapy is the medical use of ionising radiation in the treatment of disease, mostly cancer but also non-malignant disease. Modern radiotherapy makes use of highly precise collimating devices, and also offers the possibility of modulating the radiation fluence of an individual beam. Radiotherapy using charged particles such as protons or carbon ions is also a promising strategy. Although the South African large city and university hospitals have access to this modality of treatment, which is a pillar of cancer treatment, there are several gaps in terms of access for all and human resources. Hence, South Africa supports Rays of Hope, which focuses on prioritising a limited number of high-impact, cost-effective and sustainable interventions in line with national needs and commitment. There is also a need for the Programme of Action for Cancer Therapy (PACT). The IAEA established PACT in 2004 with the goal of ensuring the integration of radiotherapy in comprehensive cancer control and engaging with other international organisations, such as the World Health Organization (WHO), to address cancer control in a comprehensive way. Since then, the IAEA has worked closely with the WHO, the International Agency for Research on Cancer (IARC), the Union for International Cancer Control (UICC) and many other relevant collaborators to build a coalition of global partners committed to addressing the challenge of cancer in low- and middle-income IAEA Member States. The IAEA's contribution to this coalition focuses on radiation medicine, in line with the IAEA mandate[31]. To date, South Africa has not undertaken or invited the IAEA for a PACT mission.

The vast majority of existing facilities use X-rays or gamma rays, or photons produced by ^{60}Co or by linear electron accelerators. Accelerators are more versatile and can provide deeper penetration when necessary. Machines of 5–20 MeV or even 40 MeV are constructed industrially by several manufacturers. Major progress in cancer therapy is being achieved through improvements in local control of the tumour. This is the result of both i) improved diagnostic tools that allow better localisation of the malignant tissues and ii) the use of particle beams that permit higher energy deposition (the characteristic parameter is the linear energy transfer [LET]) and a more accurate range. Pions, protons and heavier ions offer the possibility of improving the damage ratio between malignant tumours and healthy tissues. With heavy charged particles, it is possible to achieve highly localised distribution[32]. The so-called Bragg peak (region of maximum energy deposition) is only a few millimetres wide near the end of the range, which allows a high dose to be delivered with less damage to the overlying tissues. The required penetration depths make it necessary to use machines capable of producing particles with energies of several hundred MeV. Existing installations are considered experimental and are located near accelerators built for other purposes

31 https://www.iaea.org/services/key-programmes/programme-of-action-for-cancer-therapy-pact
32 https://tlabs.ac.za/tandetron-lab/services/

(such as that of iThemba LABS until 2017). However, dedicated facilities for therapy are under design or construction.

The basis for successful radiopharmaceutical therapy is a theranostic approach that integrates diagnostic testing for the presence of a molecular target for which a specific treatment or drug is intended. Theranostics is an inclusive approach that promises improved therapy selection on the basis of specific molecular features of disease, greater predictive power for adverse effects due to improved patient-specific absorbed dose estimates, and new ways to objectively monitor the therapy response (Sathekge, 2013; Lee, et al., 2022).
Recent advances in South Africa have extended the range of radiopharmaceutical therapies that are now applied across a broad spectrum of diseases, from arthritis and benign thyroid diseases to many types of cancer such as thyroid cancer, prostate cancer, neuro-endocrine tumours, liver tumours (primary and secondary), non-Hodgkin's lymphoma and bone metastases.

5.4 Infrastructure and production

South Africa has well-established infrastructure for the production of radionuclides. Necsa has a 20 MW multipurpose reactor that has been operating since 1965 with a weekly molybdenum export production capacity of 1 000 Ci. Technetium generators, some of the radionuclides for therapy and most SPECT diagnostic kits are produced at Necsa's Isotope Production Centre.

Accelerator-based radionuclides are produced mainly at iThemba LABS by the Separated Sector Cyclotron, and will be produced in the near future (from 2023) by the new 70 MeV Cyclotron C70 of the South African Isotope Facility (SAIF), and the 11 MeV cyclotron. The radioisotope programme at iThemba LABS is a world-class effort that has developed over many years. The accelerator facilities allow for the production of a number of important radioisotopes and the Good Manufacturing Practice (GMP) production capabilities allow for these products to be used for clinical application. The radioisotope facility routinely produces ^{82}Sr, ^{68}Ge/^{68}Ga generators, ^{18}F-FDG, ^{22}Na and ^{123}I radiopharmaceuticals. iThemba LABS is the only facility in South Africa that produces short-lived accelerator-based isotopes such as ^{123}I, and the only facility in the world producing ^{22}Na. The ^{123}I, together with ^{18}F-FDG, which is produced using a dedicated 11 MeV cyclotron, currently services 25 local clients, or 10 000 patient doses, per year. A 16 MeV cyclotron is based at Necsa, with further accelerators within the private sector (PET Labs Pharmaceuticals in Pretoria).

There are 59 active nuclear medicine facilities in South Africa, 46 in the private health sector and 13 in the public health sector. Included in these facilities are:

- 19 positron emission tomography/computed tomography (PET-CT) systems (eight in the public health sector and 11 in the private health sector)
- 86 single-photon emission computerised tomography (SPECT) and SPECT/CT systems in both the private and public sectors.

5.5 Human capacity

The Nuclear Technologies for Medicine and Biosciences Initiative (NTeMBI) platform is funded by the DSI and managed on behalf of the department by Necsa. NTeMBI focuses on human capital development and is highly successful, with over 50 postgraduate students supported to date, of whom 55% were black and 65% women. Sadly, few of the graduates have been absorbed into the nuclear medicine sector of the country's hospitals, universities, Necsa and iThemba LABS, while some have been absorbed into private laboratories and others into the nuclear technology space.

The Nuclear Medicine Research Infrastructure (NuMeRI) is part of the DSI's South African Research Infrastructure Roadmap (SARIR). NuMeRI and NTeMBI are complementary programmes, with NuMeRI providing and maintaining the necessary infrastructure, and NTeMBI facilitating students and researchers who will make use of the NuMeRI infrastructure to achieve project goals.

NuMeRI is a one-stop-shop medical imaging and theranostics facility dedicated to drug development, clinical research and human capacity development at universities, iThemba LABS and Necsa. While contributing to human capacity, NuMeRI fits in well with the national Bioeconomy Strategy, as it represents a vehicle for solving grand challenges in Africa's pharmaceutical markets, which often fail to address the most fundamental impediments to innovation.

5.6 SWOT analysis

5.6.1 Strengths

- Well-established nuclear medicine in South Africa, which is standard of care in most metropolitan areas. Currently, seven of the country's teaching hospitals have a department of nuclear medicine with PET-CT and double/single head gamma cameras, including SPECT or SPECT/CT. PET radioisotopes are produced from particle accelerators and are most needed for RDI and theranostics, whereas SPECT radioisotopes are produced from research reactors.
- Infrastructure, existing and planned, in South Africa (e.g. a number of accelerators, a reactor and various research facilities).
- Existing expertise (a legacy from decades of experience at iThemba LABS and Necsa).
- Considerable growth of PET utilisation and application, particularly with the advent of prostate-specific membrane antigen (PSMA) imaging in the country. Oncology applications continue to grow; infection imaging has a long history in South Africa and is well utilised where PET is available in the public sector.
- Radioiodine therapy for differentiated thyroid cancer and hyperthyroidism, which is well established and is the most commonly employed targeted radionuclide therapy. Most training centres cover the four key areas of radionuclide therapy: benign and well-differentiated thyroid cancer, and peptide receptor radionuclide therapy (PRRT) with ^{177}Lu-PSMA and ^{177}Lu-DOTATATE.
- Education and training:
- Tertiary academic institutions in South Africa provide ongoing postgraduate training in nuclear medicine.
- Postgraduate training programmes for doctors comprise a period of at least four years with core competencies in medical physics, radiobiology, radiation protection, radiopharmacology and clinical nuclear medicine.
- Postgraduate training is also provided for physicists in nuclear medicine.
- Radiographers specialising in nuclear medicine undergo a minimum of three years' training leading to a diploma or a BTech degree. The Health Professionals Council of South Africa and the national Department of Health strictly control the training, in line with international requirements.
- Nuclear-related research, which is performed by most universities and academic centres primarily as part of master's and BTech projects. In this regard, the University of the Free State has the largest medical physics department with an excellent and long-standing publication record.

5.6.2 Weaknesses

- Nuclear medicine (in general):
    - Loss of expertise, mainly in R&D, due to the failure in knowledge transfer between generations.

  - Subcritical funding and support to R&D from government and academia.
  - Dispersion of effort and a strong silo culture among academia and research organisations.
  - Status quo attitude of many of the drivers of the field.
  - Revenue generation-driven culture.
  - Low capacity of the public health sector to offer nuclear medicine diagnostics and therapy. There is limited access for many at level II hospitals and for those outside metropolitan areas.
- PET:
    - Radioisotope production. Having only one producer without readily accessible backup makes it difficult to utilise PET throughout the year. The limited number of cyclotrons in the country is a limiting factor and needs to be addressed as soon as possible. It is impossible for only three cyclotrons to service a population of 60 million people.
    - Human resources. The limited number of radiochemists or radiopharmacists, and the regulatory requirements for these professionals to be registered, are challenging and hamper growth in this domain. This applies also to other skilled staff such as nuclear medicine physicians, medical physicists and nuclear medicine radiographers.
  - Radionuclide therapy:
    - Training centres in South Africa. These are located in different provinces, and some of these facilities do not have well-established theranostic programmes, resulting in limited access for patients and registrars in training.
    - Limited knowledge of referring physicians, funders and administrators with regard to the benefits of diagnostic and therapeutic radionuclide procedures.
    - Lack of sufficient oncologists, radiologists, nuclear physicians, radiographers, radiation therapists, radiobiologists and medical physicists.
    - Lack of funded national cancer control programmes, which leads to disorganised cancer management. Moreover, the country does not benefit from the IAEA's PACT.
- Research. In terms of regulatory approval, many of the protocols are read by reviewers who do not understand the nature of the research or the role of radionuclide therapy. This hampers the p rogress of studies taking place, especially prospective studies, and hence does not allow the field to advance as well as it could.
- Funding. This is a critical limitation for the provision of infrastructure, equipment, maintenance, human resources and services, especially given that 80% of the population depends on public infrastructure.

5.6.3 Opportunities

More robust training in South Africa to optimise theranostic oncology patient care, given the rapidly evolving theranostic agents. There is considerable scope for the growth of current and future theranostic agents on the training platforms for nuclear medicine professionals engaging with patient care related to radionuclide therapy. This will ultimately lead to enhanced patient care. The opportunities include:

- Introduction of nuclear medicine departments at level II hospitals. The output of newly qualified nuclear medicine specialists has increased over the years. This creates opportunities to introduce nuclear medicine departments at level II hospitals and relieve the workload in tertiary hospitals.
- Further research utilising nuclear medicine and molecular imaging. Once fully operational, the NuMeRI facility will galvanise further research utilising nuclear medicine and molecular imaging, including preclinical imaging, and assist with the upskilling of researchers.
- Public–private partnerships (for the effective use of resources and expertise), especially given the limited supply of some radiopharmaceuticals.

- A national initiative to drive a collective R&D effort (beyond individual organisations or entities) with the commitment of government and universities.
- A clear vision and plan for the evolution of existing RDI facilities. This has been done for iThemba LABS, as well as the NuMeRI initiative.
- Management of medical nuclear waste (e.g. spent sources), which should be a priority, especially the role of the National Radioactive Waste Disposal Institute in the rest of the sub-Saharan region.
- Commissioning a full and separate evidenced-based report on radiation oncology that can help provide sustainable solutions to RDI and service provision.

5.6.4 Threats

- Loss of R&D potential and subsequent loss of purpose of existing expertise.
- Some infrastructure potentially becoming obsolete (e.g. Proton Therapy Centre of iThemba LABS).
- Loss of revenue generation and player position in the global radioisotope market.
- Loss of human resources and expertise as a result of limited career opportunities in the public sector.

5.7 Needs and gaps

The needs and gaps identified in this section relate to human health, with an emphasis on nuclear medicine.

Access to nuclear medicine investigations

For every two million people, at least one good theragnostic centre is required with both SPECT and PET-CT capabilities, including radionuclide therapy. Currently, PET-CT is available in five of the nine provinces for both the private and public health sectors.

Insufficient access to nuclear medicine and theranostic procedures

Currently, nuclear medicine and radiotherapy procedures are confined to central university hospitals, despite broad acceptance and widespread application in clinical medicine. This is due to insufficient healthcare infrastructure to accommodate nuclear medicine facilities in terms of medical equipment, configurations of supply chains and a shortage of qualified human resources.

Objective: To introduce nuclear medicine departments in level II hospitals.

Indicator/s:

i. Each province to have a nuclear medicine department in level II hospitals with the capability for theranostics and research projects.
ii. Increase in the number of IAEA TCP projects with collaboration between academic institutions for research purposes.

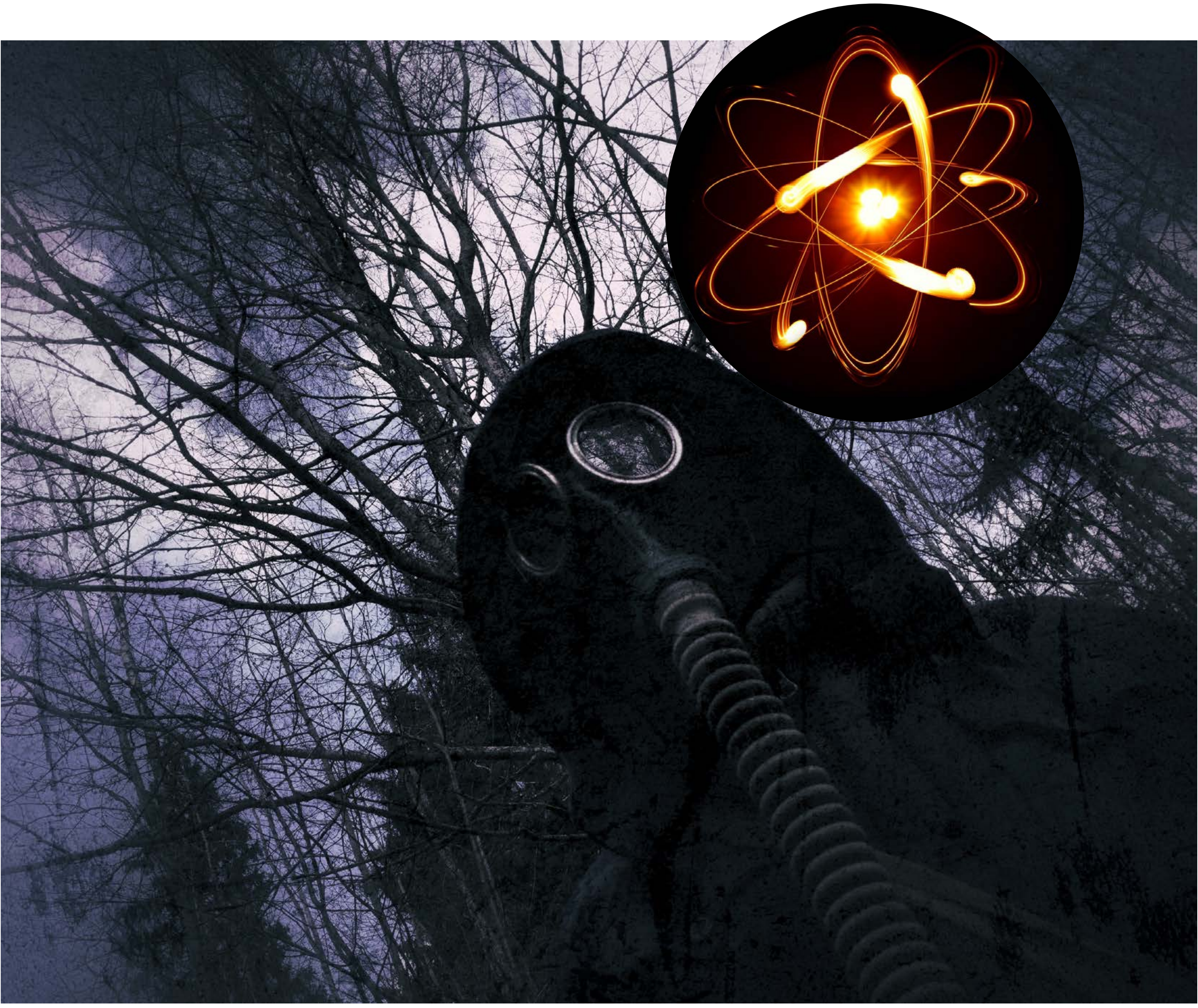
Lack of comprehensive national cancer control programme (NCCP) that includes nuclear medicine

The global community has long recommended that each country should establish a national cancer control programme (NCCP) to ensure appropriate cancer control at different levels with respect to prevention, early detection, diagnosis, treatment and palliative care. Hence, there is an urgent need to develop a comprehensive NCCP in South Africa, with actions and investments that would enhance access to imaging equipment, workforce capacity, digital technology, radiopharmaceuticals, and research and training programmes. This would produce massive health and economic benefits, and reduce the burden of cancer in the country. This would also enable South Africa to better support the IAEA Ray of Hope initiative (i.e. Cancer care for all).

Objective: To develop comprehensive NCCPs to address optimal usage of radiation medicine (radiotherapy, nuclear medicine, radiology, medical physics and radiobiology).

Indicator/s:

i. Establishment of a comprehensive NCCP by 2024.
ii. Participation in the IAEA PACT mission by 2024.
iii. Commissioning of a full and separate study into radiation oncology/medicine that can help provide sustainable solutions to RDI and service provision, similar to the National Cancer Institute of Kenya established in terms of the Cancer Prevention and Control Act of 2012. The role of this institute is to advise the Cabinet Secretary on matters related to the treatment and care of persons with cancer and to advise on priorities in implementing specific measures. Recent input from the Kenyan Ministry of Health includes the Kenya Cancer Policy 2019–2030[33].



33 https://www.health.go.ke/wp-content/uploads/2020/07/Kenya-Cancer-Policy-2020.pdf

6. RADIATION PROTECTION

6.1 Background

For workers exposed to different fields of ionising radiation at their workplace, the prospective assessment of excess health risks is implicit in the application of the principle of 'As low as reasonably achievable' (ALARA) to comply with principles of radiation protection. The health of workers is an important element of the safety management system (IAEA, 2021). Radiation protection, in line with the International Commission on Radiological Protection (ICRP), was practised mainly in the medical field as early as the advent of the first X-ray equipment and the introduction of radioisotopes to South Africa. Radiologists were responsible for training or supervising radiographers in correct radiation protection practices. This training was informal until the early 1960s, when it was legislated.

Concurrently, radioisotopes were used in medicine, nuclear facilities; for example, at Necsa, the CSIR, iThemba LABS, tertiary institutions (for research) and industries (agriculture, aviation, forensic, mining, paper, wood, road construction) (iThemba LABS, 2018). In all these areas, radiation protection was not recognised as a profession and was practised under the supervision of nuclear engineers, nuclear scientists, nuclear researchers, or even the authority holders.

This resulted in the introduction of a radiation protection officer (RPO) programme under the South African Qualifications Authority (SAQA). The curriculum was developed for radiation protection monitoring (RPM) at NQF level 3, radiation protection officer (RPO 2) at NQF level 4 and RPO 1 at NQF level 5.

In-house training of RPOs was conducted in all these fields without being accredited. Groups of these RPOs formed a professional body, the Southern African Radiation Protection Association (SARPA).

In 2010, the IAEA visited South Africa to conduct an audit of institutions that provide training in radiation protection. The aim of the visit was to establish a centre of excellence for RPO training for all English-speaking African countries. An audit was conducted at Necsa and the University of the Witwatersrand (Wits) as the only institutions that applied to be audited. Necsa received a clean audit as a centre for training RPOs. The audit was later extended to the NNR and the Department of Health's Radiation Control directorate as the authority bodies. Since it was established that the RPO training was not formalised, the two regulatory bodies were requested to publish RPO training in the *Government Gazette*. As of July 2022, the relevant paragraph has been drafted and is awaiting tabling in Parliament.

In 2011, Necsa applied for accreditation through the Energy and Water Sector Education and Training Authority (EWSETA) as a service provider for RPM, RPO 2 and RPO 1 training. Necsa was the first and only institution accredited in South Africa until 2016, when the Radiation Analytical Laboratory (RAL) and Radiation Protection Training Academy (RPTA) (Pty) Ltd were accredited to provide the same courses. To date, they are the only training centres accredited by the Quality Council for Trades and Occupations (QCTO)[34].

In the meantime, SARPA established the Radiation Protection Certification Committee (RPCC), which is responsible for certifying RPOs and Radiation Protection Specialists (RPSs). SARPA is currently affiliated to the South African Council for Natural Scientific Professions (SACNASP) and is in the process of applying to be audited by SACNASP as an RPO certifying body in South Africa.

34 https://www.sahpra.org.za/wp-content/uploads/2020/01/RPO-Training-Interim-Rev-0b-2.pdf

There is considerable focus on occupational radiation exposure; however, radioactivity is a natural phenomenon, and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to the public and the environment that may arise from these applications have to be assessed and, if necessary, controlled; hence the need for awareness of regulations and training[35]. South Africa, like other countries, therefore has an obligation of diligence and duty of care, and is expected to ensure that radiation protection and safety standards are in place.

6.2 Regulation

6.2.1 National Nuclear Regulator (NNR)

As discussed in chapter 2, the National Nuclear Regulator Act (No. 47 of 1999) established the National Nuclear Regulator (NNR), a public entity covering the full fuel cycle from mining to waste disposal, and in particular the siting, design, construction, operation and decommissioning of nuclear installations. The regulator is mandated to provide for the protection of persons, property and the environment against nuclear damage through the establishment of safety standards and regulatory practices.

The National Nuclear Regulator Act gives the NNR powers to grant, amend and revoke authorisations, and to impose such conditions upon authorisation holders as it deems necessary. It establishes the basis for regulatory control by alluding to acceptable risk as the determinant. The legislation specifies that a holder of authorisation for any facility or activity that gives rise to radiation risks has the primary responsibility for safety and is liable for any nuclear damage caused by its facilities or activities.

6.2.2 Department of Health: Radiation Control

The Directorate of Radiation Control under SAHPRA regulates all activities involving electronic generators of ionising radiation as well as radioactive sources used outside the nuclear fuel cycle. The aim is to protect patients, radiation workers, the public and the environment against overexposure to ionising radiation without limiting its beneficial use.

6.3 Infrastructure and production

The national regulatory infrastructure for radiation protection is based on a safety culture and recommendations from international organisations, along with the requirements of the South African regulatory authority (Ngubane, 2012). The regulatory authority implements a national regulatory programme for the control of radiation sources. The infrastructure comprises legislation, regulations, a regulatory authority, and general provisions or services (Figure 5). The regulator is positioned to oversee and control the application of radiation in a clinical setting.

35 https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1781_web.pdf

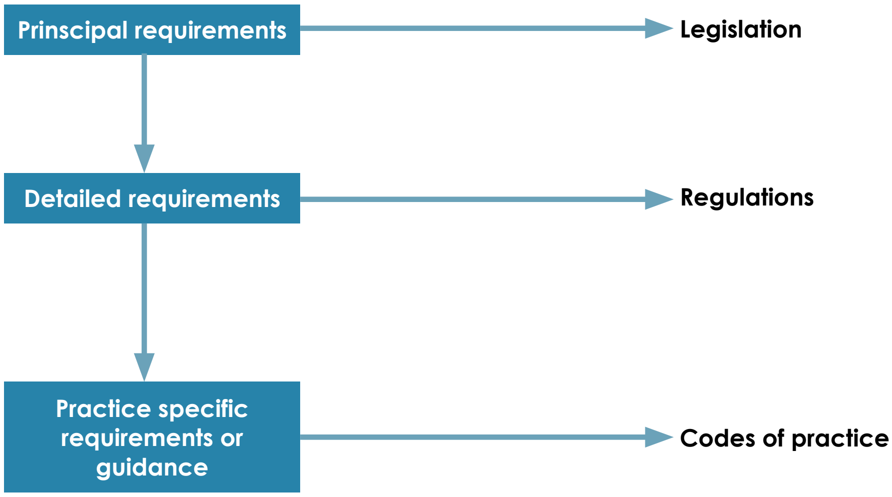


Figure 5: Structure of the legal framework as recommended by the IAEA (Ngubane, 2012)

In all facilities, (i) the amount of shielding necessary depends on the radiation type and intensity of the source, (ii) facility designs include multiple safeguards to protect worker health and the community, (iii) and the facility regulation depends on the type of radiation source used.

Some of the crucial licensing requirements for the radiation facilities include: (i) a design that incorporates multiple fail-safe measures; (ii) extensive and well-documented safety procedures; (iii) and extensive worker training (Ngubane, 2012).

The essential technical services include dosimetry services, analytical services, calibration services, radioactive waste management services, training services, and accreditation for implementation of an effective regulatory programme (Ngubane, 2012).

6.4 Human capacity

It is a requirement of the NNR that any organisation that handles radioactive material, as licensed or certified by the NNR, has a Radiation Protection Function structure. This structure must include fully trained radiation protection specialists, radiation protection officers and radiation protection monitors.

The Radiation Protection Function must be able to:
- Recognise and quantify all potential and actual radiation hazards during normal operations
- Prospectively implement control measures to ensure compliance with the dose limitation system applicable to employees and members of the public as a result of normal operations
- Recognise and quantify radiation hazards associated with abnormal situations and implement appropriate radiation protection measures
- Assess the need for and formulate mitigatory actions in the case of accidents.
- Furthermore, it is a requirement of the regulator that adequate, competent, qualified and trained staff be available to execute the Radiation Protection Function.

Over the years, numerous radiation protection training courses have been introduced by various organisations throughout the country.

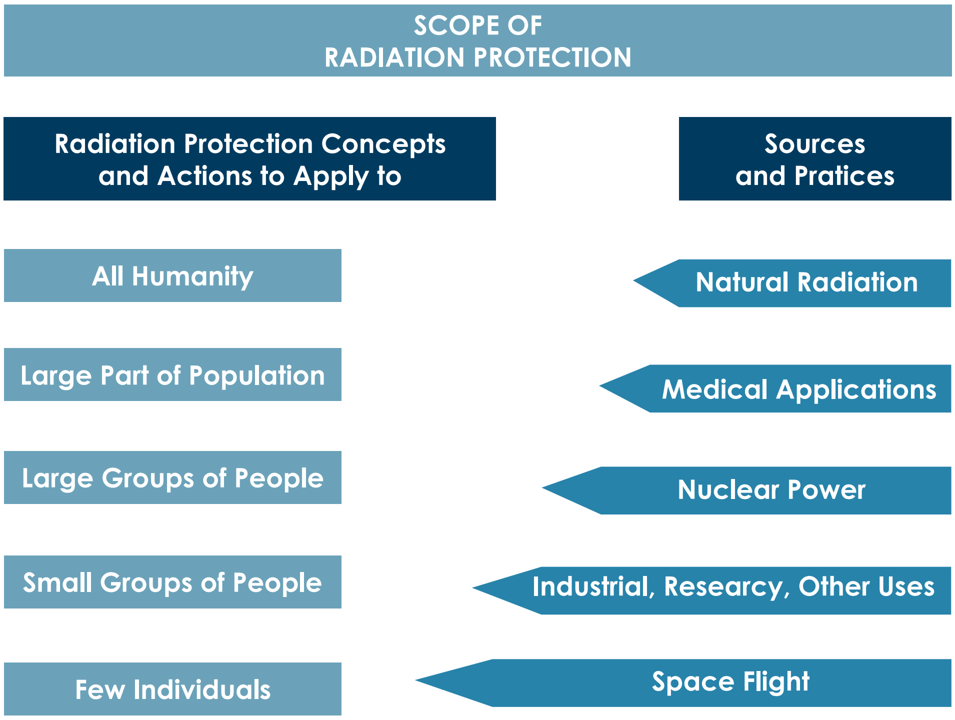


Figure 6: Scope of radiation protection [36]

Radiation protection is dynamic in nature and affects the global population; hence the prospect of new radiation practices requires coordinated efforts (Figure 6), positive public attitudes and epidemiological insight.

6.5 SWOT analysis

6.5.1 Strengths

- Improved cooperation between the IAEA and South Africa's radiation control.
- Availability of good radiation protection training infrastructure and equipment at Koeberg NPP and Necsa.
- High generation of trained professionals. More than 48 RPO level 1, 135 RPO level 2, 70 under the SAQA programme and more than 100 under other programmes have been qualified in South Africa.
- Well-established and well-run radiation protection programmes with experience of operating facilities in the nuclear fuel cycle.
- Mature, effective and experienced regulator, with a regulatory programme implemented at all radiation facilities.
- SARPA's affiliation to SACNASP. SARPA is applying to be audited by SACNASP as an RPO certifying body in South Africa. Currently, the SARPA Radiation Protection Certification Committee (RPCC), whose membership is made up of radiation protection professionals, gives recognition for the following:
  - Radiation protection specialist
  - RPO level 1
  - Candidate RPO level 1
  - RPO level 2
  - RPO level 3.

6.5.2 Weaknesses

- Lack of harmonisation with regard to the radiation protection regulatory functions of the NNR and SAHPRA.

36 https://www.oecd-nea.org/jcms/pl_27483/radiation-protection-today-and-tomorrow

- Only two centres (Necsa, and RAL & RPTA) being accredited by EWSETA for RPO training. Other training facilities, such as Koeberg NPP and companies (e.g. those that provide training in mines) are not accredited. It should be noted that the training facilities at Koeberg NPP are accredited by the NNR for the function to which they are applied. Koeberg NPP's training is also fully approved by the IAEA, the World Association of Nuclear Operators (WANO) and the Institute of Nuclear Power Operations (INPO).
- Lack of suitably skilled radiation protection personnel during outages at Koeberg NPP, as a typical refuelling outage requires a large team of additional personnel.
- Lack of suitably qualified and experienced radiation protection personnel for radioactive waste disposal facilities. NRWDI does not yet have a training programme or facilities for radiation protection and relies on Necsa (which is also a waste generator and a client of NRWDI) to provide such training. A good example of this relationship is that the radiation awareness induction programme for NRWDI employees is provided by Necsa. Furthermore NRWDI has limitations based on limited funding and training to roll out of aspects of the Radioactive Waste Management Policy.
- Lack of sufficient facilities or infrastructure for training.
- Adequate succession planning for the retirement or possible resignation of radiation protection personnel at facilities.
- Overlapping roles of the South African Radiation Protection Society (SARPS), SARPA and the future South African Radiation Protection Coordinating Body (SARPCOB).
- Limited RDI from South Africa on new models to calculate prospective cancer incidence lifetime risk for occupationally exposed individuals and radiation-related lifetime cancer risks.

6.5.3 Opportunities

- Existence and implementation of software for database on collaboration with other international programmes and the IAEA.

6.5.4 Threats

- Expansion of nuclear programmes in other countries, with the risk that this could result in South African radiation protection personnel being offered employment in those programmes and thereby depleting the country's radiation protection capacity.
- Lack of full information and awareness of radiation protection issues among the public and personnel working with ionising radiation.

6.6 Needs and gaps

The needs and gaps identified in this section relate to radiation protection.

Absence of a public–private partnership model for education, training and research

For various reasons, there is limited capacity with regard to radiation protection, such as limited posts in the public sector, and retirements without succession planning, leading to the lack of suitably skilled radiation protection personnel.

This can be alleviated through collaboration (partial rotation by trainees and researchers) and accreditation of some of the private facilities with the requisite infrastructure and skills. However, there is no national strategy for a public–private partnership model for education, training and research on radiation protection. Such a strategy would also address: (i) awareness of radiation protection and safety in veterinary medicine, (ii) establishment of a single radiation protection training body with subdivisions for various professions by 2024, and (iii) publication of RPO training in the *Government Gazette*.

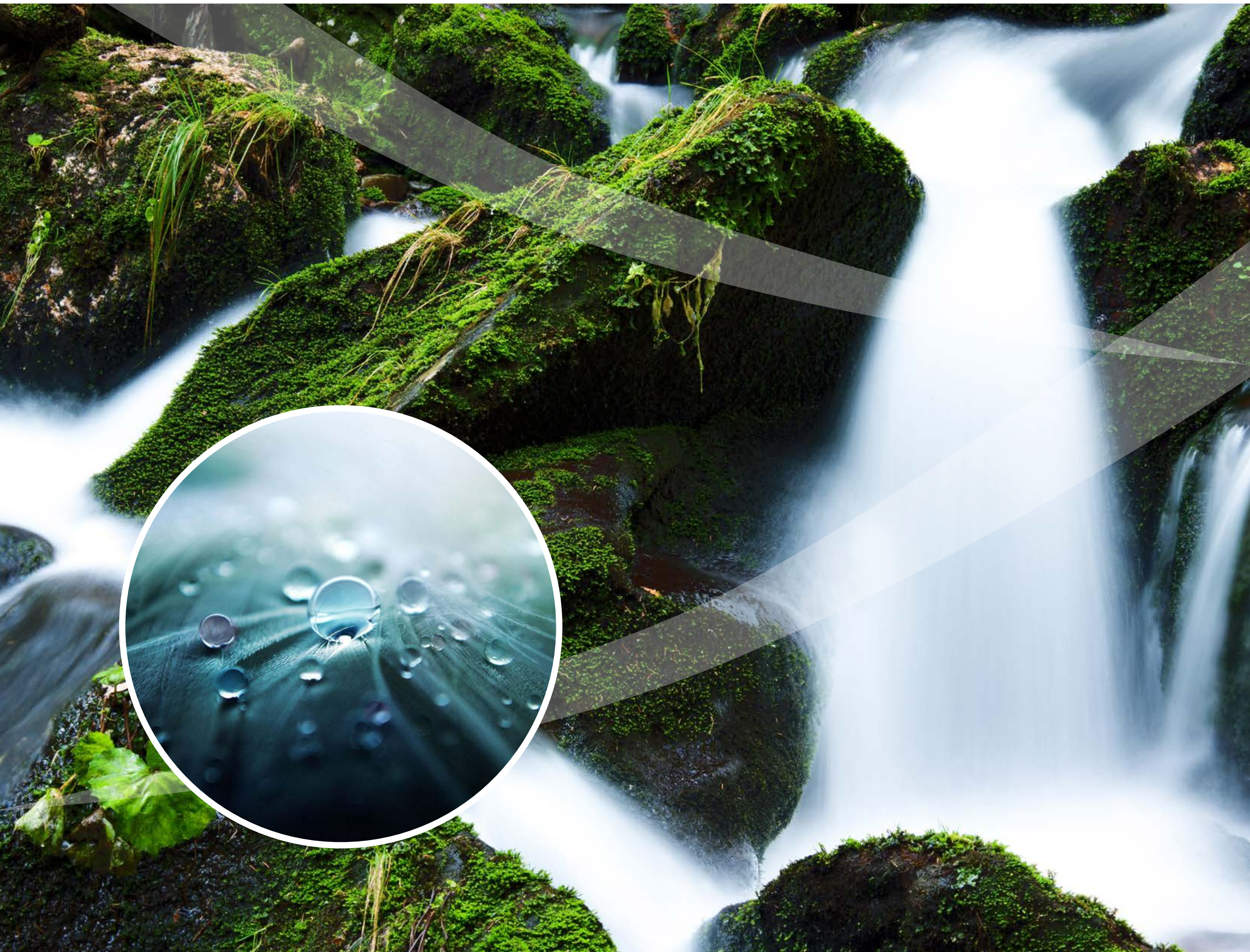
Objective: To develop and implement a public–private partnership model for education, training and research on radiation protection
Indicator/s: An accreditation system for the private sector with a view to conducting training and research in collaboration with the public sector (to be designed and implemented by 2024).

Need to harmonise the radiation protection regulatory functions of the NNR and the Department of Health

Radioisotopes in South Africa are currently regulated by two national regulatory bodies, namely the NNR and the Directorate of Radiation Control, under the South African Health Products Regulatory Authority (SAHPRA). This could lead to challenges in the provision of databases. To address this, the NNR has implemented the IAEA's Regulatory Authority Information System (RAIS), but SAHPRA has not yet done so. The RAIS is a software application developed by the IAEA to assist Member States in managing their regulatory control programmes in accordance with IAEA safety standards and guidelines, which include the IAEA Code of Conduct on the Safety and Security of Radioactive Sources, and the supplementary Guidance on the Import and Export of Radioactive Sources.

Objective: To harmonise the functioning of the NNR and the SAHPRA Directorate of Radiation Control.

Indicator/s: By 2024, creating an RAIS database system for both the NNR and the SAHPRA Directorate of Radiation Control, which will result in a comprehensive system covering all the main areas of the regulatory framework.



7. WATER AND ENVIRONMENT

7.1 Background

South Africa is a water-scarce country with average annual rainfall of 450 mm, which is well below the world average of about 860 mm. Evaporation is comparatively high, and the country does not have any truly large or navigable rivers. Furthermore, South Africa is also poorly endowed with groundwater, and the natural availability of water across the country is highly uneven, with more than 60% of the river flow arising from only 20% of the land[37]. The Water Reconciliation Strategies compiled for several key catchments supplying the large metropolitan areas in South Africa (DWA, 2010) confirm that future water requirements can only be met through a combination of:

- Development of further surface and groundwater resources
- Management of return flows and maximising reuse
- Desalination
- Rainwater harvesting
- Reduction of demand through water conservation and water demand management
- Catchment rehabilitation and management measures.

As water plays a central role in all sectors (including agriculture, energy, mining, industry, tourism, urban growth and rural development), the allocation, development and protection of water is an essential prerequisite for inclusive economic growth, poverty reduction, and addressing the high degree of inequality in South Africa.

From 2002 to 2006, South Africa was involved in the IAEA Coordinated Research Project (CRP) entitled 'Monitoring isotopes in rivers: creation of the Global Network of Isotopes in Rivers (GNIR)'. The South African contribution to this CRP originated from earlier activities of the CSIR environmental isotope group. Between 1968 and 1974, regular sampling and isotope analysis was undertaken on water from 12 river stations in southern Africa. The CSIR participated in the CRP in order to:

- Capture historical data in a database
- Set up and operate new isotope sampling stations in line with the needs of a future Global Network of Isotopes in Rivers (GNIR) programme concentrating on larger catchments
- Evaluate both new and historical riverine water stable isotopes sets of data on a sound hydrological basis.

The project was led by the CSIR in collaboration with the University of KwaZulu-Natal. These centres represented the foremost institutions for hydrological research in the country and brought in hydrological expertise that was lacking in the past.

7.2 Nuclear applications in groundwater management

Isotope hydrology is an established method used to understand hydrological processes such as recharge rates, surface water–groundwater interaction, time scales of processes (i.e. groundwater age) and sources of contamination. Isotope techniques can be used to determine:

- Origin of the water
- Age, velocity and direction of flow
- Surface water–groundwater interaction
- Aquifer characteristics such as porosity, transmissivity and dispersivity
- Sources of contamination
- Radius of influence when pumping (abstracting) groundwater.

37 https://www.un.org/waterforlifedecade/green_economy_2011/pdf/session_1_economic_instruments_south_africa.pdf

Environmental isotopes, both stable and radioactive, occur in the atmosphere and hydrosphere in varying concentrations. To date, the most commonly used environmental isotopes include those of the water molecule, hydrogen (^{2}H or D, ^{3}H or T), oxygen (^{18}O), as well as carbon (^{13}C and ^{14}C)[38].

The concept of 'idealised groundwater age' implies the time elapsed between when water entered the saturated zone (the groundwater) and when the water was sampled at a particular location and distance downstream in the groundwater system.

Age is used as a guide for the classification of the susceptibility of groundwater to near-surface contamination, and environmental isotopes are used to determine the age of groundwater. ^{14}C is used to determine the age of water that is older than 1000 years, and ^{3}H for water not older than 50 years (Irvine, Wood, Cartwright, & Oliver, 2021). Tracing groundwater by means of environmental isotopes offers unique supplementary information on the origin and movement of groundwater and its dissolved constituents, quantitative evaluation of mixing, and other physical processes such as evapotranspiration. This can already be done by the accelerator mass spectrometry facility at iThemba LABS.

7.3 Nuclear applications in water desalination

Desalination is a process that removes mineral components from saline water. Desalination is known to be an energy-intensive process, requiring low-temperature steam for distillation and high-pressure pumping power for membrane systems. Traditionally, fossil fuels such as oil and gas have been the major energy sources. However, fuel price hikes and volatility, concerns about long-term supplies and environmental impact are prompting the consideration of alternative energy sources. Several countries are already using electricity from nuclear power plants to operate desalination plants. It is expected that the implementation of advanced and innovative nuclear energy systems (such as small modular reactors) will promote the use of nuclear energy for water desalination in future.

7.4 Infrastructure and production

In terms of isotope hydrology, the following entities are key for addressing the infrastructure and RDI required:

- Trans-Caledon Tunnel Authority (TCTA), which was established in 1986 as a state-owned entity specialising in project financing, implementation and liability management. It is responsible for the development of bulk raw water infrastructure and provides an integrated treasury management and financial advisory service to the Department of Water and Sanitation, water boards, municipalities and other entities linked to bulk raw water infrastructure[39].
- Water Research Commission (WRC), which was established in 1971 to generate new knowledge and to promote the country's water research. The mandate of the WRC includes promoting coordination, cooperation and communication in the area of water research and development; establishing water research needs and priorities; stimulating and funding water research according to priorities; promoting the effective transfer of information and technology; and enhancing knowledge and capacity-building within the water sector[40].

38 http://www-naweb.iaea.org/napc/ih/documents/global_cycle/Environmental
39 https://www.dws.gov.za/Documents/Other/Strategic%20Plan
40 https://www.dws.gov.za/Documents/Other/Strategic%20Plan

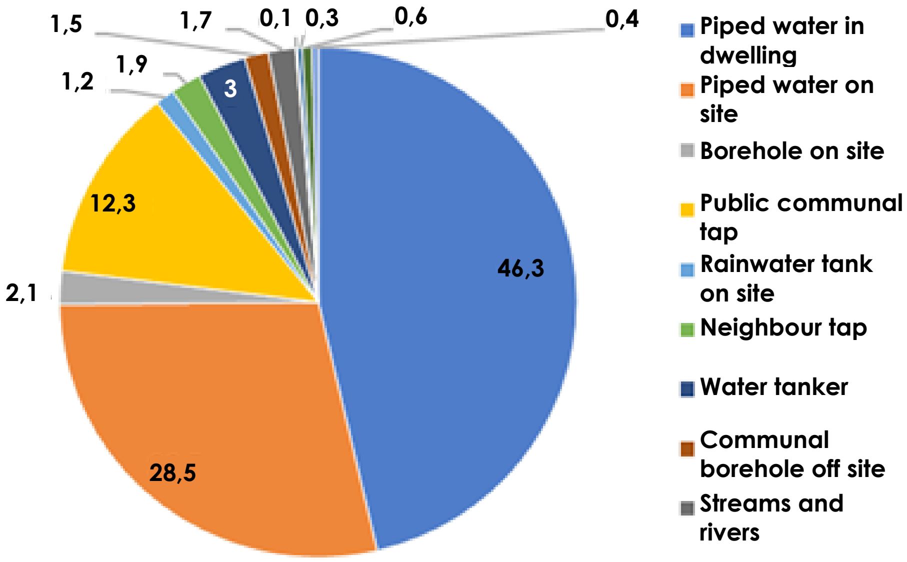


Figure 7: Distribution of drinking water sources for households in South Africa [41]

Data on the distribution of drinking water sources for South African households show that access to water infrastructure provision remains an elusive dream for many households and that thousands of South African households still depend on unimproved and unprotected sources of drinking water (Figure 7).
iThemba LABS has recently developed a portable radioactivity monitor for use in national parks. This might address the need for radioactivity measurements in water and plants in the vicinity of mines and thermal power plants, as well as in national parks.

7.5 Human capacity

Collaboration with tertiary institutions should be promoted so as to involve a broad range of disciplines and avoid the new skill sets in the water sector being dominated by engineering and technical disciplines. This would also entail opportunities and career paths in new and emerging fields such as computer science, bioinformatics, data science and artificial intelligence systems.

7.6 SWOT analysis

7.6.1 Strengths

- Several existing institutions already active in water and environmental monitoring, research and development.
- Experience in the use of nuclear techniques for groundwater management.
- A sound South African Medical Research Council (SAMRC) strategy to determine the impact of environmental hazards on the health of the population.
- An established National Water Resource Strategy.

7.6.2 Weaknesses

- Limited interaction between environmental and water departments, or with organisations utilising nuclear technology.
- Few personnel trained in the application of nuclear techniques for water and environmental management.

41 https://hsf.org.za/publications/hsf-briefs/water-infrastructure

7.6.3 Opportunities

- Increasing awareness of the use of isotope hydrology for water and environmental management.
- Maintaining and growing facilities for and expertise in the use of isotope hydrology techniques. This could be achieved through the IAEA's Global Network of Isotopes in Rivers (GNIR) programme and Coordinated Research Projects (CRPs).
- Promoting the provision of clean water through desalination using nuclear energy.
- Reassessing South Africa's involvement in the seawater desalination-related IAEA CRPs.
- Removing the 'silo mentality' evident in the Strategic Integrated Project (SIP) aimed at improving South Africa's water resources and other environmental goods and services. This intervention would integrate the work not only of the national, provincial and local spheres, but also across disciplines, with success heavily reliant on partnerships between departments and organisations that are not traditional partners.

7.6.3 Threats

- Limited understanding of nuclear techniques, resulting in negative social perceptions arising in part from limited understanding, but also from inherent beliefs about nuclear technology.
- Delays in implementing new nuclear power plants that could provide energy for desalination projects.

7.7 Needs and gaps

The needs and gaps identified in this section relate to water and environment.

Inadequate integration in the management of water resources

Almost everyone is affected by the management of water resources. South Africa faces major challenges for effective management, including limited physical resources, long cycles of inadequate rainfall, a rapidly growing population and a stagnant economy. Water resource management is crucial for human security (Molobela & Sinha, 2011).

The key to sustainable management of water resources is having the knowledge needed to make the right decisions. Isotope hydrology is a nuclear technique that uses both stable and radioactive environmental isotopes to trace the movements of water in the hydrological cycle.

Isotope hydrology has been shown to be a very cost-effective means of assessing the vulnerability of groundwater sources to pollution by specifying critical information to inform decisions on where to extract water[42].

Objective: To evaluate the availability of isotope hydrology competences in South Africa within organisations such as iThemba LABS, Necsa, the CSIR and local universities, and integrate these into a comprehensive water resource management programme for the country.

Indicator/s:

i. Number of water management plans and research programmes developed and implemented.
ii. Implementation of the findings of the 2002–2006 IAEA CRP conducted by the CSIR and the University of KwaZulu-Natal.

42 https://www.iaea.org/sites/default/files/water.pdf

New and more sustainable methods for water production by desalination

South Africa is fortunate to be flanked by the Indian and Atlantic oceans and thus stands to benefit from a considerable water supply.

The existing few desalination plants along the coast from Lambert's Bay in the west to Richards Bay in the east are insufficient to address the water shortages and only supply households in the immediate vicinity[43].

One of the methods of increasing the output would be to use proven technology that is economically viable and uses manageable levels of electricity for desalination by reverse osmosis. Hence, the use of nuclear energy for water desalination should be considered. There is a need to leverage on the envisioned 2 500 MW nuclear build as articulated in IRP2019 (RSA, 2019). This is particularly urgent given the water scarcity in the country and the projections of water deficits in the future, especially in some coastal urban areas.

Objective: To increase the water supply using practical and evidence-based large seawater desalination plants.

Indicator/s: Number of desalination plants developed and implemented that are driven by more sustainable energy supply such as nuclear power.

43 (https://sassda.co.za/news-home/stainless-steel-magazine/march-2018/desalination-plants/

8. ENERGY

8.1 Background

South Africa's National Development Plan (National Planning Commission, 2011) has made a commitment that by 2030 the country will have an energy sector that promotes:

i. Economic growth and development through adequate investment in energy infrastructure that is competitively priced, reliable and efficient
ii. Social equity through expanded services to energy services with affordable tariffs
iii. Environmental sustainability through efforts to reduce pollution and mitigate the effects of climate change.

In 2018 (Figure 8), the South African energy supply was dominated by coal, which constituted 65% of the primary energy supply, followed by crude oil at 18% and renewables at 11%. Natural gas contributed 3%, while nuclear power contributed 2% to the total primary supply during the same period (DMRE, 2022).

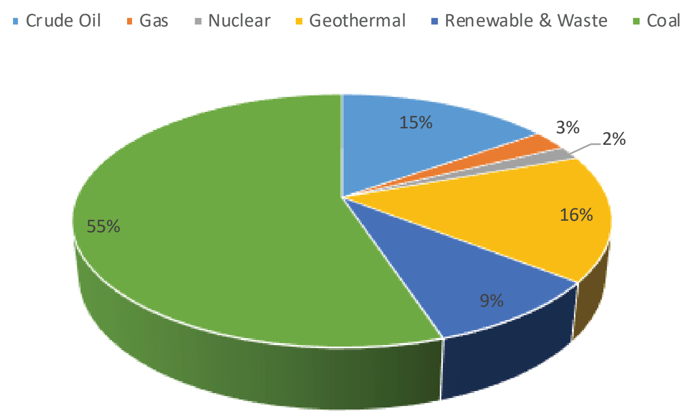


Figure 8: Distribution of primary energy supply in 2018 (DMRE, 2022)

South Africa will need to meet about 29 000 MW of new energy demand between now and 2030. Unfortunately, a further 10 900 MW of old energy capacity will be retired, resulting in about 40 000 MW of new energy capacity being required by 2030. "*To this effect optimisation and diversification of South Africa's energy generation mix is fundamental to meeting its developmental goals and enhancing the crucially important security of supply*" (Ndlovu & Inglesi-Lotz, 2019). South Africa should investigate the means to diversify its generating capacity (Ndlovu & Inglesi-Lotz, 2019). In developing the energy-generation mix, nuclear power offers a formidable complementary energy solution, especially based on the following brief history and developments. South Africa was one of the first countries in the world to become involved in the nuclear industry due to the abundance of uranium necessary for the development of nuclear weapons for the USA during World War II. The peaceful nuclear industry in South Africa, and by inference RDI in nuclear technologies, started more deliberately in 1959 with a decision by the South African government to establish a domestic nuclear industry. A number of events promoted nuclear energy RDI in South Africa:

- The establishment of a nuclear research centre at the Pelindaba site near Pretoria in 1961
- South Africa's membership in the US Atoms for Peace programme (through which South Africa received the technology to build the SAFARI-I research reactor at Pelindaba)

- The establishment of the Uranium Enrichment Corporation in 1970, and the commencement of an extensive nuclear fuel cycle programme
- The decision to purchase two 900 MWe nuclear power plants from Framatome of France in 1976, which were constructed at Koeberg and commissioned during 1984–1985
- Extending the use of highly enriched uranium beyond peaceful uses toward weapons development in the 1970s

- South Africa, as signatory to the international Treaty on the Non-Proliferation of Nuclear Weapons, having dismantled its nuclear weapons programme and redirected the use of enriched uranium to fuel the SAFARI-I research reactor (which is still one of the largest producers of molybdenum-99 for the international medical market)
- The decision to develop the Pebble Bed Modular Reactor (PBMR) in 1999. This was a highly innovative R&D effort, which positioned South Africa as a prominent international participant in this technology (McKune 2012).

Unfortunately, the financial burden of the PBMR project was heavy, leading to the PBMR company being put under care and maintenance in 2010. In practice, this meant that more than 99% of the roughly 900 engineers and scientists that worked at the PBMR were laid off. The few employees that were retained were tasked with archiving and conserving the PBMR's intellectual property.

Since the South African nuclear market was then in a contraction phase after both the Nuclear 1(a turn-key project to increase energy capacity) and the PBMR construction programmes had been cancelled and President Zuma's construction programme for 9.6 GW of new pressurised water reactors never got off the ground, few of these laid-off PBMR employees could find gainful employment in the South African nuclear industry. From personal contacts within the South African nuclear fraternity, it is common knowledge that many of them had to switch careers and thus no longer work in the nuclear industry.

It should, however, be noted that a small number of core experts from the PBMR project moved abroad to join nuclear research projects in other countries. Notably, a small number of former PBMR experts moved to the X-Energy company in the USA, where it appears that they are now, in some cases, engaged in designing and building improved versions of some PBMR technologies. If these new pebble bed technologies could be shown to be significantly different from the PBMR technologies, it would be possible to patent them internationally. This would create a problem for the South African government in that, if a future buyer were to become interested in the pebble bed technology, they might choose to buy the improved technologies from X-Energy or from another similar overseas company, thus bypassing the South African government's PBMR intellectual property.

There was a subsequent effort to revive the PBMR project again in the form of a smaller pebble bed reactor, namely the Advanced High Temperature Reactor (AHTR). Eskom drove this design project in collaboration with nuclear engineering academics from several South African universities, but after a short period Eskom terminated the funding. In South Africa, the future of energy generation, and subsequently the future of nuclear energy, is set out in the Integrated Resource Plan. The most recent version of the IRP (RSA, 2019) states the decision to prepare for new nuclear build in respect of 2 500 MW, at a "scale and pace" South Africa can afford. These new reactors are likely to take the form of small nuclear units (i.e. small modular reactors), which are considered more manageable in terms of financial investment. The DMRE is driving the process of preparation, with a request for information having been issued, and a commitment for a request for proposals to follow shortly.

Furthermore, the DMRE called for the completion of the 20-year operating lifetime extension at the Koeberg NPP to ensure continued energy supply security beyond 2024.

In parallel with the government's efforts on nuclear energy build, there are several private South African companies actively working to design and build smaller modular reactors, including:

- Mozweli, which is currently developing the Pebble Small Modular Reactor (PSMR) in South Africa
- Ultra-Safe Nuclear Corporation, a Canadian company, which is developing a small ultra-safe high-temperature, graphite-moderated, gas-cooled, prismatic block-fuelled nuclear reactor. Part of the design work is being done in South Africa.

Nuclear energy has a role to play in the development of South Africa based on a comprehensive scientific analysis (Ognan Williams).

8.2 Infrastructure and production

Given the developments in the South African nuclear energy industry discussed in the previous section, the South African government is no longer focusing on developing its own unique nuclear technologies, but rather on high-quality academic research that contributes to the international pool of nuclear knowledge.

In terms of education and training, South Africa will need well-trained nuclear engineers, nuclear scientists and nuclear technologists to operate the country's nuclear facilities and to train professionals. Therefore, nuclear education should continue at South African universities and other training institutions, and could be prioritised in order to supply the South African nuclear industry with a steady stream of well-educated professionals. Some of these professionals will be trained at postgraduate level, involving research at master's and doctoral levels. Research at master's and doctoral levels will therefore remain essential for education and training purposes.

The main entities where these nuclear research and education activities take place are:

- iThemba LABS, which has broad RDI fields that cover fundamental and applied nuclear physics, nuclear astrophysics as well as radiation bio-physics, material research at the nano-scale, environmental physics, and research into and production of radioisotopes for the medical sector.
- Necsa, which focuses on RDI in radiation science and technology, as well as commercial isotope production.
- North-West University (NWU), which has a nuclear engineering research group in the Unit for Energy and Technology Systems (UETS) focusing on educating postgraduate students in nuclear engineering and on making nuclear reactors safer and more cost-effective. This is done through applied research in the following areas:
  - Thermal fluid systems modelling
  - Reactor neutronics modelling
  - Energy policy and economics
  - Nuclear waste management
  - Uncertainty and sensitivity analysis applied to nuclear systems.
- Centre for Applied Radiation Science and Technology (CARST) at NWU, which focuses on applied research on radiation protection and other radiation application technologies.
- Nuclear Engineering research group at the University of the Witwatersrand (Wits), which focuses on research in nuclear medicine, radiotherapy and diagnostic X-rays.
- Centre for Nuclear Safety and Security at the University of Pretoria (UP), which focuses on research in nuclear safety and security, with financial backing and other support from the NNR. Its postgraduate research focuses on:

  - Light Water Reactor Heat transfer on new fuel cladding materials, with the current focus on silicon carbide
  - Asset integrity management
  - Welding of Zircaloy® core components
  - Modelling of material defects and surface interactions
  - Nuclear waste encapsulation
  - Passivation of Zircaloy® surface against steam–metal oxidation reactions
  - Fluoro-materials science and process development
- Department of Biophysics at UP, which also focuses on research in nuclear medicine, radiotherapy and diagnostic X-rays
- High-resolution transmission electron microscopy (HRTEM) group at Nelson Mandela University (NMU, which) focuses on research in:
  - Pebble bed reactor materials
  - Accident-tolerant coatings on ZIRLO™ fuel tubes for water-cooled reactors
  - Radiation effects of swift heavy ion
  - High-alloyed power plant steels
  - Radionuclide adsorbents (with Necsa)
- University of Johannesburg (UJ), which focuses on the simulation of reactors, radiation physics, environmental impacts and the use of nuclear technology
- Nuclear Medicine, Radiation and Health Physics Division at Stellenbosch University (SU), which focuses on research on theoretical computational modelling in nuclear science and its applications
- Department of Biophysics at the University of the Free State (UFS), which focuses on research in nuclear medicine, radiotherapy and diagnostic X-rays
- Departments of Nuclear Medicine, Radiology and Radiation Oncology at UP, which focus on research in nuclear medicine, radiotherapy and diagnostic X-rays
- Departments of Nuclear Medicine, Radiology and Radiation Oncology at the University of Cape Town, which focus on research in nuclear medicine, radiotherapy and diagnostic X-rays
- Departments of Nuclear Medicine, Radiology and Radiation Oncology at the University of KwaZulu-Natal, which focus on research in nuclear medicine, radiotherapy and diagnostic X-rays
- University of the Western Cape (UWC), which focuses on research in nuclear safety.

8.3 Human capacity

All the research groups mentioned in the previous section offer master’s and doctoral programmes in nuclear engineering.

At NWU, there are two options at master’s level, namely the Master of Science in Engineering Sciences with Nuclear Engineering which focuses on nuclear reactor design, and the Master of Science in Engineering Sciences with Nuclear Engineering and Nuclear Technology Management which focuses on the technology management aspects of nuclear engineering. The theoretical modules that precede these research master’s degrees are correspondingly presented in the Postgraduate Diploma (PGDip) in Nuclear Science and Technology which focuses on the theory of nuclear reactor design, and the PGDip in Nuclear Science and Technology with Nuclear Technology Management which focuses on the theory of nuclear reactor technology management, including nuclear project management and nuclear economics. Furthermore, CARST offers a master’s and doctoral degree in radiation protection.

iThemba LABS is a world-class accelerator-based research and training facility with four cyclotrons and two linear accelerators. It is a user facility, with open access to an average of 200 national and international users per year, and trains up to 80 postgraduate students per year, with an average of 200 publications per annum.

Tshwane University of Technology (TUT) offers programmes in industrial physics from undergraduate to postgraduate levels, with a strong component of nuclear technology and radiation protection. The training programmes at undergraduate level aim to produce students with practical skills and knowledge to function as nuclear technicians in a range of nuclear technology occupations including non-destructive testing, radiation metrology, environmental radiation assessment and radiation protection. TUT has formal cooperation agreements for practical training with institutions including NMISA, Necsa and iThemba LABS. The postgraduate qualifications on offer include the PGDip in Industrial Physics (NQF 8) and master's and doctoral degrees in industrial physics.

The Centre for Nuclear Safety and Security at UP presents the following education:

- Undergraduate engineering modules in nuclear science, nuclear physics and nuclear engineering
- Honours modules in nuclear science, nuclear physics and nuclear engineering.

All the medical physics departments based at universities offer a master's and doctoral qualification in medical physics. At the UFS, this is preceded by a BSc in Medical Physics. Most of these institutions, as well as some of the technical universities, also offer undergraduate and/or postgraduate training for radiographers.

8.4 SWOT analysis

8.4.1 Strengths

- South Africa's high-level and internationally respected technical RDI in nuclear energy technologies, as demonstrated by the excellent publication records of South African scientists in this field.
- The wealth of expertise and knowledge, especially at senior levels in higher education institutes. Similarly, given previous RDI programmes such as the PBMR programme, experience also exists in conceptualising and developing RDI infrastructure in the country.
- South Africa as the only country on the African continent with an operating nuclear power plant. This is a strategic strength which should be leveraged at regional level and might continue to position South Africa as a destination for RDI in nuclear energy technologies.
- South Africa, through iThemba LABS, having the largest particle accelerator complex in the southern hemisphere and the only one on the African continent, with internationally competitive scientific output in basic and applied nuclear physics research.
- The existence of uranium resources and the requisite skill to handle them, which are advantages for nuclear energy in South Africa.

8.4.2 Weaknesses

- Insufficient public education on the benefits and risks of RDI in nuclear energy technologies.
- Financial limitations with respect to large capital investment in South Africa, and uncertainty regarding the cost of building nuclear power plants, a debate which is fraught with contentious issues.
- Uncertainty around RDI in nuclear energy technologies, which is a disincentive to attracting the highly qualified personnel needed in research reactors and training programmes at higher education institutes and other training facilities.
- Reduction of local RDI, resulting in an inadequate stream of well-trained professionals available to the nuclear energy industry. This is concerning, since Koeberg NPP is undergoing an extension of its operating lifetime, and a new nuclear reactor is required to replace SAFARI-1.

8.4.3 Opportunities

- As a product of South Africa's history in RDI nuclear energy technologies, the existence of RDI (and nuclear) infrastructure that can and should be utilised to promote further RDI.
- With the rapid international RDI developments in emerging nuclear energy technologies (e.g. SMRs), opportunities for South Africa to leapfrog international developments, leveraging existing infrastructure to boost local RDI in nuclear energy technologies.
- United Nations, IAEA and European Union support for nuclear energy by including this form of energy generation among the 'green' power sources, provided that there is a suitable and sustainable waste solution.
- South Africa's natural resource endowment to support nuclear technology applications, especially given the growing demand for electricity.

8.4.4 Threats

- Negative perceptions of nuclear energy technologies applications in the country, which limit public participation to embrace the technology.
- Stagnation of the nuclear energy industry in South Africa since the commissioning of the Koeberg NPP in 1985, with resultant loss of skills for the future of RDI in nuclear energy technologies in South Africa. This could lead to a reduction of local research on certain crucial fields of nuclear energy applications.
- Rapid progress in the development of alternative forms of electricity generation technologies (e.g. solar and wind), which could threaten the worldwide future of nuclear energy.
- Cost of building a new nuclear power plant, which has increased drastically, especially since the Fukushima accident in Japan in 2011.
- Stagnation of the nuclear energy industry, which has reduced the job opportunities available to graduates and emerging professionals. Many researchers who have spent years studying in nuclear engineering can thus not enter the workforce. The result is a reduced intake of students pursuing nuclear engineering studies, causing many nuclear engineering departments at South African universities to face partial collapse. Consequently, many nuclear engineering lecturers and trainers have resigned or changed career path, adding to the threats to the South African nuclear energy industry and RDI.

8.5 Needs and gaps

The needs and gaps identified in this section relate to RDI in nuclear energy technologies.

Development of comprehensive models to analyse energy supply and demand to complement the IRP 2010–2030

Several studies have been done to forecast growth in energy demand, with varying results. These variations could potentially give rise to doubt with regard to planning and implementation. Currently, the electricity supply mix is dominated by power generation from fossil fuels such as coal, oil and gas, which are the major contributors to pollution. The electricity sector needs to shift from primary reliance on fossil fuels to alternative energy solutions (Foster, Royer, & Lunt, 2017). As outlined in IRP2019, the electricity demand projections indicate the need for nuclear power. Given the uncertainty that still prevails, more detailed studies are required using comprehensive models to analyse energy supply and demand; strengthen analytical capacity to justify the inclusion of nuclear energy based on databases, indicators, various scenarios and sustainable development for energy; and provide clarity on the future of nuclear energy, and whether South Africa can afford to build new nuclear power capacity.

Objective: To strengthen analytical capacity for developing energy supply and demand models/scenarios for the medium and long term.

Indicator/s:

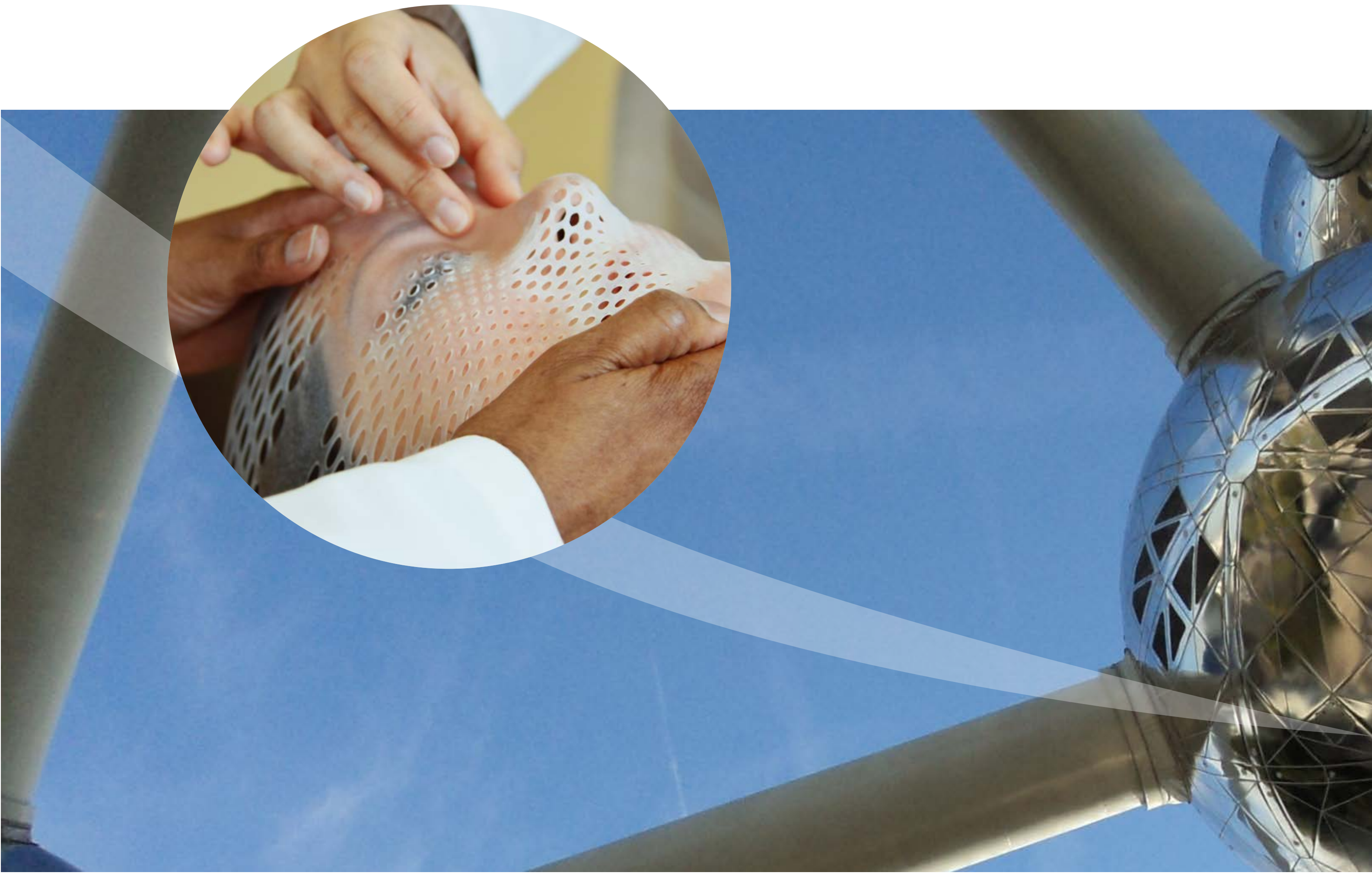
i. Number of comprehensive models for analysing energy supply and demand.
ii. Number of projects participating in IAEA Technical Cooperation Projects on energy.
iii. Inclusion of uranium exploration or extraction in strategic planning.

Improved communication and education on nuclear energy

For various reasons, there are negative perceptions of the nuclear energy industry in South Africa. The reasons include safety, technical factors, radioactive waste, and political and economic miscommunication. Therefore, there is a need to implement an honest and transparent information programme to increase the understanding and education of the public with regard to the benefits and risks of nuclear energy. The roles of traditional communication channels are well known. In the current digital age, social media 'organisations' such as Africa Young Generation in Nuclear, with offshoots such as Africa4Nuclear, are reaching spaces frequented by those who are technologically minded. Measuring the impact of such groups could yield valuable data.

Objective: To develop better information and education approaches with respect to requirements for the development of a nuclear energy programme.

Indication/s: Number of communication and training activities developed with appropriate usage and impact measurement.



9. INDUSTRY

9.1 Background

The use of nuclear and radiation technology in industry enhances life in a range of areas, including the processing of advanced materials, environmental management, coastal engineering, medicine, water management, industrial processes and production, natural resources and inspection technologies (Table 8).

The principles and applications of radiation technology include:

- Radiation processing technology. The use of high-energy radiation from gamma sources (mainly ^{60}Co), electron beams or X-rays to induce biological, chemical and physical changes in materials
- Short-lived radiotracers (such as ^{22}Na, ^{99m}Tc, ^{131}I, ^{82}Br and ^{140}La) used for diagnosis in industrial processes, including troubleshooting, underground leaks, residence time and residence time distribution, flux patterns and flow rates
- Nucleonic control systems, including various systems for quality control of industrial processes and products to obtain significant gains in industry; for example, in controlling the thickness of laminated steel or the filling of bottles in the food industry, and in mineral content (Am-Be, Cf-252)
- Analytical techniques: nuclear analytical techniques can be used for laboratory analysis. They can also be configured for online analysis for process control. The most important analytical techniques are neutron activation analysis, X-ray fluorescence, prompt gamma neutron activation analysis and particle-induced X-ray emission.
- Non-destructive testing. This category includes nuclear and non-nuclear techniques to determine the status of industrial components. The most widely used nuclear technique is radiography (e.g. for detecting welding defects in pipework and tanks using gamma rays and X-rays). Computed tomography and neutrography are also important (IAEA, 2013; 2015).

Table 8: Industrial areas and principles of nuclear technology applications

Application areas	Principles and applications of radiation technology				
	Radiation processing	Short-lived radiotracers (T)	Nucleonic control systems (NCS)	Analytical techniques (L)	Non-destructive testing (NDT)
Cultural heritage	• Preservation of historic objects • Disinfection of archives, • documents, paintings	Preservation of objects		Authenti-cation and charac-terisation of objects	Preservation of objects
Processing of advanced materials	Polymer modification and treatment	Measurement of wear using thin layer proton activation			
Environment	Treatment of gaseous effluents	• Discharge from industries • Sediment transport			
Coastal engineering		Protecting coasts from erosion	Protect-ing coasts from ero-sion		
Medicine	• Sterilisation of medical prod-ucts • Sanitisation of recipients • Irradiation of blood • Irradiation of biological tis-sues • Production of radioisotopes				
Water	• Treatment of water for reuse or discharge • Treatment of sludge	• Optimisa-tion of water treatment processes • Measure-ment of pre-cipitation			

Application areas	Principles and applications of radiation technology				
	Radiation processing	**Short-lived radiotracers (T)**	**Nucleonic control systems (NCS)**	**Analytical techniques (L)**	**Non-destructive testing (NDT)**
Industrial processes and production		Optimisation of processes	Quality control		
Natural resources	*Food* • Food-preservation • Packaging with natural polymers	Optimisation of processes	Quality control		
	Agriculture • Sterilisation of soils • Plant growth promoters • Super water absorbers • Biocides • Sanitisation of animal feed • Sanitisation of agricultural products (flowers, wood, tobacco, seeds)	• Soil erosion studies • Studies of fertiliser and pollutant transfer			
	Mining		• Exploration • Procession		
Inspection technologies					• Metals, welding, pipework, energy plants, oil and gas, aerospace industry • Concrete, roads, bridges, buildings • Power plants

9.2 Infrastructure and production

Given that there are several industrial areas in both the private and public sectors, the Southern African Institute of Welding (SAIW) is highlighted as an example and priority in this report.

SAIW was established in 1948, and initiated formal non-destructive testing (NDT) training in 1980. The SAIW was designated as the IAEA Anglophone Regional Designated Centre (RDC) for NDT in 2001. Since inception, the SAIW has trained over of 15 000 people in the six basic NDT methods and up to the relevant qualification levels (i.e. levels 1, 2 or 3).

Apart from its direct involvement with the IAEA, the SAIW continued to develop its service delivery in the region, resulting in the formation of a separate legal entity named SAIW Certification in 2005. The goal of SAIW Certification is to facilitate the qualification and certification of personnel in accordance with the ISO/IEC 17024 standard (describing the requirements for a personnel certification body) and, under the scope of ISO 9712, the global standard for NDT personnel qualification and certification.

SAIW Certification was accredited by the South African National Accreditation System (SANAS) as an ISO/IEC 17024 personnel certification body in July 2005 under the scope of ISO 9712, and has sustained this accreditation ever since. International recognition through the International Committee for NDT (ICNDT), under the World Organisation for NDT, was obtained in February 2016 when SAIW Certification was registered under the ICNDT Mutual Recognition Agreement schedule 2, becoming the first African personnel certification body established by Africans, managed and maintained by Africans for an African market.

SAIW Certification was further instrumental in certifying more than 11 000 individuals in various NDT methods and at various qualification levels, totalling more than 22 000 different NDT certificates.

Furthermore, the SAIW was one of the founding members of the African Federation of NDT in 1999, which is one of four regional federations of the ICNDT. The SAIW has been the secretariat of the African Federation for Non-Destructive Testing (AFNDT) since its inception.

Both the SAIW and SAIW Certification are self-sustaining non-profit companies and continue to serve South African industry and support NDT development on the African continent.

Collaboration between the SAIW and the IAEA was initiated in 2000 as part of a regional project to raise awareness related to NDT and to facilitate NDT infrastructure development in Africa.

9.3 Human capacity

9.3.1 Non-destructive testing

Non-destructive testing provides essential engineering measurables in relation to manufacturing, construction, operation, maintenance, replacement and decommissioning in various industries such as, but not limited to:

- Power generation (nuclear, conventional and renewables)
- Petrochemicals
- Mining
- Transport (aviation, rail, marine/shipping, vehicles, trucks and pipelines)
- Water and sanitation
- Paper and pulp

- Fabrication and construction (foundries; machining, welding and civil engineering structures).

To this end, NDT is an invaluable tool utilised across all industries and engineering faculties. NDT is a critical tool used to ensure quality control and assessment of operations and to maintain employee and public safety as required by the Occupational Health and Safety Act (No. 85 of 1993). Industrial radiography and related radiation protection are directly associated with the peaceful application of nuclear technology, and the supporting role that NDT provides within the engineering process makes it invaluable across all industries.

9.3.2 Radiation protection

Industrial radiography requires the training (through NDT training schools), qualification (through the South African Institute for NDT [SAINT]), certification (through SAIW Certification) and licensing (through the South African Health Products Regulatory Authority [SAHPRA]) of industrial radiographers and radiation protection officers to ensure that radiographic testing is performed according to regulatory requirements.

9.3.3 Energy and industry

NDT provides essential information utilised within engineering processes, from the design phase, through to manufacture, construction, operation, maintenance, replacement and decommissioning. Furthermore, NDT is related not only to the energy sector but to industry in its entirety, since it provides a means for establishing a baseline, developing in-service inspection programmes to ensure optimum operation, planning maintenance interventions, and making predication on remnant life.

NDT training, qualification and certification provide a means whereby a sustainable salary could be earned within a reasonably short period and at very low initial cost. The principle of 'earn as you learn' facilitates career growth and continuous professional development, giving an individual the opportunity to become economically self-sustainable and providing a living wage to members of poor communities. The income generated is directly proportional to the skills and competencies acquired through the training, qualification and certification process, and an individual would be able to control and increase this income through continuous professional development.

The economic potential of NDT infrastructure development and personnel qualification and certification within industry in general is far from being realised within the African continent, since most NDT personnel and expertise are imported from European and other countries. The potential of the available workforce therefore needs to be unlocked through infrastructure development and upskilling of local citizens.

9.3.4 Nuclear safety, security and safeguards

Continuous monitoring and maintenance of nuclear-related establishments and facilities is done through NDT methods and processes. The localisation of NDT skilled personnel is therefore essential to maintaining nuclear safety.

To this end, the SAIW and Necsa are planning to initiate a national project to establish a nuclear school of excellence that will focus not only on nuclear-related NDT, but also on expanding nuclear welding and welding inspection capabilities in South Africa.

9.4 SWOT analysis

The strengths, weaknesses, opportunities and threats related to several industrial areas are covered in various sections of the report. This section therefore only briefly lists some that are pertinent to nuclear industrial applications.

9.4.1 Strengths

- Efficient and effective technologies that are validated.

9.4.2 Weaknesses

- Limited information about the technologies.
- Limited usage of radiotracers in some sectors of industry.

9.4.3 Opportunities

- Very high potential for industrial development using nuclear technology.
- Nuclear technology applications, which assist the country to respect the environment and combat climate change.

9.4.4 Threats

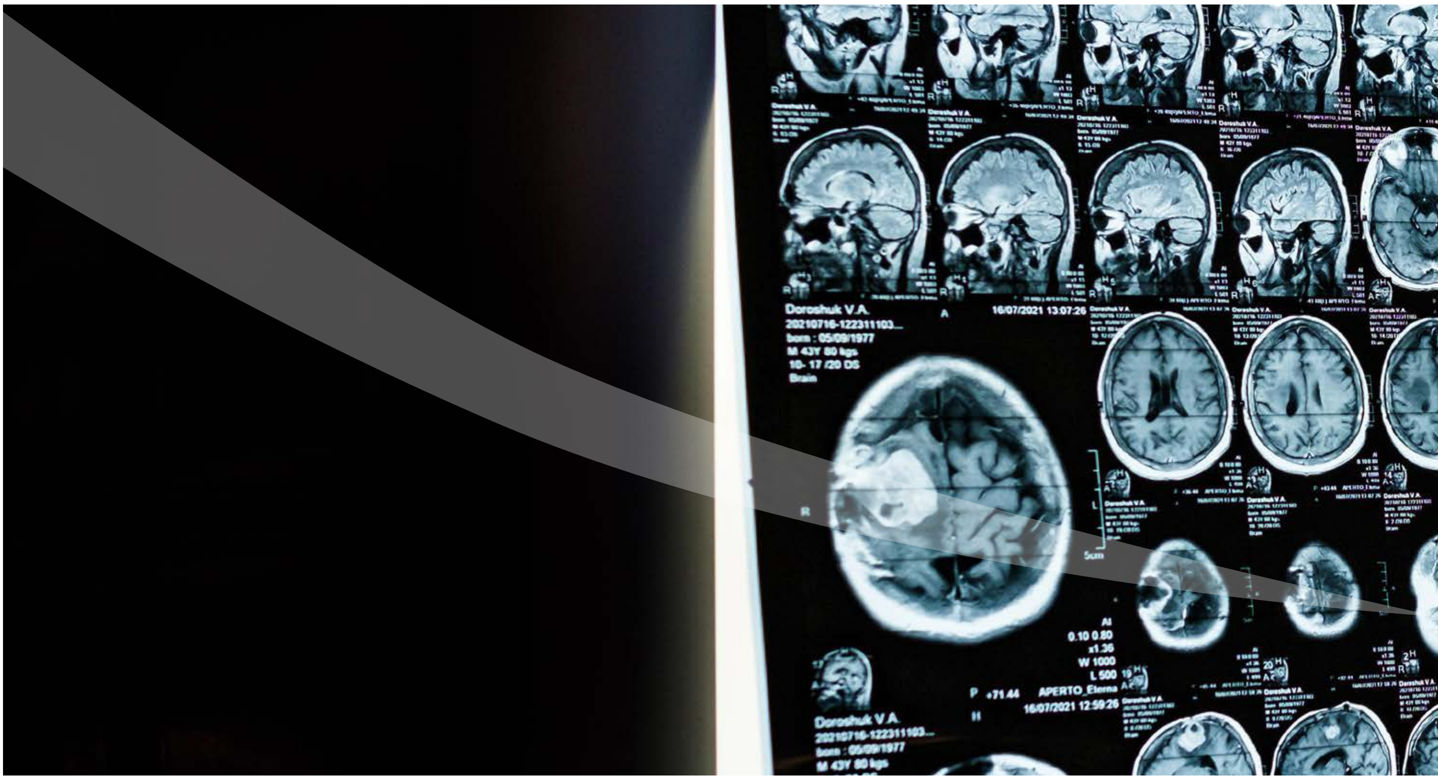
- Lack of public understanding of radiation, and hence lack of acceptance of nuclear technologies.
- Competition from alternative technologies.

9.5 Needs and gaps

The needs and gaps identified in this section are related to RDI in the nuclear industry.

Need to increase the competitiveness of nuclear technology in industry and contribute to combating climate change

Several industries, such as mining as well as the processing, production and food and agriculture industries, face a number of problems, including relatively low competitiveness, the impact of their activities on climate change, and inefficient energy consumption.



Objective: To improve the competitiveness and quality of the products of industries through the use of radiation technologies

Indicator/s: Number of industries that use radiation technologies in industrial processes, leading to successful commercialisation

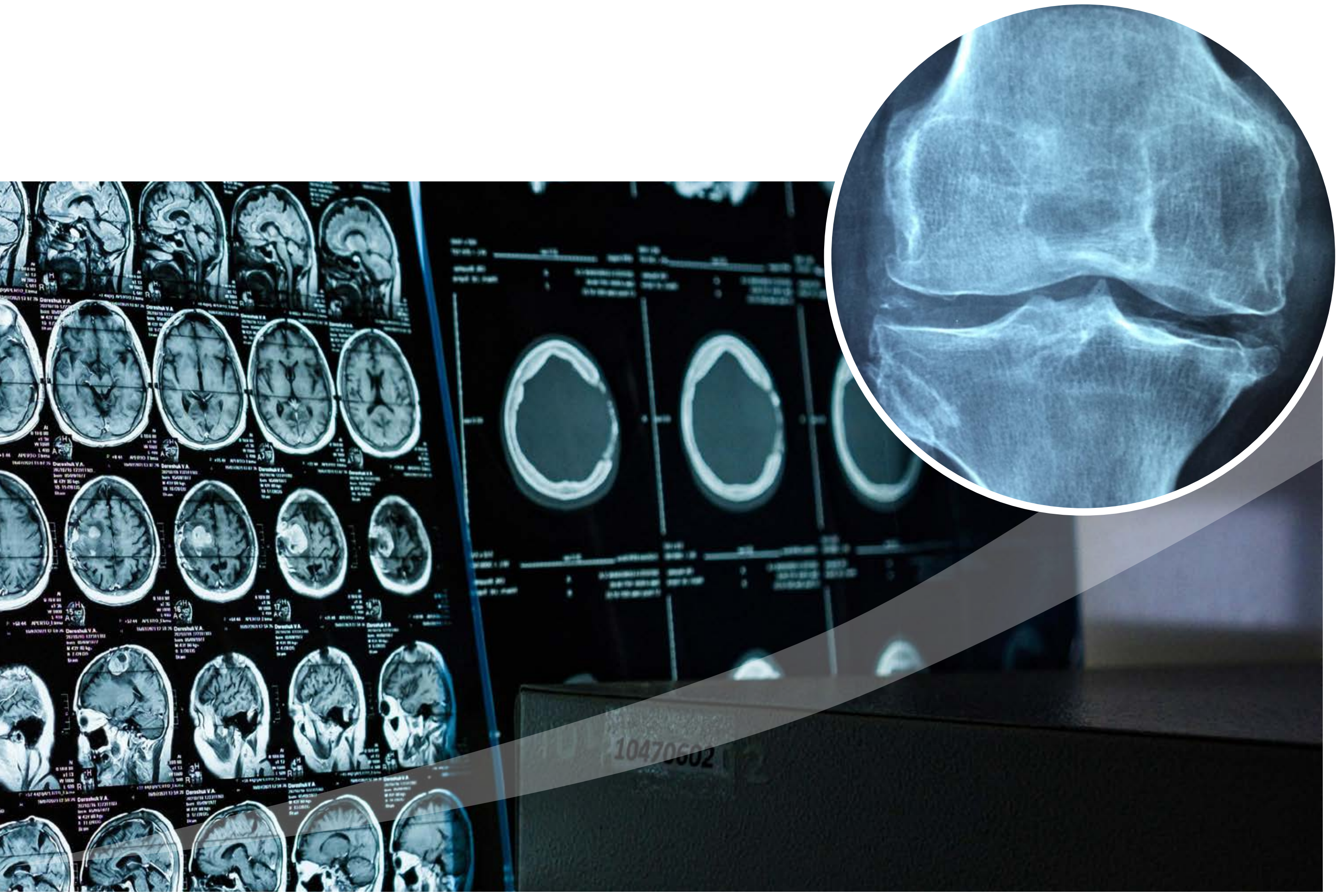
Need to sustain and optimise training and R&D in NDT and related areas in industry

The SAIW's three-year QCTO-affiliated apprenticeship scheme offers theoretical and workplace learning and key benefits to company sponsors, including Sector Education and Training Authority (SETA) grants towards training costs, tax breaks from the South African Revenue Service (SARS), and Broad-Based Black Economic Empowerment (B-BBEE) skills development. To this effect and by way of an example, Kenyans that trained in South Africa at NDT levels II and III have either started local firms in Kenya (doing NDT work and/or offering training at levels I and II) or have left Kenya to work in other countries, including South Africa. Kenya has found it more cost-effective to send Kenyans to train in South Africa, rather than in the USA as in the past, since most of those previously trained in the USA did not return, or relocated elsewhere upon completion of their studies. This places the SAIW in a strategic position not only to train South Africans, but also candidates from other African countries.

Objectives: To sustain and optimise training and R&D in NDT and related areas in industry.

Indicator/s:

1. Number of local citizens who have obtained skills and upskilling (at levels I, II and II)
2. Number of IAEA TCP and AFRA projects in NDT and related areas in industry.



10 NUCLEAR SAFETY, SECURITY AND SAFE GUARDS

10.1 Background

South Africa, through the NNR and in collaboration with the IAEA, upholds nuclear law and its four pillars, namely: safety, security, safeguards and civil liability for nuclear damage. Traditionally, South Africa has taken an active role in the shaping of international nuclear policy and was involved in establishment discussions for the IAEA from 1954 as part of the Eight-Nation Negotiating Group. In 1957, South Africa became one of the founder members of the IAEA, and was one of the world's key producers of uranium.

Originally, South Africa had a seat on the IAEA board of directors, but lost this in 1976 due to international opposition to apartheid policies in the country. South Africa eventually took up a seat again in 1995. When approached in 1970 to sign the Treaty on the Non-Proliferation of Nuclear Weapons, South Africa initially refused for several reasons, and finally acceded in 1991 after the dismantlement of the six weapons that had been built in the country during the 1980/90s (Van Wyk, 2014). For more detailed information on the complex history of South Africa and the International Atomic Energy Agency, refer to Albright and Stricker (2016). Since regaining its seat in 1995, South Africa has strongly promoted nuclear safety, security and safeguards. To this end, SAFARI-1 has been under IAEA safeguards, and Koeberg has been under IAEA safeguards from the outset in 1983/84. A trilateral agreement was signed between South Africa, France and the IAEA in this regard.

Nuclear safety involves operating conditions, prevention of accidents and mitigation of consequences, resulting in the protection of workers, the public and the environment from undue radiological hazards. Nuclear security involves the prevention and detection of, and response to, sabotage, unauthorised access or other malicious acts involving nuclear material, other radioactive substances or their associated facilities. Nuclear safeguards are related to prevention and detection, through the use of material control and accountancy, of theft or diversion of special nuclear material from civilian facilities.

A Safeguards Agreement with the IAEA (INFCIRC/394) came into force in October 1991, and the Additional Protocol was acceded to 11 years later[44]. However, the Convention on the Physical Protection of Nuclear Material (CPPNM) was only signed in October 2007, and the Amendment to the CPPNM was adopted in May 2016. The South African government has yet to take any action on this agreement. The original CPPNM is out of date and deficient in several areas of nuclear security, particularly as it does not address the protection of nuclear facilities. On 14 September 2021, the South African Cabinet agreed to submit the amended CPPNM to Parliament for approval, although it is uncertain when this will be tabled for discussion in both houses[45].

South Africa ratified the African Weapons-Free Zone Treaty (the Pelindaba Treaty) on 15 July 2009, committing the country to maintain the highest standards of physical protection of nuclear material, facilities and equipment, which are to be used exclusively for peaceful purposes[46]. However, the Amendment to the CPPNM has not been signed, nor have any of the actions demanded by the Amendment been addressed by the relevant government departments.

New technologies represent another important cross-cutting area of nuclear law, in

44 https://www.iaea.org/sites/default/files/publications/documents/infcircs/1959/infcirc1r14.pdf
45 https://www.agbiz.co.za/document/open/final-cabinet-statement-20-sep-2021
46 https://www.afcone.org/wp-content/uploads/2021/04/MEETING-REPORT-25th-Anniversary-of-the-PT-OfS-12-April-2021-.pdf

particular with the introduction of advanced reactors, including small modular reactors (SMRs) and transportable nuclear power plants (TNPPs).

Although the IAEA safety standards can generally be applied to SMRs, global experts from the SMR Regulators' Forum are working on a tailor-made solution to help national authorities regulate this new class of reactor. To facilitate the deployment of SMRs, there are also calls in some forums for the global harmonisation of safety requirements, recommendations and guidance.

Recognising the increasing global interest in SMRs, the IAEA recently established an agency-wide SMR platform to provide integrated support to Member States on all aspects of their development, deployment and oversight.

The IAEA actively works towards making the existing legal and normative framework as robust as possible. There are opportunities to perform outreach to regional organisations such as the African Commission on Nuclear Energy (AFCONE) (Grossi, 2022).

Studies conducted at South African universities contribute towards making generation II and even generation III reactors safer, including through the development of accident-tolerant fuel. Importantly, nuclear power is undoubtedly the safest of the various energy supply technologies considered, even taking into account the confirmed fatalities as well as suggested latent fatalities that may eventually result from the accidents at Chernobyl and Fukushima Daichii (Table 9).

Table 9: Fatalities per power-producing technology

Power technology	Fatalities per year per terawatt-hour (TWh) produced
Coal (world average)	161
Coal (China)	278
Coal (USA)	15
Oil	36
Gas	4
Wind	0.15
Hydro (world)	0.10
Hydro (world)*	1.40
Nuclear*	0.09

** The figure includes the 170 000 deaths from the failure of the Banqiao Reservoir Dam in China in 1975.*

10.2 Infrastructure

South Africa's main nuclear organisations (the NNR, Necsa, iThemba LABS, Eskom, Koeberg and NRWDI) have adopted the global nuclear safety regime illustrated in Figure 9.

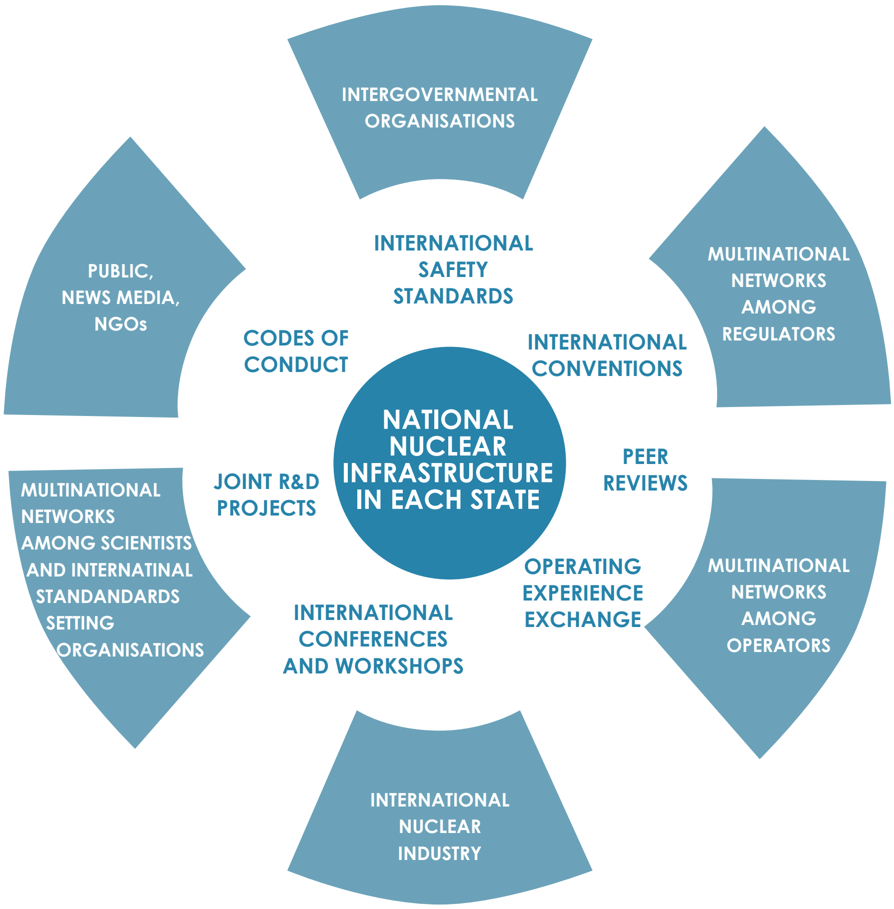


Figure 9: Components of the global nuclear safety regime (Meserve, 2022)

10.3 Human capacity

The NNR, in partnership with UP, officially launched the first Centre of Excellence for Nuclear Safety and Security (CNSS) in South Africa in 2016.

Until then, South Africa did not have a centre or an institution dedicated to nuclear safety. Such a centre will provide a continuous supply of personnel trained in nuclear safety to serve the needs of the nuclear regulatory body and the nuclear industry in general. Other needs identified include the provision of continuous professional development programmes in nuclear safety, researching nuclear safety to support regulatory activities and decision-making, and providing technical support services in nuclear safety to the regulatory body and the nuclear industry.

The CNSS is the first applied research and training establishment dedicated to developing essential skills required by South Africa's nuclear sector outside the traditional university sector. It will house training facilities for NNR staff, as well as a selection of state-of-the-art irradiation and analysis equipment for use by researchers and students, including analysis and inspection laboratories and computer-modelling facilities. Importantly, non-state actors such as the African Young Generation in Nuclear, Africa4Nuclear and, in particular, the South African Young Nuclear Professionals Society, need to be included.

10.4 SWOT analysis

10.4.1 Strengths

- South Africa's high level of competence and experience in nuclear energy, having commissioned, licensed, operated and maintained a research reactor at Pelindaba and power reactors at the Koeberg NPP.

- South Africa being the only country in the world to have developed and subsequently completely dismantled all its atomic weapons. The correctness and completeness of this claim were acknowledged by the IAEA board of governors and the IAEA general conference.
- South Africa having a broad range of nuclear and radiological technologies in use in the country and taking a leading role internationally in the use of these technologies.
- South Africa having several globally ranked universities that offer world-class education in the nuclear and radiological sciences required for nuclear and radiological programmes.

10.4.2 Weaknesses

Continuing global and local political and economic challenges with regard to the issues of nuclear safety, nuclear security and safeguards.

- Uncoordinated structuring of the various regulatory bodies in South Africa.
- Lack of adequately qualified staff in key positions within the various regulatory bodies.
- Lack of succession planning in some nuclear and radiological arenas.

10.4.3 Opportunities

- South Africa being the continental lead in the provision of nuclear and radiological expertise, training and education in many arenas of nuclear and radiological technology.
- Opportunities for collaboration, which may result in lowered competition, from the current number of universities and other organisations offering training, while at the same time recognising that the potential number of students will continue to be small, and that mechanisms need to be developed to attract and recruit students to nuclear science.

10.4.4 Threats

- Continued emigration of qualified staff.
- Low staff morale in the various nuclear organisations.
- Inefficient management at some of the nuclear facilities.
- Uncertain and tenuous position of the South African government with regard to nuclear power. Various members of the South African Cabinet have taken different stances on whether nuclear power will form part of the country's future electricity mix. This uncertainty is detrimental to the interests of the nuclear industry.
- Potential loss of the investment to date, as South Africa will probably cease to be the continental leader in the research, development and use of nuclear and radiological technologies and techniques. Many other countries on the African continent are pursuing their own nuclear and radiological technology programmes.
- Universities and other educational organisations ceasing to support nuclear and radiological programmes of various types if deemed to be too costly in relation to the benefits derived, and in the context of limited justification and support,

10.5. Needs and gaps

The needs and gaps identified in this section relate to RDI in safety, security and safeguards.

Increasing nuclear RDI to promote high standards in safety, security and safeguards

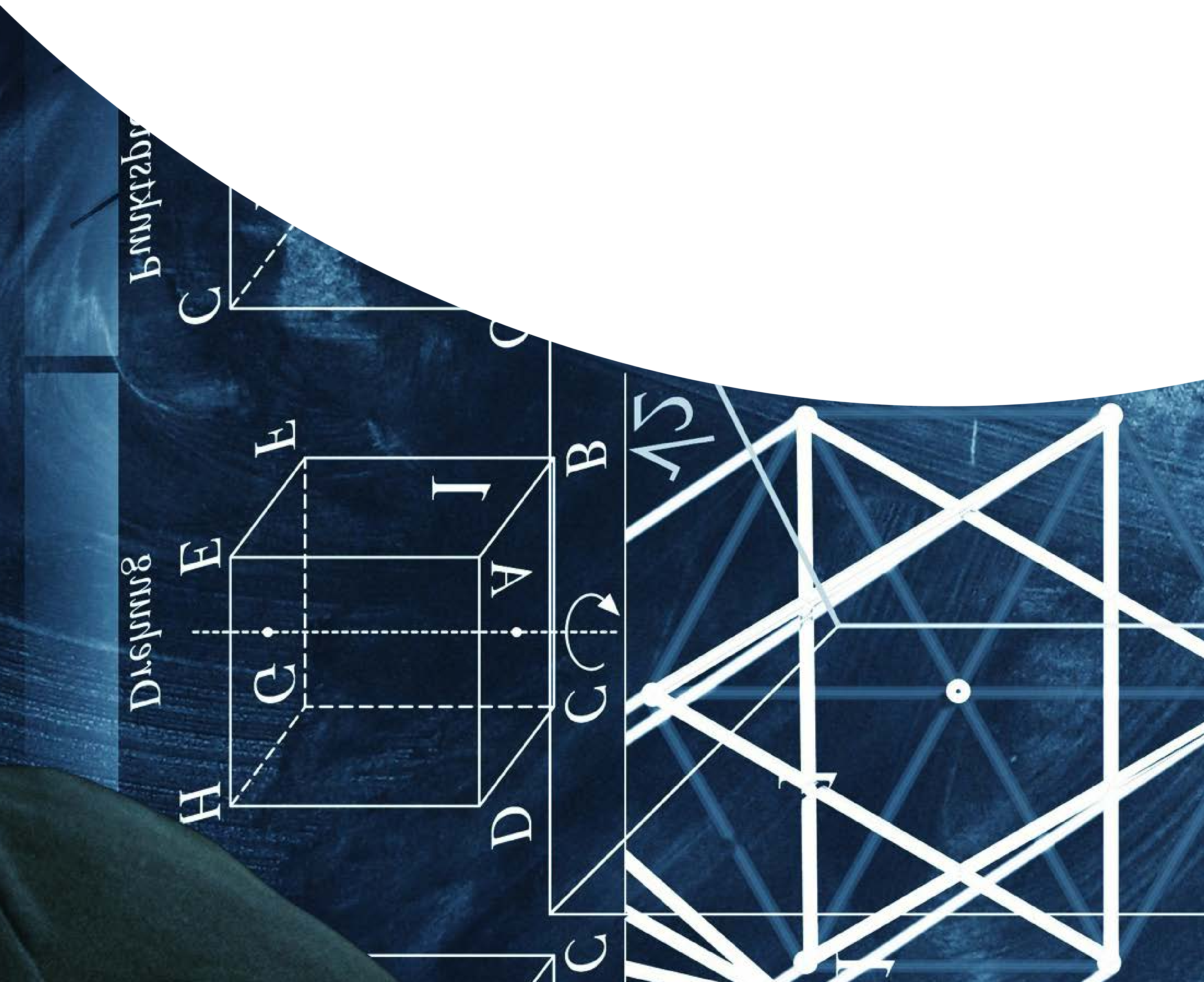
Rapid Cabinet approval of the Multipurpose Reactor (MPR) is needed. The MPR is intended to succeed SAFARI-1 when it reaches its end of life. SAFARI-1 boasts a proud safety record, having operated for over 56 years without any major incidents. Cabinet approval would allow for sufficient lead time required to roll out the procurement and construction of the MPR so that the radioisotope production, RDI and related nuclear technology innovations continue without interruption, thus ensuring that South Africa retains its nuclear technology global footprint. To this effect, the promotion of integrated safety, security and safeguards will lead to:

- Promoting sustainability and reduced operating cost
- Increasing reliability through a collective focus on development, implementation, and improvement of safety, security and safeguards
- Opportunities for cross-training of the workforce, and enhancing worker morale and retention
- Promoting a 'system' analysis and solutions approach, resulting in effective and efficient outcomes (Forden, 2011).

Objective: To ensure the promotion of high standards in safety, security and safeguards.

Indication/s:

i. Increased number of IAEA TCPs in safety, security and safeguards.
ii. Addressing human capacity building through the number of projects concerning research reactor safety elements (nuclear safety, radiation safety, transportation safety, and radioactive waste safety in relation to spent fuel and use products).



11. SOUTH AFRICAN INSTITUTIONS WITH NUCLEAR TECHNOLOGY FOCUS AREAS

There are several existing world-class nuclear technology institutions with nuclear education initiatives and RDI that are uncoordinated, leading to suboptimal collaborative efforts. Currently, the IAEA relies on most of the South African institutions for training and skills developments, yet some of the South African institutions do not participate in the relevant technical cooperation projects. Table 10 outlines the South African nuclear institutions and their primary nuclear-related function, areas of RDI and infrastructure, and linkages to recent IAEA TCPs.

Table 10: South African institutions with nuclear technology focus areas

Institution	Primary nuclear-related function/ department	Areas of nuclear RDI and infrastructure	Linkages to IAEA recent TCPs
Department of Science and Innovation (DSI)			
Academy of Science of South Africa (ASSAf)	Provides evidence-based scientific advice on issues of public interest to government and other stakeholders	• Undertakes secondary research by collating evidence to support policy and decision-making.	SAF1006, SAF7004
iThemba Laboratories for Accelerator Based Sciences (LABS)	Accelerators as analytical tools	• Ion beams are utilised in many complementary processes as an analytical tool for element analysis. • The Tandetron Accelerator (Cape Town) and the Tandem Accelerator (Johannesburg) offer facilities for ion bean analysis (IBA) and accelerator mass spectrometry (AMS).	
	Accelerators for medicine (diagnostics)	• External detection offers a non-invasive way to follow changes in the distribution of tagged atoms, observe anomalies of metabolism or detect tumours. • Existing 11 MeV cyclotron and the separated sectors cyclotron (SSC) are major producers of short-life radioisotopes. • Dedicated 70 MeV new cyclotron for radioisotope production by the end of 2022.	
	Accelerators for medicine (therapy)	• Progress in cancer therapy is being achieved by improvement in the local control of the tumour. • The use of particle beams permits a higher energy deposition and a more accurate range.	
	Industrial (ion implantation)	• Semiconductor substrate doping to achieve the required circuit pattern.	
	Industrial (irradiation processing)	• Charged and uncharged fragments of molecules resulting from bond breaking have high chemical activity and tend to react quickly with one another or with other molecules.	

Institution	Primary nuclear-related function/ department	Areas of nuclear RDI and infrastructure	Linkages to IAEA recent TCPs
iThemba Laboratories for Accelerator Based Sciences (LABS)	Industrial (food preservation)	• Radiation sterilisation of food avoids the chemical additives usually used for food preservation.	
Council for Scientific and Industrial Research (CSIR)	Nanostructures and advanced materials	• Radiopharmaceutical compound encapsulated in a microemulsion delivery system and evaluated for uptake and biodistribution. • Orally administered nanoparticles.	
Council for Geosciences (CGS)	Providing an information repository and delivery platform that facilitates actionable decisions and the accessibility of relevant information by relevant stakeholders[47]	Probabilistic seismic hazard analysis (PSHA) that was recently completed for the Thyspunt nuclear site west of Gqeberha.[48]	RAF2012
Agricultural Research Council (ARC)	Tropical and subtropical crops	• Mutation breeding for subtropical fruit.	
	Infruitec, and tropical and subtropical fruits	• Use gamma radiation for mutation breeding.	
	Small grain	• Mutation breeding for disease resistance. • Improvement of crop genotypes. • Transboundary diseases threats.	
	Veterinary research (OVR)	• Radiation biology for sterile insect technology.	SAF5015, RAF5073, RAF5074, RAF5078, RA5082, RAF5080
	Vegetables, industrial and medicinal plants	• Mutation breeding of amaranth, cowpea and moringa. • Potentially looking at rose geranium and cannabis mutation breeding. • Regional Designated Centre for Mutation Breeding and related Biotechnology (IAEA).	SAF5016
	Plant health and protection	• Organic contaminants in pesticide residue.	SAF 2020001 (SAF2018)
Technology Innovation Agency (TIA)	Bridging the innovation chasm between RDI (by higher education institutions, science councils, public entities, and the private sector) and commercialisation.	• Does not directly work on RDI projects. • Provides risk funding and support for innovators to progress ideas towards market entry and commercialisation.	

47 https://www.geoscience.org.za/index.php/about-us
48 https://www.geoscience.org.za/index.php/news/439-statement-on-thyspunt-seismic-hazard-assesment-a-council-for-geoscience-perspective

Institution	Primary nuclear-related function/ department	Areas of nuclear RDI and infrastructure	Linkages to IAEA recent TCPs
Nuclear Medicine Research Infrastructure (NuMeRI)	Main centre at Steve Biko Academic Hospital	• Commercial exploitation of new radioisotopes that will be developed by NuMeRI. • NUMeRI works closely with NTP (for the supply of reactor-based radioisotopes) and iThemba LABS (for the supply of high-energy cyclotron-based radioisotopes). • NuMACS will comprise pre-clinical and clinical imaging facilities, a research cyclotron bunker and a research radiopharmacy, a commercial cyclotron bunker, as well as a commercial radiopharmacy.	RAF6043, RAF6044, RAF6050
	Node for Infection Imaging (NII) at Tygerberg Hospital	• The aim of the NII is to support and advance molecular medicine research within the nuclear medicine community of South Africa as part of NuMeRI, with an emphasis on (TB) infection imaging. • The NII houses a dedicated PET/ CT scanner for research use, and is exploring various options to commission an onsite cyclotron.	RAF6051
	Interim Pre-clinical Imaging Facility (iPCIF) at Pelindaba	• The iPCIF is a one-stop laboratory supporting projects with a focus on, but not limited to, preclinical tracer or drug development. • The following molecular imaging equipment is available: microSPECT/ CT, high resolution microPET/CT, and benchtop optical imaging camera.	SAF6017

Institution	Primary nuclear-related function/ department	Areas of nuclear RDI and infrastructure	Linkages to IAEA recent TCPs
Department of Mineral Resources and Energy (DMRE)			
South African Nuclear Energy Corporation (Necsa)	Radiation science	• Beamline facilities • SAFARI-1 neutron beamlines for collaborative research and training. This includes neutron diffraction studies (residual stress analysis, powder diffraction, crystallography) and neutron radiography. Non-destructive testing services are also offered to local industry. • A small-angle neutron scattering capability has been established with IAEA assistance. • The neutron diffraction facility upgrade comprises two world-class neutron diffraction instruments, namely the Materials Probe for Internal Strain Investigations (MPISI), which is a neutron strain scanning instrument, and the Powder Instrument for Transition in Structure (PITSI). • Centre of Competence in Neutron Beamline Research in Africa with an extensive and active South African user group (IAEA) • Radiation and Reactor Theory (RRT) • RRT maintains an expert knowledge base in both reactor simulation and radiation transport, both from a research and industrial support perspective. • Computational analysis in the areas of radiation shielding, criticality, activation as well as nuclear reactor neutronic and thermal-hydraulic modelling has resulted in the development of the OSCAR reactor calculational software system.	SAF1005, SAF0007, SAF2020003 (SAF1007), RAF0047, RAF1007, INT2020

South African Nuclear Energy Corporation (Necsa)	Applied chemistry	• Plasma Gasification Development Programme. For nuclear waste treatment, Necsa is developing several plasma waste treatment pilot systems for the treatment of liquid and solid low-level waste (LLW) as well as polytetrafluoroethylene (PTFE) waste. • R&D on the conditioning and immobilisation of radioactive waste. • IAEA CRP entitled 'Ion beam irradiation for high-level nuclear wasteform development' (INWARD).	
	Radiochemistry	• Development of a range of new medical diagnostic and therapeutic radioisotopes. • Undertaking RDI on radioisotopes for NTP (the commercial arm of Necsa responsible for isotope production). • Managing and operating NuMeRI's interim Pre-clinical Imaging Facility (iPCIF). See NuMeRI iPCIF above.	
	Analytical and Calibration Services (ACS)	• Radon monitoring	
	Nuclear Technologies in Medicine and the Biosciences Initiative (NTeMBI)	• NTeMBI develops human capacity through research projects that involve postgraduate students. Funding via TIA and industry. • Comorbidity of HIV and cervical cancer studies. • Malaria sterile insect technique.	

	SAFARI-1 and Multipurpose Reactor (MPR)	• The existing SAFARI-1 research reactor is planned to be decommissioned by the end of 2030. • Commercial products based on SAFARI-1 are bulk radio chemicals such as fission Mo-99, fission I-131 and Lu-177. • SAFARI-1 also supplies a substantial part of the international demand for neutron transmutation doped silicon. • Other commercial applications are related to materials modification, neutron activation analysis and the provision of general irradiation services. • The intention is to replace SAFARI-1 with a Multipurpose Reactor (MPR). • Adequate commercial isotope production capability, high neutron flux in a large volume and adequate materials modification testing capability can be achieved with a 20 MWt MPR reactor. • The reactor will be able to provide excellent training and RDI support to the national system of innovation and for a nuclear build programme.	

National Radioactive Waste Disposal Institute (NRWDI)	Develop radioactive waste acceptance and disposal criteria, and manage and operate radioactive waste disposal facilities	• A feasibility study is being conducted for a Centralised Interim Storage Facility (CISF), including regulatory approvals for siting and construction. • Regional Designated Centre for Radioactive Waste Management (IAEA)	RAF9062
National Nuclear Regulator (NNR)	Granting nuclear authorisations and exercising regulatory control related to the safety of nuclear installations	The CNSS is the first applied research and training establishment dedicated to developing essential skills required by South Africa's nuclear sector outside the traditional university sector. It will house training facilities for NNR staff, a selection of state-of-the-art irradiation and analysis equipment for researchers and students to use, including analytical and inspection laboratories, computer modelling facilities, meeting and seminar rooms, and office accommodation[49]	SAF9005, SAF9006, SAF9007, SAF9008, RAF7017, RAF9058, RAF9049, RAF9060, RAF9061, RAF9063, RAF9066

49 https://nnr.co.za/cnss/)

Mintek	Conducting mineral technology research, development and technology transfer	• Uranium RDI includes evaluating uranium recovery from sulphide flotation concentrates, heap leaching, flotation for the Karoo deposit, acid mine drainage (AMD) and ion exchange. • Thorium RDI includes evaluating the extraction of thorium from rare earth element (REE) deposits in the Northern Cape.	
Department of Public Enterprises (DPE)			
Eskom	Nuclear Engineering – Nuclear Operating Unit (NOU)	• Corrosion, electronics and metals application support for electronics, and metals application support for long-term operation (LTO).	
	PBMR (NOU)	• Currently investigating the possibility of recommissioning the nuclear fuel plant at Necsa. • NNR and NWU are currently working on research concerning accident-tolerant fuel for Koeberg NPP.	• Development of advanced high-temperature gas-cooled reactor technology options for Eskom in the next five years.
	Research, testing and development (RT&D)		

Department of Higher Education and Training (DHET)			
University of Cape Town (UCT)	Metrological and Applied Sciences University Research Centre (MeASURe)	• The RDI focus is on applications that require novel measurement techniques, particularly using neutron and gamma radiation, and nanoelectronics at ultracold temperatures. • Research in applied nuclear physics, mainly featuring the development and use of radiation detectors and associated instrumentation, and computational and stochastic modelling. • Central to these activities is access to particle beams and radioisotopes through niche fast neutron facilities, proton therapy research beamline, and position emission particle tracking laboratories at UCT and iThemba LABS. • Infrastructure at UCT includes the n-lab featuring a 14 MeV sealed tube neutron generator and associated equipment, and three PET scanners. • Nuclear measurement and measurement modelling services for external stakeholders.	
	Energy Systems Research Group (ESRG)	• The ESRG includes nuclear energy in its modelling of energy and economic systems, but does not undertake nuclear RDI. • Regional Designated Centre for Energy Planning (IAEA).	

University of Johannesburg (UJ)	Proposed Nuclear Research Centre (NRC)	• Six proposed focused study committees: • Nuclear Science, Engineering and Technology Study Committee • Nuclear Energy Relationship to Nuclear Physics in the Faculty of Science • Medical applications • Nuclear waste and environmental studies • Nuclear nexus of applications • Nuclear education.	
North-West University (NWU)	Nuclear engineering research group in the Unit for Energy and Technology Systems (UETS)	• Thermal fluid systems modelling: • Thermal fluid systems modelling applications. • Generation III / Generation IV plant and components. • Fuel cycle plant components and safeguards. • Reactor neutronics modelling. • Energy policy and economics. • Nuclear waste management. • Uncertainty and sensitivity analysis applied to nuclear systems.	SAF0006
	Centre for Applied Radiation Science and Technology (CARST)	• Applied research on radiation protection and other applications of radiation technologies. • Nuclear forensic science. • Radiological environmental impact assessment.	
	Health Sciences (Nutrition)	• Improving nutritional status and body composition in children for optimal health. • Use of stable isotope techniques to measure nutritional status, body composition and energy expenditure.	SAF6020, SAF2020004 (SAF 6022)

University of Pretoria (UP)	Department of Nuclear Medicine	• Research on nuclear medicine, radiotherapy and diagnostic X-rays. • Advanced imaging equipment including: • Single and dual head gamma cameras • SPECT/CT • Multi-slice PET/CT.	SAF 2020002, RAF 6043, RAF 6044, RAF6055, RAF6056, RAF6057, INT6064
	Faculty of Engineering, Built Environment and Information Technology	• An undergraduate course in nuclear engineering is offered, as well as postgraduate courses, focusing on nuclear reactors.	• Faculty of Natural Science offers an MSc in Nuclear Sciences. • Research focuses on nuclear safety. • Measurement of radon in mines. • Participation in nEXO experiment, an international collaboration that aims to search for neutrinoless double beta decay.

	Nuclear physics	• Nuclear reactor materials: • Migration behaviour of different fission products in cladding layers of nuclear fuel in the environment similar to nuclear reactors. • Nuclear waste storage: • Behaviour of glassy carbon in the environment similar to nuclear waste storage environment.	
	Centre of Excellence for Nuclear Safety and Security (CNNS) (Funding and other support provided by NNR)	• Undergraduate and honours modules are offered in nuclear sciences, nuclear physics and nuclear engineering. • Postgraduate research focuses on nuclear safety and security, including: • Light water reactor (LWR) heat transfer on new fuel cladding materials with the current focus on silicon carbide • Asset integrity management • Welding of Zircaloy® core components • Modelling of material defects and surface interactions • Nuclear waste encapsulation • Passivation of Zircaloy® surface against steam–metal oxidation reactions • Fluoro-materials science and process development.	
	Veterinary science	Food security and zoonosis	RAF5073, RAF5082
University of Stellenbosch (US)	Department of Medical Imaging and Clinical Oncology	• Comprises the divisions of Nuclear Medicine, Radiodiagnosis, Radiation Oncology and Medical Physics.	RAF6050, RAF6043, RAF6044, RAF6053, RAF6054, RAF6055
	Department of Physics	• The Nuclear, Radiation and Health Physics Division focuses on theoretical computational modelling in nuclear science and its applications.	

University of the Witwatersrand (Wits) Radiation and Health Physics Unit at Wits	Faculty of Engineering and the Built Environment	Collaboration with iThemba LABS (Johannesburg)	
	Medical physics		RAF6044,
	Nuclear physics	• Nuclear structure (in collaboration with iThemba Labs). • Applied nuclear physics (in collaboration with the CNNS of the NNR). • Reactor physics (in collaboration with Necsa and the NNR).	
	Developmental Pathways for Health Research Unit (DPHRU)	See NWU Heath Science above.	SAF2020004 (SAF6022)
University of the Free State (UFS)	Faculty of Health Sciences	• Qualifications offered include bachelors, master's and doctoral degrees in medical biophysics.	
Nelson Mandela University (NMU)	Centre for High-resolution Transmission Electron Microscopy (HRTEM)	• Research focus areas include: • Pebble bed reactor materials • Accident-tolerant coatings on ZIRLO™ fuel tubes for water-cooled reactors • Radiation effects of swift heavy ions • High-alloyed power plant steels • Radionuclide adsorbents.	
University of the Western Cape (UWC)	UWC focuses on basic nuclear research, and the application and measurement of radon and thoron	• Faculty of Natural Science offers an MSc in Nuclear Sciences. • Research focuses on nuclear safety. • Measurement of radon in mines. • Participation in nEXO experiment, an international collaboration that aims to search for neutrinoless double beta decay.	
University of Zululand (UNI-ZULU)	Nuclear physics	• Development of radiation detectors and components for a new and inexpensive type of positron emission tomography (PET) scanner for medical imaging.	

Tshwane University of Technology (TUT)	Physics Department	• Training programmes in industrial physics from undergraduate to postgraduate levels, with a strong component of nuclear technology and radiation protection. • Training programmes at undergraduate level provide students with practical skills and knowledge to function as nuclear technicians in a range of nuclear technology occupations including NDT, radiation metrology, environmental radiation assessment, and radiation protection. • Formal cooperation agreements for practical training with institutions such as NMISA, Necsa and iThemba LABS. • Postgraduate qualifications include postgraduate diploma, master's and doctoral degrees in industrial physics.	
Department of Health (DOH)			
South African Health Products Regulatory Authority (SAHPRA)	SAHPRA is tasked with regulating all health products. It has the added responsibility of overseeing radiation control in South Africa		SAF9007
National Institute for Communicable Diseases (NICD)	Provides reference microbiology, virology, epidemiology, surveillance and public health research and training to support South Africa's response to communicable disease threats		SAF5013, SAF5014, SAF5016, SAF5017
Department of Trade, Industry and Competition (the dtic)			
National Metrology Institute of South Africa (NMISA)	Provides traceability and specialised measurement techniques for users of nuclear products and techniques.	• Optimisation of protection and safety in medical radiation exposure (through calibration). • Diagnostic analysis with ionising radiation and environmental monitoring in the vicinity of Koeberg Nuclear Power Station. • Regional Designated Centre for Secondary Standards Dosimetry Laboratory (IAEA).	SAF6018, SAF6021, SAF9009, RAF5078, RAF5084, RAF6056, RAF9059, RAF9064

South African Bureau of Standards (SABS)	Radiation Protection Service (RPS) and Radiation Calibration Metrology	• Regional intercomparison exercises on individual monitoring are conducted, focusing on external monitoring, specifically on passive dosimeters.	RAF9057
Provincial Government			
Steve Biko Academic Hospital (SBAH)	UP Department of Nuclear Medicine	See UP Department of Nuclear Medicine above.	RAF6050, RAF6051, RAF6056, RAF6057
Tygerberg Hospital	SU Division of Nuclear Medicine	• Radiopharmacy (e.g. optimisation of radiopharmaceutical preparation). • Medical physics (e.g. image reconstruction optimisation, dosimetry of radionuclide therapies). • Nuclear medicine procedures (e.g. optimisation of kidney function measurement). • Use of functional imaging to study in vivo pathological processes in human disease (e.g., infection imaging in tuberculosis, brain function in dementia, and lesion detection in cancer). • Regional Designated Centre for Clinical Radiotherapy and Medical Physics (IAEA)	RAF6049, RAF6051, RAF6503, RAF6054, RAF6055
	NuMeRI Node for Infection Imaging (NII)	See NuMeRI Node for Infection Imaging (NII) above.	
Institutes and Industry Associations			
Southern African Institute of Welding (SAIW)	Non-destructive testing (NDT)	• Effective utilisation of expertise and infrastructure in the field of NDT. • Radiation safety. • Derived NDT techniques that include digital radiographic testing using isotopic and X-ray exposure. • IAEA Anglophone Regional Designated Centre for NDT	RAF8032, RAF8043, RAF0046, RAF1008

Agri SA	Projects that Agri SA may have been involved in will have been allocated to other institutions in partnership		
Nuclear Chapter of the South African Institute of Electrical Engineers (SAIEE)	Coordinates national efforts to build capacity in the R&D of nuclear science, engineering and technology.	Use of 'fibre optics in-core'	
Nuclear Industry Association of South Africa (NIASA)	NIASA is an industry body that promotes nuclear RDI.	NIASA does not execute nuclear RDI projects/programmes.	
Private companies			
Steenkampskraal	The monazite mine has significant thorium deposits.	See Mintek above	
Synergy Sterilisation	Contract sterilisation, laboratory testing, and product and packaging testing services	• Use of cobalt-60 as a radioactive source for sterilisation. • All RDI work is completed by the parent company STERIS.	
Mozweli SA	Turnkey solutions for the design, manufacture, construction, commissioning, operation and decommissioning of SMRs	• Designed high temperature reactor (MHTR100).	SMR CRP

Note: IAEA project numbers may have been altered since project inception

12. STATUS OF NUCLEAR TECHNOLOGY EDUCATION IN SOUTH AFRICA

Given the rate of graduations at South African universities, it seems likely that the country's education system will be in a position to produce the much-reduced number of scientists, engineers and technologists to support the 'scaled-down', affordable nuclear expansion programme announced in IRP2019.

Table 11 is taken from the draft report 'Status and trends in nuclear education', compiled by Prof Frederik van Niekerk, North-West University, Potchefstroom, dated 31 October 2021. Table 12 lists South African higher education institutions with nuclear-related programmes in health sciences.

Table 11: South African higher education institutions with nuclear-related programmes (excluding health sciences)

Institution	Postgraduate qualifications					Qualifier
	PhD	MEng	MSc	BSc (Hons)	PG Dip	
University of Cape Town	x		x			Nuclear Physics
University of Johannesburg			x			Science and Organisation of Nuclear Energy
North-West University (CARST)	x		x			Radiation Science and Technology
					x	Physics, Engineering and Safety of NPP
				x		BSc (Hons) Nuclear Security
			x			Nuclear Security
North-West University (Faculty of Engineering)	x	x				Nuclear Engineering
	x		x			Nuclear Engineering Science and Technology
					x	Nuclear Science and Technology
					x	Nuclear Technology and Management
University of Pretoria	x					Mechanical with thesis in Nuclear Engineering
		x				Mechanical with dissertation in Nuclear Engineering
				x		Mechanical with Nuclear Engineering elective modules
University of the Witwatersrand					x	Radiation Protection
					x	Physics, Engineering and Safety of NPP
		x				Mechanical with Nuclear spec

Institution	Postgraduate qualifications					Qualifier
	PhD	MEng	MSc	BSc (Hons)	PG Dip	
Stellenbosch University			x			Research dissertation in nuclear-related topic
				x		Radiation and Health Phys-ics
				x		Nuclear Physics
University of the Western Cape			x			Accelerator and Nuclear Sciences

Table 12: South African higher education institutions with nuclear-related programmes in health sciences

Institution	Post Graduate qualifications					Qualifier
	PhD	MMed	MSc	BSc (Hons)	BTech/ BRad	
University of Cape Town	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x		x	x		Medical Physicist
						Radiography(Oncology, Nuclear Medicine, Radiology)
University of KwaZulu-Natal	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x		x	x		Medical Physicist
						Radiography(Oncology, Nuclear Medicine, Radiology)
Sefako Makgatho University	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x	x	x	x		Medical Physicist
						Radiography(Oncology, Nuclear Medicine, Radiology)

Institution	Post Graduate qualifications					Qualifier
	PhD	MMed	MSc	BSc (Hons)	BTech/ BRad	
University of the Free State	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x		x	x		Medical Physicist
	x	x	x	x	x	Radiography(Oncology, Nuclear Medicine, Radiology)
University of Pretoria	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x	x	x	x		Medical Physicist
	x		x	x	x	Radiography(Oncology, Nuclear Medicine, Radiology)
University of the Witwa-tersrand	x	x				Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x		x	x		Medical Physicist
						Radiography(Oncology, Nuclear Medicine, Radiology)
Stellenbosch University	x	x	x			Nuclear Medicine Physician
	x	x				Radiation Oncologist
	x	x				Radiologist
	x	x	x	x		Medical Physicist
						Radiography(Oncology, Nuclear Medicine, Radiology)
University of Johannes-burg	x		x	x	x	Radiography(Oncology, Nuclear Medicine, Radiology)
Cape Peninsula Univer-sity	x		x	x	x	Radiography(Oncology, Nuclear Medicine, Radiology)
Durban University of Technology	x		x	x	x	Radiography(Oncology, Nuclear Medicine, Radiology)

12.1 Overview of format of nuclear-related programmes

The main mode of delivery of nuclear programmes is lecturing for undergraduate and postgraduate taught modules. Most postgraduate programmes entail a significant research component, mostly performed by individual students on their approved research projects, mentored by a study leader and co-study leader (the latter could be internal and/or external). Taught modules are typically synchronous, while research work is done asynchronously. Since the outbreak of the COVID-19 pandemic, there has been a significant move towards synchronous online and asynchronous offline distance learning for taught modules. Typically, asynchronous online communication and consultation sessions involve study leaders and co-study leaders. For all computational work, the offline mode works well when students have remote access to high-performance clusters. The exceptions in general are experimental work that requires laboratory and/or field measurements, in which case COVID-19 social distancing protocols are observed and additional safety precautions are instituted as far as possible. Several universities, such as NWU and Wits, use a block mode for taught modules.

Most universities use modern lecturing technology, applicable to the classroom or remote delivery. Lecturing and consultation technology includes Zoom, MS Teams, WebEx, Skype, WhatsApp and other platforms. Multiple features enhance the students' experience. Lectures are infused with suitable learning objects, such as video clips, slides, simulations and interactive websites, in addition to traditional textbooks and lecture notes. Assessments have shifted somewhat to assignments and open-book assessments, in addition to online examination and traditional closed-book written examinations taken at approved distributed examination locations, overseen by an appointed invigilator. Teaching and research aids include a range of licensed and open-source computer codes and simulators.

Training and teaching in health sciences involve practicals, patient interactions and rotations at hospitals. Work-based assessments and entrustable professional activities are monitored via the portfolio.

12.2 Needs and gaps

There is a need for support for deeper investment in nuclear technology, training and research on nuclear science in general.

There is a need for training and development to focus on supplying an articulated and approved strategy and roadmap.

13. COMMERCIALISATION

This report will, among other crucial developments, lead to better commercialisation as it demonstrates the benefits and risks, and the needs and gaps. All the nuclear industry areas discussed in section 11 have demonstrated their cost-effectiveness, although not at their full potential due to some negative perceptions and lack of education and information on nuclear applications.

Thus, in addition to the other objectives, the summary and recommendations of this report should form part the roadmap for commercialisation.

The indicators for the objectives under the needs and gaps should be regularly monitored.

It should be noted that NTP Radioisotopes SOC Ltd currently supplies up to a third of global demand for Mo-99, the most widely used medical isotope. The daughter or decay product of Mo-99, technetium-99m (Tc-99m), is used in more than 40 million medical diagnostic-imaging studies every year.

NTP's clients include global leaders in nuclear medicine imaging and diagnostics, such as Lantheus Medical Imaging, GE Healthcare, Mallinckrodt Pharmaceuticals, Nihon Medi-

Physics, Jubilant DraxImage, IBA Molecular Imaging, HTA Co. Ltd, Samyoung Unitech and the Eczacıbaşı-Monrol group.

NTP is also a leading supplier of high-quality irradiation services and radioactive sealed sources, including caesium-137, iridium-192 and cobalt-60[47].

Another South African nuclear-technology success is iThemba LABS, which carries out routine isotope production of ^{82}Sr (covering 25% of the global supply of irradiated material), $^{68}Ge/^{68}Ga$ generators (covering 30% of the global market), ^{18}F-FDG, ^{22}Na (covering 100% of the global market), ^{123}I and ^{67}Ga. The $^{68}Ge/^{68}Ga$ generators (used for PET imaging of neuroendocrine tumours, prostate cancer, and infection and inflammation) and ^{22}Na (used for positron annihilation studies) are produced for the international market and service some 100 global clients. The ^{123}I and ^{67}Ga that are used as SPECT tracers, and the ^{18}F-FDG that is used for cardiac and neurological applications, are produced exclusively for 25 local clients[48].

The sterile insect technique (SIT) activities have expanded as a result of a well-funded Area-Wide Integrated Pest Management (AW-IPM) programme, resulting in the decline of wild Mediterranean fruit fly populations in the SIT areas by up to 73%, to the extent that the South African Mediterranean fruit fly SIT programme now aims to declare some of the fruit-production areas as areas of low pest prevalence. Furthermore, augmented finance and a stable income stream have also enabled FruitFly Africa to implement early-detection and rapid-response programmes for invasive pests such as *Bactrocera dorsalis* in relevant areas (Venter, Baard, & Barnes, 2021).

47 https://www.ntp.co.za/about-us/
48 https://tlabs.ac.za/wp-content/uploads/pdf/NRF-iThemba-report.pdf

14.FUNDING

Huge nuclear-technology facilities are expensive and highly regulated in most countries, and South Africa is no exception in this regard. Government is the owner and funder of such projects, which are funded mainly through the DMRE or DPE. The Nuclear Industry Association of South Africa (NIASA) recently suggested six funding approaches that could be applied to nuclear technologies, namely: (i) state funding for the entire project or with state-backed loan guarantees; (ii) an intergovernmental loan; (iii) corporate financing; (iv) financing by the plant vendor; (v) project financing using a special investment vehicle; and (vi) 'build, own, operate'[49].

Nuclear power plants have positive long-term attributes as energy systems, but they require significant advance capital cost. Unfortunately, modern economic analysis methods (involving the time value of money) weigh the early costs far higher than later costs, with the result that front-loaded nuclear energy struggles. The equipment required for nuclear-technology applications is high-tech, with relatively high costs. Furthermore, large-scale facilities such as accelerators or reactors, apart from their high initial costs, have high operation and maintenance expenses, with the result that any investment in a new project is a long-term commitment.

As part of providing alternative funding models, a portion of the income generated from Koeberg NPP should be directed towards funding RDI for advanced and innovative nuclear energy systems such as small modular reactors, which are currently attracting global interest due to their ease of deployment, the modular approach to construction, and the use of an alternative coolant to water, which is an important consideration in the face of climate-change impacts in water-scarce regions (National Infrastructure Plan 2050 (NIP), 2022; National Water Resource Strategy, 2013). However, it should be noted that according to standard economic theory, targeted taxation, such as taxing the profits from Koeberg NPP to fund nuclear research, reduces the efficiency of government's taxing and spending. Therefore the standard theory, which is endorsed by the South African National Treasury, is that all taxes should be collected into the national fiscus and then allocated to different projects according to the annual budget drawn up by the Minister of Finance and approved by Parliament. It is unlikely that Treasury will approve a special taxation model for nuclear funding in South Africa. Therefore, the standard way to obtain funding for South Africa's proposed nuclear power projects would be to show through proper research that their level of profitability is high enough to make them economically attractive. Government would then allocate a budget, and National Treasury would supply the budgeted funds for nuclear power plant construction projects.

Funding for non-power applications of nuclear technology, and specifically the RDI aspects

Due to their extremely high construction costs, the funding of new nuclear power plants dwarfs the funding of all non-power nuclear projects. The funding of non-power nuclear projects is therefore not usually a serious discussion topic in South African news media. The funding of these non-power projects normally happens through the standard funding channels of the South African government, such as the research budgets of universities, and funding from the National Research Foundation (NRF) and institutions that are directly responsible for nuclear research, including Necsa and the National Nuclear Regulator (NNR), which funds research on radiation protection.

Lastly, it should be noted that a new large nuclear power plant construction programme would inject a large amount of funding into all nuclear-related research projects. If the construction of new nuclear power plants were to go ahead, there would automatically be a trickle-down effect to other non-power nuclear research projects, which would greatly enhance the funding of such research.

With regard to the non-power applications of nuclear technology, consideration is given to the economic risk with reference to safety, security and safeguards, and thus exploitation of the benefits of international collaboration and private enterprises for new models of funding.

49 https://www.world-nuclear-news.org/Articles/NIASA-sets-out-funding-options-for-South-African-n

15. RECOMMENDATIONS

The following general recommendations should be monitored by the South African National Energy Development Institute (SANEDI):

1. **Improve integration and interdepartmental approaches to nuclear RDI**

   Integration and interdepartmental approaches to RDI on nuclear technologies must be achieved, based on national priorities. Currently, the strategies and plans of the departments of Health; Higher Education and Training; Public Enterprises; Agriculture, Land Reform and Rural Development; and Water and Sanitation make almost no mention of nuclear technology. It is therefore recommended that a central coordinating desk should be placed under the control of ASSAf, tasked with addressing the poor record of collaboration and the present failure to integrate the results of nuclear technology research into a coherent body of knowledge that can contribute to the national economy.

2. **Increase the number of institutions and RDI projects collaborating in the TCPs and AFRA**

   An integrated interdepartmental approach will be formulated, based on national priorities, which will lead to maximum benefits and input from IAEA.

3. **Formulate a human capital development strategy for sustainable nuclear applications**

   The economic potential of nuclear technology infrastructure development and personnel qualification and certification within general industry is far from being realised in South Africa or elsewhere on the African continent. The potential of the available workforce therefore needs to be unlocked through infrastructure development and upskilling of local citizens.

   A strategy will be developed for a holistic approach that acknowledges skills, experience, knowledge, concepts and innovative ideas on transformation. The current state of human resource development in the nuclear field must be strengthened. Nuclear education at South Africa's universities and other training institutions should continue, and could be prioritised, in order to supply the South African nuclear industry with a steady stream of well-educated professionals. Practical solutions will be provided by using existing and new interdisciplinary centres of excellence to support the country's priorities and the safe and sustainable operation of nuclear power programmes. The development strategy and funding of these centres should be based on collaborative strength and high-level skills, leading to high productivity, advanced manufacturing capability and job creation in the nuclear field.

   The following recommendations are related to specific themes.

4. **Agriculture and food security**

   4.1 Improve routine practices for soil and water management with combinations of nuclear techniques through a dedicated RDI programme

   This will provide direct benefits to farmers by fostering climate-smart agricultural practices to enhance and continuously improve agricultural productivity through various technologies, including novel uses of isotopes. Although nuclear techniques offer good prospects for improving routine practices for soil and water management, they are not routinely used by farmers. RDI activities focused on mutation induction to broaden the genetic base of crop germplasm in seed and vegetatively propagated crops could assist in removing certain production constraints, an initiative that is much needed in South Africa. Flagship RDI collaborative programmes should be included in the strategic planning of the Department of Agriculture, Land Reform and Rural Development (DALRRD).

4.2 Develop human capacity and RDI to increase the application of isotope ratio mass spectrometry (IRMS) to enable the monitoring of food fraud

Stable isotope analysis has become a powerful tool for food authentication and traceability due to its advantages of high precision and efficiency. There is a need to review the current limitations and improve future research directions of isotope analysis in food authentication and traceability. The monitoring of food fraud must be improved by increasing the number of laboratories using improved IRMS methods for food authentication and traceability.

4.3 Take an integrated approach to animal health and zoonotic infections

The complex links between human, animal and environmental health require coordinated multidisciplinary and multipronged collaboration to address the threats from zoonotic disease. While the global public health community needs to act decisively now, South African institutions should take an integrated approach to collaboration and investment with regard to nuclear applications.

5. Human health

5.1 Introduce nuclear medicine departments in level II hospitals using human capacity development and RDI

Insufficient access to nuclear medicine and theranostic procedures leads to increased morbidity and mortality. Health technology assessments have demonstrated the benefits and cost-effectiveness of making nuclear medicine and theranostic procedures available outside central hospitals.

5.2 Develop a comprehensive national cancer control programme (NCCP) to address optimal usage of radiation medicine (radiotherapy, nuclear medicine, radiology, medical physics and radiobiology)

There is a need to develop a comprehensive NCCP with actions based on the mission of the IAEA Programme of Action for Cancer Therapy (PACT), and to make investments that would enhance access to imaging equipment, workforce capacity, digital technology, radiopharmaceuticals, and research and training programmes in South Africa. Such an initiative would have massive health and economic benefits and reduce the global burden of cancer. This would also enable better support for the IAEA Ray of Hope initiative, ‘Cancer care for all’.

6. Radiation protection

6.1 Develop and implement a strategy including a public–private partnership model for education, training and research for radiation protection

A national strategy for a public–private partnership model for education, training and research with regard to radiation protection would maximise usage of the limited skills and infrastructure. This would also address (i) awareness of radiation protection and safety in veterinary medicine, (ii) establishment of a single radiation protection training body with subdivisions for various professions by 2024, and (iii) publication of radiation protection officer (RPO) training in the *Government Gazette*.

6.2 Harmonise the radiation protection regulatory functions of the National Nuclear Regulator (NNR) and the Department of Health

A framework needs to be designed to harmonise the functioning of the two independent national regulatory bodies, namely the NNR and the Directorate of

Radiation Control under the South African Health Products Regulatory Authority (SAHPRA), an entity of the national Department of Health. This could be facilitated by SANEDI with the assistance of ASSAf, as stated in Recommendation 1, and would assist with the exchange of accurate data that could be used for RDI, increased participation in TCPs, help with planning, and improved regulatory control programmes in accordance with IAEA safety standards and guidelines, without compromising the legislative mandates of each body.

7. Water and environment

7.1 Improve integrated management of RDI on the isotope hydrology of water resources

The management of RDI on the isotope hydrology of water resources is currently inadequate. Isotope hydrology is a very cost-effective means of assessing the vulnerability of groundwater sources to pollution. There is thus a need to support collaborative RDI projects on the use of isotope hydrology competences in South Africa in organisations such as Necsa, the CSIR and local universities, and to integrate them into a comprehensive of water resource management programme for the country.

7.2 Develop new and more sustainable methods for water production by desalination

One of the methods of increasing water production is to apply proven technology that is economically viable and uses manageable levels of electricity for desalination by reverse osmosis. The use of nuclear power for water desalination should be considered. There is a need to leverage the envisioned 2 500 MW nuclear build programme, as articulated in the Integrated Resource Plan (IRP) of 2019 (RSA, 2019). This flagship investment and RDI are particularly urgent, taking into consideration the water scarcity in the country and the projections of a water deficit in the future.

8. Energy

8.1 Strengthen analytical capacity to develop energy supply and demand models and scenarios for the medium and long term

Given the uncertainty that still prevails, more detailed studies are needed using comprehensive models to analyse energy supply and demand. These studies will strengthen analytical capacity to justify the inclusion of nuclear energy based on evidence from databases, indicators, scenarios and sustainable development for energy. This approach will provide clarity on the future of nuclear energy and on whether South Africa can afford to build new nuclear energy capacity. Furthermore, this will demonstrate the need for a sustained and established nuclear fuel cycle and a lower carbon footprint, thus justifying participation in IAEA TCPs and other international grand challenge RDI projects. These RDI projects could contribute to better understanding and planning for small nuclear units (i.e. small modular reactors), which are considered more manageable in terms of financial investment.

8.2 Improve communication and education on nuclear energy

There are negative perceptions of the nuclear energy industry in South Africa for various reasons, ranging from concerns about safety, technical understanding and radioactive waste. to political and economic miscommunication. Hence, there is a need to conduct an honest and transparent information programme that will increase the understanding and education of the public with regard to the benefits and risks associated with nuclear energy. Importantly, it is crucial to state that nuclear energy has a role to play in the development of South Africa based on a comprehensive scientific analysis.

9. Industry

9.1 Increase the competitiveness of nuclear technology in South African industries, and contribute to combating climate change

Several industries, such as mining and the processing, production, food and agriculture industries, face a number of problems, including relatively low competitiveness, the impact of their activities on climate change, and inefficient energy consumption. Increasing the competitiveness of nuclear technology in South African industries will help provide opportunities for employment and RDI. It is strategic to include uranium exploration, prospecting and final extractions in the planning and prioritisation, given that during exploration, many inexpensive research opportunities become available to assist in capacity building. Training and RDI in non-destructive testing (NDT) and related areas in industry must continue to be sustained and optimised.

10. Nuclear safety, security and safeguards

10.1 Increase nuclear reactor RDI to promote high standards of safety, security and safeguards

Cabinet approval of the Multipurpose Reactor (MPR) proposal allows South Africa to retain its nuclear technology global footprint so that radioisotope production, RDI and related nuclear technology innovations can continue without interruption. This will provide an opportunity to increase the number of IAEA TCPs in the safety, security and safeguards space, as well as related human capacity development through projects concerning research reactor safety elements (nuclear safety, radiation safety, transportation safety, and radioactive waste safety related to spent fuel and use products). The signing of the Amendment to the Convention on the Physical Protection of Nuclear Material (CPPNM) is encouraged, as well as relevant government departments addressing the actions demanded by the Amendment.

While these recommendations are not exhaustive, they will help to develop a national strategy that articulates the strategic priorities of the country in line with existing policy documents, such as the NDP, and would inform consultations on the Country Programme Framework and proposals on how to define a South African nuclear technology RDI flagship programme.

The application of nuclear technologies, once integrated with existing local and international development initiatives, will result in the realisation of plans that support the identification of areas in which these technologies may be successfully deployed. These research focus areas will aim to contribute to both global and local arenas, identifying opportunities that could be considered to be low-hanging fruits, and providing avenues for building partnerships between institutions (both national and international) and individual researchers. The recommendations define a South African nuclear technology RDI flagship programme for the 2030 Agenda for Sustainable Development, thus informing the Country Programme Framework (CPF). Importantly, South Africa should leverage on the strong and healthy relationship with the IAEA to address national needs and priorities through the CPF and its individual projects.

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Appendices

Appendix 1: Biographies of panel members

Machaba Michael Sathekge (Chair)

Prof Machaba Michael (Mike) Sathekge is a professor and head of the Department of Nuclear Medicine at the University of Pretoria (UP) and Steve Biko Academic Hospital (SBAH). He is head of the South African Nuclear Medicine Research Infrastructure (NuMeRI). Internationally, he is the editor-in-chief of the *Seminars in Nuclear Medicine Journal*. He serves as president of Radiopharmaceuticals and Molecular Therapy (WARMTH). Prof Sathekge serves as an IAEA expert for nuclear medicine. He has performed several of the first-in-human studies and introduced peptide receptor radionuclide therapy and peptide radioligand therapy in Africa, as well as 225 Ac-PSMA for prostate cancer. He is the recipient of several key awards for research, leadership and clinical service. His publication and presentation record internationally and nationally has earned him editorial roles on peer-reviewed journals and election as a member of the Academy of Science of South Africa (ASSAf). He holds the highest honour of the Colleges of Medicine of South Africa (CMSA), an honorary fellowship, and was admitted as a fellow of the Academy of Medicine, Singapore.

Faïçal Azaiez

Dr Faïçal Azaiez has been the director of iThemba LABS since 2016. Dr Azaiez obtained his PhD from L'institut de physique nucléaire d'Orsay (IPNOrsay) in France in 1984. His fields of expertise include experimental nuclear physics, accelerator physics, nuclear physics applications, large-scale organisation management and large-scale project management. He has a clear vision of the present and anticipated future activities worldwide in those fields and consequently the ability to lead the research effort within iThemba LABS. He also plays a key role in defining, with the National Research Foundation and the stakeholder community, a national strategy for accelerator-based science in South Africa. Dr Azaiez has an international reputation and enjoys membership of many international committees (Nuclear Physics European Collaboration Committee [NuPECC], Academia Europaea, European Physical Society). Not only has he been involved in defining scientific roadmaps and strategies, but also in steering various scientific and technological projects.

James Larkin

Prof James Larkin is the director of the Radiation and Health Physics Unit (RHPU) at the University of the Witwatersrand (Wits). He serves as chairman of the university's National Institutes of Health [NIH]-mandated Institutional Biosafety Committee (IBC) and is a past chairman of the IAEA International Nuclear Security Education Network (INSEN). At Wits he teaches various courses in nuclear security, radiation protection and nuclear facility leadership, and serves as the university's radiation safety officer.

He continues to be heavily involved in international nuclear security education, and over the past ten years has visited numerous different countries to share his nuclear security knowledge and experiences with national, regional and international audiences. He works closely with the IAEA's sections on nuclear security (NSNS) and nuclear knowledge management (NKM) and the European Union's Joint Research Centre, the European Safeguards Research and Development Association (ESARDA) in Italy, on several nuclear security and nuclear safeguards projects, most recently on an International Nuclear Safeguards qualification currently under development.

Prof Larkin is a Fellow of the Royal Society of Medicine, UK (FRSM), a member of the Institute for Nuclear Materials Management, USA (INMM) and a founding member of the Southern African Radiation Protection Association (SARPA). He is also the project leader on the Rhisotope Project, a rhinoceros antipoaching and antitrafficking project.

Moshe Modiselle

Dr Moshe Modiselle is the current president of the South African Society of Nuclear Medicine. Having trained as a nuclear medicine registrar at the University of Pretoria, he has gained much experience in general nuclear medicine, especially in theranostics, which the university is currently leading in the country. He is currently in private practice at Kritzinger, Van Niekerk and Ramjee Molecular Imaging Inc. His special interests include positron emission tomography (PET) imaging and novel tracers in nuclear medicine.

Tebogo Motlhabane

Tebogo Motlhabane was announced as the newly elected president of Women in Nuclear South Africa (WiNSA) in August 2020. She obtained a BSc and MSc degree in applied radiation science and technology from the NWU. She has been working in the nuclear sector for more than 16 years. Her work experience includes a stint at the National Nuclear Regulator, AngloGold Ashanti, Malepa Holdings, the Department of Mineral Resources and Energy and the IAEA. Ms Motlhabane also served on the executive committee of the Southern African Radiation Protection Association.

Gaopalelwe Santswere

Gaopalelwe Santswere is a nuclear physicist with many years' experience of nuclear regulation and licensing, working for South Africa's Department of Energy, Eskom and Necsa. He is a professional natural scientist registered with the South African Council for Natural and Scientific Professions (SACNASP). He holds a master's degree in applied radiation science from NWU's Mafikeng Campus. Over the years, Mr Santswere has gained extensive experience in building community awareness, volunteer training and coordination, developing working relationships between communities and local businesses, working with government, and delivering education programmes. He has successfully coordinated a number of public education and awareness programmes, generating financial support from local organisations and achieving tangible community outcomes. Mr Santswere has devised proactive responses to changing socioeconomic conditions, which have allowed him to make significant contributions to the nuclear industry.

Mr Santswere is the former executive chairperson of the South African Young Nuclear Professional Society (SAYNPS), which is affiliated to the International Nuclear Youth Congress (IYNC), and acting president of the Nuclear Industry Association of South Africa (NIASA). He is president of the newly established African Young Generation in Nuclear (AYGN), a member of the board of directors of the International Youth Nuclear Congress (IYNC) and chairperson of the South African Radiation Protection Association (SARPA).

Dawid Serfontein

Dr Dawid Serfontein obtained his master's degree in physics cum laude from North-West University (NWU). In 1988, he started a career in medical physics at the University of the Free State. As a medical physicist, he was trained in medical physics for radiotherapy, nuclear medicine and diagnostic X-rays. As the medical physicist responsible for radiation protection in hospitals, he was responsible for the implementation of the new regulations of the International Commission on Radiation Protection (ICRP), contained in its ICRP-60 report. This entailed the revision of the radiation protection programme at the hospitals and training of radiation workers. Dr Serfontein then left his career as a medical physicist in order to follow a calling to the Christian ministry. Because of a doctrinal difference with the church regarding the teaching on infant baptism, Dr Serfontein was expelled from his office as pastor at the beginning of 2005. In 2006 he was appointed as a junior researcher in the Post Graduate School of Nuclear Science and Engineering at NWU, Potchefstroom Campus, where he lectured, revised and developed several modules in nuclear engineering. He simultaneously enrolled for a PhD in nuclear engineering, which was awarded to him in 2012. He has an intense interest in technical and policy studies on the prevention of nuclear weapons proliferation. He has been appointed as a senior lecturer in nuclear engineering in the NWU School of Mechanical and Nuclear Engineering since 2012.

Appendix 2: Biographies of reviewers

Vishana Naicker, North-West University

Prof Vishana Naicker is an associate professor within the Unit for Energy and Technology Systems at NWU. Prior to this she was a senior lecturer at the NWU School of Mechanical and Nuclear Engineering between 2011 and 2018. Before joining NWU, she was a senior nuclear engineering analyst for the Pebble Bed Modular Reactor programme. Other vocations include technical advisor to Watts-On Electrical Wholesalers and senior physicist at Eskom. Prof Naicker has been a member of the NWU Engineering Faculty Board since 2021.

Her active research is in reactor core multiphysics, uncertainty and sensitivity analysis, and nuclear waste analysis.

David Otwoma, National Commission for Science Technology and Innovation (Kenya)

Dr David Otwoma is a past chairman and founding member of the Eastern Africa Association for Radiation Protection. He holds a PhD in Radiation Physics, an MSc in Nuclear Science and a BSc in Physics, and supervises MSc and PhD candidates at public universities. Currently, he is the chief research analyst at Kenya's National Commission for Science, Technology and Innovation. He was secretary (Nuclear) in the Ministry of Energy and Petroleum seconded to the Nuclear Electricity Project (2011–2013); he served as the chief science secretary for the National Council for Science and Technology (2007–2011); and was a nuclear safeguards inspector at the International Atomic Energy Agency (IAEA) in Vienna, Austria (1999–2006). From 1988 to 1998, he was the senior radiation protection officer at the Radiation Protection Board.

Dr Otwoma's impressive portfolio of awards includes the 2005 Nobel Peace Prize as IAEA staff, shared with the IAEA director-general Dr Mohamed ElBaradei, and the Kenya National Commission for Science, Technology and Innovation award in 2013 in recognition of research contributions in radiation protection dosimetry at both national and international levels. In 2014, he participated in the production of a technopolicy brief entitled 'Mainstreaming gender in the national science, technology and innovation policy in Kenya', and his paper entitled 'Challenges and opportunities as Kenya grapples with how to introduce a nuclear regulator', published in ESI Africa's Power Journal, formed part of the discussion at the August 2015 East African Power Industry Convention (EAPIC). He also spoke on 'How is the price of generation sources influencing the attractiveness of power plants powered by imported coal and nuclear?' at the EAPIC function. From 2018, he was appointed as a board member of the Radiation Protection Board (RPB) until 2021, when the enactment of the Nuclear Regulatory Act transformed the RPB into the Nuclear Regulatory Authority. He has been a member of the Kenya Space Agency board since 2019.

Anthony Stott, Vienna Center for Disarmament and Non-Proliferation (Austria)

Mr Anthony Stott is an international expert on nuclear power infrastructure development, environmental protection and stakeholder engagement. He provides consulting services to the International Atomic Energy Agency (IAEA) and international NGOs.

Between December 2014 and March 2020, Mr Stott was employed by the IAEA in the Nuclear Infrastructure Development Section, Division of Nuclear Power. He was the team leader for Integrated Nuclear Infrastructure Review (INIR) missions to several countries embarking on new nuclear power programmes, led national workshops and expert missions on environmental impact assessment and stakeholder engagement, and lectured in interregional training courses on nuclear infrastructure development topics.

Prior to joining the IAEA, Mr Stott accumulated more than 30 years' experience in the nuclear industry in South Africa, in the national electricity utility, Eskom.

Appendix 3: Institutions represented at the stakeholder workshop of 3 May 2022

1	iThemba LABS
2	Agricultural Research Council
3	Cape Peninsula University of Technology
4	Council for Scientific and Industrial Research
5	Department of Health
6	Department of Mineral Resources and Energy
7	Drs Van Niekerk Ramjee Modiselle and Lengana Inc.
8	Durban University of Technology
9	Eskom
10	Mozweli Group
11	Mpact R&D
12	National Metrology Institute of South Africa
13	NTeMBI
14	North-West University
15	NTP Radioisotopes/Necsa
16	South African Bureau of Standards
17	South African National Energy Development Institute
18	South African Nuclear Energy Corporation
19	South African Society of Nuclear Medicine
20	Southern African Institute of Welding
21	Stellenbosch University
22	TLABS Library
23	Tshwane University of Technology
24	University of Cape Town
25	University of Fort Hare
26	University of Global Health Equity, Rwanda
27	University of Johannesburg
28	University of KwaZulu-Natal
29	University of Pretoria
30	University of the Free State
31	University of the Witwatersrand

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