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RESEARCH ARTICLES

Transformative Role of Nuclear Technologies in the Healthcare System of Pakistan: Advancements and Impact

Shazia Fatima[*]

Abstract

Nuclear technology and techniques have become the foundation of modern medicine, revolutionizing the diagnosis, treatment, and management of various pathologies and disease processes. The healthcare sector in Pakistan has also witnessed transformative developments, especially in the fields of oncology, cardiology, and neurology, among others, contributing directly to the United Nations (UN) Sustainable Development Goal 3 (SDG 3). Pakistan, from the outset, has continued to invest in healthcare facilities and developed a comprehensive network of 51 nuclear medicine facilities and 49 oncology centers, including 19 Atomic Energy Cancer Hospitals (AECHs). These centers offer state-of-the-art diagnostic and therapeutic services, including hybrid imaging with Positron Emission Tomography/Computed Tomography (PET/CT), Single Photon Emission Computed Tomography/Computed Tomography (SPECT/CT), conventional gamma cameras, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) mammography, and radiation treatment with teletherapy machines like linear accelerators, gamma and cyberknife, brachytherapy units as well as trailblazing theragnostic technologies. The production of indigenous radiopharmaceuticals, radioisotopes, and in-house cyclotron-based isotopes production has upgraded nuclear medicine facilities, including hospitals and diagnostic centers, by promoting self-reliance and reducing healthcare

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costs. In this regard, the Pakistan Nuclear Regulatory Authority (PNRA) ensures safety and standardization across these facilities through its regulatory framework and legislation. Although Pakistan has successfully established a comprehensive infrastructure of healthcare facilities using nuclear techniques, these facilities, primarily concentrated in major cities, are insufficient for its 250 million population. To overcome this challenge, there is a need for continued capacity building through infrastructure development, human resource training, and enhanced local isotope production. This article discusses Pakistan's historical developments in the field of healthcare, its current infrastructure, socioeconomic impact, and strategic direction of nuclear medicine and radiotherapy. This article further highlights the transformative role of nuclear technologies in improving public health outcomes and national healthcare resilience.

Keywords: Nuclear Applications in Healthcare Systems, Transformation in Understanding Diseases, Modern Medicines, PNRA, PAEC.

Introduction

Nuclear technology plays a key role in healthcare settings such as screening, early diagnosis, accurate treatment, and prognosis of several pathologies. Ionizing radiation, like X-rays, gamma rays, and particulates, enabling healthcare professionals to manage a wide array of diseases with remarkable precision. The integration of nuclear technology and techniques in healthcare infrastructure has led to an unprecedented transformation in understanding diseases at the molecular level and targeting them with unmatched precision. In addition, the integration of nuclear technology into medicine has enhanced diagnostic and therapeutic approaches worldwide.

In Pakistan's case, this transformation has been driven by sustained investment, strategic capacity building, and fruitful international partnerships. Moreover, the adoption of nuclear applications in healthcare systems has enabled early detection, accurate treatment, and significantly improved patient outcomes in Pakistan, particularly in the fields of oncology, cardiology, and neurology. The healthcare infrastructure in Pakistan has gradually incorporated nuclear techniques in the management of varied pathologies, particularly non-communicable diseases, especially cancer, cardiovascular ailments, and neurological disorders. This article explores the advent of nuclear technologies in the healthcare infrastructure of Pakistan, its current state, and future directions. This transformative journey directly aligns with the objectives of UNSDG 3,[1] which focuses on ensuring health and well-being for all age groups. Additionally, nuclear techniques play an instrumental role in achieving SDG 3.4 by enabling early detection and comprehensive treatment of non-communicable diseases (NCDs), particularly cardiovascular diseases and cancer. SDG 3.4 emphasizes the importance of reducing premature mortality from non-communicable diseases by one-third by the year 2030. This goal encompasses both prevention and treatment initiatives, along with a strong commitment to promoting mental health and overall well-being.

The field of medical diagnostics irreversibly changed with the discovery of X-rays by German physicist Wilhelm Conrad Roentgen in 1895.[2] Shortly after their discovery, X-rays were employed in the treatment of dermatological conditions, including skin cancers. Their diagnostic utility quickly expanded beyond skin ailments, offering unprecedented visual access to internal pathologies. Until the revolutionary advent of CT in 1971, conventional X-ray radiography remained the primary imaging tool in medicine.[3]

The mid-twentieth century brought another milestone with the discovery of radium, which led to its application in high-dose external beam radiation

[1] World Health Organization, "SDG Target 3.4: Reduce by One Third Premature Mortality from Non-Communicable Diseases through Prevention and Treatment and Promote Mental Health and Well-Being," *World Health Organization*, https://www.who.int/data/gho/data/themes/topics/sdg-target-3_4-noncommunicable-diseases-and-mental-health

[2] Hyun Do Huh and Seonghoon Kim, "History of Radiation Therapy," *Progress in Medical Physics* 31, no. 3 (September 2020): 124–131, https://www.progmedphys.org/journal/view.html?doi=10.14316/pmp.2020.31.3.124

[3] Raymond A. Schulz, Jay A. Stein, and Norbert J. Pelc, "How CT Happened: The Early Development of Medical Computed Tomography," *Journal of Medical Imaging* 8, no. 5 (October 2021): 052110, https://doi.org/10.1117/1.JMI.8.5.052110

therapy and brachytherapy for cancer treatment. These innovations gave rise to the specialized field of radiotherapy by the 1930s.[4] Subsequently, in 1946, the production of radioisotopes at Oak Ridge Laboratory and the publication of pioneering research on radioactive iodine in the Journal of the American Medical Association (JAMA) marked the beginning of nuclear medicine as a recognized field.[5]

What began as a simple iodine-based treatment for thyroid disorders has now evolved into an advanced field known as theranostics. In this field, diagnostic and therapeutic techniques are integrated to personalize treatment, especially in fields like oncology and nuclear medicine. In addition, early imaging tools like rectilinear scanners have been succeeded by cutting-edge hybrid technologies such as PET-CT and SPECT-CT. These modern modalities enable detailed exploration of the underlying physiological and biochemical mechanisms of diseases such as cancer, cardiovascular disorders, neurological conditions, infections, inflammatory processes, and disorders of the lungs and kidneys.[6]

The continuous evolution of nuclear-based medical technologies is reshaping the global healthcare landscape at an unprecedented pace. It is now nearly inconceivable to envision a modern healthcare facility devoid of nuclear technologies, including radiology, nuclear medicine, and radiotherapy. These innovations are not only enhancing the quality of patient care but also contributing to broader access and operational efficiency within healthcare systems worldwide.

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[4] Gönül Kemikler, "History of Brachytherapy," *Turkish Journal of Oncology* 34, suppl. 1 (2019): 1–10, https://doi.org/10.5505/tjo.2019.1

[5] Saul Hertz and Arthur Roberts, "Radioactive Iodine in the Study of Thyroid Physiology VII: The Use of Radioactive Iodine Therapy in Hyperthyroidism," *Journal of the American Medical Association* 131, no.2(1946). https://doi.org/10.1001/jama.1946.02870190005002

[6] John Dennis Ehrhardt Jr. and Seza Güleç, "A Review of the History of Radioactive Iodine Theranostics: The Origin of Nuclear Ontology," *Molecular Imaging and Radionuclide Therapy* 29, no. 3 (2020): 88–97. https://doi.org/10.4274/mirt.galenos.2020.83703

Historical Development of Nuclear Technologies for Healthcare in Pakistan

Early Beginnings (1950s–1970s)

The application of nuclear technology in the health sector in Pakistan had a humble beginning in 1947 with an X-ray teletherapy machine being installed in Mayo Hospital, Lahore. Following the establishment of the Pakistan Atomic Energy Commission (PAEC) in 1956, a vision to harness nuclear science for energy, agriculture, industry, and healthcare emerged.[7] Thereafter, PAEC spearheaded the use of nuclear technologies in healthcare through its mandate for the peaceful, safe, and secure application of nuclear technology.

In 1960, Pakistan established its first nuclear medicine center, known as the Atomic Energy Medical Centre (AEMC) in Jinnah Postgraduate Medical Center (JPMC), Karachi. The center aimed to provide diagnostic and therapeutic services using radioactive isotopes for cancer treatment. Shortly thereafter, it was followed by the establishment of similar facilities by PAEC in Lahore, Hyderabad, Multan, Peshawar, among others. Most of these facilities initially provided nuclear medicine facilities with the help of a rectilinear scanner and uptake system. In the early 1970s, many radiation-based treatment machines and techniques like superficial and deep X-ray therapy equipment, strontium, gold wires and tubes, and a Co-60 teletherapy unit were developed. Historically, Pakistan inherited only a single X-ray-based teletherapy machine at the time of partition in 1947, which was placed in Mayo Hospital, Lahore.[8] Pakistan's first C0-60 unit was installed in the Nuclear Institute of Medicine and Radiotherapy (NIMRA), Jamshoro, in 1974. After becoming a member of the International Atomic Energy Agency (IAEA) in 1957, Pakistan began collaborating with it in the 1970s through its technical cooperation program.

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[7] Pakistan Atomic Energy Commission, "*The Pakistan Atomic Energy Commission Ordinance, 1965: Ordinance No. XVII of 1965*," Islamabad, 1983. https://inis.iaea.org/records/6nvmr-hf844
[8] Muhammad Mohsin Fareed, Muhammad Yahya Hameed, and Eileen Samuel, "Radiation Oncology Health Disparities in Pakistan," *The National Center for Biotechnology Information*, *Global Oncology* 9 (2023): e2300199, https://doi.org/10.1200/GO.23.00199

This collaboration was aimed at building capacity in the application of nuclear techniques in the health sector.[9]

Expansion and Institutionalization (1980s–1990s)

During the 1980s to 1990s, Pakistan steadily expanded its healthcare facilities by advancing nuclear technology in both public and private sectors. PAEC remained at the forefront by consistently establishing cancer treatment centers. These centers utilize advanced nuclear techniques for precise diagnosis and advanced management of noncommunicable diseases, especially cancer.

After the establishment of Pakistan's first nuclear medical center in 1960, PAEC expanded its mission of cancer care by adding five more cancer care facilities during the 1980s and 1990s. A significant landmark was the inauguration of the Nuclear Medicine, Oncology, and Radiotherapy Institute (NORI) Islamabad in 1983. Since then, the AECH-NORI has become the premier cancer care facility of Pakistan that offers cutting-edge cancer diagnosis, treatment, and academic training in the respective fields. It was also the first cancer care facility in the country to install a modern Linear Accelerator machine, paving the way to a new era of modern radiotherapy. Subsequently, NORI evolved as a comprehensive cancer care center, and in 2022, IAEA declared it as an Anchor Center under its "Ray of Hope" initiative for education and training in nuclear technology for cancer care.[10]

Another milestone was the establishment of the Institute of Nuclear Medicine and Oncology (INMOL) Lahore in 1984, which strengthened the national network of specialized cancer care institutions established by PAEC. Due to its achievements, the IAEA declared AECH INMOL a center

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[9] International Atomic Energy Agency, "*List of Member States*, International Atomic Energy Agency," https://www.iaea.org/about/governance/list-of-member-states
[10] Razya Khan, "NORI Cancer Hospital gets IAEA 'Anchor Centre," *Express Tribune*, 23 September 2023: https://tribune.com.pk/story/2437929/nori-cancer-hospital-gets-iaea-anchor-centre-status:also see, Amin Ahmed, "NORI cancer hospital designated 'anchor center' by IAEA," *Dawn*, 2023. https://www.dawn.com/news/1778038

of excellence and a referral center for Asia Pacific countries. AECH-INMOL is currently the largest cancer care facility within PAEC.[11] By adding these services, quality cancer care became accessible to populations that previously lacked adequate access.

During the 1990s, Pakistan's private sector also incorporated nuclear techniques in healthcare settings. Ziauddin Hospital in Karachi established the country's first private nuclear medicine in 1993.[12] Moreover, in 1994, Shaukat Khanum Memorial Cancer Hospital and Research Centre was inaugurated, which is Pakistan's first privately funded comprehensive cancer care facility providing an international standard of care to oncology patients. At the global level, there were many significant technological upgrades with the invention of gamma cameras for diagnostic scanning and widespread adoption of linear accelerators for radiotherapy, resulting in the improvement of disease detection and treatment capabilities.

Furthermore, Pakistan Institute of Nuclear Science and Technology (PINSTECH), a research and development facility of PAEC, helped in achieving self-sufficiency through the indigenous production of radioisotopes and radiopharmaceuticals. This journey began with the production of Iodine-131 (I-131) in the 1980s, which is used for the treatment of various thyroid pathologies. This was a major landmark toward reducing dependency on foreign sources and ensuring cost-effectiveness in treatment.[13]

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[11] Omar Yusuf, "IAEA Support Helps Pakistan to Conduct Novel Theranostic Interventions for the First Time, Expanding Cancer Care and Improving Outcomes", *International Atomic Energy Agency*, March 23, 2021. https://www.iaea.org/newscenter/news/iaea-support-helps-pakistan-to-conduct-novel-theranostic-interventions-for-the-first-time-expanding-cancer-care-and-improving-outcomes

[12] Maseeh uz Zaman and Nosheen Fatima, "Status of Nuclear Medicines in Pakistan,", *Pakistan Journal of Radiology,* Vol. 31 No. 3 (2021). https://www.pakjr.com/index.php/PJR/article/view/1435

[13] Mushtaq Ahmed, "Production of Radioisotopes in Pakistan Research Reactor: Past, Present and Future," paper presented at the IAEA Technical Meeting, Vienna, 2010 (Islamabad: Pakistan Institute of Nuclear Science and Technology), 4–13, https://www-pub.iaea.org/MTCD/Publications/PDF/SupplementaryMaterials/TECDOC_1713_CD/template-cd/datasets/papers/Mushtaq%20Production%20of%20RI%20PARR%20Mar2011.pdf

In the late 1990s, PINSTECH advanced its facilities by successfully developing the Molybdenum-Technetium (Mo-Tc) generator system, which is used in the daily operations of nuclear medicine departments for a wide range of diagnostic procedures. Simultaneously, PINSTECH also developed radiopharmaceutical kits, which are used in the imaging of various organs and disease processes. These initiatives collectively contributed to enhanced self-reliance, reduced operational costs, and uninterrupted supply chains for nuclear medicine centers across Pakistan.[14] Currently, PINSTECH is the major supplier of radioisotopes, radiopharmaceutical kits, and Mo-Tc generators to public and private sector nuclear medicine facilities across Pakistan.

The Era of Modernization and Technological Advancement (2000s–Present)

Nuclear technology in the healthcare sector of Pakistan entered a new era of development in the twenty-first century. This new era was marked by the installation of cutting-edge diagnostic and therapeutic equipment. In nuclear medicine, the most notable advancements were the development of hybrid imaging systems, including PET/CT and SPECT/CT. These hybrid systems provide high-resolution images with anatomical precision that help clinicians to visualize the underlying metabolic activities combined with anatomical aspects of diseases, resulting in enhanced diagnostic accuracy.

In 2009, Pakistan had its first public sector PET-Cyclotron facility at INMOL Lahore, a monumental landmark that helped in the local production of short-lived radiotracers used in PET imaging. This development transfigured cancer care in Pakistan, in addition to providing other benefits like reduced radioisotope costs and minimized reliance on imports.

Establishment of Cyberknife radiosurgery facility at Jinnah Postgraduate Medical Centre (JPMC) Karachi in 2012, further strengthened the usage of

[14] J. H. Zaidi, Mohammad Wasim, Mohammad Arif, and Mushtaq Ahmad, "Development of Radiochemistry in Pakistan – 1960 to 2010," *Radiochimica Acta* 100, no. 8–9 (April 2014): 555–568, https://www.researchgate.net/publication/236013073_Radiochemistry_in_Pakistan

nuclear technology for cancer care. Cyberknife is a non-invasive radiation treatment modality that allows for ultra-precise treatment of small-sized unapproachable tumors. The addition of Cyberknife expanded the range of treatment options for different types of cancers, which were once considered inoperable or difficult to manage with conventional radiotherapy.

By the mid-2010s, PAEC had established 18 cancer care hospitals, providing nuclear medicine and radiotherapy services to all provinces and major cities of Pakistan. This network has not only improved accessibility but also contributed to early diagnosis and better management outcomes for countless patients. These AECHs treat more than one million patients annually, with a constant increase in numbers every year.[15]

Along with clinical advancements, Pakistan has also excelled as a regional leader in nuclear medicine education and training. Several AECHs have gained national, international, and regional recognition, including endorsements from the IAEA and other local regulatory bodies, establishing the country as the center point for capacity-building and professional development in nuclear techniques.

Current Infrastructure and Facilities

Rise of Nuclear Medicine: From Modest Beginnings to a National Network

With a humble beginning in 1960, nuclear medicine has been transformed into a thriving network of nearly 51 nuclear medicine setups across Pakistan. This remarkable growth is a testament to the country's sustained commitment to integrating nuclear technology into healthcare infrastructure. Today, nuclear medicine is a critical pillar of diagnostic and therapeutic services nationwide, along with conventional and modern radiology.

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[15] Begum, N., Nasreen, S. and Shah, A.S. (2012) "Quantification of Trends in Radiation Oncology Infrastructure in Pakistan," 2004-2009. *Asia-Pacific Journal of Clinical Oncology,* 8, 88-94, http://dx.doi.org/10.1111/j.1743-7563.2011.01435

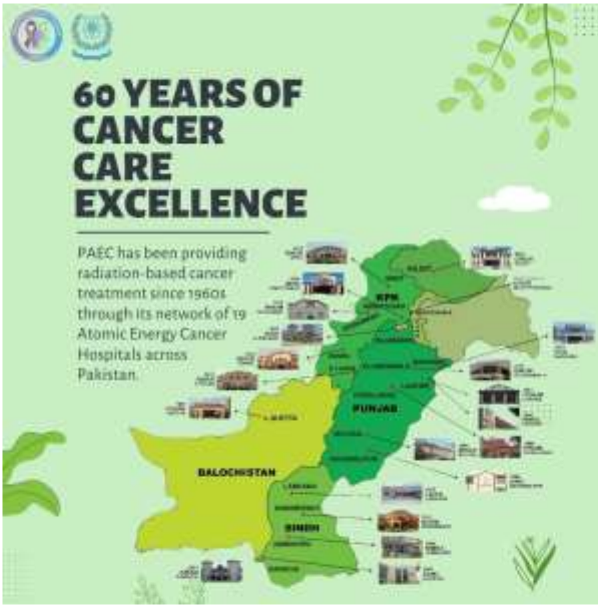

Fig. 1 Pakistan Atomic Energy Commission's Cancer Care Hospitals

The field of nuclear cardiology has seen substantial expansion with the introduction of sophisticated hybrid imaging SPECT/CT and PET/CT systems. Currently, 21 specialized centers are offering nuclear cardiology services across the country, helping in the early diagnosis and effective management of ischemic heart disease and other cardiovascular conditions. These centers utilize non-invasive nuclear imaging techniques that have improved the accuracy of cardiac assessments and disease management.

Modern nuclear medicine with hybrid imaging technologies and techniques, such as PET/CT and SPECT/CT, has added precision to the traditional diagnostic methods. Artificial intelligence (AI) incorporated in modern-day machines is proving to be a quantum leap in diagnostic capabilities. These innovations have resulted in increased image resolution and detailed insights into both anatomical and functional aspects of diseases. Nuclear Medicine has now become the integration of hybrid imaging, which has elevated the diagnostic capabilities of nuclear medicine to a level where it often becomes the decisive factor in clinical management, especially in complex cases like cancer.

Since the introduction of the first PET imaging facility in Pakistan in 2009, molecular imaging has gradually grown. Over the past 16 years, the country has established 15 PET and molecular imaging facilities, supported by 13 cyclotron facilities responsible for producing the short-lived radiotracers essential for PET imaging. This infrastructure is continually expanding, with a few more PET centers currently in the planning and development phase. At present, there are a total of 20 PET/CT cameras functioning in the country.

Likewise, the installation of approximately 25 SPECT/CT gamma cameras has further fortified the diagnostic arsenal available to nuclear medicine practitioners. These devices offer highly precise imaging across a wide spectrum of diseases, enabling timely and accurate diagnoses in oncology, cardiology, neurology, and other disciplines.

As reported by the IAEA's Medical Imaging and Nuclear Medicine Global Resources Database (IMAGINE), Pakistan has fewer than one PET scanner per million inhabitants, and similarly, the availability of SPECT gamma cameras stands at less than 2.5 units per million people.[16] This is significantly less than developed countries; however, there is a gradual improvement in the last few years, and the situation will improve in the years ahead.

Therapeutic Advances and the Emergence of Theranostics

The growth of nuclear medicine in Pakistan has not been limited to diagnostics alone. Therapeutic nuclear medicine has also witnessed a period of rapid advancement, driven by the approval and clinical adoption of novel radioisotopes for the treatment of various cancers. These agents are now used to target tumors with minimal impact on surrounding healthy tissue, offering patients safer and more effective treatment options.

[16] International Atomic Energy Agency, *IAEA DIRAC - International Atomic Energy Agency,* https://www.iaea.org/resources/databases/dirac

Theranostics is a concept that combines diagnostics and therapy using matched pairs of radioisotopes. Recent advances in matched radioisotopes and radiopharmaceutical production have transformed cancer therapy. However, the theranostic concept is not new, as Iodine-131 (I-131) has been a longstanding theranostic agent used in nuclear medicine since the start of the specialty. However, the development of numerous new radiopharmaceutical and radioisotopes pairs has opened new avenues for therapeutic nuclear medicine, which has dramatically expanded the scope of nuclear medicine.

Lutetium-177 (Lu-177) based therapies, using peptides like prostate surface membranous antigen (PSMA) and DOTATAE have changed the treatment landscape for neuroendocrine tumors and metastatic prostate cancer. These therapies received Food and Drug Administration (FDA) approvals in 2020 and 2023, respectively, as standard-of-care treatments in clinical oncology. In Pakistan, AECH-INMOL established the first full-fledged theranostic facility in 2017, where Gallium-68 (Ga-68) PET imaging is paired with Lu-177-labeled therapeutic radiopharmaceuticals.[17] Since the establishment of this theranostic facility, the center has successfully treated over 500 cancer patients using state-of-the-art protocols.

Thus far, six AECH have started theranostic treatment modality, namely INMOL, NORI, The Institute of Radiotherapy and Nuclear Medicine (IRNUM), Karachi Institute of Radiotherapy and Nuclear Medicine (KIRAN), PINUM Cancer Hospital, and Gujranwala Institute of Nuclear Medicine and Radiotherapy (GINUM). Additionally, three private sector hospitals have also begun offering theranostic services, demonstrating growing confidence and investment in this domain from both public and private healthcare institutions.

The range of new radioisotopes has further broadened the therapeutic options. These include Actinium-225 (Ac-225), labeled PSMA for advanced

[17] "First Theranostic Lab at INMOL Hospital," *The Nation*, November 7, 2017. https://www.nation.com.pk/07-Nov-2017/first-theranostic-lab-at-inmol-hospital

prostate cancer, Yttrium-90 (Y-90) TheraSphere for liver tumors, and various beta and alpha emitters used in bone pain palliation and metastatic cancer therapy. These agents have given flexibility for clinicians to personalize cancer treatment, improve patient quality of life, and extend survival.

Evolution and Expansion of Radiation Therapy in Cancer Care

The role of nuclear technologies in cancer management extends far beyond diagnostics; it is at the very heart of treatment for a significant portion of patients. Globally, and in Pakistan alike, approximately 70% of cancer cases require external beam radiation therapy (EBRT), also known as teletherapy, either as a standalone treatment or in combination with chemotherapy or hormonal therapy. Radiation therapy has emerged as a cornerstone in oncological care, especially in solid tumors, where it delivers curative and palliative outcomes with increasing precision and safety.

According to GLOBOCAN,[18] in 2022, there were about 0.18 million new and 0.39 million prevalent (5-year) cancer patients in Pakistan.[19] According to Radiotherapy and Theranostics, a Lancet Oncology Commission,[20] and the Directory of Radiotherapy Centers (DIRAC),[21] there are 1-3 radiotherapy machines for a population of 1 million in Pakistan. Although this number still needs a huge improvement, there has been a constant improvement in the radiotherapy landscape of Pakistan.

Indeed, Pakistan's journey in this field reflects a remarkable transformation. What began with a solitary X-ray machine decades ago has now evolved

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[18] Global Cancer Observatory, *Global Cancer Fact Sheet: World* (Lyon, France: International Agency for Research on Cancer, 2023), https://gco.iarc.who.int/media/globocan/factsheets/populations/900-world-fact-sheet.pdf

[19] J. Ferlay et al., *Global Cancer Observatory: Cancer Today*, Lyon, France: International Agency for Research on Cancer. https://gco.iarc.who.int/media/globocan/factsheets/populations/586-pakistan-fact-sheet.pdf

[20]May Abdel-Wahab et al., "Radiotherapy and Theranostics: A Lancet Oncology Commission," *The Lancet Oncology*, https://www.thelancet.com/journals/lanonc/article/PIIS1470-2045(24)00407-8/abstract

[21]International Atomic Energy Agency, *IAEA DIRAC - International Atomic Energy Agency*. https://www.iaea.org/resources/databases/dirac

into a sophisticated national infrastructure featuring cutting-edge technologies like Cyberknife and Linear Accelerators (LINACs).[22] PAEC, with its 19 cancer hospitals, is the largest public-sector cancer treatment network in Pakistan. PAEC is leading the technological revolution in cancer care across the country. These centers are equipped with state-of-the-art facilities for radiation treatment planning, simulation, and radiation treatment delivery, providing hope to thousands of cancer patients every year. In addition to the PAEC cancer care network, there are about 30 cancer care facilities offering medical or radiation treatment to cancer patients.

In terms of equipment, Pakistan's radiotherapy facilities encompass an array of teletherapy machines. Traditional Cobalt-60 (Co-60) machines,[23] once the backbone of radiation treatment, are still in use in many public and private sector hospitals, especially in resource-limited settings. These machines continue to serve both palliative and curative purposes, particularly in regions where advanced technology is still lacking. However, technological progress has seen a widespread shift toward Linear Accelerators, which now number around 58 units, including single and dual-energy LINACs.

This transition is not merely an upgrade in hardware, but it's a game-changer in radiation treatment. Modern radiotherapy techniques such as Intensity-Modulated Radiation Therapy (IMRT), Image-Guided Radiation Therapy (IGRT), Volumetric-Modulated Arc Therapy (VMAT), Stereotactic Radiosurgery (SRS), and Stereotactic Body Radiation Therapy (SBRT) are used in many cancer centers in Pakistan.[24] These advanced techniques result

[22] Muhmmad Mohsin Fareed et al., "Evolution of Radiation Oncology in Pakistan," *International Journal of Radiation Oncology, Biology, Physics* 105, no. 4 (2019): 766–772, https://www.redjournal.org/article/S0360-3016(19)30648-0/fulltext

[23] B. J. Healy et al., "Cobalt-60 Machines and Medical Linear Accelerators: Competing Technologies for External Beam Radiotherapy," *Clinical Oncology* 29, no. 2 (2017): 110–115, https://doi.org/10.1016/j.clon.2016.11.002

[24] Franjo Cmrečak, Iva AndraŠek, Meliha Solak Mekić, Mirna Ravlić, and Lidija Beketić-Orešković, "Modern Radiotherapy Techniques," *Libri Oncologici* 47, no. 2–3 (2019): 91–97, https://doi.org/10.20471/LO.2019.47.02-03.17

in remarkable precision in radiation delivery, delivering high radiation doses to tumors while sparing healthy tissues, improving patient outcomes.

Further advancement in radiation treatment is through the installation of Cyberknife and Gamma Knife systems in both public and private sector hospitals. This highly sophisticated equipment is specially designed to treat small and deeply located tumors with extraordinary precision. Utilizing highly focused beams of radiation, these machines can often achieve therapeutic effects in just a few treatment sessions, as opposed to the twenty to thirty treatment sessions required with conventional teletherapy machines. Currently, six such systems are operational in Pakistan, offering targeted radiation treatment for conditions such as brain tumors, spinal lesions, and early-stage cancers in other critical areas.

Additionally, there is another advanced teletherapy machine, the MR LINAC, a hybrid machine, that combines MRI with a Linear Accelerator.[25] This cutting-edge technology allows real-time imaging during treatment. Three MR LINAC systems have recently been installed in leading hospitals of Sindh province, marking Pakistan's venture into the global elite of radiotherapy providers.

Regulation and Safety

The PNRA plays a pivotal role as the guardian of safety and standardization in treatment and diagnosis using ionizing radiation.[26] PNRA has been mandated to oversee the responsible use of radiation in medical and healthcare settings. It ensures that all healthcare institutions using nuclear techniques operate within a framework of stringent licensing, regulatory compliance, and international safety protocols, particularly those laid out by the IAEA. From the quality assurance (QA), quality control (QC), calibration of diagnostic equipment like gamma cameras, SPECT/CT, and

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[25] Muhammad Atif Mansha and Shahzaib Naeem, "Welcoming the First Magnetic Resonance-Integrated Linear Accelerator in Pakistan," *Journal of the College of Physicians and Surgeons Pakistan* 35 (2025): 481, https://doi.org/10.29271/jcpsp.2023.04.481

[26] Pakistan Nuclear Regulatory Authority, "Radiation Protection," https://www.pnra.org/r-safety.html

PET scanners, to the use of high-energy radiation machines for cancer treatment including Co-60 units, LINACs, and Cyberknife system, PNRA's oversight ensures that the benefits of these technologies are delivered without compromising human health or environmental safety.[27] PNRA not only facilitates the safe integration of nuclear science into medicine but also strengthens public trust in technologies that are vital to the diagnosis and treatment of cancer, cardiovascular diseases, and other life-threatening conditions.

Socioeconomic Impact

Applications of nuclear techniques have revolutionized the health sector in many ways. First and foremost, the diagnosis of diseases has almost totally shifted to radiation techniques or technologies. Whether it's cancer detection, cardiac diseases, renal pathologies, GIT related ailments, neurological disorders, musculoskeletal or joint pathologies, infection or inflammation, nuclear medicine and radiological imaging techniques, using radiation has become a part of the many diagnostic guidelines. These modern modalities ensure early disease detection, help in the assessment of the efficacy of the treatment, and guide the recurrence of the disease. This has led to improved quality of life and enhanced overall survival. Early detection and tailored management using these techniques have a high impact on the healthcare sector. These advancements help in cost saving through early detection and comprehensive management by facilitating timely intervention and reducing the need for prolonged or invasive therapies. Training and employment opportunities have increased in fields like radiotherapy, medical physics, radio pharmacy, and nuclear medicine technology.

Nuclear medicine and radiological techniques have significantly transformed disease detection and Pakistan's healthcare landscape, offering advanced diagnostic and therapeutic options that enhance patient outcomes

[27] International Atomic Energy Agency, *Quality Assurance for SPECT Systems*, Human Health Series No. 6 (Vienna: IAEA, 2009). https://www.iaea.org/publications/8119/quality-assurance-for-spect-systems

and contribute to the nation's economy through cost savings. The PAEC has been at the forefront of integrating nuclear technology into healthcare. Through its established 19 AECHs across the country, it provides diagnostic and treatment services to over 40,000 new cancer patients annually and performs approximately one million diagnostic and treatment procedures each year.[28] These facilities utilize state-of-the-art imaging technologies, including SPECT and PET scans, enabling early and accurate disease detection.[29] About 200,000 nuclear medicine procedures are performed annually across Pakistan for diagnosing various pathologies, including cancer.[30]

In radiotherapy, Pakistan has made remarkable advancements. Currently, there are 58 radiation treatment units in the country, comprising 27 linear accelerators and 31 Cobalt-60 machines. These facilities have improved access to cutting-edge cancer treatment. In PAEC cancer hospitals, nearly 75000 radiotherapy procedures were performed in 2024.

The expansion of nuclear medicine and radiological services also has economic implications. By facilitating early diagnosis and effective treatment, these technologies reduce the burden of disease, lower healthcare costs, and enhance workforce productivity. Moreover, the development of local expertise and infrastructure in nuclear medicine has fostered job creation and technological innovation, contributing to economic growth.

To sum up, the integration of nuclear medicine and radiological techniques into Pakistan's healthcare system has not only improved patient care but also supported economic development through cost savings, job creation, and technological advancement.

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[28] Associated Press of Pakistan, "PAEC Serve over 40,000 New Cancer Patients Each Year," *APP*. https://www.app.com.pk/national/paec-serve-over-40000-new-cancer-patients-each-year/

[29] Fawaz F. Alqahtani, "SPECT/CT and PET/CT, Related Radiopharmaceuticals, and Areas of Application and Comparison," *Saudi Pharmaceutical Journal* 31, no. 3 (2023): 279–291, https://doi.org/10.1016/j.jsps.2022.12.013

[30] S. J. Khurshid, "Nuclear Medical Centers of PAEC," *The Nucleus* 42, no. 1–2 (2005): 93–96, http://thenucleuspak.org.pk/index.php/Nucleus/article/view/1051/704

Positioning Pakistan's Healthcare Facilities within the Global Landscape

Healthcare infrastructure involving nuclear technologies and techniques has significantly evolved in Pakistan since its independence. However, considerable gaps continue to exist due to the high capital cost involved in procuring and running these high-end technologies. Pakistan has most of the modern diagnostic and treatment equipment commonly used globally, surpassing many LMIC; however, cutting-edge equipment remains an unfulfilled aspiration.

When we compare the nuclear medicine landscape in Pakistan with global standards, it is satisfying to document tremendous growth from a rectilinear scanner to hybrid and molecular imaging technology, providing information at the cellular level. Although Pakistan has attained most of the high-end technology and techniques in Nuclear Medicine and related fields but comparison with the Western world shows that we still are deficient in equipment like Whole body PET system, PET-MR, SPECT-MR. Although these machines are highly specialized and are beneficial in very few pathologies but there should be availability of this equipment in any of our highly specialized nuclear Medicine setups. Acquisition of these innovative technological inventions is hindered due to the high capital cost of this equipment.

Radionuclide therapies (RNTs) and theranostic techniques are in vogue. Although 5-6 hospitals in Pakistan are offering established RNT/Theranostic techniques to patients, we are lagging in the production of novel radioisotopes and radiopharmaceuticals, which are currently available for experimental and clinical use globally. New radioisotopes like Ac225, Bi212/213, Cu 64/ Cu 67, Rd223, Tb (149, 152, 155 and 161), Zr89, Y90, etc, which are currently used globally for diagnosis and treatment, are not available in Pakistan. We direly need indigenous production to save huge import costs and to benefit patients with these specialized radioisotopes for the management of various cancers. PINSTECH is diligently working to supply the currently utilized Lu-177 for therapeutic purposes.[31] However, the growing demand from various nuclear medicine centers necessitates an expansion of the current production capacity.

In the field of radiotherapy, despite an inadequate ratio of population to EBRT (External Beam Radiotherapy) machines, Pakistan does possess several state-of-the-art teletherapy units, starting from a time-tested C0-60 teletherapy machine to highly precise Robotic Cyberknife machines. These high-end units are mainly limited to the bigger cities like Karachi, Lahore, Islamabad, and their distribution in the country is skewed. Pakistan, despite having most of the teletherapy machines, lacks advanced particle therapy technologies such as proton therapy, Carbon ion radiotherapy (CIRT), and Boron Neutron Capture Therapy (BNCT). This extremely expensive equipment uses sophisticated techniques for radiation treatment, but these are currently unavailable in Pakistan. Currently, a proton therapy unit is under consideration, but it will take a few years before it can be available for therapeutic purposes to cancer patients in Pakistan.

Advanced teletherapy techniques like Flash radiotherapy,[32] novel three-stage nanotechnology- chemo-radiation combinatorial approach, interoperative radiotherapy, and combined photodynamic therapy are showing promising and favorable results in comparison with conventional techniques.[33] However, these techniques are still not available in the country. These techniques can be implemented after the necessary infrastructure development.

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[31] Pakistan Atomic Energy Commission, "Pakistan: Strategy for Self-Reliance and Sustainability of Radiopharmaceutical Production Facility in Pakistan," in *Sustainability and Self-Reliance of National Nuclear Institutions: Proceedings of a Workshop*, IAEA-TECDOC-1943 (Vienna: International Atomic Energy Agency, 2020), 77–84. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1943web.pdf

[32] R. Tang, J. Yin, Y. Liu, and J. Xue, "FLASH Radiotherapy: A New Milestone in the Field of Cancer Radiotherapy," *Cancer Letters* 587 (April 10, 2024): 216651, https://doi.org/10.1016/j.canlet.2024.216651

[33] K. Koka, A. Verma, B. S. Dwarakanath, and R. V. L. Papineni, "Technological Advancements in External Beam Radiation Therapy (EBRT): An Indispensable Tool for Cancer Treatment," *Cancer Management and Research* 14 (April 11, 2022): 1421–1429, https://doi.org/10.2147/CMAR.S351744

In addition, AI in diagnostic imaging and treatment has transformed the healthcare landscape. Most of the diagnostic and treatment equipment is already laced with advanced AI software. Pakistan needs substantial investment in the AI sector to develop AI algorithms based on local data, which will aid in swift and accurate diagnosis and treatment.

Furthermore, Pakistan needs to strengthen the nuclear technology-based diagnostic and therapy network, as currently our machine-to-population ratio is dismal even in comparison with LMIC. Pakistan currently has 19 PET scanners. Optimally, a population of one million requires at least 1-2 scanners,[34] meaning approximately 230 scanners are needed for the entire population, which does not seem to be possible shortly. The situation is similar in teletherapy equipment. According to a comprehensive study published in Lancet Global Health, there is a huge gap (58 existing units compared to ˜200 machines needed) in radiation treatment machines in the country. So, in addition to upgrading technological infrastructure, there is an urgent need to expand and increase the number of diagnostic and treatment machines. There should also be a homogeneous distribution of facilities across the country instead of concentration in larger cities for better access to patients living in remote areas of Pakistan.

Although Pakistan has made significant progress since its independence, access to nuclear medicine and radiotherapy facilities remains uneven, with rural and underdeveloped areas still underserved. Moreover, some novel radiopharmaceuticals, especially therapy-related ones, are not locally available; hence, they must be imported. Lastly, keeping abreast of the rapidly evolving technological horizons warrant continuous training of the workforce.

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[34] Agency, International Atomic Energy (IAEA). 2023: *https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINEMaps4.html.* Jan. https://www.iaea.org/resources/hhc/nuclear-medicine/databases/imagine#section-5

Strategic Priorities

To cater to the ever-increasing utilities and demands of these nuclear technologies in healthcare, Pakistan needs to expand its network of healthcare facilities with these specialized techniques to Balochistan, rural Punjab, Khyber Pakhtunkhwa (KPK), and Sindh. Pakistan needs further investment in local isotope production and cyclotron facilities. One way of enhancing these capabilities is by strengthening public-private partnerships for sustainable growth. Additionally, Pakistan needs to leverage emerging technologies by integrating AI into imaging interpretation and radiation planning.

Despite significant advancements, challenges persist, including the need for more widespread access to nuclear medicine services, especially in remote areas. Future efforts should focus on expanding infrastructure, enhancing local production of radiopharmaceuticals, and fostering international collaborations to stay abreast of technological innovations.

Conclusion

The integration of nuclear applications into Pakistan's healthcare system has had a profound and lasting impact. From humble beginnings in the 1960's to the establishment of world-class institutions offering cutting-edge diagnostics and therapies, Pakistan's progress is commendable. As the country continues to face rising cancer and cardiac disease rates, nuclear medicine will play a central role in managing this burden. Sustained support, innovation, and equitable access are critical for its future trajectory.

Leveraging Space Science and Technology for Climate-Induced Disaster Management in Pakistan

Ibrar ul Hassan Akhtar and Maryam Mehboob[*]

Abstract

The frequency and severity of climate-related disasters, such as floods, droughts, heatwaves, and glacier melt, are on the rise and pose serious threats to vulnerable countries. Due to warming temperatures, changing rainfall patterns, and glacier melting, Pakistan is facing increased risks to its agriculture, water resources, infrastructure, and human security. This paper discusses how space science and technology can play a pivotal role in improving Pakistan's ability to deal with climate-led disasters. It also examines the institutional arrangements, technological tools, and national politics that facilitate the integration of Earth Observation (EO), satellite remote sensing, Geographic Information Systems (GIS), and Artificial Intelligence (AI) in Disaster Risk Reduction (DRR) and Early Warning Systems (EWS). Efforts of Space and Upper Atmosphere Research Commission (SUPARCO), its collaborations with national and international agencies, satellite programs like Remote Sensing Satellite System (PRSS) and Pakistan Remote Sensing Satellite - Earth Observation 1 (PRSC-EO), as well as its contribution to research initiatives like the Space Application Center for Response in Emergency and Disaster (SACRED) and the Natural Catastrophe Modelling (NatCat) initiative are discussed in detail in this study. Drawing on international best practices from countries such as China, Japan, and the United States, this paper examines how emerging technologies like big data analytics, Machine

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Learning (ML), and high-performance computing are transforming disaster management. While Pakistan has made significant progress in this area, it still faces major challenges, including a lack of satellite infrastructure, inadequate funding, poor inter-agency coordination, and difficulties with last-mile data application. The paper concludes that with continued investment, improved institutional cooperation, and capacity-building efforts, Pakistan can effectively leverage space-based solutions to enhance climate resilience and reduce disaster risks.

Keywords: Space Science, Earth Observation, Climate Change, Natural Disasters, Pakistan

Introduction

Climate change has become one of the major issues of the twenty-first century, and its effects are becoming more noticeable due to the increasing rate and intensity of natural disasters like floods, droughts, heat waves, and wildfires. In addition to causing massive human loss, these climate-related disasters also cause massive socio-economic losses, especially in developing countries where infrastructure and adaptive capacities are usually insufficient. Pakistan, located at the crossroads of various climate zones and unstable ecosystems, is especially susceptible. Whether it is the long-term drought in Balochistan, the devastating floods in Sindh, or the melting of glaciers in the highlands, the country is exposed to complex climate risks that endanger food security, water supply, human health, and national growth.

To counter these mounting threats, advanced technologies, particularly space-based technologies, like EO, GIS, and Satellite Remote Sensing (SRS), are becoming central. These technologies provide immeasurable assistance at every stage of disaster management. For example, they can support EWS, help conduct a quick damage assessment and guide the development of long-term resilience strategies. At the international level, other countries such as China, Japan, and the US have shown how the incorporation of space science in DRR systems can revolutionize response systems and reduce the effects of climate change.

In Pakistan, SUPARCO has been at the forefront in incorporating satellite-based technologies in the disaster management systems, such as the SACRED and NatCat Risk Modelling for major disasters of flood, drought, landslides, cyclones, and heatwaves. Nonetheless, these efforts are still faced with challenges such as insufficient satellite resources, reliance on foreign launch services, and data integration and policy implementation gaps. This study aims to assess the role of space science and technology in climate-related disaster management in Pakistan, outline the current institutional frameworks, technology, global good practices and policies, as well as define the key challenges and future development opportunities.

Climate Change and Disaster Risks

Climate Change is a long-term change in weather patterns across land, ocean, and atmosphere, and is considered one of the most significant global challenges in today's world. It affects various sectors, including agriculture, biodiversity, human health, and the economy. It results from both natural aspects, like volcanic eruptions, and anthropogenic activities such as deforestation and burning fossil fuels. This has led to extreme weather events, sea-level rises, and shifts in ecosystems, which threaten species' survival and biodiversity. Its impacts are felt globally, but the degree of impact varies, based on regional factors and the level of disaster preparedness.[1] Hence, there is a need to adopt interdisciplinary approaches combining AI, data science, environmental science, and policymaking to address climate change.[2]

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[1] Abbass, Kashif, Muhammad Zeeshan Qasim, Huaming Song, Muntasir Murshed, Haider Mahmood, and Ijaz Younis, "A review of the global climate change impacts, adaptation, and sustainable mitigation measures" *Environmental science and pollution research* 29, no. 28 (2022), pp. 42539-42559. https://link.springer.com/article/10.1007/s11356-022-19718-6

[2] Ahmed Hussein Ali and Rahul Thakkar, "Climate Change Through Data Science: Understanding And Mitigating Environmental Crisis," *Mesopotamian Journal of Big Data* Dec 2 (2023), pp. 125-137, https://mesopotamian.press/journals/index.php/bigdata/article/view/177

The increasing severity and frequency of natural disasters, exacerbated by climate change, have highlighted gaps in current disaster management systems. Traditional disaster response approaches are often inadequate for managing the complexity and unpredictability of modern disasters.[3] Climate-related disasters affect developing countries the most, where vulnerable populations are increasingly threatened by rising temperatures and unpredictable weather patterns. Vulnerability to climate change is driven by poor socioeconomic conditions, exposure to risks, and the lack of disaster management systems.[4] The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) synthesizes the current state of knowledge regarding climate change, its impacts, risks, and potential mitigation and adaptation responses.[5] The document highlights that despite the advancements made in adaptation activities, there are still major gaps. Although there are some policy improvements, the existing national commitments are not sufficient to keep global warming to 1.5°C or even 2°C. It stresses that mitigation and adaptation solutions exist, but the time to act effectively is running out, and the world needs to act now.

Regional Vulnerabilities and Disaster Trends

Arid and Semi-Arid (ASA) regions cover 41% of the Earth's land surface and are home to approximately 2.5 billion people. These regions often face challenges like irregular climatic conditions, droughts, and political instability.[6] South Asia is highly vulnerable to natural hazards, with over

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[3] Justin Diehr, Ayorinde Ogunyiola, and Oluwabunmi Dada, "Artificial Intelligence and Machine Learning-Powered GIS for Proactive Disaster Resilience in a Changing Climate," *Annals of GIS* (2025), pp. 1–14; Ibrar ul Hassan Akhtar, "Managing Urban Flooding," (2017), https://tribune.com.pk/story/1502156/managing-urban-flooding/; Ibrar ul Hassan Akhtar, "Pakistan Needs a Fresh Disaster Mitigation Strategy," (2015), http://www.scidev.net/global/disasters/opinion/pakistan-disaster-mitigation-strategy.html

[4] Linpei Zhai and Jae-Eun Lee, "Investigating Vulnerability, Adaptation, And Resilience: A Comprehensive Review Within the Context of Climate Change," *Atmosphere* 15, no. 4 (2024), p. 474 (April 11, 2024). https://www.mdpi.com/2073-4433/15/4/474.

[5] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Core Writing Team, H. Lee, and J. Romero (Geneva: IPCC, 2023), https://mural.maynoothuniversity.ie/id/eprint/17886/1/IPCC_AR6_SYR_SPM.pdf

[6] Sarchil Hama Qader, Jadu Dash, Victor A. Alegana, Nabaz R. Khwarahm, Andrew J. Tatem, and Peter M. Atkinson. "The Role of Earth Observation in Achieving Sustainable Agricultural

70% of its population living in poverty, and faces increasing vulnerability due to urbanization, environmental degradation, and political instability.[7] The region has high economic losses from disasters, with Average Annual Losses (AAL) reaching over USD 153 billion. Countries like Bangladesh, India, and Nepal experience the highest losses relative to their GDP.[8] Natural disaster management challenges in South Asia include a lack of preparedness, inefficient EWS, poor infrastructure, limited resources, and coordination challenges. This emphasizes the need for targeted interventions like the integration of DRR and Climate Change adaptation (CCA) into national policies to improve the resilience of South Asian countries.[9]

The region has flood-prone countries that have distinct geographic and climatic features, which lead to a variety of floods, including riverine and flash floods. Such floods tend to cause extensive loss of lives and destruction of crops, infrastructure, and local economies, which are particularly devastating in low-income and highly populated regions. Conversely, droughts are among the most complicated and least studied natural hazards, which impact more individuals in the world than any other category of disaster. Droughts are influenced not only by meteorological abnormalities like a deficit of precipitation but also by anthropogenic activities like unsustainable land use, water management, and bad governance. Droughts are especially hard to track and react to, due to their slow-onset nature, which can result in a delayed response and a long-term

Production in Arid and Semi-Arid Regions of the World," *Remote Sensing* 13, no. 17 (2021), pp. 3382. https://www.mdpi.com/2072-4292/13/17/3382

[7]Shesh Kanta Kafle, "Disaster risk management systems in South Asia: Natural hazards, Vulnerability, Disaster Risk and Legislative and Institutional Frameworks," *Journal of Geography & Naural Disasters* 7, no. 207 (2017), pp. 2167-0587. https://www.researchgate.net/publication/321228880_Disaster_Risk_Management_Systems_in_South_Asia_Natural_Hazards_Vulnerability_Disaster_Risk_and_Legislative_and_Institutional_Frameworks

[8]ESCAP, UN, "The Disaster Riskscape Across South Asia: Key Takeaways for Stakeholders," (2020). https://www.unescap.org/sites/default/d8files/knowledge-products/IDD-APDR-Subreport-SSWA-v1-8-P.pdf

[9]Muhammad Ahsan Samad, Kadir Arifin, and Azlan Abas. "A systematic literature review on the challenges of Southeast Asian countries in natural disaster management," *Cogent Social Sciences* 11, no. 1 (2025) https://www.tandfonline.com/doi/epdf/10.1080/23311886.2024.2435590

socio-economic effect especially in agrarian societies. Such accumulating weaknesses require the application of superior technologies like space-based Earth Observation Systems (EOS), which may assist in tracking climatic trends, early warning indicators, and evidence-based policy responses in the South Asian region.

Pakistan's Climate Vulnerabilities

Pakistan faces increased climate risks, including temperature rise, glacier retreat, altered rainfall patterns, and more frequent extreme weather events such as floods and droughts. The Indus Delta is vulnerable to rising sea levels, coastal erosion, saline intrusion, and increased flooding, threatening agriculture (food security) and biodiversity.[10] Pakistan's vulnerability to climate change has increased since 1999, with many extreme climate events affecting water resources and agriculture. The recent extreme events in Pakistan are floods (2010, 2013, 2014, 2015, and 2022) and a long-term drought in 1998-2002, which have severely affected the agriculture, water resources, infrastructure, and livelihoods in Pakistan, indicating the increasing vulnerability of the country to climate change.[11]

Pakistan experienced record-breaking monsoon rainfall in 2022, leading to severe flooding, particularly in the provinces of Sindh and Balochistan. Climate change has likely increased rainfall intensity by up to 50%.[12] Communities living near glaciers face the brunt of these natural hazards. Despite low carbon footprints, these communities are highly vulnerable to

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[10]Rasul, Ghulam. "Climate data and modelling analysis of the Indus region," *Pakistan Meteorological Department* (2012).https://wwfasia.awsassets.panda.org/downloads/climate_data_modelling_analysis_of_the_indus_ecoregion.pdf

[11] Sohail Abbas et al., "Spatial-Temporal Seasonal Variability of Extreme Precipitation under Warming Climate in Pakistan," *Atmosphere* 14, no. 2 (2023): 210, https://www.mdpi.com/2073-4433/14/2/210

[12] Friederike E. L. Otto et al., "Climate Change Increased Extreme Monsoon Rainfall, Flooding Highly Vulnerable Communities in Pakistan," *Environmental Research: Climate* 2, no. 2 (2023): 025001, https://iopscience.iop.org/article/10.1088/2752-5295/acbfd5.

the consequences of climate change.[13] The 2022 mega-flood in Pakistan was one of the most severe, affecting two-thirds of the country and causing considerable damage to agriculture, infrastructure, and livelihoods. Climate Change is also impacting mountainous areas, which are extremely sensitive to climate change, with visible indicators like glacier retreat and temperature shifts. These changes have significant implications for water supply, biodiversity, and infrastructure.[14]

Besides environmental impacts, climate-related catastrophes in Pakistan have led to serious socio-economic impacts such as mass displacement, poverty, destruction of essential infrastructure, and agricultural losses. The agriculture sector, which supports a significant number of people in the rural areas of Pakistan, is especially vulnerable to altered precipitation patterns and rising temperatures. In the same way, glacier melting and erratic hydrological cycles pose a threat to the energy and water security of the country. These interrelated weaknesses require a multi-sectoral and science-based response. Although Pakistan has advanced in climate adaptation planning with policy tools such as the National Climate Change Policy and the National Adaptation Plan, implementation is disjointed and under-funded. The combination of space-based technologies, including EO and remote sensing, offers a pivotal possibility to strengthen the disaster risk reduction and EWS in the country.

Space-Based Technologies for Disaster Management

Satellite remote sensing is important in delivering timely and precise data in disaster preparedness, response, and recovery. The rising rate and intensity of climate-related disasters require new and prompt solutions to disaster management. Technologies like Synthetic Aperture Radar (SAR)

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[13] Misha Shahid, "Confronting Glacial Hazards: A Study of Disaster Impact and Community Adaptation to Glacial Lake Outburst Floods in Hunza, Pakistan," PhD diss., *Massachusetts Institute of Technology*, 2024. https://dspace.mit.edu/handle/1721.1/156156

[14] Thomas Kohler and Daniel Maselli, "*Mountains and climate change. From Action Understanding*", Geographica *Bernensia*, 2009. https://www.activeremedy.org/wpcontent/uploads/2014/10/kohler_t._et_al_2009_%E2%80%98mountains_and_climate_change.pdf

are especially useful, since they can be used to acquire high-resolution imagery independent of cloud cover or lighting, and are therefore invaluable during flood events, cyclones, and other rapidly changing hazards. Such systems enable authorities to evaluate the effects of disasters in near real-time, distribute resources more efficiently, and introduce informed relief measures.[15]

In addition to the observation satellites, the use of Information and Communication Technologies (ICTs) like the Flood Early Warning Systems (FEWS) has enhanced the ability to predict, track, and act on the hydrometeorological threats.[16] When coupled with Geo-Information Technologies (GIT) such as Remote Sensing (RS), GIS, and Global Positioning System (GPS), disaster managers have an effective set of tools to detect hazards, map risks, and assess damage after the event. The technologies facilitate multi-hazard monitoring and allow decision-makers to visualize risk in both spatial and temporal dimensions, which helps in rapid response and long-term planning.[17]

Nevertheless, disaster management is not only a matter of technological capacity. The perception of disaster risks, i.e., how people and communities learn to interpret and react to risks, is the central factor that determines preparedness and behavioral response. Research has shown that the more a population is aware of the dangers of floods, the more likely they are to take precautionary measures, evacuate early, and recover quicker. Unfortunately, there is still a disconnect between the real risk and perceived risk in most

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[15] Julie Rolla et al., "Satellite-Aided Disaster Response," *AGU Advances* 6, no. 1 (2025), https://doi.org/10.1029/2024AV000109; Ibrar ul Hassan Akhtar and H. Athar, "Contribution of Changing Precipitation and Climatic Oscillations in Explaining Variability of Water Extents of Large Reservoirs in Pakistan," *Scientific Reports* 9, no. 1 (2019), https://doi.org/10.1038/s41598-019-50020-1 ; Ibrar ul Hassan Akhtar and H. Athar

[16] Farhan Shafiq and Kamran Ahsan, "An ICT-Based Early Warning System for Flood Disasters in Pakistan," *Research Journal of Recent Sciences* 3, no. 9 (September 2014): 108–118, http://www.isca.in

[17] M. Hussain, Mudassar Hassan Arsalan, Kashif Siddiqi, and Bushra Naseem, "Emerging Geo-Information Technologies (GIT) for Natural Disaster Management in Pakistan: An Overview," in *Proceedings of the 2nd International Conference on Recent Advances in Space Technologies (RAST 2005)*, 2005, 204–209, https://doi.org/10.1109/RAST.2005.1512618

vulnerable areas. The result of this disconnect is frequently poor individual preparedness, opposition to early warning, and poor community-based response plans. To fill this gap, it has increasingly been acknowledged that technological solutions should be supported by community involvement, education programs, and risk communication at the local levels. Space-based tools can be critical in the process, as they can visualize the hazards in an accessible way and alter risk information to specific geographic and social situations. Finally, the combination of space-based advanced technologies and inclusive disaster risk governance can become a powerful tool to enhance national and local capacities to manage climate-induced disasters.

Emerging Technologies and Global Best Practices

The rising complexity and severity of climate-related disasters have triggered the adoption of emerging technologies in disaster risk management systems across the globe. One of the most revolutionary advancements is the application of high-performance computing (HPC) to process and analyze the large amounts of satellite data collected by polar-orbiting and geostationary EO satellites. HPC greatly improves the rate and accuracy of disaster detection and allows real-time creation of geospatial products needed to provide early warnings, situational awareness, and coordinated response.

Additionally, these developments have been revolutionized with the emergence of Big Data analytics, which have transformed disaster monitoring and forecasting. Big Data technologies can keep track of the disaster evolution and the community-level vulnerabilities by combining observations of satellite images, sensor networks, crowdsourcing, and even social media. AI, along with machine learning (ML) and deep learning (DL) algorithms, are gaining more prominence in such platforms, and they can enhance pattern identification, risk evaluations, and optimize the decision-making process in case of an emergency.[18]

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[18]Manzhu Yu, Chaowei Yang, and Yun Li, "Big Data in Natural Disaster Management: A Review," *Geosciences* 8, no. 5 (2018): 165, https://www.mdpi.com/2076-3263/8/5/165

The examples of global best practices of countries like China, Japan, and the US demonstrate how the integration of satellite systems, AI, and geospatial intelligence can be used to create robust integrated disaster management ecosystems. For example, the small satellite constellations of China and the EO satellites of Japan, used to conduct post-disaster surveys, demonstrate the potential of highly developed technology to offer real-time surveillance and high-resolution damage evaluation. The models provide important lessons to countries like Pakistan, where space-based systems are still developing. The NatCat Risk Modeling project of SUPARCO is a step in the right direction, and the project is expected to replicate such international standards by using localized satellite data to map hazards and assess vulnerability.[19]

Moreover, there has been significant advancement in post-disaster damage assessment using satellite imagery, unmanned aerial vehicles (UAVs), and LiDAR technologies. Convolutional Neural Networks (CNNs) and deep learning architectures have become the most common ML models to identify and categorize structural damage more quickly and accurately. Nevertheless, the fusion of multi-source data is still a significant challenge due to differences in spatial resolution, data formats, and imaging conditions, which makes the seamless fusion of data difficult and slows down its operational implementation.[20]

Technologies Used	Purpose	Key Benefits
Satellite Imagery (SAR, Optical)	Building damage assessment, disaster monitoring	Large-scale damage detection, continuous monitoring
UAV-based Imagery	High-resolution damage analysis, building inspection	Detailed surface damage, portability, and flexible deployment

[19] Amna Rauf and Usman W. Chohan, *Role of Space Technologies in Disaster Risk Management: Lessons for Pakistan*, January 25, 2020, SSRN, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3530032
[20] Sultan Al Shafian and Da Hu, "Integrating Machine Learning and Remote Sensing in Disaster Management: A Decadal Review of Post-Disaster Building Damage Assessment," *Buildings* 14, no. 8 (2024): 2344, https://www.mdpi.com/2075-5309/14/8/2344

LiDAR (Light Detection and Ranging)	Structural integrity analysis, terrain mapping	High precision, weather-independent data collection
Machine Learning (ML)	Damage classification, model enhancement	Increased accuracy, automated damage detection
Deep Learning (DL)	Post-disaster building damage prediction	Improved detection in complex environments

Table 1: Different Technologies Integration for Disaster Management[21]

Following these trends, the use of AI in disaster prediction, monitoring, and response, especially in the case of floods, earthquakes, droughts, and wildfires, is gaining popularity worldwide. To increase the accuracy and timeliness of EWS, ML models and AI are being increasingly used to automate damage assessments based on satellite imagery and to provide support with scenario-based risk forecasting. States such as China, the US, India, and the United Kingdom (UK) are on the front line of disaster research using AI, with China being the leader in flood forecasting models and the US playing a major role in earthquake EWS. Although several AI models have demonstrated positive outcomes, there are still issues to be addressed, particularly regarding data quality, the accuracy of models, and the absence of real-time operational integration in disaster-prone areas.[22]

One of the most important developments in the area is the application of data fusion techniques, in which AI algorithms receive and merge information streams of multisource datasets (satellite imagery, ground sensors, and social media streams) to enhance disaster prediction and situational awareness. Besides improving decision-making, these tools can also produce fast visual results, which are essential to emergency managers and responders. However, the question of explainability of models, data privacy, and bias of algorithms is a major barrier to the large-scale adoption,

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[21] Al Shafian and Hu, "Integrating Machine Learning," 2344.
[22] Arief Wibowo, Ikhwan Amri, Asep Surahmat, and Rusdah Rusdah, "Leveraging Artificial Intelligence in Disaster Management: A Comprehensive Bibliometric Review," *Jàmbá: Journal of Disaster Risk Studies* 17, no. 1 (2025): 1–9, https://doi.org/10.4102/jamba.v17i1.1776.

especially in low-resource settings. To maximize the potential of AI in disaster management, they should be integrated into well-coordinated institutional frameworks, which are facilitated by high-performance computing infrastructure, transparent data-sharing practices, and capacity building.

Comparative Assessment of Pakistan's Space Development within Asia-Pacific Space Cooperation Organization (APSCO) Member States

The following table is drawn to compare the space capabilities and legal frameworks of the APSCO member states to evaluate the relative position of Pakistan in the regional space development.

APSCO Member State	National Space Agency	LEO Satellite Capability	GEO Satellite Capability	Satellite Launch Capability	Space Law	National Space Policy
China	China National Space Administration (CNSA)	Yes (1970)	Yes (1984)	Yes (1970)	Yes (2000)	Yes (2000)
Iran	Iranian Space Agency (ISA)	Yes (2005)	Yes (2011)	Yes (2009)	Yes (2012)	Yes (2005)
Pakistan	SUPARCO	Yes (1990)	Yes (2011)	No	Yes (2011)	Yes (2024)
Turkey	Turkish Space Agency (TSA)	Yes (1990)	Yes (1994)	No	Yes (2016)	Yes (2016)
Bangladesh	Space Research & Remote Sensing Organization (1980)	No	Yes (2018)	No	No	Yes (2009)
Mongolia	Communication and Information Technology	Yes (2017)	No	No	No	No

	Authority (CITA)					
Peru	National Commission for Aerospace Research and Development	Yes (2013)	No	No	No	Yes (2009)
Thailand	Geo-Informatics & Space Technology Development Agency	Yes (1998)	Yes (1993)	No	No	Yes (2016)

Table 2: National Space Agencies of APSCO Member States and Space Capacities

The above table provides a comparative analysis of space capabilities and governance systems of the APSCO member states. It points out the position of each national space agency, the ability to operate Low Earth Orbit (LEO) and Geostationary Equatorial Orbit (GEO) satellites, the national capability to launch its satellites, and the presence of national space laws and policies. China and Iran are among the members with full-spectrum space capabilities, including satellite launch. Although Pakistan and Turkey have operational LEO and GEO satellites and a space policy, they do not have launch capabilities. Whereas Thailand has a well-developed satellite operation but remains undeveloped in legal and launch aspects.

Space Science and Technology in Pakistan

Space science and technology, especially EO, are the outcome of nineteenth-century research. EO is the science of collecting data information about the Earth's surface through satellite and aerial platforms. Satellite data are essential for understanding the Earth's physical, chemical, and biological systems. Satellite EO evolution history began with topographic mapping in the 1840s, the emergence of satellite platforms, and gained prominence with National Aeronautics and Space Administration's (NASA) Landsat program, which began in 1972. The availability of open-access satellite data has democratized the use of EO data, especially in developing countries that lack the infrastructure for independent satellite launches.[23] In Asia, APSCO member states, along with Peru, have a long history in the domain of space science and technology for national development through space as a strategic sector.

Space science and technology, particularly EO tools, play a crucial role in implementing these development agendas by providing reliable data for monitoring and assessing progress toward Sustainable Development Goals (SDGs).[24] Pakistan's National Space Agency, SUPARCO, was established in 1961 to promote the applications of space science and technology in Pakistan through various sectors including environmental monitoring, agriculture and natural resource management, satellite communication, urban planning and infrastructure development, education, disaster management, remote sensing, and earth observation, etc. SUPARCO has been operating LEO and GEO since 2011, along with a National Space Policy; however, it lacks an indigenous satellite launch capability (see Table 1).[25]

SUPARCO utilizes satellite data for disaster management in Pakistan, enhancing mitigation, response, and relief operations.[26] The GIS has been used for disaster management; however, integrating AI and ML enhances its ability to analyze large datasets, predict disaster events, and support decision-making in real time. The study aims to explore how the integration

[23] Pratistha Kansakar and Faisal Hossain, "A Review of Applications of Satellite Earth Observation Data for Global Societal Benefit and Stewardship of Planet Earth," *Space Policy* 37 (2016): 46–54, https://www.sciencedirect.com/science/article/abs/pii/S0265964616300133

[24] A. Senthil Kumar, Sergio Camacho, Nancy D. Searby, Joost Teuben, and Werner Balogh, "Coordinated Capacity Development to Maximize the Contributions of Space Science, Technology, and Its Applications in Support of Implementing Global Sustainable Development Agendas—A Conceptual Framework," *Space Policy* 51 (2020): 101346, https://www.sciencedirect.com/science/article/abs/pii/S0265964619300761

[25] Yongliang Yan, "Capacity Building in Regional Space Cooperation: Asia-Pacific Space Cooperation Organization," *Advances in Space Research* 67, no. 1 (2021): 401–410, https://doi.org/10.1016/j.asr.2020.10.022

[26] Rahmatullah Jilani, Subhan Khan, Mateeul Haq, et al., "Pakistan 2010 Floods Monitoring Using MODIS Data," *Proceedings of the International Workshop on Recent Advances in Space Technologies (RAST)*, November 17–20, 2010. https://www.researchgate.net/publication/241277267_Pakistan_2010_Floods_Monitoring_Using_MODIS_Data_proceedings_17-20_November_2010

of GIS with AI and ML can improve disaster preparedness, response, and resilience, particularly in the face of a changing climate.[27]

Institutional Framework and SUPARCO's Role in Disasters

In its space applications program, SUPARCO has specifically focused on disaster risk management. In 2013, it created the SACRED to support disaster management authorities with satellite remote sensing and GIS technical assistance.[28] The mandate of SACRED is to monitor different natural hazards, produce early warnings, map the extent of disasters, and evaluate ground damage.[29] In case of any major disaster, SUPARCO coordinates with the National Disaster Management Authority (NDMA) and the provincial authorities to provide near-real-time satellite images and analytical reports. As an example, SUPARCO has generated rapid inundation maps and damage estimates of catastrophic floods like the 2010 and 2014 floods and has been updating the flood extent maps regularly during the monsoon season.[30] It is also the point of contact in Pakistan to activate the International Charter on Space and Major Disasters, which allows free access to high-resolution satellite data of other space agencies if a major calamity is declared. This international cooperation was critical in the case of the 2022 super-floods, when cloud-penetrating radar imagery of foreign satellites (e.g., Sentinel-1) was employed together with SUPARCO

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[27] Justin Diehr, Ayorinde Ogunyiola, and Oluwabunmi Dada; A. S. Albahri et al., "A Systematic Review of Trustworthy Artificial Intelligence Applications in Natural Disasters," *Computers and Electrical Engineering* 118 (2024), https://doi.org/10.1016/j.compeleceng.2024.108517; Arief Wibowo et al., "Leveraging Artificial Intelligence in Disaster Management: A Comprehensive Bibliometric Review," *Jàmbá: Journal of Disaster Risk Studies* 17, no. 1 (2025): 1–9, https://doi.org/10.4102/jamba.v17i1.1776; Sheikh Kamran Abid et al., "Toward an Integrated Disaster Management Approach: How Artificial Intelligence Can Boost Disaster Management," *Sustainability* 13, no. 22 (2021), https://doi.org/10.3390/su132212541.

[28] Space and Upper Atmosphere Research Commission (SUPARCO), "Disaster Monitoring and Mitigation," https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/#:~:text=SUPARCO%E2%80%99s%20Space%20Application%20Center%20for,SACRED

[29] "Disaster Monitoring and Mitigation: Rehabilitation and Mitigation Support."

[30] Space and Upper Atmosphere Research Commission (SUPARCO), *SUPARCO: Effective use of Space-based information to monitor disasters and its impacts: Lessons Learnt from Floods in Pakistan* (Islamabad: SUPARCO, 2015) https://www.un-spider.org/sites/default/files/150112_SUPARCOBooklet_online.pdf#:~:text=During%20the%20floods%2C%20SUPARCO%20updated,areas%20was%20developed%20on%20the.

data to map one-third of the country submerged under water. The institutional structure of SUPARCO, through SACRED and its status as an UN-SPIDER Regional Support Office, has made the agency the most important source of space-based information in disaster management in Pakistan.

Agreements and specific platforms have been established between SUPARCO and disaster management authorities to coordinate their efforts. SUPARCO collaborates with NDMA and provides space-based information to the NDMA and provincial disaster management agencies at every stage of disaster management, including risk mapping and preparedness, emergency response, and recovery. A notable project is the creation of a NatCat risk modeling system in collaboration with the National Disaster Risk Management Fund (NDRMF). In this project, a geo-referenced exposure and hazard database is being developed to simulate the effects of floods, droughts, cyclones, and other hazards in the current and future climatic conditions.[31] The NatCat model is the first of its kind in the region, which incorporates historical satellite data, climate change projections, and socioeconomic exposure to give granular risk assessments and financial loss estimates at the sub-district level. These initiatives demonstrate an institutional awareness in Pakistan that climate change is increasing the risks of disasters, and that space science (i.e., Earth observation data) should be used to plan long-term resilience. Remarkably, SUPARCO also supports international frameworks; it helps NDMA report for the Sendai Framework 2015-2030 and the Paris Climate Agreement objectives through satellite-based environmental monitoring and hazard mapping.

Space-Based Technologies and Tools Utilized

In managing climate-related disasters, Pakistan uses various space technologies, with a focus on EO satellites and geospatial analytics. One of

[31] Pakistan Delegation to the United Nations, *Statement by Pakistan at the 62nd Session of the Scientific & Technical Subcommittee (STSC) of the Committee on the Peaceful Uses of Outer Space (COPUOS)*, February 2025, https://www.unoosa.org/documents/pdf/copuos/stsc/2025/Statements/3_Pakistan_for_upload.pdf

the greatest achievements was the introduction of indigenous remote-sensing satellites that offer high-resolution imagery to be used domestically. In 2018, SUPARCO launched the Pakistan Remote Sensing Satellite-1 (PRSS-1), which provides ~1 m panchromatic and ~3 m multispectral imagery with a 4-day revisit time, allowing the country to have access to current imagery of its terrain without relying on foreign sources.[32] Applications like land use mapping, agricultural monitoring, environmental observation, and natural disaster management are explicitly assigned to PRSS-1.

In early 2025, Pakistan launched its first fully indigenous Electro-Optical Satellite (PRSC-EO1), further enhancing its Earth observation capability.[33] EO-1 satellite has optical sensors to measure reflected sunlight and thermal radiation emitted, which will be utilized to monitor deforestation and glacier retreat, monitor water resources, and give timely information on floods, landslides, and other calamities. This new satellite is a giant leap towards self-reliance and will significantly improve the capability of Pakistan to respond to natural hazards through the provision of on-demand imagery to support early warning and damage assessment applications. Pakistan also accesses data of international Earth observation systems (MODIS, Sentinel) and commercial providers through the Disaster Charter and other partnerships, to provide coverage even in cases (such as heavy cloud-cover floods) where foreign radar or high-resolution imagery is required. SUPARCO has satellite ground stations in Islamabad and Karachi, which are capable of receiving feeds from various satellites and acquiring images of Pakistan and the region within a short time.[34] This multi-source approach indicates an awareness that space-based observation is an important

[32]Space and Upper Atmosphere Research Commission (SUPARCO), *"PRSS-1,"* https://suparco.gov.pk/major-programmes/projects/prss-1/#:~:text=PRSS,reliant%20in

[33]Jamal Shahid, "Pakistan's First Indigenous Observation Satellite Launched," *Dawn*, February 18, 2025, https://www.dawn.com/news/1885968#:~:text=ISLAMABAD%3A%20The%20Pakistan%20Space%20and,Centre%20in%20China%20on%20Friday

[34]SUPARCO, *Effective Use of Space-Based Information to Monitor Disasters and Its Impacts: Lessons Learnt from Floods in Pakistan* (Islamabad: Space and Upper Atmosphere Research Commission, n.d.), https://www.un spider.org/sites/default/files/150112_SUPARCOBooklet_online.pdf

instrument in the management of climate-induced disasters, i.e., constant satellite observation is deemed as essential to offer forecasting services to avert water-related disasters like floods and droughts, which are currently being performed regularly by SUPARCO.[35]

In addition to the orbiting satellites, Pakistan has also made ground-based remote sensing and GIS tools to convert space data into actionable information. The disaster management teams at SUPARCO employ advanced methods of image analysis (multi-temporal change detection and GIS mapping) to outline flood extents, map vulnerable assets, and assess the effects on agriculture or infrastructure. In case of major floods, SUPARCO updates inundation maps daily, giving district-wise figures of submerged areas and crop losses, which are directly used in relief planning.[36] The agency also has an Integrated Flood Analysis System and multi-hazard vulnerability assessments (floods, earthquakes, cyclones, droughts) based on remote sensing inputs. To share this information, a web-based Disaster Watch portal has been established to enable NDMA and provincial authorities to access near-real-time satellite analysis in times of emergencies.[37]

At the end-user level, the NDMA itself has led the way in incorporating space-based data. NDMA has created the new National Emergencies Operation Center (NEOC) that has real-time satellite feeds and sophisticated analytics to predict disasters three months in advance.[38] NEOC uses an integrated approach that combines GIS, remote sensing,

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[35] Suhaib Bin Farhan, *Space Technology to Combat Global Climate Change* (Islamabad: Center for International Strategic Studies, 2022), https://ciss.org.pk/PDFs/Space-Technology-to-Combat-Global-Climate-Change.pdf#:~:text=One%20of%20the%20most%20important,measuring%20sea%20levels%2C%20glacier%20mass

[36] *Effective Use of Space-Based Information To Monitor Disasters and its Impacts.*

[37] "Disaster Monitoring and Mitigation: Rehabilitation and Mitigation Support," https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/

[38] National Disaster Management Authority (NDMA), "National Emergencies Operation Centre (NEOC)," https://www.ndma.gov.pk/neoc#:~:text=Equipped%20with%20the%20latest%20tools,By%20analyzing

climatology, meteorology, hydrology, and data science information to monitor changing hazards and climate anomalies to allow a proactive approach to disaster risk. In addition, NDMA also installed an electronic Multi-Hazard Vulnerability and Risk Assessment (e-MHVRA) system, which uses remote sensing images to conduct dynamic risk mapping. The platform enables real-time data entry and hazard mapping, facilitating evidence-based contingency planning and more rapid dynamic response to the emerging threat. Such utilization of geospatial tools implies that Pakistan is no longer just amassing satellite data, but it is actively using it, like mapping of flood plains, monitoring of glacier lakes, drought risk zoning, and analysis of landslide susceptibility to update disaster management strategies.

There is a growing interest in leveraging AI and ML to complement these abilities, including automating the process of classifying satellite images to identify damage quickly and making use of AI models to better predict flooding. Although in the early phase, Pakistani scientists have started exploring the flood mapping and prediction of forest fires by satellite-generated data driven by AI.[39] Pakistan communication satellites (PakSat-1R launched in 2011) also offer auxiliary support as they allow broadband and telecommunication services to remote or disaster-affected regions.[40]

Policy Frameworks and National Strategies

Pakistan's commitment to utilizing space science for disaster risk reduction is reinforced at the policy level. In 2023, the government endorsed a detailed National Space Policy, developed by SUPARCO, that clearly states the need to use space technology to address socio-economic issues such as natural calamities and climate risks.[41] The vision of the policy is to incorporate

[39]GSMA, *Combatting Forest Fires with AI: Pakistan Case Study*, May 2024, https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-for-development/wp-content/uploads/2024/05/GSMA_CombattingForestFiresWithAI_Pakistan_Web-1-1.pdf
[40] *Statement by Pakistan at the 62nd Session of the Scientific & Technical Subcommittee (STSC) of the Committee on the Peaceful Uses of Outer Space (COPUOS),* https://www.unoosa.org/documents/pdf/copuos/stsc/2025/Statements/7_Pakistan.pdf
[41]New Space Economy, "Pakistan's National Space Policy: A Roadmap to the Stars," March 1, 2025, https://newspaceeconomy.ca/2025/03/01/pakistans-national-space-policy-a-roadmap-to-the-

space applications into daily life and development planning, emphasizing the application of satellite data in enhancing agriculture, urban planning, and disaster management, as well as the self-reliance of the country in space capabilities. It is worth noting that disaster risk management is a significant area of focus in the policy. It requires the creation of EWS for floods and droughts, mapping hazards with the help of EO, and leading post-disaster recovery with the help of satellite assessment. This is in line with national climate adaptation plans and the Sendai Framework, which represents a strategic realization that space-based data is essential to developing climate resilience. The Space Policy also focuses on international collaboration (e.g., data sharing, satellite missions' collaboration) and human resource development so that Pakistan remains abreast of international best practices in space-enabled disaster management. In addition to the space-specific policy, the place of technology in the overall disaster management and climate change strategies of Pakistan is also recognized. The National Disaster Management Plan (NDMP) 2015-2030 and the National Disaster Risk Reduction Policy promote remote sensing and GIS in hazard assessment and the modernization of early warning infrastructure (flood forecasting models and drought monitoring) in collaboration with technical agencies such as SUPARCO.

Likewise, the climate change policy of the country - the National Climate Change Policy and Climate Change Act - highlights the importance of scientific data and risk mapping to guide adaptation strategies, which in turn implicitly depends on satellite-based measurements of changing environmental patterns (glacial melt, sea-level rise along the coast, land cover changes, etc.). Such policy guidelines are realized in the form of projects such as the NatCat risk model and the working Memorandum of Understanding (MoU) between SUPARCO and NDMA. The NDMA has formalized space data integration into its Standard Operating Procedures (SOPs), e.g., the official NDMA NEOC Projections now incorporate satellite-monitored climate indices to predict seasonal hazard outlooks, and

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stars/#:~:text=Pakistan%E2%80%99s%20National%20Space%20Policy%20represents,article%20breaks%20down%20the%20policy%E2%80%99s situation reports during disasters regularly include satellite imagery analysis (maps of flooded areas). This policy and practice convergence shows that Pakistan acknowledges space technology as a strategic resource in disaster risk reduction. More importantly, the government proposed a large increase in funding for SUPARCO, with an 850 percent increase in development funding in 2024-2025, in part to increase satellite infrastructure and "develop space technology capabilities" to serve national requirements such as disaster management.[42] Such an investment supported by the policy implies a willingness to fill historical gaps and a desire to ensure that space-based tools are used systematically to protect communities against climate-related disasters.

Leveraging Space Technologies: Challenges and Way Forward

Although there is a visible improvement, there are still major obstacles that hinder the effective utilization of space science in managing climate disasters in Pakistan. The absence of domestic launch capability and limited satellite assets is one of the significant gaps. Pakistan has not yet developed its satellite launch vehicle (rocket) to place satellites in orbit, and it depends on foreign launches (mainly through China) to place its satellites in orbit. Such reliance may limit the ability to rapidly grow the EO infrastructure and expose the most important missions to the whims of other schedules and geopolitical factors. The existing EO constellation of the country is also limited, with three functioning optical satellites (PRSS-1, PakTES-1A, and PRSC-EO1) and no SAR satellites, which implies a lack of all-weather imaging. In cloudy monsoon conditions, Pakistan resorts to foreign SAR data (European Sentinel-1 or commercial providers) to map flood inundation.

The integration of data sources and agencies is still an improvement point, although platforms such as e-MHVRA are a step in the right direction, there

[42] 4 News HD, "Federal Budget Proposes 850 Percent Increase in SUPARCO Development Budget," June 10, 2024, https://24newshd.tv/10-Jun-2024/federal-budget-proposes-850-percent-increase-in-suparco-development-budget#:~:text=Federal%20budget%20proposes%20850,significant%20rise%20from%20the

is still fragmentation between meteorological data (Pakistan Meteorological Department), hydrological data (river flow sensors), and satellite imagery analysis (by SUPARCO). There is a continuing challenge to create a single, interoperable data system of early warning, a system that integrates space-based data with ground sensor networks and socio-economic data. Resource limitation, in terms of finance and infrastructure, is another challenge. The budget of SUPARCO was not very large in the recent past, which limited ambitious projects. The general performance of the space agency in its 50+ years has been termed as a snail's pace, mainly due to the lack of steady funding. To illustrate, when the neighboring nations were busy investing in space-based crop monitoring and climate observation satellites, the programs in Pakistan were sometimes stagnated due to funding cutoffs and sanctions (during the 1990s, international embargoes restricted the use of advanced technology, slowing down the development of satellite projects). The influx of new funds in 2024-2025 is a positive development; however, the effective use of these funds will be critical.

Infrastructural constraints like the lack of domestic image processing and distribution network at local scales also exist - many end-users in provincial disaster management or local planning departments remain untrained or lack the tools to access satellite-derived products on their own. It implies that SUPARCO and NDMA produce useful data, but the uptake of the last-mile into the district-level disaster preparedness or climate adaptation planning may be slow or inconsistent. This gap will have to be bridged through capacity-building and decentralization of some of the geospatial capabilities to provincial units. Also, inter-agency coordination can be enhanced further to achieve effective early warning. It is important to have climate scientists, meteorologists, and satellite remote sensing analysts working together, such as combining climate models and satellite monitoring of glaciers and weather patterns.

Conclusion

The rising number and severity of climate-related catastrophes in Pakistan point to the necessity of an effective disaster management system that is technology-driven. This paper has established that space science and technology, especially EO, GIS, and SRS, have become an essential component in disaster preparedness, response, and recovery. Although nations such as China, Japan, and the US have managed to institutionalize such technologies, Pakistan has done well in this regard through its national space agency, SUPARCO. Moreover, SACRED, NatCat Risk Model, and Disaster Watch portal are the initiatives that demonstrate the increased use of space-based solutions in Pakistan to enhance risk assessment, early warning capabilities, and situational awareness in emergencies.

However, several systemic loopholes still exist. Pakistan has no indigenous satellite launch capability, a small constellation of EO satellites, and still relies on foreign partners to provide it with essential imaging, particularly in poor weather conditions. Also, the complete operationalization of space-based data into subnational and local disaster management systems is not fully consistent, and it is frequently constrained by infrastructural, technical, and institutional shortcomings. In addition, despite the recent progress in policy, such as the National Space Policy (2023) and the increment of development funding to SUPARCO, a renewed national interest is evident, but the successful implementation of the policy needs long-term inter-agency coordination, investment, and capacity building across all administrative levels.

To realize the full potential of space technologies, Pakistan needs to institutionalize a multisectoral approach of fusing scientific innovation with inclusive governance. This involves the development of synergies among space scientists, climate modelers, and disaster response practitioners; the strengthening of regional and international collaboration; and the decentralization of space-derived information to be used in making community-level decisions timely manner. Finally, a sustainable future of Pakistan is not only about the technological progress but also the political determination to integrate space science in the national development and disaster risk reduction plans.

The Role of Nuclear Energy in Pakistan's Low-Carbon Future

Huma Rehman*

Abstract

Pakistan faces significant energy challenges, including rising energy demand and excessive reliance on fossil fuels, which contribute to greenhouse gas emissions and increased climate vulnerability. To address these issues, Pakistan should shift toward a sustainable and viable low-carbon future by diversifying its energy mix through the integration of clean energy sources. Nuclear energy, with its low-carbon footprint and high energy density, offers a viable solution to meet baseload electricity demand while reducing emissions. This article discusses the theoretical framework for nuclear energy in a low-carbon future. It examines the prospects of nuclear energy in Pakistan's energy transition by analyzing current nuclear power generation capacity, future expansion plans, and policy frameworks. The paper evaluates the economic, environmental, and security aspects of nuclear power compared to renewables such as solar and wind. Additionally, it addresses important challenges, including high capital costs, nuclear waste management, and public perception, while highlighting developments in nuclear reactor technology and exploring opportunities for international cooperation. The findings suggest that the peaceful use of nuclear energy, alongside renewables, can significantly contribute to decarbonization while enhancing energy security and promoting sustainable development. Strategic investments, regulatory reforms, and public engagement are essential to realizing this potential.

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Keywords: Energy Security, Low-carbon Future, Renewable Energy, Climate Change, Sustainable Development.

Introduction

Pakistan faces a dual challenge of energy scarcity,[1] and climate change vulnerability.[2] With a growing population and increasing industrialization, it is estimated that the energy demand in Pakistan will increase dramatically. Simultaneously, Pakistan's Nationally Determined Contributions (NDCs),[3] under the Paris Agreement,[4] include a pledge to cut greenhouse gas (GHG) emissions.

Nuclear energy stands out as a clean, reliable, and scalable means to support Pakistan's growing energy needs while reducing dependence on fossil fuels, particularly coal and domestic gas. In contrast to intermittent sources like solar and wind, nuclear energy provides steady baseload power and contributes to grid reliability.

Pakistan has made substantial investments in its nuclear energy infrastructure, with several operational reactors already contributing to the national grid. These facilities offer a consistent and dependable electricity supply while reducing reliance on other sources like coal and natural gas which are the primary contributors to carbon emissions. The government's determination to expand nuclear capacity is demonstrated by ongoing

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[1] Mian Ahmad Naeem Salik, "Pakistan's Energy Crisis: The Need for a Transition to Alternate Energy," *Issue Brief: Centre for Strategic Perspectives (CSP), Institute of Strategic Studies Islamabad (ISSI)*, October 30, 2023, https://issi.org.pk/wp content/uploads/2023/10/IB_Salik_Oct_30_2023.pdf

[2] *Pakistan UN-Habitat Country Report 2023* (UN-Habitat, 2023), https://unhabitat.org/sites/default/files/2023/06/4._pakistan_country_report_2023_b5_final_compressed.pdf

[3] *Pakistan's Intended Nationally Determined Contribution (Pak-INDC)* (Government of Pakistan, 2022), https://unfccc.int/sites/default/files/NDC/2022-06/Pak-INDC.pdf

[4] United Nations, *Paris Agreement*, 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

projects aimed at increasing electricity generation capacity and enhancing safety measures.

In addition to providing clean energy, the development of nuclear power in Pakistan can stimulate economic growth by enhancing local manufacturing capabilities and creating employment opportunities in the construction, operation, and maintenance of nuclear facilities. Pakistan has produced components for nuclear power plants through its local industry. This capability can also be utilized to manufacture parts for fossil fuel-fired power plants within the country, thereby strengthening the role of local industry.

Furthermore, it positions s Pakistan as a major actor in the regional energy cooperation initiatives focused on promoting sustainable development. As Pakistan progresses toward a low-carbon future, nuclear energy will be pivotal in achieving environmental objectives and guaranteeing long-term energy security for its growing population.[5]

Nuclear power generation in Pakistan holds significant potential, but unlocking this potential requires technological innovation, detailed planning, as well as strict adherence to international safety and regulatory standards. As population growth, urbanization, and industrialization continue to increase energy demands, nuclear energy is a potential and sustainable way that Pakistan can use to reduce the widening gap between electricity demand and supply.

Understanding Nuclear Energy in a Decreased-Carbon Future

The shift to a low-carbon future necessitates a fundamental restructuring of global energy systems to mitigate climate change while ensuring energy security, affordability, and sustainability. Nuclear energy, as a zero-emission

[5] Yusuf Raza Zaidi and Ghulam Rasool Athar, "Nuclear Power – An Essential Part of Solution for Energy Crisis in Pakistan," chap. 7 in *Sustainable Future: Energy, Climate and Policy in Pakistan*, Islamabad Policy Research Institute (IPRI), 2015, http://www.ipripak.org/wp-content/uploads/2016/01/sfecpii.pdf

baseload power source, presents a theoretically viable solution; however, its integration into future energy systems requires a multidisciplinary framework encompassing technological, economic, environmental, political, and social dimensions.

Core Theoretical Foundations

Energy Transition Theory (ETT)

Societies transition from high-carbon to low-carbon energy systems in phases.[6] Nuclear energy acts as a bridging technology between fossil fuels and a future grid dominated by renewables, providing dispatchable and stable baseload power where intermittent renewables (solar and wind) fall short. Nuclear energy can serve either as a complementary or competing technology with renewables in decarbonization pathways.

Technological Innovation Systems (TIS) Theory

The TIS theory examines how new energy technologies, such as advanced nuclear reactors, are developed, diffused, and ultimately achieve market penetration.[7] The nuclear applications[8] entails the following options:

- Large-scale Reactors (Gen III/III) for baseload power in high-demand economies.
- Small Modular Reactors (SMRs) for decentralized grids, industrial heat, and hydrogen production.
- Fusion and Gen-IV Reactors as long-term game-changers but require sustained research and development (R&D) investment.

[6] Vaclav Smil, *Energy Transitions: History, Requirements, Prospects* (Santa Barbara: Praeger/ABC-CLIO, 2010), 15–29, https://www.environmentandsociety.org/mml/energy-transitions-history-requirements-prospects
[7] Anna Bergek, S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne, "Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis," *Research Policy* 37, no. 3 (2008): 407–429, http://dx.doi.org/10.1016/j.respol.2007.12.003
[8] International Atomic Energy Agency (IAEA) Bulletin, "Nuclear Innovations," September 2023. https://www.iaea.org/sites/default/files/nuclearinnovations_0.pdf

Environmental Economics and Externalities

The viability of nuclear energy should be evaluated through the assessment of its full lifecycle emissions[9] and associated negative externalities, such as nuclear waste and accident risks. Key considerations include its carbon avoidance potential. As per Intergovernmental Panel on Climate Change (IPCC) data (AR5, WG III, Section 7.8.1), nuclear energy emits ~12 gCO_2-equivalent per kWh, as compared to coal at ~820gCO_2-equivalent per kWh. In cost-benefit analysis, the high upfront capital costs must be weighed against the long-term decarbonization benefits. In addition, concerns regarding nuclear waste management and safety risks highlight internal challenges that can significantly influence public perception.

Energy Justice Framework

The Energy Justice Framework[10] introduces essential considerations of equity and distributional impacts, questioning how nuclear deployment affects different communities and future generations. Meanwhile, political economic perspectives reveal how geopolitical factors, policy stability, and incumbent energy interests shape nuclear energy's adoption trajectory.

Nuclear Justice Implications: Balancing Energy Security and Equity

The nuclear justice viewpoint highlights both advantages and disadvantages, emphasizing the value of balancing energy security with equity. The advantages mainly underline nuclear energy's potential to enhance energy security for developing nations by providing reliable, low-carbon electricity to fast-growing economies such as Pakistan and India. It decreases reliance on volatile fossil fuel markets, promotes energy independence, and supports economic development while mitigating climate change.

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[9] Intergovernmental Panel on Climate Change (IPCC), *Global Warming of 1.5 ℃: An IPCC Special Report*, https://www.ipcc.ch/sr15/

[10] K. E. H. Jenkins, D. McCauley, R. Heffron, H. Stephan, and R. W. M. Rehner, "Energy Justice: A Conceptual Review," *Energy Research and Social Science* 11 (2016): 174–182, https://doi.org/10.1016/j.erss.2015.10.004

However, the disadvantages and several drawbacks cannot be discounted in this process. First, centralized control risks cannot be overlooked. Nuclear programs often concentrate power within governments or corporations, limiting community participation and potentially marginalizing local voices in the energy transition process. Second, nuclear energy raises land displacement concerns. The construction of nuclear power plants and uranium mining can displace communities, often disproportionately affecting indigenous groups and rural populations. Third, there is another concern surrounding the intergenerational waste burden, as the long-term storage of radioactive waste poses both ethical and logistical challenges. While nuclear energy can advance climate and energy justice, its deployment must prioritize inclusive governance, fair siting, and waste responsibility to avoid perpetuating systemic inequities.[11]

Political Economy of Energy Transition

Energy systems are shaped by policy, geopolitics, and vested interests.[12] Nuclear energy's political challenges cover three main areas: one, geopolitical dependencies including Uranium supply chains, export controls (i.e., Nuclear Suppliers Group - NSG restrictions); two, policy stability, which is a significant need for long-term government commitments (i.e., France vs. Germany's nuclear policies); three, fossil fuel incumbency that relates to resistance from coal/oil lobbies in some regions.

An Integrated Framework for Nuclear Energy in a Low-Carbon Future

A holistic approach should address the following aspects to achieve the goals of a low-carbon future.

- *Techno-Economic Viability:* Cost reductions via modularization, state support, and private investment.

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[11]Benjamin K. Sovacool, *Contesting the Future of Nuclear Power: A Critical Global Assessment of Atomic Energy* (Singapore: World Scientific Publishing, 2011), https://doi.org/10.1142/7895
[12] Mathieu Blondeel, Michael J. Bradshaw, Gavin Bridge, and Caroline Kuzemko, "The Geopolitics of Energy System Transformation: A Review," *Geography Compass* (Wiley), June 7, 2021, https://doi.org/10.1111/gec3.12580

- *Environmental Trade-offs:* Balancing low-carbon benefits with waste/safety risks.
- *Social Acceptance:* Addressing public fears via transparency, education, and participatory governance.
- *Policy and Geopolitics:* Stable regulations, international cooperation, and just transition strategies.

Nuclear energy's role in a low-carbon future is not predetermined but shaped by innovation, policy choices, and societal values. A robust theoretical framework helps navigate trade-offs between decarbonization urgency, energy security, and sustainability justice. Future research should explore optimal energy mixes where nuclear complements renewables rather than competing with them.

Global Nuclear Energy Expansion and Low-Carbon Objectives: A Path to Climate Mitigation and Energy Security

The world is increasingly turning to nuclear energy as a crucial component of its low-carbon future, driven by the urgency to combat climate challenges while meeting rising electricity demands. As countries work toward achieving net-zero emissions by mid-century, nuclear power, with its near-zero operational carbon footprint and high energy density, is being reevaluated as an indispensable baseload energy source alongside renewables. The International Energy Agency (IEA) and the IPCC both recognize nuclear energy as essential for decarbonizing power grids, particularly for industrial economies and rapidly growing states.[13]

Globally, nuclear expansion is gaining momentum, with over 50 reactors under construction primarily in China, India, and Russia, and 100+ more planned, including advanced SMRs in the US, Canada, and Europe. Countries like France, Sweden, and South Korea, which rely heavily on nuclear power, have demonstrated their effectiveness in reducing emissions,

[13] Aviel Verbruggen and Erik Laes, "Sustainability Assessment of Nuclear Power: Discourse Analysis of IAEA and IPCC Frameworks," *Environmental Science & Policy* 51 (August 2015): 170–80, https://doi.org/10.1016/j.envsci.2015.04.011

while emerging economies view it as a pathway to energy independence. At the United Nations Climate Change Conference of the Parties (COP28) held in the United Arab Emirates (UAE) in December 2023,[14] Nuclear energy gained prominence as 20 nations committed to doubling nuclear power capacity by 2050.

The International Atomic Energy Agency (IAEA) highlighted that achieving worldwide net-zero carbon emissions by 2050 necessitates prompt, continuous, and substantial investments in nuclear energy as it significantly contributes to climate change mitigation and reduces energy insecurity.[15] Even traditionally anti-nuclear nations such as Germany and Japan are reconsidering phase-outs due to energy security concerns in the post-Ukraine conflict.[16]

The world's 9.2% energy needs are currently fulfilled by nuclear energy with 408 Nuclear Power Reactors (NPRs) and a combined production of 366736 MW operating in 31 nations (see below Fig.1). Furthermore, 57 additional NPRs are under construction. Among the 31 nations, France stands out as it uses nuclear power to produce 63% of its electricity. In the 1970s, France started growing its nuclear power sector to cut greenhouse gas emissions and reduce reliance on foreign oil. Following France, Ukraine and the Slovak Republic rely on NPRs for over 50% of their electricity output.[17]

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[14] United Nations Framework Convention on Climate Change (UNFCCC), "COP28 Agreement Signals 'Beginning of the End' of the Fossil Fuel Era," press release, December 13, 2023, https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era

[15] International Atomic Energy Agency (IAEA), "IAEA Statement on Nuclear Power at COP28," December 1, 2023, https://www.iaea.org/newscenter/statements/iaea-statement-on-nuclear-power-at cop28#:~:text=Resilient%20and%20robust%20nuclear%20power,industry%20processes%20and%20hydrogen%20production

[16] Anna J. Davis, *The Role of Nuclear Energy in the Global Energy Transition*, Oxford Institute for Energy Studies Paper ET14, August 2022, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/08/The-Role-of-Nuclear-Energy-in-the-Global-Energy-Transition-ET14.pdf

[17] International Atomic Energy Agency (IAEA), *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050*, IAEA Reference Data Series No. 1, 2024 Edition, https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-44_web.pdf

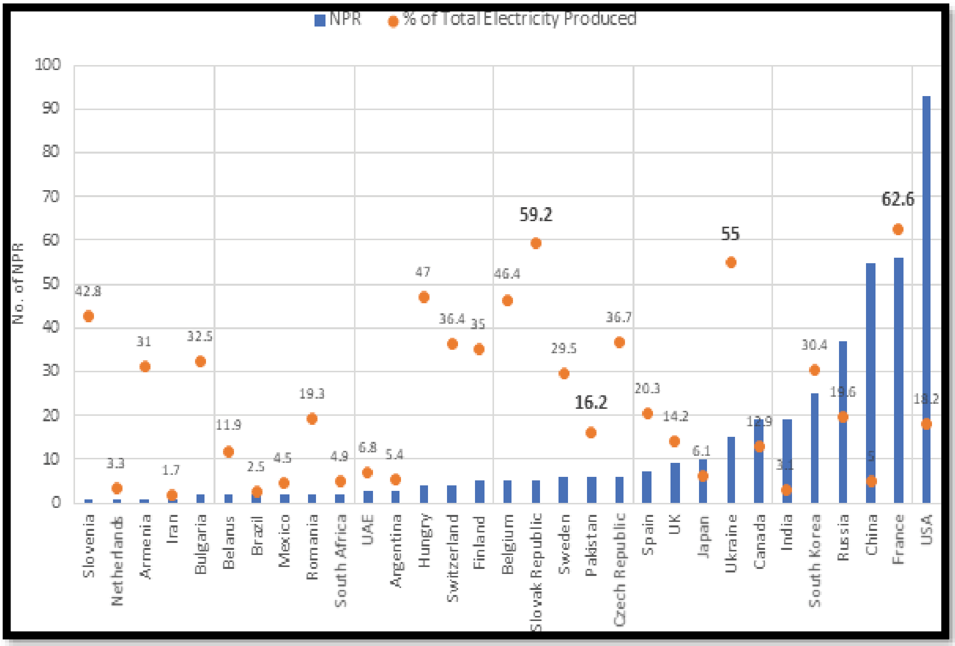

Figure 1: World Nuclear Power Capacity
Source: The IAEA Database on Nuclear Power Reactors[18]

According to IAEA estimates, 31 countries + one economy (Taiwan) globally operate 416 nuclear reactors for energy generation, with 61 more nuclear facilities under construction.[19] Nuclear energy generates around 10% of the global electricity, and roughly 26% of global low-carbon electricity.[20] IAEA's annual nuclear power outlook projection sees installed nuclear capacity of 372igawatts at present, doubling to 514-950 gigawatts by 2050.[21]

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[18] International Atomic Energy Agency (IAEA), *The Database on Nuclear Power Reactors (PRIS)*, https://pris.iaea.org/PRIS/home.aspx

[19] International Atomic Energy Agency (IAEA), "Operational Reactors by Country," *Power Reactor Information System (PRIS)*, https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx

[20] "Nuclear Power in the World Today," *World Nuclear Association*, updated November 2023, https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

[21] Jeffrey Donovan, "Nuclear Energy Makes History as Final COP28 Agreement Calls for Faster Deployment," December 13, 2023, https://www.iaea.org/newscenter/news/nuclear-energy-makes-history-as-final-cop28-agreement-calls-for-faster-deployment

However, on the downside, there exist some challenges, including increased upfront expenses, radioactive waste concerns, and public opposition, which vary by region. Innovations in Gen-IV reactors, molten salt designs, and fusion technology promise safer, more efficient alternatives, while international collaborations like the IAEA's Net-Zero Nuclear Initiative aim to harmonize regulatory and financing frameworks. For nuclear energy to fulfill its potential in global decarbonization, governments must implement stable policies, public-private partnerships, and streamline licensing while integrating nuclear energy with renewables in a hybrid clean energy system. Ultimately, nuclear power's scalability and reliability make it a vital tool in the transition away from fossil fuels, but its success hinges on overcoming economic, political, and societal barriers to align with the world's low-carbon objectives.

Salient Features of Nuclear Power Reactors Aid a Low-Carbon Future

Nuclear power reactors are a key clean energy solution, producing large-scale, reliable electricity with near-zero direct carbon emissions.[22] They operate on controlled nuclear fission, primarily using uranium-235 or plutonium-239, and can run continuously for 18-24 months without refueling, ensuring stable baseload power. Advanced designs such as SMRs and Generation IV reactors enhance safety, minimize waste, and improve efficiency with features such as passive cooling systems and increased thermal efficiency. Unlike intermittent renewables, nuclear plants provide grid stability and can complement solar/wind energy in a decarbonized future. Additionally, breeder reactors and nuclear recycling technologies minimize long-lived radioactive waste, supporting sustainable fuel cycles. With a small land footprint and high energy density,

[22] The Role of Nuclear Energy in a Low-Carbon Energy Future, Nuclear Energy Agency Organization For Economic Co-operation and Development (OECD), NEA No. 6887.2012. https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/nea6887-role-nuclear-low-carbon.pdf

nuclear power is a scalable and low-carbon substitute for fossil fuels, crucial for achieving net-zero emissions.[23]

The Role of Nuclear Energy in Reducing Carbon Emissions

a) *Low CO_2 Emissions Compared to Fossil Fuels*

- Nuclear power emits ~12 grams of CO_2 per kWh over its lifecycle (construction, operation, decommissioning), comparable to wind (~11gCO_2-equivalent per kWh) and solar (~45gCO_2-equivalent per kWh).[24]
- In contrast, coal emits ~820 gCO_2/kWh, and natural gas emits ~490 gCO_2/kWh.[25]

Karachi Nuclear Power Plant (K-2, K-3) of Pakistan contributes 2,200 MW of stable electricity, avoiding ~15 million tons of CO_2 equivalent annually compared to coal (Pakistan Atomic Energy Agency - PAEC, 2023).

b) *Baseload Power for Grid Stability*

- Unlike intermittent renewables (solar and wind), nuclear energy provides 24/7 baseload power, reducing reliance on fossil fuel backups.[26]

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[23] Andrea Galindo, "What Is Nuclear Energy? The Science of Nuclear Power," November 15, 2022, https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power

[24] UNECE (2022). Lifecycle Assessment of Electricity Generation Options. https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options

[25] IEA (2021). *Nuclear Power in a Clean Energy System,* https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

[26] World Nuclear Association, "*Nuclear Power in Pakistan*" (London: World Nuclear Association, 2023), https://world-nuclear.org/images/articles/World-Nuclear-Performance-Report-2024.pdf

c) Land and Resource Efficiency

- Nuclear requires less land than solar/wind farms for similar output.[27]
- A single uranium pellet which is the size of a pencil eraser produces the same amount of energy as a ton of coal.[28]

Pakistan's Approach towards Nuclear Energy and Decarbonization

Nuclear energy, a low-carbon power source, generates electricity through nuclear fission which involves splitting uranium atoms to release energy. Unlike fossil fuels, nuclear energy emits little greenhouse gas (GHG) during operation, due to which it is considered as a key answer for decarbonizing energy systems.[29] Pakistan relies heavily on coal (32.6%) and natural gas (30%) for power generation, so nuclear energy offers a sustainable alternative to cut carbon emissions and support energy security.[30]

Pakistan signed the Paris Agreement and ratified it in 2016.[31] It is an international agreement aimed at addressing climate change. Pakistan intends to establish a cumulative aggressive conditional goal of a 50% reduction in anticipated emissions by 2030, with a 15% reduction from domestic resources and a 35% reduction contingent on the provision of foreign grant funds.[32] To meet the target, Pakistan intends to transition to 60% renewable energy and 30% electric vehicles by 2030, as well as limit coal imports and expand natural solutions. The modified NDC also includes

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[27] Massachusetts Institute of Technology (MIT), "*The Future of Nuclear Energy in a Carbon-Constrained World*" (Cambridge, MA: MIT Energy Initiative, 2019), https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/
[28] Nuclear Energy Institute, "*Nuclear Fuel*," https://www.nei.org/fundamentals/nuclear-fuel.https://www.nei.org/fundamentals/nuclear-fuel
[29] Special Report, "Global Warming of 1.5 ºC", https://www.ipcc.ch/sr15/
[30] Federation of Pakistan Chambers of Commerce and Industry (FPCCI), " *Evaluating Energy Security Paradigm of Pakistan: Challenges and Opportunities*," Energy Report Working Paper No. WP02.2024 (Karachi: FPCCI, 2024), https://fpcci.org.pk/wp-content/uploads/2024/01/Evaluating-Energy-Security-Paradigm-of-Pakistan-Challenges-and-Opportu.pdf
[31] Carbon Brief, "*The Carbon Brief Profile: Pakistan*," 2023, https://interactive.carbonbrief.org/the-carbon-brief-profile-pakistan/index.html
[32] Pakistan Climate Promise, UNDP. https://climatepromise.undp.org/what-we-do/where-we-work/pakistan

new sectors and gases for increased contributions.[33] The updated NDC anticipates a more comprehensive adaptation strategy that addresses adaptation needs across all sectors, with a focus on loss and damage.

Outlook of the Energy Sector in Pakistan

Pakistan's energy sector is facing issues due to its strong reliance on imported fossil fuels. A transition to hydropower, renewables, and domestic resources is critical for long-term sustainability, economic growth, and energy security. Pakistan's installed electric power generation capacity stands at approximately 45,885 MW, comprising 51.5% thermal (oil, gas, coal), 25.9% hydroelectric, 18.3% nuclear, 4.0% renewables, and 0.3% imported electricity. The electricity generation mix in FY2022–23 shows coal at 27%, gas at 23%, hydro at 22%, oil at 15%, nuclear at 10%, and renewables at 2.5%.[34]

Current Status of Nuclear Energy in Pakistan

Pakistan's exclusion from nuclear technology commerce as a non-signatory to the Nuclear Non-Proliferation Treaty (NPT) has slowed progress toward nuclear capacity expansion.[35] The Western ban on providing nuclear power generation gear, materials, and technical assistance stalled progress even more. However, China's support under a bilateral agreement signed in 1986 has been vital to the progress of Pakistan's civil nuclear energy project.

[33] Federation of Pakistan Chambers of Commerce and Industry (FPCCI), "*Evaluating Energy Security Paradigm of Pakistan: Challenges and Opportunities"*, Energy Report Working Paper No. WP02.2024 (Karachi: FPCCI, 2024), https://fpcci.org.pk/wp-content/uploads/2024/01/Evaluating-Energy-Security-Paradigm-of-Pakistan-Challenges-and-Opportu.pdf

[34] National Electric Power Regulatory Authority (NEPRA), *State of Industry Report 2023* (Islamabad: NEPRA, 2024), https://www.nepra.org.pk/publications/State%20of%20Industry%20Reports/State%20of%20Industry%20Report%202024.pdf; Ministry of Finance, *Pakistan Economic Survey 2023–24* (Islamabad: Government of Pakistan, 2024), https://www.finance.gov.pk/survey/chapters_24/12-Energy.pdf; National Transmission and Despatch Company (NTDC), *Power System Statistics 2023* (Lahore: NTDC, 2024), https://ntdc.gov.pk/

[35] A. H. Nayyar, '*A Pakistani Perspective on Nuclear Disarmament and Non-proliferation*,' FES Briefing Paper 9, Bonn: Friedrich-Ebert-Stiftung, August 2008:. https://library.fes.de/pdf-files/iez/global/05652.pdf

Starting with Chashnupp-1 in 1993, the relationship has resulted in the commissioning of other plants, including Chashnupp-2, -3, and -4, as well as two 1,017 Mwe net each facility in Karachi, commissioned throughout 2021-22[36].

Currently, Pakistan has a total nuclear power capacity of 3,227 MWe, ranking 17th in the world for nuclear energy production, with an annual output of over 24 billion kilowatt-hours. The IAEA technical document covers the period from 1993 to 2023 and was published in July 1998, well before the approval of Pakistan's Energy Security Action Plan. In 2005, the Government of Pakistan launched a 25-year Energy Security Action Plan (2005–2030) to meet growing energy demands and ensure a reliable power supply to support economic growth. The plan aimed to expand generation capacity from 19,786 MW to 162,590 MW by 2030, utilizing a balanced mix of thermal, nuclear, hydro, and renewable sources. Specifically, the plan set a target of 8,800 MW of nuclear power capacity by 2030.[37]

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[36]Engr Hussain Ahmad Siddiqui, "*Nuclear Power: Road to Carbon-Free Future*," *The Business Recorder*, January 10, 2025, https://www.brecorder.com/news/40342020/nuclear-power-road-to-carbon-free-future

[37] Report prepared by a team of experts from Pakistan with the guidance of the International Atomic Energy Agency, 'Energy and nuclear power planning study for Pakistan (covering the period 1993-2023). *IAEA-TECDOC-1030*. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1030_prn.pdf

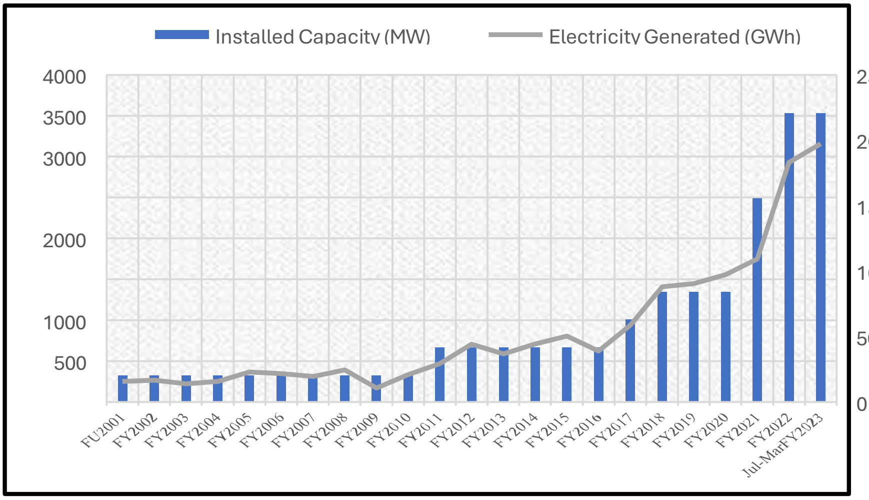

Figure 3: Pakistan Nuclear Power
Source: NTDC Power System Statistics, 47th Edition, 2022, and GOP, 2023.

Nuclear Energy in Pakistan's Low-Carbon Strategy

Pakistan's nuclear energy strategy is going in the right direction. The share of nuclear energy in Pakistan's electricity generation was 17.4% in the fiscal year 2022–23 and 18.1% in the fiscal year 2023 -2024. With an installed nuclear capacity of around 3620 MWe, it avoids ~20 million tons of CO_2 per year, which is equivalent to taking 4 million cars off the road.[38]

The layout of nuclear versus other low-carbon sources underlines the estimates of Pakistan's commitment to reducing carbon footprints in the environment. To reduce CO2 emissions and exposure to local air pollution, it must transition its energy systems away from fossil fuels and toward low-carbon alternatives. Nuclear and renewable technologies are low-carbon energy sources.[39]

[38] Pakistan Atomic Energy Commission (PAEC), *Annual Report on Nuclear Power Generation* (Islamabad: PAEC, 2023), https://www.pnra.org/upload/pnrarpt/PNRA%20Annual%20Report%202023.pdf.
[39] John Stephenson and Peter Tynan, "Is Nuclear Power Pakistan's Best Energy Investment? Assessing Pakistan's Electricity Situation," in *Pakistan's Nuclear Future: Reining in the Risk*, ed.

Reactor Name	Model	Reactor Type	Net Capacity (MWe)	Construction Start	First Grid Connection
Chashma Nuclear Power Plant 1 (CHASNUPP-1)	CNP-300	PWR	300	1993-08	2000-06
Chashma Nuclear Power Plant 2 (CHASNUPP-2)	CNP-300	PWR	300	2005-12	2011-03
Chashma Nuclear Power Plant Unit 3 (CHASNUPP-3)	CNP-300	PWR	315	2011-05	2016-10
Chashma Nuclear Power Plant Unit 4 (CHASNUPP-4)	CNP-300	PWR	313	2011-12	2017-06
Karachi Nuclear Power Plant 2 (KANUPP-2)	HPR1000 (also known as ACP1000/ Hualong One)	PWR	1,017	2015-08	2021-03
Karachi Nuclear Power Plant-3 (KANUPP-3)	HPR1000 (also known as ACP1000/ Hualong One)	PWR	1,017	2016-05	2022-03

Table I: Annual Report on Nuclear Power Generation, PAEC

Energy Source	CO_2 Emissions	Cost (Rs. /kWh)	Scalability in Pakistan[40]
Nuclear	~12 gCO_2/kWh	Rs. 12.5	Moderate (requires investment)

Henry Sokolski (Carlisle, PA: Strategic Studies Institute, U.S. Army War College, 2009), 165–199, http://www.jstor.org/stable/resrep12045.7.

[40] Muhammad Tariq Majeed, Ilhan Ozturk, Isma Samreen, and Tania Luni, "Evaluating the Asymmetric Effects of Nuclear Energy on Carbon Emissions in Pakistan," *Nuclear Engineering and Technology* 54, no. 5 (May 2022): 1664–1673, https://pdf.sciencedirectassets.com/312207/1-s2.0-S1738573322X00053/1-s2.0-S1738573321006653/main.pdf

Coal	~820 gCO_2/kWh	Rs. 48.1	High (but environmentally harmful)
Solar/Wind	~20–50 gCO_2/kWh	Rs. 29.3- 28.7	High (intermittency issues)
Hydropower	~24 gCO_2/kWh	Rs 4.96	Limited (climate-dependent)

Table II: Summary of the Cost of Pakistan's Energy Production
Sources: IPCC 2018, IEA 2021, UNECE 2022

Benefits of Nuclear Energy for Pakistan

An important feature supporting nuclear energy' s potential in Pakistan is its ability to provide a dependable, low-carbon energy supply. Nuclear power, unlike fossil fuels, emits zero greenhouse gases during operation, making it a key component of a diverse energy mix aimed at mitigating climate change.[41] By investing in nuclear power, Pakistan can reduce its reliance on imported fuels and increase energy security.[42] Moreover, the reduced dependence on imported LNG and coal will improve the trade balance. Additionally, it will provide a long-term fuel supply (uranium reserves and agreements with China) and align with worldwide initiatives to shift to cleaner energy systems.[43] It will help Pakistan meet its NDC target of 60%[44] renewable energy by 2030. It also aligns with global Net-Zero by 2050 initiatives.

To reap the benefits of nuclear energy, Pakistan should prioritize the development and expansion of nuclear power generation, which is still one of the world's most cost-effective energy sources for CO_2 mitigation. It

[41] A Report, "Revised NDCs Show Commitment to Ambitious Climate Action: PRGMEA", *Business Recorder*. December,31,2024. https://www.brecorder.com/news/40340255, https://unfccc.int/sites/default/files/NDC/2022-06/Pakistan%20Updated%20NDC%202021.pdf
[42]Fahad Bin Abdullah et al., "Energy Security Index of Pakistan (ESIOP)," *Energy Strategy Reviews* 38 (November 2021): 100739, https://doi.org/10.1016/j.esr.2021.100739
[43] Sikander Ali Abbasi, "Is Nuclear Power Generation a Viable Alternative to the Energy Needs of Pakistan?: SWOT-RII Analysis," *International Journal of Energy Economics and Policy*, May 2021, https://www.econjournals.com/index.php/ijeep/article/download/11122/5952
[44] United Nations Development Program (UNDP), "Pakistan Climate Promise," *UNDP Climate Promise*, November 24, 2023, https://climatepromise.undp.org/what-we-do/where-we-work/pakistan

promotes industrialization by providing reliable and affordable electricity. Also, it generates high-skilled jobs in engineering, construction, and maintenance.

As reported by the National Electric Power Regulatory Authority (NEPRA) in its 2024 State of the Industry Report, the average cost of electricity produced by nuclear power plants in the fiscal year 2023-2024 stood at Rs12.5 per kWh. It was nearly one-third of the cost associated with coal-fired power plants. When compared to oil-based thermal generation, which costs Rs48.1 per kWh, and renewables such as wind and solar, priced at Rs29.3 and Rs28.7 per kWh respectively, nuclear energy emerges as a significantly more economical option.

In comparison, despite high initial capital expenses, nuclear energy has emerged as a more cost-effective option. According to the International Energy Agency, nuclear power's levelized cost of electricity has fallen below that of coal and natural gas, with nuclear power now produced for $60 per megawatt-hour (MWh), compared to $80 per MWh for coal and $70 per MWh for natural gas. In the case of Pakistan, the forecast indicates that the expansion of renewable capacity, including wind, solar, and bagasse, is expected to gain momentum over the next eight years. The total generation capacity is projected to rise to 21%, increasing from 2,949 MW to 13,686 MW by 2030.[45] This accounts for 7,932 MW, 5,005 MW, and 749 MW of solar, wind, and bagasse contributions, respectively. The Government of Pakistan has updated its forecasts, reflecting enhanced policy support and the ambitious climate targets set forth during the 26th Conference of the Parties (COP 26). This includes the Alternative Renewable Energy (ARE) Policy, which aims for a 30% share of solar and wind energy, the Indicative Generation Capacity Expansion Plan (IGCEP), the National Electricity Policy 2021, and the Nationally Determined

[45] Muhammad Usman et al., "Do Nuclear Energy, Renewable Energy, and Environmental-Related Technologies Asymmetrically Reduce Ecological Footprint? Evidence from Pakistan," *Energies* 15, no. 9 (May 9, 2022): 3448, https://doi.org/10.3390/en15093448

Contributions (NDCs), which target a 60% capacity share of renewables and hydro by 2030 (GoP, 2021).[46]

Pakistan's goal of producing 40,000 megawatts (MWe) of nuclear power by 2050 is equivalent to building about 11 large dams like the Kalabagh Dam, according to Pakistan's leading Director General of the Strategic Plans Division, General Khalid Ahmed Kidwai. This comparison shows the huge potential of nuclear energy. Despite these cost benefits, nuclear energy's share in Pakistan's electricity generation was only 17.4% in the fiscal year 2022–23 and 18.1% in 2023–24 of total power fed into the national grid, limiting its capacity to lower consumer electricity prices.

Benefit	Description
Low Carbon Emissions	Zero CO_2 during operation.
Energy Security	Reduces reliance on imported fossil fuels (e.g., LNG, coal).
Baseload Power	Provides 24/7 stable electricity (unlike intermittent renewables).
Economic Growth	Supports industrial decarbonization, development) and job creation.

Table III: Summary of Benefits of Nuclear Energy for Pakistan's Low-Carbon Future

Increasing Pakistan's Energy Dependence on Clean Energy Sources

Currently, Pakistan has six operational nuclear power plants. Launched in April 2022, the 1100 MW KANUPP-3 (K-3) nuclear power plant in Karachi enhanced Pakistan's nuclear power capacity significantly. Nuclear power's share in the national grid has increased from 8% before to around 17.4% because of K-2 and K-3.[47] K3 is the second overseas nuclear power plant to employ Hualong One, a third-generation nuclear reactor developed by China. While K-2 production began in May 2021, marking the first export

[46] Sustainable Development Policy Institute (SDPI), "Annual State of the Renewable Energy Report Pakistan 2021–2022", 1st ed. (Islamabad: SDPI, September 2022), https://sdpi.org/assets/lib/uploads/SDPI-RENEWABLE%20ENERGY%20REPORT-2022.pdf

[47] Faseeh Mangi and Kamran Haider, "Pakistan Launches $2.7 Billion China-Designed Nuclear Plant," *Bloomberg*, February 2, 2023, https://www.bloomberg.com/news/articles/2023-02-02/pakistan-launches-2-7-billion-china-designed-nuclear-plant.

of China National Nuclear Corporation's (CNNC) Hualong One or HPR1000, construction of K-3 commenced in May 2016. Ten billion kWh of electricity may be produced annually by each Hualong One reactor, which is sufficient to power four million houses in Pakistan. In detail, 1100 MW x 1000 kW/MW x 8760 hours/year/1000000000 =9.636 billion kWh. This level of production cannot be sustained continuously, as the plant should undergo periodic shutdowns for refuelling and maintenance. The production of energy is the same as avoiding the annual release of 15 million tons of CO_2 and lowering the consumption of coal by 3.12 million tons. In addition to providing for Pakistan's energy needs, the K-2 and K-3 have directly created over 10,000 jobs and indirectly created over 40,000 jobs through the industrial chain.[48]

Pakistan already operates four CNP-300 pressurized water reactors (C-1, C-2, C-3, and C-4) in Chashma, Punjab. In 2017, China signed a cooperation agreement with the Pakistan Atomic Energy Commission (PAEC) to build a Hualong One as the fifth unit at Chashma or C-5. In September 2021, PAEC and China Zhengyuan Engineering signed a "Framework Agreement on Deepening Nuclear Energy Cooperation" for enhancing collaboration and maintenance of Pakistan's nuclear power projects.[49] To achieve sustainable development goals (SDGs), Pakistan is planning for electricity generation, and under the low-carbon scenario, it is projected to grow from 3.1 GW in 2025 to 16.5 GW in 2040 and to 36 GW in 2050, when it would supply 29% of energy demand.[50]

[48] Yasmin Ghazala, "Nuclear Energy in Pakistan: Prospects and Challenges", *Issue Brief* (Islamabad: Institute of Strategic Studies Islamabad, December 21, 2022), https://issi.org.pk/wp-content/uploads/2022/12/IB_Ghazala_Dec_21_2022.pdf

[49] "China–Pakistan Civil Nuclear Cooperation," *Energy Update*, February 28, 2022, https://www.energyupdate.com.pk/2022/02/28/china-pakistan-civil-nuclear-cooperation

[50] *Asian Development Bank (ADB)*, "Pakistan's Low-Carbon Energy Outlook and Technology" Road Map (Manila: ADB, November 2024), http://adb.org/sites/default/files/publication/1007766/pakistan-low-carbon-energy-outlook.pdf.

Pakistan's Nuclear Trade Potential Options

Pakistan holds significant trade potential in nuclear energy, supported by its indigenous nuclear infrastructure and strategic partnerships. China-Pakistan Nuclear Cooperation underlines Pakistan's largest nuclear partner, with one Hualong One reactor currently under construction at Chashma (Chashma Unit 5), while two others are already operational at Karachi (KANUPP-2 and 3). China provides fuel, technology, and financing under a safeguarded bilateral agreement. China Pakistan Economic Corridor (CPEC) includes nuclear energy as a strategic sector for energy security.[51]

Pakistan benefits from IAEA's programs in nuclear safety, agriculture (mutant crop strains), and cancer treatment (Pakistan Institute of Nuclear Science and Technology - PINSTECH isotopes),[52] and exports nuclear medicine products to regional markets, i.e., Bangladesh and Sri Lanka. Potential future partners for Pakistan's nuclear trade may include Russia. Rosatom, Russia's state nuclear company, has been actively promoting VVER-1200 reactor technology, part of its Generation III+ reactor line, to several countries. Additionally, Turkey[53] and Saudi Arabia[54] have demonstrated interest in SMR technology for desalination and power, creating potential avenues for collaboration with Pakistan.

Global warming serves as a wake-up call for Pakistan to increase its use of nuclear energy in its energy mix to combat rising GHG emissions. Building

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[51] Sher Ali Kakar, "Pak-China Nuclear Energy Cooperation," *The Nation*, January 11, 2025, https://www.nation.com.pk/11-Jan-2025/pak-china-nuclear-energy-cooperation

[52] Michael Amdi Madsen, "Pakistan and IAEA Accelerate Nuclear Cooperation to Address Climate, Food and Health," *IAEA News*, accessed June 30, 2025, https://www.iaea.org/newscenter/news/pakistan-and-iaea-accelerate-nuclear-cooperation-to-address-climate-food-and-health

[53] "Potential of Modular Reactors in Türkiye's Nuclear Energy Landscape," *Nuclear Business Platform*, January 2, 2024, https://www.nuclearbusiness-platform.com/media/insights/potential-of-modular-reactors-in-trkiyes-nuclear-energy-landscape

[54] International Atomic Energy Agency, "Nuclear Desalination: A Sustainable Solution for Water Security in the Arab Region," *IAEA News*, May 5, 2025, https://www.iaea.org/newscenter/news/nuclear-desalination-a-sustainable-solution-for-water-security-in-the-arab-region.

a nuclear power plant takes at least seven years; thus, it is critical to make progress in the short term if Pakistan aims to achieve carbon neutrality by 2050. Despite these hurdles, Pakistan has planned to grow its nuclear energy contribution to 40,000 MW by 2050, which is a step in the right direction, according to the Pakistan Energy Security Plan.

Challenges for Pakistan's Nuclear Energy Goals

Pakistan's pursuit of nuclear energy as a cornerstone of its low-carbon energy future faces multifaceted challenges that span financial, technical, geopolitical, and socio-political domains.

Financially, the exorbitant capital costs of nuclear power plants, ranging from $6–9 billion per GW, strain Pakistan's fragile economy, which already grapples with debt and limited foreign reserves. Reliance on Chinese financing under CPEC exacerbates debt dependency, while exclusion from the NSG restricts access to global investment and technology. Financing remains a major concern; therefore, innovative strategies, such as public-private partnerships and international funding systems, can help overcome financial constraints.

According to the report from the Asian Development Bank (ADB), the Pakistan Low-Carbon Energy Outlook and Technology Road Map, the essential energy expansion plans necessitate significant investment commitments. In the low-carbon scenario, hydropower generation costs $153 billion, nuclear power costs $103 billion, wind power costs $62 billion, and solar power costs $51 billion. To accommodate rising electricity demand and preserve grid stability, a $22 billion investment in transmission and distribution is also needed.[55] These large investments in the power sector are in addition to the investments required in the transport and domestic sectors to achieve energy efficiency savings.

[55]Khaleeq Kiani, "Pakistan Needs $390bn for Low-Carbon Transition by 2050: ADB," *Dawn*, November 18, 2024, https://www.dawn.com/news/1873060

Technically, Pakistan's modest domestic uranium reserves and dependence on China for fuel pose long-term sustainability risks compounded by the absence of advanced fuel cycle technologies like thorium reactors or breeder programs.

Safety and public acceptance remain critical hurdles with public fears over nuclear accidents, seismic risks, and inadequate waste management systems, such as the lack of a deep geological repository, and fueling opposition due to factors including economic disparities, social injustice, political grievances, and perceived threats to individual liberties.

Geopolitically, Pakistan's non-signatory NPT status and its nuclear weapons program invite international scrutiny, limiting its access to cutting-edge reactor technologies and uranium imports. Meanwhile, the rapid decline in renewable energy costs makes solar and wind more attractive to investors, though nuclear energy's baseload reliability remains unmatched.

Additionally, reliance on foreign expertise hinders local capacity-building. Addressing these challenges demands strategic reforms, including diversifying financing, enhancing fuel security, strengthening safety protocols, improving public engagement, and pursuing diplomatic avenues like NSG membership.[56] Without such measures, Pakistan's nuclear ambitions may falter, undermining its energy security and climate goals.

Possible Way Forward and Recommendations

To overcome the challenges hindering Pakistan's nuclear energy ambitions, a multi-pronged strategic approach is essential. Financially, Pakistan can explore novel funding structures such as public-private partnerships, sovereign green bonds, and multilateral financing from friendly states while negotiating better conditions under the CPEC to decrease debt burdens.

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[56]Abu Hurrairah, "Nuclear Energy: A Path to Sustainable Development in Pakistan," *Issue Brief – Institute of Strategic Studies Islamabad (ISSI)*, October 12, 2022, https://issi.org.pk/wp-content/uploads/2022/10/IB-Abu_Hurrairah_Oct_12_2022.pdf

Technologically, the country should invest in the indigenous R&D sector for advanced reactor designs like SMRs and thorium-based systems, while simultaneously upgrading its fuel cycle capabilities through partnerships with China and other nuclear-capable, friendly nations. Pakistan's thorium reserves are unproven and unexplored as of now; therefore, if Pakistan chooses to invest in thorium-based reactors, it must systematically explore, quantify, or economically evaluate its reserves as a precursor. On the fuel security front, Pakistan should accelerate exploration of domestic uranium reserves, pursue nuclear fuel banking arrangements with the IAEA, and develop strategic reserves to mitigate supply chain vulnerabilities.[57]

To address public concerns, a comprehensive nuclear communication strategy should be implemented, featuring transparency initiatives, community engagement programs near nuclear sites, and educational campaigns to build national consensus. Strengthening regulatory frameworks through enhanced PNRA capabilities, adopting international safety standards, and developing a robust nuclear waste management policy with potential regional cooperation for waste disposal solutions will be crucial.[58] Geopolitically, Pakistan should pursue a diplomatic offensive to gain NSG membership or seek exemptions, while diversifying its nuclear technology partnerships beyond China to include Russia and other potential collaborators.[59]

To counter renewable energy competition, Pakistan should position nuclear as a complementary baseload source within a diversified energy mix, leveraging its high-capacity factor and grid stability advantages. Human resource development requires urgent attention through the expansion of

[57]Syed Akhtar Ali, "COP28: Emerging Role of Nuclear Power," *Business Recorder*, December 14, 2023, https://www.brecorder.com/news/40278491; also see Suriya Jayanti, "Nuclear Power Is the Only Solution," *Time*, December 4, 2023, https://time.com/6342343/nuclear-energy-climate-change/

[58] Taha Amir, "Nuclear Balancing Act: Pakistan's Energy & Climate Future," *Stratheia*, April 15, 2025, https://stratheia.com/nuclear-balancing-act-pakistans-energy-climate-future/

[59] Samreen Shahbaz, "Small Modular Reactors: A Strategic Solution to Pakistan's Energy Crisis," December 15, 2024, https://csspr.uol.edu.pk/smr/

nuclear engineering programs, the establishment of specialized training centers, and incentives to retain technical expertise.

Additionally, Pakistan should explore niche applications of nuclear technology, such as seawater desalination and hydrogen production, to enhance the economic viability of its nuclear program. By implementing this comprehensive strategy with strong political commitment and long-term policy consistency, Pakistan can realistically achieve its nuclear energy goals while addressing energy security needs and climate commitments, though the path will require sustained effort over decades. This comprehensive strategy will not only meet the country's energy demands but will also help drive economic growth, protect the environment, and accelerate the global transition to cleaner energy systems.

Challenge	Possible Solutions
High Capital Costs	International financing (China, multilateral banks) and technical support from the IAEA
Public Opposition	Transparency, safety audits, and public awareness campaigns
Waste Management	Advanced reprocessing, long-term storage solutions
Geopolitical Barriers	Diversification of nuclear partners (beyond China)

Conclusion

Pakistan's pursuit of a low-carbon future necessitates an energy transition that balances climate commitments with growing electricity demands. Within this context, nuclear energy emerges as a vital, though complex solution. Applying the Energy Transition Theory, nuclear power offers Pakistan a stable baseload energy source to complement intermittent renewables, ensuring energy security while reducing reliance on fossil fuels. The Technological Innovation Systems (TIS) framework underscores the potential of advanced nuclear technologies, such as SMRs and Generation III+ designs, to enhance Pakistan's energy infrastructure, provided the country overcomes barriers like high capital costs and limited indigenous technical expertise in specific areas such as advanced fuel cycle development (including thorium utilization), reactor core and system designs, digital instrumentation and control systems etc.

From an Environmental Economics perspective, nuclear energy's near-zero operational carbon emissions align with Pakistan's climate goals under the Paris Agreement, offering a pathway to mitigate its current dependence on coal and gas. However, this advantage should be weighed against challenges such as uranium supply constraints, radioactive waste management, and high initial investments.

The Carbon Framework further highlights nuclear power's role in decarbonizing Pakistan's energy-intensive sectors, particularly industrial processes and large-scale electricity generation, where renewables alone may not suffice. For example, using SMRs to provide electricity to factories and delivering high-temperature heat to industrial processes, which renewables alone cannot handle.

The Energy Justice Framework introduces critical social and ethical considerations, emphasizing that nuclear expansion must prioritize equitable citing, community consent, and intergenerational equity to avoid displacing vulnerable populations or burdening future generations with waste management liabilities. Additionally, the Political Economy lens reveals that Pakistan's nuclear trajectory is shaped by geopolitical dependencies (such as reliance on Chinese technology), domestic policy stability, and competing energy interests.

For nuclear energy to fulfill its potential in Pakistan's low-carbon future, a multidimensional strategy is essential, as highlighted below:

1. Policy and Financing: There is a need to implement long-term energy policies, attract international investment, and explore public-private partnerships to reduce financial barriers.

2. Technological Advancement: It is timely to invest in local R&D, foster international collaborations for SMRs, and upgrade regulatory frameworks to ensure safety and efficiency.

3. Social Equity: There is a need to engage communities in nuclear planning, ensure transparent governance, and develop fair waste disposal solutions.

4. System Integration: The combining of nuclear with renewables will offer a hybrid energy model that will lead to optimizing grid reliability and sustainability.

In conclusion, nuclear energy can be a cornerstone of Pakistan's low-carbon transition—but its success hinges on addressing economic, technological, and justice-related challenges. By adopting a balanced, inclusive, and innovation-driven approach, Pakistan can harness nuclear power to achieve energy security, climate resilience, and sustainable development, while ensuring no community is left behind in the process. The journey requires not just infrastructure development but a commitment to equitable and forward-thinking energy governance.

Bridging the Gap: Women's Evolving Role in Nuclear Science

Sitara Noor*

Abstract

Nuclear science has played a transformative role in shaping societies, policies, and technologies for over a century. As the world turns to nuclear energy as a key solution to climate change and sustainable development, the nuclear sector should embrace an innovative, diverse, and inclusive workforce. The trailblazing journeys of pioneering women in nuclear science offer a powerful context for understanding women as bridge builders in a historically male-dominated field. Their groundbreaking work in nuclear and medical physics laid the foundations for modern innovations. While highlighting the contributions of pioneering female figures, this study aims to shed light on the structural dynamics that continue to influence women's participation in the nuclear sector. The paper also offers a way forward to promote inclusivity and equity through proposed changes at the grassroots level.

Keywords: Women in Nuclear, IAEA, UNESCO, STEM, Marie Sklodowska-Curie, Lise Meitner, Nuclear Energy, WiN Global, WiN IAEA.

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Introduction

The discovery of uranium by Martin Heinrich Klaproth in 1789 marked the beginning of progress in nuclear science. Over a century later, in 1895, Wilhelm Conrad Röntgen revolutionised scientific thought by discovering X-rays, opening a new window into invisible forms of energy. Just a year afterward, in 1896, the ground-breaking discovery of radioactive elements Radium (Ra) and Polonium by Maria Salomea Skłodowska Curie, alongside her husband Pierre Curie, paved the way for future developments in nuclear science.

What began as the study of invisible rays and previously unknown elements evolved into a vast field that now encompasses energy production, medicine, agriculture, space exploration, environmental protection, and many other applications. The twentieth century witnessed landmark achievements from the development of nuclear reactors and medical isotopes to the use of nuclear technology for peaceful purposes under international frameworks. This evolution is the result of the collaborative efforts of many scientists and engineers who carried out cutting-edge research in fusion energy, advanced reactors, and nuclear medicine. However, despite a remarkable contribution of many pioneering women to this evolution, such as Marie Curie, it remains a male-dominated field. As the world turns to nuclear science to deal with critical issues including climate change, global health, and energy security, there is a growing need to recognize the contribution of women and to work harder to achieve the goal of gender equality in this field.

For safe and effective application of nuclear technologies in today's rapidly advancing nuclear sector, more scientists and engineers are required to support new projects, advance research and development, and enforce effective regulation. While there is greater acknowledgment in general that women bring strength in the form of diverse and innovative perspectives to the nuclear sector, they are largely underrepresented in the nuclear sector, particularly in leadership roles. As a result, many countries around the world are losing access to a vast pool of talent. Various studies show that the lack of female representation in the nuclear field is due to systemic discrimination that starts with unequal education opportunities. According to the World Bank Report, "[a]lthough girls often perform as well as or better than boys in math and science at the primary and secondary levels, they are underrepresented in some Science, Technology, Engineering, and Mathematics (STEM) subjects, particularly engineering and computer science, at the tertiary level."[1]

Despite these challenges, women have contributed significantly to the talent pool of science and technological development, especially in the nuclear field, as we learn from the revolutionary contributions of pioneering women like Marie Curie, Lise Meitner, and many others. Some other studies, such as Catalyst 2007[2] and Finish Business and Policy Forum EVA 2007[3] have shown that having women in leadership positions at the management and board level results in elevated organizational performance.

Despite the data proving women's important contribution, women are still underrepresented and make up only a fifth of the nuclear workforce at the global level.[4] This gender gap highlights the missed opportunities for innovation and growth, posing a threat to the long-term stainability of the nuclear workforce and the continued relevance of the field. In this context, bringing more women engineers, scientists, and leaders into the nuclear

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[1] Schomer, Inka, and Alicia Hammond. *Stepping up Women's STEM Careers in Infrastructure: An Overview of Promising Approaches*. ESMAP Paper. World Bank Group, 2020. https://documents1.worldbank.org/curated/en/192291594659003586/pdf/An-Overview-of-Promising-Approaches.pdf

[2] Catalyst, *Only Wrong Way Stop No Stopping: The Double-Bind Dilemma for Women in Leadership—Damned If You Do, Doomed If You Don't* (2007), https://assets.catalyst.org/1d656b05-9af0-422a-b5da-b25e01470102/The_Double_Bind_Dilemma_for_Women_in_Leadership_Damned_if_You_Do_Doomed_if_You_Dont_Original%20file.pdf

[3] Annu Kotiranta, Anne Kovalainen, and Petri Rouvinen, *EVA Analysis: Female Leadership and Firm Profitability* (Finnish Business and Policy Forum, 2007), https://www.eva.fi/wp-content/uploads/files/2133_Analyysi_no_003_eng_FemaleLeadership.pdf

[4] Sara Kouchehbagh, "International Women's Day: Hundreds of Women Building a Career in Nuclear Gather at the IAEA," *International Atomic Energy Agency*, March 7, 2024, https://www.iaea.org/newscenter/news/international-womens-day-hundreds-of-women-building-a-career-in-nuclear-gather-at-the-iaea

workforce is crucial for maintaining the viability of the nuclear sector and its contribution to the society. Moreover, achieving gender-balanced leadership in laboratories, boardrooms, and on public stages is essential to ensure inclusivity. Diverse teams foster more innovative and collaborative approaches in research, gender balance in boardrooms leads to stronger governance, and public representation of leaders is essential for visibility and inspiration.

While addressing the gender gap in the nuclear sector is a moral imperative, it is also a strategic necessity. Global efforts are underway to transform the landscape of the nuclear workforce for women. At present, various international organizations like the International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), and other associations such as Women in Nuclear (WiN) and more, recognize the valuable role women have played in scientific discovery historically and the utilization of nuclear energy. Initiatives such as the Marie Sklodowska-Curie Fellowship Programme (MSCFP), the Lise Meitner Programme (LMP), and WiN are actively working to create a more inclusive, equitable workforce.

Based on the above premise, this paper aims to assess women's role in the development of nuclear science through a historical and analytical perspective. It highlights the trailblazing journeys of pioneering women in nuclear science. This paper aims to address three interconnected questions: Why does a gender gap still exist in the nuclear sector? What obstacles do women encounter when trying to enter, succeed, and remain in this field? How do the contributions of pioneering women and global initiatives shape a more inclusive future?

Trailblazing Journeys of Pioneering Women in Nuclear Science

From pioneering discoveries to leading advancements in nuclear science, medicine, and energy, women have played a vital role in shaping the field of nuclear science across generations. A closer look into the journeys of pioneering women who overcame gender based and other systemic barriers with their passion, dedication, and resilience informs us about some of the persistent challenges that women face even today. The paths of these pioneering women were often marked by obstacles such as poor lab arrangements, institutional sexism, work-life balance, pay disparity, and underrepresentation. However, through sustained passion and determination, these women achieved ground-breaking contributions which paved the way for future generations of women aspiring to work in the nuclear sector.

As we speak of the female pioneers and the role models, a name that stands out amongst all is *Maria Salomea Skłodowska,* well known *as Marie Curie (1867 – 1934)*.[5] For over a century, she has been a role model for the scientific community—women and men alike—due to her groundbreaking contributions to the fields of physics and chemistry, particularly her discovery of radioactivity. Born and raised in Warsaw, she, along with her husband, studied the spontaneous radiations discovered by Becquerel, discovered elements polonium and radium, and developed methods for isolating radium, enabling its study and use in medicine. This discovery was recognized, and they both Curie and her husband, were awarded the Nobel Prize in Physics (1903). Later, Marie also received a Nobel Prize in Chemistry in 1911 for these discoveries. She was the first woman in nuclear physics to be awarded a Nobel Prize and the first individual to be awarded two Nobel Prizes in two different categories.

Marie proved to be a true symbol of sacrifice. She died in 1934 from an illness likely caused by prolonged exposure to radiation, leaving behind a profound legacy in science and medicine. Through her example and mentoring, including mentoring her daughter Irène Joliot Curie, who later won a Nobel Prize in Chemistry for discovering artificial radioactivity. She paved the way for women in scientific research, education, and leadership. Curie's life was marked by resilience, determination, and intellectual brilliance. Marie's partnership with her husband remains a powerful

[5] Jenny Rydén, "MARIE CURIE - NobelPrize.org," *NobelPrize.org*, April 29, 2025, https://www.nobelprize.org/stories/women-who-changed-science/marie-curie/4

testament to the strength of collaboration in scientific discovery and a gender-inclusive work environment.

Another pioneering woman in nuclear science is *Lise Meitner (1878-1968)*[6] also known as the woman who split the atoms. She was also among those who dedicated their lives to the pursuit of knowledge and became only the second woman in the University of Vienna's history to earn a PhD in Physics, which she completed in 1906. She worked with Otto Hahn for over thirty years in exploring the emerging science of radioactive decay and leading the ground-breaking discovery of nuclear fission. Later, however, in a classic case of gender discrimination, Hahn downplayed her role in the discovery and did not even include her name in the publication of the finding. Despite her crucial role, Hahn, who did the experimental work alone, received the Nobel Prize in Physics in 1944. Meitner was excluded, partly due to antisemitism and sexism, showing systemic bias and discrimination.

Although nominated 48 times for Nobel Prizes in both Physics and Chemistry, Meitner never received the award, despite endorsements from renowned scientists like Bohr and Max Planck. Although the Nobel Committee never corrected its oversight, the error was partially addressed in 1966 when Lise Meitner, Otto Hahn, and Fritz Strassmann were jointly awarded the *Enrico Fermi Award*. Meitner's moral integrity did not allow her to work on the atomic bomb, and she courageously stated that "I will have nothing to do with a bomb." In recognition of her contributions, element 109 was named *Meitnerium (Mt)* in her honour in 1992.

During the same timeframe, another brilliant physicist was forging her path. Chien-Shiung Wu (1912-1997), often called the "First Lady of Physics," was a pioneering Chinese American physicist who made trailblazing

6 See Lise Meitner's Biography at Chemeurope.com, 2025, https://www.chemeurope.com/en/encyclopedia/Lise_Meitner.html

contributions to nuclear and particle physics.[7] While studying physics under Nobel Laureate Ernest Lawrence at UC Berkeley, she faced significant cross-cultural shock, adapting to a completely different society, environment, and language, all while pursuing advanced studies in physics. She joined the Manhattan Project in 1944, and there she worked on radiation detection and uranium enrichment for the atomic bomb. Wu's most famous contribution came in 1956, when she designed and executed an experiment disproving the law of conservation of parity in beta decay, confirming a theory proposed by Tsung-Dao Lee and Chen-Ning Yang. Although her experiment was critical to the discovery, only Lee and Yang received the Nobel Prize in Physics in 1957, while Wu was underrecognized – a pattern seen repeatedly in the treatment of women in science.

As nuclear science expanded beyond the laboratory, women like Edith Quimby were instrumental in applying nuclear technologies to improve public health, especially in cancer treatment and medical imaging. She introduced the "Quimby rules," which became the gold standard for placement of radioactive needles in radiotherapy until computerized methods emerged decades later. She also co-developed a "film-badge" system to monitor radiation exposure for workers, enhancing safety in labs and hospitals. In 1942, she joined Columbia University, where she became a full professor in 1954 and mentored future Nobel Laureate Rosalyn Yalow. There, her work helped establish nuclear medicine by radioactive isotopes for treating thyroid disease and diagnosing brain tumors. Quimby also contributed to research on radiation equivalence and cumulative exposure, helping assess long-term health impacts. She authored over 70 scientific papers and co-wrote the foundational textbook *Physical Foundation of Radiology.* Quimby's legacy lives on in the safer practices and principles of modern radiology and nuclear medicine. Her work not only saved lives but also helped transform a hazardous field into a scientifically rigorous and trusted branch of medical science.

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7 National Park Service, "Dr. Chien-Shiung Wu, the First Lady of Physics (U.S. National Park Service)," January 23, 2020, https://www.nps.gov/people/dr-chien-shiung-wu-the-first-lady-of-physics.htm

Like her predecessors and contemporaries in the nuclear field, Leona Woods Marshall Libby (1919 – 1986)[8] a brilliant American physicist played a pivotal role in the development of nuclear science. Her exceptional skill in vacuum technology and reactor diagnostics earned her a place on Enrico Fermi's Manhattan Project team, making her the only woman present during the historic 1942 Chicago Pile-1 experiment, which achieved the first human-engineered, self-sustaining nuclear chain reaction. Woods contributed significantly to nuclear research by developing the boron trifluoride counter, a critical device for detecting neutron activity. She was also central to diagnosing Xeon poisoning in the Hanford B Reactor in 1944 – an unexpected obstacle that threatened plutonium production. Her insight helped identify the issue as xenon-135 build-up, allowing engineers to adjust the reactor's design. This ultimately enabled the production of plutonium used in both the Trinity Test and the "Fat Man" atomic bomb dropped on Nagasaki.

The remarkable devotion to research, visionary leadership, and ground-breaking achievements of these pioneering women have established them as enduring role models not only for women but for society, even in the twenty-first century. Diving into their personal and professional journey underlines that women in that era confronted persistent social norms, sexism, and institutional barriers that sought to dim their light, limit their opportunities, and recognition. The same challenges continue to impact women in today's nuclear sector, manifesting as workplace bias, lack of mentorship, work-life balance difficulties, and limited career advancement opportunities. The legacy of these remarkable women highlights both the progress made and the efforts still needed to create an inclusive environment in the nuclear workforce where all women can thrive.

8 Faith Bennett, "Leona Woods Marshall Libby," U.S. National Park Service, accessed July 2, 2025, https://www.nps.gov/articles/000/leona-woods-marshall-libby.htm

Challenges Faced by Women in Nuclear Science

Despite the trailblazing contributions of women in nuclear science over the century, the world is still struggling with gender equality in all fields, but more importantly, in STEM fields. According to the European Commission's analytical report "Addressing the gender gap in STEM education across educational levels, "despite significant advances in STEM education and a growing emphasis on gender equality in research and policy circles, women across Europe remain under-represented in STEM careers and among graduates majoring in STEM-related fields."[9] The report further highlights the main causes of gender imbalance that include lower self-efficacy, the role of family and the broader social context, societal stereotypes, non-inclusive curricula, certain teaching practices that reinforce stereotypes, as well as a lack of female role models in STEM.[10] Lack of equal educational opportunities feeds into further imbalance in female representation in employment and leadership roles. According to the World Economic Forum, despite an increase, women are largely underrepresented in STEM roles and comprise only 28.2% of the STEM global workforce in 2024, as compared to non-STEM roles, which is 47.3%.[11]

In a poll conducted by the author among a diverse group of women researchers in science, nuclear, and security studies from different parts of the world, about 88% of the women responded affirmatively to the question of gender-based discrimination in their workplace. Nearly 40% cited the workplace culture as the primary reason for persistent discrimination, 31% referred to general gender biases, 14.1 % marked work-life balance as a cause of discrimination, and 12 % marked the lack of advancement

9 Evagorou, Maria, Beatriz Puig, Dilek Bayram, and Hana Janečková. "Addressing the Gender Gap in STEM Education Across Educational Levels." *NESET report*. Luxembourg: Publications Office of the European Union, 2024. p.8. https://nesetweb.eu/wp-content/uploads/2024/05/NESET-AR02-Analytical-report-with-identifiers-1.pdf
10 Addressing the Gender Gap in STEM Education Across Educational Levels.
11 World Economic Forum, Global Gender Gap Report 2024 (Geneva: World Economic Forum, 2024), 8, https://www3.weforum.org/docs/WEF_GGGR_2024.pdf

opportunities as a primary cause of discrimination. Almost 02% cited other reasons.

The availability of comprehensive data on the challenges faced by women in nuclear sciences remains limited. Nonetheless, the report entitled "Gender Balance in the Nuclear Sector," published by the Nuclear Energy Agency Organization for Economic Cooperation and Development (OECD-NEA), stands as the first publicly available source that systematically addresses gender-based challenges in the nuclear workforce internationally.[12] In many organizations, such issues are not openly discussed due to institutional sensitivity, confidentiality restrictions, and limited transparency, limiting the scope of comparative analysis.

The report is based on the data collected from 96 nuclear organizations in 17 NEA member countries, such as Argentina, Australia, Belgium, Canada, France, Hungary, Italy, Japan, Korea, Norway, Poland, Romania, Slovenia, Spain, Sweden, and the United Kingdom. The report findings highlight the gender disparity as women make up less than a quarter (24.9%) of the overall nuclear sector workforce. It also emphasizes that only one-fifth (20.6%) of STEM roles in the nuclear sector are held by women, and women represent only 18.3% of senior leadership, highlighting a substantial gender gap.[13] This is because women often don't pursue careers in STEM due to gender stereotypes, dissatisfaction with the workplace culture, the lack of advancement opportunities, and the challenges presented by work-life balance.[14]

The NEA report highlights that while physical working conditions are equal to a greater extent, shortcomings in management's commitment to gender inclusion and inadequate institutional frameworks remain a persistent issue, particularly in leadership and decision-making representation. In that study,

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[12] OECD Nuclear Energy Agency, Gender Balance in the Nuclear Sector (Paris: OECD Publishing, 2023), https://www.oecd.org/en/publications/gender-balance-in-the-nuclear-sector_f11a652d-en.html

[13] Gender Balance in the Nuclear Sector.

[14] Gender Balance.

fewer than 50% of women surveyed responded affirmatively to the question about whether the gender balance policies in their organizations helped them feel satisfied with their career and be optimistic about their prospects. Women in regulatory agencies, government entities, and fuel cycle organizations gave higher ratings to their employers, whereas women employed at the decommissioning sites and within original equipment manufacturers or nuclear supply chain organizations scored their employers lower.

Furthermore, work-life challenges like family responsibilities, pregnancies, or maternity leaves are perceived to have a negative impact on the career; over 70% of the women surveyed in the NEA report overwhelmingly agree in the nuclear sector. One of the top five barriers, specifically related to nuclear sector, is that the career advancement in nuclear power plants is challenging for nursing mothers as well as for those with the young children because career progression in nuclear power plants involve roles that require on-call and shift work. The second barrier is that most of the nuclear facilities are in areas lacking spousal employment opportunities or inaccessible to family support. These barriers, concluded from the NEA survey, highlights the reasons behind lower female retention rates in non-management and junior management levels in the nuclear sector. The lower retention of mid-career women creates a bottleneck in the leadership pipeline, resulting in a smaller pool of skilled women who are eligible for progressively senior positions.[15]

The authors sought opinions from professional women from diverse backgrounds and different geographical locations working in nuclear science and nuclear policymaking on facing gender biases and discrimination in the work environment.[16] Many women pointed out the framing issue and shared that nuclear science is largely seen as a masculine policy domain, which by design leaves less or no space for women to thrive.

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[15] OECD, "*Joining Forces for Gender Equality*. Paris": OECD Publishing, 2023. https://www.oecd.org/en/publications/2023/05/joining-forces-for-gender-equality_bb1768d0.html

[16] Based on personal interviews conducted by the author with 10 female experts in nuclear science and nuclear policy, 2025.

One respondent shared that because of that thinking and mindset, male counterparts are given more credit and preferred for undertaking more visible roles, such as delivering presentations, when female team members have contributed equally or more in the actual presentation. Some other participants cited limited career advancement opportunities, unequal pay scales, and assumptions about lower leadership capabilities among women. Another participant highlighted fewer training opportunities, leading to limited career growth opportunities. They also highlighted the fact that in most cases, women have to put double the effort as compared to men to receive equal respect and acknowledgment. Some women highlighted discrimination even in companies and organizations that are making efforts to promote gender equality. One participant shared her experience where a company disregarded her qualifications and told her that they needed to hire a female to ensure gender balance, whereas her education and relevant experience matched the job description, but that was not seen as meeting the criteria. Some women highlighted their inability to command policy or make decisions independently despite being in a leadership role. They shared that this affects their ability to fully exercise their leadership role, affecting both accountability and initiative. Another participant cited societal barriers and limited opportunities at the beginning of her career that affected her professional growth, but at the same time acknowledged a supportive environment at her current appointment at an international organization.

In some other reports, female professionals shared personal and anecdotal experiences and highlighted some structural biases. For example, Rumina Velshi, Ex-President of the Canadian Nuclear Safety Commission (CNSC), spoke about her experience as a professional in the nuclear field in Canada and stated that "plant was not built ever expecting women to work there…there was no radiation protection clothing in women's sizes and no changing rooms for women."[17] While Canada has largely addressed these

[17] Nathalie Mikhailova and International Atomic Energy Agency "Women in the Nuclear Field Share Their Stories at International Women's Day Event." *IAEA*, March 7, 2019.

structural and organizational issues, as also acknowledged by Velshi, this remains a reality in various other countries to date.

Findings of the reports, polls, and interviews cited above underline the fact that gender discrimination and gender biases against women in general and those pursuing careers in nuclear science are systemic and start even during the educational phase. Some of the key issues, as reflected in the cumulative data, reflect that women continue to experience hostility, including sexual harassment, in STEM roles. Furthermore, workplace culture and stereotypes inhibit women's careers with biases about leadership characteristics, such as women are stereotyped as 'caretaker' and men as 'charge taker', and insufficient support for the professional development of women. Almost two-thirds of the females reported that stereotyping, microaggressions, or unconscious bias, and a male-dominated work culture that inhibits the full contribution of women negatively impact women's careers in the nuclear sector, thereby lowering the retention rate.

More flexibility, access to childcare, and upward career pathways compatible with parenthood are required to facilitate women in the nuclear sector. Furthermore, the lack of female leaders to serve as mentors and role models in the current era is another barrier in the nuclear sector. Moreover, socio-cultural perceptions that nuclear energy is a man's field are included in the top five barriers specific to the nuclear sector according to the NEA survey. These perceptions discourage many women from pursuing a career or progressing in the nuclear sector, also contributing to the gender gap in the nuclear sector. These barriers signify the underrepresentation of women in the nuclear sector.

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https://www.iaea.org/newscenter/news/women-in-the-nuclear-field-share-their-stories-at-international-womens-day-event

Way forward

There has been significant progress in female representation in nuclear science in recent years. The IAEA, for instance, has championed gender equality over the years and achieved gender parity in 2025, by meeting the target of having women in half of the professional and higher-level positions, that is a 30% increase since 2019.[18] Other indicators also point to a positive shift in gender equality and inclusion. For example, the 2017–2022 review cycle of the meetings of the Nuclear Non-Proliferation Treaty (NPT) witnessed a significant increase in working papers and statements highlighting the importance of gender equality in the NPT.[19] The working paper submitted by Australia, Canada, Colombia, Ireland, Mexico, Namibia, Panama, the Philippines, Spain, Sweden, and the United Nations Institute for Disarmament Research called for gender mainstreaming in the Treaty on the Non-Proliferation of Nuclear Weapons.[20] Likewise, the Treaty on the Prohibition of Nuclear Weapons (TPNW) has picked up the debate in a more nuanced manner. In the clause mandating states parties to assist survivors of nuclear weapons use and testing, the TPNW has required a gender-sensitive approach.[21] In this way, it has addressed the gender issue from a technical lens, thereby giving further credence to this entire discussion.

While the IAEA has set a high standard and other international forums concerning nuclear science and policy are putting in place the effort and

[18] International Atomic Energy Agency (IAEA). "IAEA Board Briefed on Ukraine, Iran, Gender Parity, AI and More." *IAEA News Centre*, March 3, 2025. https://www.iaea.org/newscenter/news/iaea-board-briefed-on-ukraine-iran-gender-parity-ai-and-more

[19] Renata Hessmann Dalaqua, ed., *From the Margins to the Mainstream: Advancing Intersectional Gender Analysis of Nuclear Non-Proliferation and Disarmament* (Geneva, Switzerland: United Nations Institute for Disarmament Research, March 25, 2024), 10

[20] *From Pillars to Progress: Gender Mainstreaming in the Treaty on the Non-Proliferation of Nuclear Weapons,* Working Paper NPT/CONF.2020/WP.54, submitted to the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 17 May 2022. https://undocs.org/NPT/CONF.2020/WP.54

[21] Singh, Nidhi, "Victim Assistance under the Treaty on the Prohibition of Nuclear Weapons," *Journal for Peace and Nuclear Disarmament* 3, no. 2 (2020): 265–82. https://doi.org/10.1080/25751654.2020.1856554

catching up, various countries and other organizations have to cover a long distance. Recognizing the importance of diversity in the workplace and overcoming the gender disparity in nuclear science, Gwen PerryJones the Executive Director of Operations Development at the Wylfa Newydd nuclear power plant in the United Kingdom rightly noted that "[a]lthough there are many talented and highly skilled women within the nuclear industry, we are still vastly under-represented. There is still work to do. Diversity in the workplace benefits us all, and I fully support initiatives that encourage women to enter the industry and help them see routes to senior positions."[22]

According to the United Nations Institute for Disarmament Research (UNIDIR) study, two main issues hinder progress in that regard. One, despite the significant developments, there are still many entities that do not recognize the importance of gender equality and gender perspectives. The second issue is equating gender with women or women's issues.[23]

In that regard, first and foremost, it is important to create awareness about the importance of gender equality and the need to adopt a gender sensitive approach. According to a study, "Examining 'Gender-Sensitive' Approaches to Nuclear Weapons Policy: a Study of the Non-Proliferation Treaty," gender sensitive approaches centre on the inclusion of women and women are constructed as a homogenous category of outsiders; and women's inclusion is understood mainly as a means of increasing institutional efficiency.[24] While this study discusses gender sensitivity from

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[22] International Atomic Energy Agency (IAEA), "Toward Closing the Gender Gap in Nuclear Science," *IAEA News Centre*, February 11, 2019, https://www.iaea.org/newscenter/news/toward-closing-the-gender-gap-in-nuclear-science

[23] Renata Hessmann Dalaqua, ed., *From the Margins to the Mainstream: Advancing Intersectional Gender Analysis of Nuclear Non-Proliferation and Disarmament* (Geneva, Switzerland: United Nations Institute for Disarmament Research (UNIDIR), March 25, 2024), 10, https://unidir.org/wp-content/uploads/2024/03/UNIDIR_From_the_Margins_to_the_Mainstream_Advancing_Intersectional_Gender_Analysis_of_Nuclear_Non_Proliferation_and_Disarmament.pdf

[24] Laura Rose Brown and Laura Considine, "Examining 'Gender-Sensitive' Approaches to Nuclear Weapons Policy: A Study of the Non-Proliferation Treaty," *International Affairs* 98, no. 4 (July 2022): 1249–66, https://doi.org/10.1093/ia/iiac114, p:50

the perspective of the NPT, it is very much applicable in other organizations dealing with nuclear sciences.

Secondly, there is a need to have an overhaul of the existing system, make space for a new gender sensitive approach, and address the structural issues, as highlighted and recommended by some of the participants interviewed for this study. The NEA study provides recommendations based on the "Attract, Retain, and Advance Framework" that aims for a long-term strategy for a reversal of existing negative trends and introduction of structural reforms to support the gender inclusive workforce in the nuclear industry.[25] To attract young women to the nuclear field, the study recommends introducing public communication campaigns to shape gender perceptions regarding careers in nuclear sector, illustrating the impact and social value of nuclear science and technology, while also highlighting attractive opportunities in nuclear careers. These campaigns should also promote women's leadership and remarkable contributions to the nuclear field, targeting both women and men to highlight how maintaining gender balance benefits the nuclear sector and enriches STEM fields.

The second pillar is to "retain" women by ensuring equal wages, showing increased flexibility regarding their family responsibilities outside work, providing them access to childcare and lactation facilities, and an integration program on their return from parental or family leave, along with eliminating harassment and build inclusive work environment. The third pillar is to support and empower women as leaders, increasing their contributions by requiring unconscious bias and inclusivity training for those who make hiring and promotion decisions, providing leadership and career advocacy training with targeted support for women, especially in STEM fields, and training managers to support and encourage the career development of diverse staff. This pillar also involves creating inclusive support systems, encouraging the career advancement of diverse staff, establishing inclusive resource groups and all-gender networks, including

[25] Nuclear Energy Agency (NEA), *Gender Balance in the Nuclear Sector* (Paris: OECD-NEA, 2023), 11, https://www.oecd-nea.org/jcms/pl_78831/gender-balance-in-the-nuclear-sector

male allies, and conducting regular pay equity reviews to ensure fair compensation based on experience and role.

Lastly, women's representation should not be framed only as a human rights issue.[26] As underscored by the European Institute for Gender Equality (EIGE), gender equality is also a precondition for sustainable development.[27] Despite improvements implemented in various countries and organizations, many women in the nuclear fields continue to face gender stereotypes, unconscious bias, and underrepresentation in leadership and technical roles, pay disparities, limited advancement opportunities, and workplace cultures that lack inclusivity. Issues such as pregnancy discrimination, sexual harassment, and difficulties balancing work and life further hinder retention and progression. Psychological challenges such as impostor syndrome and the long-term effects of unemployment scarring also impact career continuity.

Therefore, inclusivity, gender balance, and gender sensitivity must be incorporated in real essence, and it should not be a mere token representation, as also highlighted by some of the interview participants that they were either given certain positions without real authority or their role was only to meet the target of female representation. Ensuring gender equality, therefore, must remain a work in progress, and only a continuous push will evolve into an impactful change.

Global Initiatives to Enhance Women's Participation

There are several global initiatives that seek to enhance the participation of women in nuclear industry and improve current policies as well as the working environment.

[26] Muhammed Ali Alkış and Polina Sinovets, "Nuclear Security: Making Gender Equality a Working Reality," *International Journal of Nuclear Security* 8, no. 2 (2023): Article 9, https://doi.org/10.7290/ijns220431

[27] European Institute for Gender Equality, *Gender Equality*, June 17, 2025, https://eige.europa.eu/thesaurus/terms/1168

One such initiative is the Marie Sklodowska-Curie Fellowship Programme (MSCFP) launched by the IAEA's Director General, Rafael Mariano Grossi.[28] It is a pioneering initiative that seeks to bridge the gender gap in the nuclear field by empowering young women to pursue careers in this sector. Named after the physicist and twice Nobel Prize laureate Marie Skłodowska-Curie, the program aims to foster a more inclusive and diverse workforce, driving global scientific and technological innovation.

The MSCFP provides highly motivated female students with scholarships to pursue master's programs in nuclear-related studies at accredited universities. Additionally, selected students are offered an opportunity to gain hands-on experience through internships facilitated by the IAEA. This comprehensive approach enables students to acquire theoretical knowledge and practical skills, preparing them for successful careers in the nuclear field.

Another initiative launched by the IAEA is the Lise Meitner Program (LMP).[29] This unique initiative is designed to support the career development of women already working in the nuclear sector, with a focus on the nuclear energy field. Named after the renowned Austrian-Swedish physicist Lise Meitner, the program aims to empower women professionals by providing them with opportunities to gain hands-on experience, expand their professional networks, and develop their skills in a dynamic and interactive environment.

The LMP offers visiting professionals the chance to participate in professional visits to various nuclear facilities, and the program's content is tailored to match the visiting professionals' profiles and interests, ensuring a personalized and enriching experience. The program generally spans two to four weeks, with 10 to 15 visiting professionals participating in each

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[28] IAEA, *The Marie Sklodowska-Curie Fellowship Programme (MSCFP)*, 2025, https://www.iaea.org/services/key-programmes/together-for-more-women-in-nuclear/iaea-marie-sklodowska-curie-fellowship-programme

[29] IAEA, *The Lise Meitner Programme*, 2025, https://www.iaea.org/services/key-programmes/together-for-more-women-in-nuclear/lise-meitner-programme

cohort. The IAEA Member States and other donors fund LMP through extra-budgetary and in-kind contributions, ensuring that visiting professionals do not incur any financial costs.

WiN Global, a non-profit organization, has been a strong advocate for gender equality since its inception in 1992. With around 35,000 members and over 20 partners, WiN Global is a robust network with an active presence in more than 145 countries including Pakistan, and engagement with various international organizations. Furthermore, the association actively invests in defining nuclear policies and gender equality strategies in the nuclear sector.

As an international network of women professionals, it empowers members by creating opportunities for cross-cultural exchange, leadership development, and active participation in decision-making processes. By promoting the integration of a gender perspective, WiN ensures that women's unique needs, experiences, and insights are recognized and addressed. Additionally, WiN Global advocates for inclusive communication strategies to reshape public perception of nuclear energy, emphasizing the value of collective action for sustainable progress.[30]

As one of the active chapters of WiN Global, the Women in Nuclear IAEA, a group of 650+ volunteers working at the IAEA, has been instrumental in highlighting the needs of women working at the IAEA and promoting a supportive and inclusive workplace.[31] The WiN IAEA supports underrepresented groups in the nuclear and radiation fields, especially women and the younger generation, where their presence remains limited, by actively working towards its objective, i.e., peace.

As the world faces pressing challenges such as population growth, food insecurity, high energy demand, and climate change, the nuclear sector

[30] ANIMUS, "About WiN - Women in Nuclear," *Women in Nuclear*, May 21, 2024, https://win-global.org/about-win/
[31] "Women in Nuclear IAEA," 2025, https://win-iaea.org/

plays a vital role in addressing these issues. To drive innovation and progress, it is essential for nuclear organizations to "attract, maintain, and retain" a qualified and diverse workforce. A diverse workforce, where everyone can contribute equally and be recognized for their skills, expertise, and achievements, is crucial for the industry's success and sustainability.

Conclusion

From the splitting of the atom to the frontiers of fusion and producing nuclear energy to nuclear medicine, the journey of nuclear science has proven nuclear technology as a viable solution to contemporary challenges related to the socioeconomic growth of countries worldwide. With this realisation and acknowledging the importance of gender inclusivity, efforts should be made to engage more women in advancing this field. By prioritizing diversity, gender balance, and an inclusive working environment, the nuclear sector can build a strong, innovative, and productive workforce that is equipped to tackle the challenges of the future.

The contemporary challenges, like gender biases and stereotypes, are affecting women's choice of career in STEM roles, particularly in the nuclear sector. While pursuing a career in the nuclear sector brings challenges like limited representation in leadership, lack of mentorship, and maintaining work-life balance, the journeys of trailblazing women in nuclear science establish a foundation for aggressive policies to encourage girls in STEM education. The women in leadership roles exhibiting leadership qualities, such as resilience, curiosity, and brilliance, and breaking barriers, should be presented as role models for the next generations.

As there exists limited data on nuclear sector-specific challenges faced by women, there is a need to have more regional surveys to identify barriers that will help to assess workplace experiences and inform policies to promote gender equity and inclusion. The OECD-NEA report reveals that systematic gaps still exist, while also highlighting promising strategies, such as the "Attract, Retain, and Advance Framework", to close them. The strategies are augmented through initiatives like the Marie Sklodowska-Curie Fellowship Program and the Lise Meitner Program by the IAEA and associations like WiN Global, WiN IAEA, and other national chapters, empowering young women in nuclear. These efforts should be strengthened through the support from international, regional, governmental, and national organizations, but also through the active contribution of each individual.

Collaboration in Nuclear Science and Technology: Prospects and Challenges for Pakistan's Regulator

*Noreen Iftakhar and Hamid Saeed Raza**

Abstract

A nuclear regulator cannot be complacent due to the peculiar nature of its job. The regulator continuously strives to be the best and a role model for others. However, this persistent striving for excellence requires several factors. Among these factors, the most important is the collaboration with its peers and other organizations at the international level, in the sharing of knowledge, information, feedback, experience, and capacity building. Pakistan, being the pioneer member of the International Atomic Energy Agency (IAEA), has a long history of cooperation with the international community. Pakistan Nuclear Regulatory Authority (PNRA) was established in 2001 as the national nuclear regulatory authority, in compliance with the Convention on Nuclear Safety (CNS) - through the promulgation of PNRA Ordinance, i.e., Ordinance III of 2001. It was assigned the responsibility to regulate all nuclear installations, radiation facilities, and associated activities in Pakistan for the protection of workers, the general public, and the environment. PNRA, like other international Regulatory Bodies (RBs) in the nuclear domain, has developed mechanisms for international collaboration to bring its performance and processes at par with the international standards. PNRA regularly

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participates in global nuclear forums and bilateral as well as multilateral arrangements, assigns experts to participate in international activities, and also presents itself for peer review. Despite these efforts, Pakistan faces certain challenges related to international cooperation. Alongside, PNRA also faces several complications while achieving its mission and vision. These primarily include limited access to codes and standards for ensuring nuclear safety, technology denials, and international emphasis on Pakistan's defense initiatives, which sometimes limits the visibility of its efforts and achievements in the peaceful applications of nuclear technology. Against this backdrop, this paper offers two sets of proposals to overcome these challenges, both at the regulatory and policy level.

Keywords: Global Nuclear Collaboration, International Cooperation, Pakistan Nuclear Regulatory Authority, Inclusive Partnership, Multilateralism.

Introduction

Over the years, the global nuclear sector has undergone significant changes, placing greater importance on international cooperation to enhance nuclear safety and security and promote the peaceful application of the nuclear field. Among other key players in this field, Nuclear Regulators hold a crucial responsibility of ensuring nuclear safety and security while encouraging collaboration with their counterparts in other nations. However, at the same time, the need for a common platform to discuss mutually affecting issues such as nuclear safety, security, or preparing against a nuclear accident or radiological emergency, is undeniable.

At the global level, the IAEA serves as a collaborative platform for Member States, facilitating cooperation in the nuclear sector. Its mission is to promote the safe, secure, and peaceful utilization of nuclear technologies. Whether sharing best practices or providing support during nuclear accidents or radiological emergencies, the IAEA remains actively engaged with its Member States. For Pakistan, a country with a growing nuclear energy program and a pioneer member of the IAEA, international cooperation is a necessary instrument for promoting activities at the international fora. Nevertheless, engaging in global collaboration presents both opportunities and challenges for Pakistan.

As one of the first countries to implement "Atoms for Peace,"[1] Pakistan's nuclear program was initiated in the 1960s and has gradually evolved from operating a single research reactor to developing several nuclear power reactors, and from limited applications to its broader use in medicine, industry, and agriculture. Today, nuclear technology is widely utilized in various sectors of Pakistan. While Pakistan has achieved significant milestones in nuclear technology, its journey has been marked by significant challenges, such as the need for updated infrastructural build-up, qualified and trained manpower.

Nevertheless, Pakistan's national nuclear regulator, the PNRA, is committed to ensuring that nuclear safety remains a top priority while utilizing nuclear technology for civilian purposes. In the contemporary interconnected world, PNRA has realized the importance of global collaboration among nuclear regulatory authorities. It understands that a collective approach is essential to addressing shared risks and leveraging shared opportunities. To achieve this, PNRA has established a comprehensive institutional mechanism related to international cooperation. From establishing a dedicated wing to fulfilling the country's obligations concerning different nuclear-related conventions, entering into cooperation agreements with other countries' regulatory bodies, providing its experts to IAEA-run training activities, and presenting itself for peer reviews, PNRA is actively collaborating with the international community.

[1] Mark Fitzpatrick, *Overcoming Pakistan's Nuclear Dangers* (London: Routledge, 2014), 13, https://sanipanhwar.com/uploads/books/2024-08-28_10-43-30_65dcbce3ca07380a9463fc32326df5ac.pdf

In this backdrop, the paper aims to analyze how PNRA is cooperating with the international community at bilateral and multilateral fronts, with particular emphasis on exploring its institutional mechanism for international cooperation. It also explores the prospects and challenges for Pakistan related to global collaboration. The significance of the study lies in analyzing the current state of the PNRA mechanism for international cooperation and seeks to provide actionable recommendations for policymakers, regulators, and other stakeholders to navigate the complex landscape of global nuclear governance. By fostering a deeper understanding of the benefits and challenges associated with international collaboration, the paper aims to contribute to the discourse on peaceful nuclear applications.

The paper is divided into three sections. Section one describes the importance of global collaboration from a regulatory perspective by highlighting the role of the IAEA in facilitating its Member States in different partnerships. Section two discusses PNRA's institutional mechanism in detail to explore potential avenues for international cooperation. This section also elaborates on different actions PNRA has taken to enhance its international visibility, thereby highlighting Pakistan's responsible behavior internationally. The last section presents international cooperation-related challenges faced by PNRA and suggests ways to overcome these challenges in the future.

Significance of International Cooperation for Nuclear Regulators

The international nuclear landscape has undergone considerable transformation over the years, with nuclear technology emerging as a critical component in energy production and its widespread application in medicine, agriculture, and industry. Climate concerns and attaining net-zero targets are pushing countries to consider nuclear as a sustainable and secure energy source.[2] However, at the same time, this shift has been accompanied

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[2] Jan Horst Keppler, "Nuclear Energy in the Global Energy Landscape: Advancing Sustainability and Ensuring Energy Security," *Oxford Energy Forum*, no. 139 (February 2024): 8, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/02/OEF-139-.pdf

by growing concerns about the transboundary nature of nuclear accidents, emphasizing the need to expand and deepen international collaboration.[3] The devastating consequences of nuclear accidents/incidents such as the 1986 Chernobyl accident and the 2011 Fukushima accident have underscored the importance of establishing stringent regulatory frameworks and promoting effective collaboration among nuclear regulatory authorities worldwide.[4]

At the international level, organizations like the IAEA facilitate the Member States by providing guidance, setting standards, and fostering international partnerships.[5] This facilitation for cooperation is particularly essential for nuclear regulators to ensure the safe use of nuclear technology and address transnational challenges that are affecting all Member States in one way or another. These challenges include climate change, energy security, environmental concerns, technological advancements, and so on. In an email interview conducted on 6 May 2025, Zia Hussain Shah, Director General PNRA,[6] emphasized the importance of global collaboration, particularly under the ambit of the IAEA, and commented that the IAEA pursues international cooperation, specifically regarding nuclear safety, security, and peaceful uses of nuclear applications. While highlighting the Technical Cooperation of the IAEA, Shah explained that the IAEA assists its members in different areas, including nuclear power development, nuclear safety and security, food and agriculture, human health and nutrition, water resource management, climate change adaptation and mitigation, with a particular focus on developing countries. In response to a

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[3] Pablo Fernández-Arias, Georgios Lampropoulos, Álvaro Antón Sancho, and Diego Vergara, "Progress, Challenges, and Sustainable Perspectives in Nuclear Energy Strategies," *Applied Sciences* 14, no. 24 (December 2024): 11864, https://doi.org/10.3390/app142411864

[4] Mycle Schneider, Antony Froggatt, Steve Thomas, "Nuclear Power in a Post-Fukushima World", The World Nuclear Industry Status Report 2010–2011, (Washington: World Watch Institute, 2011), https://www.worldnuclearreport.org/IMG/pdf/2011MSC-WorldNuclearReport-V3.pdf

[5] IAEA, Governmental, Legal and Regulatory Framework for Safety, General Safety Requirements No. GSR Part 1 (Rev. 1), (Vienna, 2016), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1713web-70795870.pdf

[6] Email interview with Zia Hussain Shah, Director General, Pakistan Nuclear Regulatory Authority (PNRA), May 6, 2025. Shah previously served in the Department of Nuclear Safety at the International Atomic Energy Agency (IAEA), 2016–2024.

question on the regulatory body, Shah elaborated that the IAEA has established different forums for strengthening and enhancing regulators' competence. To be specific, international cooperation enhances the effectiveness of regulatory bodies in many ways, highlighted in the subsequent section:

i. Mutual Learning and Sharing Best Practices

Collaboration allows regulators to learn from each other's experiences, adopt proven methods, and enhance regulatory frameworks. Multilateral forums provide their Member States with a platform where they can share their experiences and learn from each other. The most relevant case in reference, amongst others, is the Review Meeting platform of the Convention on Nuclear Safety (CNS), which takes place once every three years under Article 21(3) of the Convention.[7] Review Meetings offer a platform for evaluating the National Reports, facilitating discussions and assessments of all CNS Contracting Parties (CPs), by which CPs learn from each other's good practices. By identifying common issues being faced by all parties, CPs can also adopt a common approach to solve those problems. In addition, the Regulatory Cooperation Forum (RCF), established by the IAEA, focuses on collaboration among its members (Providers and Recipients) for enhancing the capacity of individual regulators to address complex issues effectively.[8] Some other notable multilateral forums for mutual learning and sharing of good practices include the Commission on Safety Standards (CSS), Advisory Group on Nuclear Security (AdSec), Global Nuclear Safety and Security Network (GNSSN), Technical Support Organization Forum (TSOF), Nuclear Safety Standard Committee (NUSSC), Transport Safety Standards Committee (TRANSSC), Waste Safety Standards Committee (WASSC), Radiation Safety Standards

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[7] International Atomic Energy Agency (IAEA), *Convention on Nuclear Safety (CNS): Introduction to the CNS and Its Associated Rules of Procedure and Guidelines, Technical Booklet*, CNS Booklet 2024 (Vienna: IAEA, 2024), https://www.iaea.org/sites/default/files/24/08/cns_technical_booklet_august_2024_final.pdf

[8] International Atomic Energy Agency (IAEA), "Regulatory Cooperation Forum (RCF)," IAEA, https://gnssn.iaea.org/regnet/embarking/rcf/Pages/default.aspx

Committee (RASSC), Nuclear Security Guidance Committee (NSGC), and Emergency Preparedness and Response Standards Committee (EPReSC).

ii. Setting Global Safety and Security Standards by Harmonizing Regulatory Practices

In addition, the above-mentioned forums also provide a kick-start for establishing safety fundamentals, requirements, and guidelines of future documentation in particular technical areas related to Nuclear Power Plants (NPPs). Cooperation among regulatory bodies facilitates the development of consistent and internationally accepted safety standards with the aim of minimizing risks and ensuring the safety of the public and the environment. Although member states devise their independent regulations, there is a need for a harmonized approach related to regulatory practices that facilitates cooperation and trade across the countries by minimizing regulatory barriers.

iii. Facilitating Multilateralism against Transnational Nuclear Accidents / Radiological Emergencies

Availing nuclear technology is a national prerogative, but its impact, in case of unsafe handling, can go beyond national boundaries. On the premise that radiation does not respect boundaries, collaboration among countries is essential to share information, coordinate, and assist in the case of a nuclear accident or radiological emergency. There are two conventions,[9] i.e., the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE) and the Convention on Early Notification of a Nuclear Accident (CENNA), to facilitate swift actions among its member states. These conventions require the designation of a national competent authority to deal with notifications and requests for assistance in case of a nuclear accident or radiological emergency. The actions can be either

[9] IAEA, *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, INFCIRC/336 (Vienna: IAEA, 1987), https://www.iaea.org/sites/default/files/infcirc336.pdf; and IAEA, *Convention on Early Notification of a Nuclear Accident*, INFCIRC/335 (Vienna: IAEA, 1986), https://www.iaea.org/sites/default/files/infcirc335.pdf

related to the notification of an emergency or to responding during a nuclear accident / radiological emergency. The referred emergency-related conventions were devised out of a consensus built up by IAEA member states after the 1986 Chernobyl accident, where they agreed to establish a framework for cooperation. This framework for cooperation is based on the rationale of facilitating assistance in case of nuclear accidents or radiological emergencies. Once there is increased cooperation among member states, there will be more facilitation to prepare against transnational accidents/emergencies. Thus, collaboration and cooperation are the key to devising a common approach for emergency preparedness and response.

iv. Building Capacity through Collaborative Ventures

Cooperation among regulators can stimulate capacity building by enhancing expertise and improving each other's regulatory infrastructure. In this regard, the role of the IAEA is crucial as it provides a common platform for its Member States to discuss their training needs and infrastructure build-up requirements. The Technical Cooperation (TC) Program, a flagship of the IAEA, assists Member States in addressing their nuclear knowledge development and management / infrastructure-related issues. The IAEA also entertains member states' requests related to strengthening training needs by arranging training courses, fellowships, scientific visits, and workshops under different regional and inter-regional projects. In addition, the IAEA has also designated Collaborating Centers (CCs) in some Member States as institutions supporting the IAEA's programmatic activities. Besides other activities, CCs also support IAEA training activities, including research training courses, or the development of training or other educational materials. Such collaborative ventures are significant for assisting member states in preparing their workforce to better deal with regulatory challenges.

v. Promoting Trust and Transparency

Besides the IAEA, countries also cooperate bilaterally in areas of nuclear regulatory interest to learn and support each other. In this way, international collaboration also contributes to building trust and transparency among nations, thereby dispelling suspicions. Countries' active engagement in international regulatory networks exhibits their commitment to global norms. It also enhances their credibility while fostering mutual respect.

To sum up, there is a need to recognize the fact that no nation can tackle global challenges alone; thus, international cooperation is not only a need but also a compulsion in this interconnected globalized world. By fostering international partnerships for enhancing technical capabilities and ensuring safe and secure use of nuclear technology, regulatory bodies can create a safer and more sustainable future for all.

Whether it is the mitigation of leaked radioactivity after nuclear accidents or radiological emergencies, or the management of nuclear waste, one aspect is omnipresent: global issues require global cooperation. For this, countries need to have effective coordination and communication among themselves. Specifically, nuclear regulators need to balance national interests with international cooperation goals, which can be achieved through the harmonization of regulatory standards and practices across countries. In addition, considering regional and global needs, cooperation among nations is particularly required in emerging areas like Small Modular Reactors (SMRs), digitalization, advanced modalities, and so on. It is worth mentioning that hindrances to international cooperation can impact the effectiveness of nuclear regulatory bodies. The sharing of information related to regulatory business plays a significant role in strengthening the capacity building and infrastructure of regulatory bodies and, in turn, contributes to the establishment of trust and transparency among regulators, a prerequisite for effective global cooperation.

Besides enhancing mutual learning, sharing best practices among the regulators and continual improvement in regulatory processes and activities, review meetings under conventions and peer review mechanisms adopted by the IAEA are also important in overcoming challenges associated with trust, transparency, and confidentiality. However, resource disparities, either in terms of expertise or infrastructure, make it difficult for states to collaborate with each other. Developing countries require funding to build their competence and strengthen their infrastructure, due to which collaboration becomes difficult.

Institutional Mechanism for International Cooperation: Regulatory Perspective

Being the pioneer member of the IAEA,[10] Pakistan has a long history of international cooperation with the IAEA and its Member States for developing its nuclear energy capabilities and regulatory mechanisms. Pakistan's nuclear regulatory regime evolved gradually and strengthened through participation in capacity-building programs conducted by the IAEA and other Member States.

i. Pakistan's Nuclear Regulatory Journey

The concept of nuclear regulation in Pakistan is as old as the advent of nuclear technology in Pakistan since 1965, when the first research reactor, PARR-I, was commissioned.[11] It was further improved with the commissioning of the first NPP in 1971, in Karachi. Although at that time, a nuclear safety and licensing division was established in the Pakistan Atomic Energy Commission (PAEC) to act as a regulatory body till it was upgraded to the Directorate of Nuclear Safety and Radiation Protection (DNSRP) after the promulgation of the Pakistan Nuclear Safety and Radiation Protection Ordinance 1984.[12] This directorate had regulatory wings; however, with the expansion of the nuclear power program and with the increasing use of nuclear technology in the non-power sector, the need to have a regulatory setup independent from a promotional body was

[10] Ghazala Yasmin Jalil, *Deepening IAEA-Pakistan Partnership for Peaceful Nuclear Cooperation*, March 3, 2025, https://issi.org.pk/wp-content/uploads/2025/03/IB_Ghazala_March_03_2025.pdf

[11] Feroz Hassan Khan, "Eating Grass: The Making of the Pakistani Bomb", (California: Stanford University Press, 2013), p. 57.

[12] Mazzammal Hussain, Rizwan Ali Khan, and Bushra Nasim, "Regulatory Framework for Occupational Exposure Management in Pakistan," paper presented at the ISOE Symposium 2009, Vienna, Austria, October 2009, https://www.isoe-network.net/publications/pub-proceedings/symposia/international-symposia/vienna-austria-october-2009/papers-5/session-4-occupational-exposure-in-npps-1/1304-nasim2009-pdf/file.html

realized. This independence was sought gradually as DNSRP led to the creation of the Pakistan Nuclear Regulatory Board in 1994.[13] The quasi-independence was established in 2001 with the establishment of PNRA as a legally and administratively independent nuclear regulatory body with the mandate to regulate the use of nuclear energy, radioactive sources, and ionizing radiation.

ii. Functions of Nuclear Regulator

Since its establishment, PNRA has been mandated to formulate and implement safety regulations. PNRA ensures effective regulatory oversight nationwide. PNRA's core functions include establishing the regulatory framework, reviewing and assessing, granting authorizations, issuing licenses, performing inspections, and enforcing regulations for all nuclear and radiation facilities as well as activities in Pakistan.

In addition, PNRA is leading the national efforts to ensure that emergency preparedness and response mechanisms are implemented by its licensees. At PNRA headquarters, the National Institute of Safety and Security (NISAS) plays a vital role in the competency development of not only the regulatory workforce but also of other related entities. Following the IAEA's recognition of PNRA training capabilities, NISAS has also been designated as an IAEA Collaborating Center for Nuclear Safety and Security.

iii. Institutional Arrangements for International Cooperation

PNRA recognizes the importance of bilateral and multilateral cooperation for the improvement of its contribution to enhancing global nuclear safety and security. Upon the twentieth anniversary of its inception, PNRA issued a Twenty-Year Report highlighting significant achievements made by the

[13] *Creation of Pakistan Nuclear Regulatory Board*, Prime Minister's Secretariat Notification, Islamabad, October 30, 1994, https://www.vertic.org/media/National%20Legislation/Pakistan/PK_No_F8_52_94_PAEC_F_Creation_Nuclear_Board.pdf

regulator during this period.[14] Much of the information related to international accomplishments is taken from that report. It is important to highlight that PNRA has adopted a very systematic approach to increase its visibility at the global level. The contours of this systematic approach are discussed below.

iv. Establishment of a dedicated International Cooperation Office

Over the years, PNRA has made commendable efforts to project and promote Pakistan's nuclear safety and security record at the international level. It has established a dedicated department, the Directorate of International Cooperation (ICD), to promote and enhance its regulatory visibility internationally. As one of the oldest directorates, ICD is coordinating with international organizations, including the IAEA, for international affairs and capacity building of PNRA officials. It also ensures implementation of obligations of international conventions, resolutions, safety and security committees, forums, networks, etc., on behalf of the Government of Pakistan. It is also responsible for developing, coordinating, and implementing Memoranda of Understanding (MoUs) / agreements with international organizations.

v. Implementing Pakistan's International Obligations

The Government of Pakistan has signed several international conventions and has designated PNRA as the national point of contact. PNRA is implementing country obligations related to a few conventions to which Pakistan is a party. These include Conventions on Nuclear Safety (CNS), Conventions on Early Notification of a Nuclear Accident (CENNA), Conventions on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE), and Conventions on Physical Protection of Nuclear Materials (CPPNM) and its amendment. Either compilation of country report for submission in review meeting of CNS or participating/hosting IAEA emergency exercises under the emergency-

[14] Pakistan Nuclear Regulatory Authority, "20 Years OF PNRA, Pakistan Nuclear Regulatory Authority (2001 – 2020)" (Islamabad: PNRA, 2021), https://www.pnra.org/upload/pnrarpt/PNRA%20Report%202020.pdf

related conventions, PNRA is implementing national obligations in true letter and spirit.

Besides obligatory responsibilities, PNRA is also ensuring the non-obligatory requirements arising from Pakistan's subscription related to the safety of research reactors and the safety and security of radioactive sources.

vi. Participation in Multilateral Forums

PNRA is actively participating in multilateral forums, particularly those of the IAEA, to foster cooperation and address shared challenges. Aiming to develop technical standards and guidance documents, PNRA officials are members of various IAEA Safety Standard Committees, including Nuclear Safety Standards Committee (NUSSC), Transport Safety Standards Committee (TRANSSC), Waste Safety Standards Committee (WASSC), Radiation Safety Standards Committee (RASSC), Emergency Preparedness and Response Standards Committee (EPReSC), Nuclear Security Guidance Committee (NSGC), and Commission on Safety Standards (CSS). It also participates in the Response and Assistance Network (RANET), Global Nuclear Safety and Security Network (GNSSN), Regulatory Cooperation Forum (RCF), Radiation Safety Information Management System (RASIMS), International Generic Ageing Lessons Learned (IGALL), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Technical Support Organization Forum (TSOF), National Nuclear Security Support Centre (NSSC), and the International Nuclear Security Education Network (INSEN), and so on. Pakistan has the honor of hosting the first-ever meeting of NSSC outside Vienna, Austria.[15] In addition, PNRA has also hosted CANDU Senior Regulator's Meetings twice in 2005 and 2022.

IAEA has also established various non-binding reporting mechanisms for member states to learn from each other's experience by reporting on

[15] "Ambassador Jenkins Travels to Pakistan for the IAEA International Network for Nuclear Security Meeting", March 17, 2016: http://www.nss2016.org/news/2016/3/18/xewb29qm3pdj8sqxblr2v4djvu0td

relevant issues. PNRA also contributes to such forums as the International Nuclear and Radiological Event Scale (INES), Incident Reporting System (IRS), Incident Reporting System for Research Reactors (IRSRR), International Physical Protection Advisory Services (IPPAS), Good Practices Database, Denials of Shipment of Radioactive Material (DoS), and Incident and Trafficking Database (ITDB).[16]

vii. Provision of Expert Manpower

PNRA, as reflected below in Figure 1, regularly provides its experts' services to the IAEA for the conduct of IAEA peer review missions, consultancies for the development of IAEA documents and training material, and resource persons for training courses and workshops held at the IAEA and its Member States.[17] Further statistics about the provision of experts are available in PNRA annual reports. [18]

viii. Execution of TC Projects

PNRA also participates in various Technical Cooperation projects of the IAEA, which have reinforced the regulatory infrastructures. It also participates in various IAEA Coordinated Research Projects (CRPs) to strengthen its organizational capabilities.

[16] Pakistan Ministry of Foreign Affairs, *Pakistan Nuclear Security Regime*, booklet presented at the IAEA International Conference on Nuclear Security, May 2024, https://www.iaea.org/sites/default/files/24/05/cn-321_pakistan.pdf

[17] Rahila Hammad, *Managing Nuclear Safety Knowledge – PNRA Experience*, https://gnssn.iaea.org/main/Activity%20Documents1/Technical%20Meeting%20on%20Managing%20Nuclear%20Safety%20Knowledge%20%E2%80%93%20Approaches%20and%20National%20Experiences/Presentations/Day%202/PAKISTAN.%20Rahila%20Hammad.pdf

[18] Pakistan Nuclear Regulatory Authority, "Reports," Pakistan Nuclear Regulatory Authority, https://www.pnra.org/report.html

Figure 1: Expert Mission from PNRA: 2002-2024

Source: The author has consulted various annual reports of the PNRA to create a consolidated graph.

ix. Honoring Bilateral Commitments

Besides collaboration at multilateral forums, as shown below in Figure 2, PNRA has established bilateral cooperation agreements with three relevant organizations in China. These organizations include the National Nuclear Safety Administration (NNSA), Nuclear Safety and Radiation Protection Centre (NSC), and China Nuclear Power Operations Technology Corporation Ltd. (CNPO).[19] In addition, PNRA has also signed an MoU with the Nigerian Nuclear Regulatory Authority (NNRA) and the Nuclear Regulatory Authority (NRA) of the Republic of Ghana for capacity building of their regulatory staff.[20]

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[19] Dr. Hamid Saeed Raza, Noreen Iftakhar, Faiza Batool, "Pakistan-China Cooperation: A [Nuclear] Regulator Perspective", *Science Diplomacy Perspective*, COMSTECH, March 2022. p: 62. https://www.comstech.org/wp-content/uploads/2022/03/Compiled-Special-Issue-10-3-2022.pdf

[20] Noreen Iftakhar, "Emerging Nuclear Countries and International Cooperation: What Can Pakistan Offer?" *Journal of Security and Strategic Analyses* 9, no. 2 (2023), https://jssa.thesvi.org/index.php/ojs/article/view/261

Figure 2: Bilateral Agreements of PNRA

Source: The author has reviewed various annual reports of the PNRA to create a consolidated graph.

x. International Benchmarking through Peer Reviews and Advisory Services

PNRA has developed mechanisms for internal oversight and regularly conducts such monitoring and assessment activities at the internal level periodically as a self-check to measure its performance and processes. However, it can also request relevant international organizations, such as the IAEA, for an independent review. The IAEA also offers its Member States peer review and advisory services on nuclear safety and security.[21]

PNRA has also set provisions for independent external review in its organizational management system to oversee the consistency of its

[21] International Atomic Energy Agency (IAEA), *Supporting Member States: IAEA Peer Reviews and Advisory Services*, *Nuclear Safety and Security Program of IAEA*, https://www.iaea.org/sites/default/files/20/07/supporting-member-states-iaea-peer-reviews-and-advisory-services.pdf

regulatory framework, processes, and practices in agreement with international standards and best practices. As highlighted below in Figure 3, PNRA has invited several IAEA peer review & advisory missions to demonstrate openness and transparency, which are critical for any nuclear regulator to grow positively.[22] The outcome of these missions helped PNRA in enhancing its regulatory oversight and capacity building related to nuclear safety and radiation protection. Furthermore, after the successful conduct of the internal International Physical Protection Advisory Service (IPPAS), Pakistan is planning to host IAEA IPPAS in 2026, as announced by the Head of Pakistan's delegation during the International Conference on Nuclear Security (ICONS): Shaping the Future, which was held in Vienna from 20-24 May 2024.[23]

Figure 3: International Appraisals and Peer Review Missions to Pakistan
Source: The author has consulted various annual reports of the PNRA to create a consolidated graph.

[22] Pakistan Nuclear Regulatory Authority (PNRA), *20 Years of PNRA, Pakistan Nuclear Regulatory Authority* (Islamabad: PNRA, 2021), https://www.pnra.org/upload/pnrarpt/PNRA%20Report%202020.pdf; also see *Convention on Nuclear Safety: National Report for Joint Eighth and Ninth Review Meeting*, Islamic Republic of Pakistan, 2023, 6, https://www.pnra.org/upload/pnrarpt/NR%20for%208th%20and%20%209th%20RM.pdf; also see *Education and Training Appraisal in Radiation Protection and the Safety of Radiation Sources: Preparatory Mission Pakistan, 10–15 November 2013* (Vienna: IAEA), https://www-ns.iaea.org/downloads/rw/training/eduta/prep-eduta_2013-pakistan.pdf

[23] National Statement, International Conference on Nuclear Security: Shaping the Future (Vienna, 20-24 May 2024), https://www.iaea.org/sites/default/files/24/05/cn-321_pakistan.pdf

To understand the dynamics of PNRA and international cooperation, an in-person interview with Faizan Mansoor, currently leading the PNRA, was conducted on 6 May 2025.[24] Mansoor explained that "being a contact point for international conventions related to nuclear safety, physical protection, nuclear accident and radiological emergency, PNRA in collaboration with other national organizations, is fulfilling Pakistan's commitment in true letter and spirit."[25] He was of the view that "a comprehensive inter-agency process is being established and practiced maximizing global footprints of PNRA." [26] Explaining his personal experience of interacting with other regulatory bodies, he maintained that "expertise of PNRA officials either in the areas of nuclear safety, security, radiation protection, emergency preparedness, are well reputed at IAEA level and now PNRA officials, from resource person of training courses to the experts of review missions, are participating in different programs of IAEA." Regarding areas of cooperation that PNRA can offer to other countries, Mansoor believes that "having proficiency in all regulatory core functions, PNRA is willing to share its expertise in the development of regulatory framework, review and assessment, authorization and licensing, inspection and enforcement."[27] Mansoor stated that excellence in regulatory affairs requires constant learning and equipping with advanced technologies; however, resource constraints sometimes create difficulties. While acknowledging the role of the IAEA in supporting its Member States, Mansoor applauded the IAEA in strengthening the regulatory competence of PNRA.

To sum up, PNRA has a well-established mechanism at the organizational level for international cooperation. This global collaboration has helped Pakistan to contribute to shaping international nuclear safety and security-related norms and policies. The PNRA is playing a proactive role in addressing common challenges for the peaceful use of nuclear applications.

[24] Faizan Mansoor, Chairman of the Pakistan Nuclear Regulatory Authority (PNRA), interview by the authors, Islamabad, May 6, 2025
[25] Mansoor, interview, May 6, 2025
[26] Mansoor, interview.
[27] Mansoor, interview.

However, realizing these benefits requires overcoming significant challenges, which are discussed in the following section.

PNRA and International Cooperation: Challenges and Future Prospects

The retrospective analysis of the institutional mechanism adopted by PNRA for enhancing its global presence exhibits that since its inception, PNRA has been aware of the importance and usefulness of international cooperation. It remains committed to ensuring the peaceful use of nuclear and radiation technology in the country through the highest standards of safety, security, and regulatory oversight. The supporting role of international and experienced regulatory bodies is vital for the capacity building and organizational improvement of a growing organization like PNRA. Therefore, PNRA worked on obtaining maximum support from the IAEA and with the nuclear regulators of other countries through bilateral relations. Hence, PNRA is using all possible international avenues for competence building, knowledge sharing, and strengthening its regulatory oversight.

Nevertheless, there are certain challenges related to international cooperation faced by PNRA, which are more embedded due to restrictions imposed on the other side of its nuclear coin. Even with restrictions and limited access, PNRA has attained the required knowledge and skill to perform regulatory functions in the true spirit. PNRA's experts are recognized by the IAEA, and based on the training provided by the IAEA in the initial years of PNRA, the organization is now contributing to enhancing nuclear safety globally by transferring knowledge and sharing experience. However, this knowledge and skill require continuous update, and hence, PNRA is facing a challenge to be at par with technological advancements. Based on the discussions with the teams involved in the organizational conduct related to global collaboration, the following challenges are worth pondering:

i. Limited Access to Codes and Standards for Ensuring Nuclear Safety

PNRA has a mandate for ensuring the safe and secure application of nuclear technology. This assurance is guaranteed through different core processes, such as review and assessment. PNRA carried out the review and assessment of the licensees' submissions against PNRA regulations and other agreed industrial codes and standards. These industrial codes and standards are developed by internationally accepted/recognized organizations/bodies[28] provide acceptance criteria for the implementation of regulatory requirements. With the advancements in technology, these codes are also updated. Therefore, it is essential for regulators to not only understand the criteria and technical requirements related to the design, construction, operation, and maintenance of nuclear installations but also have expertise to perform an audit analysis of the results presented by the licensee in the safety analysis report. Unfortunately, PNRA has limited access to some industrial codes and standards. This limited access is due to high cost and licensing restrictions by the developer. This barrier can be reduced by collaboration and partnerships between standard-setting organizations and regulatory bodies through the IAEA, for open access to these critically significant industrial codes and standards necessary for ensuring nuclear safety.

ii. Technology Denials

Ensuring radiation protection and maintaining emergency preparedness is one of the primary tasks of PNRA. To achieve this, PNRA needs to have updated and state-of-the-art radiation monitoring equipment, safety analysis software, and emergency preparedness tools. Nevertheless, PNRA faces challenges in the procurement of these essential technologies. These technologies' denials and restrictions are usually imposed by supplier states. There should be recognition of the fact that ensuring safety is a shared responsibility of all nations, and this responsibility should never be

[28] Pakistan Nuclear Regulatory Authority (PNRA), *Convention on Nuclear Safety: National Report for Joint Eighth and Ninth Review Meeting* (Islamabad: PNRA, 2023), 13–14, https://www.pnra.org/upload/pnrarpt/NR%20for%208th%20and%20%209th%20RM.pdf

compromised by any other factors. Hence, there should be non-discriminatory access to safety-related technologies. Supplier countries should also re-evaluate that, regardless of geopolitics, access to the equipment and technology is essential to ensure protection of the public and the environment.

iii. Underrepresentation of Pakistan's Peaceful Nuclear Initiatives in the International Discourse

PNRA has a noble cause of ensuring nuclear safety and radiation protection related to the peaceful application of nuclear and radiation technology. Regardless of this clearly defined mandate and the administrative, technical, and financial autonomy of PNRA, its international cooperation is often hindered by the global emphasis on its national defense imperatives, which have, at times, limited the visibility of its efforts and achievements in the peaceful applications of nuclear technology. Consequently, Pakistan faces restricted technological access under the pretext of political sensitivities and trust deficit. Owing to this misperception, nuclear safety tools and equipment are often caught in broader export restrictions despite PNRA's strong commitment to international safety norms. As a result, PNRA's achievements and contributions to nuclear safety are underreported or underacknowledged in global forums due to broader political narratives.

This study proposes two sets of proposals for the regulatory and policy levels to overcome these challenges. PNRA should focus on the following areas:

i. Diversify and expand its bilateral cooperation with IAEA, other regulatory bodies, and with countries outside technology denial cartels by building technical partnerships. Broadening international partnerships will benefit PNRA in enhancing its international credibility and gaining greater acceptance in multilateral platforms.
ii. Leverage IAEA Technical Cooperation Programs and advocate free and equitable access to nuclear safety codes and standards as cooperation agenda.

iii. Continue active participation in IAEA's capacity-building and safety enhancement projects, as well as hosting regional IAEA workshops or training programs in its Collaborating Center (NISAS). In this way, PNRA can exhibit its leadership and expertise in the nuclear regulatory domain.

iv. Sensitize the international community to assess the regulatory credentials of PNRA based on its performance, not through a political lens.

v. Engage researchers and think-tanks, for focused published academic literature to overcome perception issues as a cooperation barrier. Since its legal and regulatory framework is openly available, PNRA should pursue targeted science diplomacy to maximize its national outreach and strengthen its international profile.

At the policy level, these challenges can be overcome by adopting two approaches:

i. ***More Inclusive Partnerships:*** A more globalized world means a more interdependent community. Ensuring nuclear and radiation safety is the prime job of the nuclear regulator. Since leaked radiation does not respect geographical jurisdiction, so shared threat needs a shared response. All countries should be part of international arrangements without any attribution of size, economy, or political concerns. Thus, there is a need to have inclusive partnerships. No country should be barred from joining any forum on the pretext of differing national interests. Neither regional biases nor preferential treatment should be exercised in international partnerships. Excluding countries for promoting certain geopolitical and geo-strategic interests should not be the desirable agenda of any international partnership.

ii. ***Advocating Multilateralism:*** Multilateralism[29] has three distinguished principles: equality without discrimination, dispute settlement, and durability; henceforth, multilateralism, being a "uniquely inclusive vehicle," can serve as a coordination mechanism during "heightened geopolitical tension and big power rivalry."[30] While unilateral initiatives are good in achieving short-term results but their impact does not last.[31] International cooperation is more effective under multilateral forums like the IAEA, which serves the purpose of providing a multilateral forum. With its near-universal membership, the IAEA provides a central forum for its Member States to address areas that require international cooperation. Addressing emerging global threats, developing harmonizing regulatory standards, providing training and capacity-building programs, discussing technological differences, and building understanding on different legal and liability issues, a multilateral forum like the IAEA plays a significant role in establishing regular dialogue and clear communication channels by identifying shared goals and interests to facilitate cooperation.

Conclusion

To sum up, cooperation among countries is necessary to ensure nuclear and radiation safety, security, and the peaceful use of technology. All nuclear regulatory bodies have the common objective of protecting the people and environment by ensuring and upholding safety and security standards. International cooperation enhances the effectiveness of nuclear regulatory bodies by mutual learning and sharing best practices and by setting global

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[29] United Nations, "The Multilateral System," United Nations, https://www.un.org/en/global-issues/multilateral-system

[30] Ulrika Modéer and Tsegaye Lemma, The value of strong multilateral cooperation in a fractured world, UNDP: April 20, 2023.https://www.undp.org/blog/value-strong-multilateral-cooperation-fractured-world

[31] Noreen Iftikhar, "International Nuclear Law: A Case Study of Pakistan," *Strategic Studies* 38, no. 4 (2018): 75, 85, https://issi.org.pk/wp-content/uploads/2019/01/5-SS_Noreen_Iftakhar_No-4_2018.pdf

safety standards to harmonize regulatory practices. While facilitating a multilateral approach against transnational nuclear accidents or radiological emergencies, international cooperation is also essential for building the capacity of all countries through collaborative ventures, hence promoting trust and transparency.

With its commendable record, Pakistan's civilian nuclear program is managed by PAEC, while PNRA ensures the safe and secure use of nuclear technology. Though Pakistan started its regulatory journey in the 1960s, its independent regulatory setup has been fully functional since 2001. Within the short span of twenty-four years, PNRA has made commendable efforts to establish a robust regulatory framework, comprehensive processes for review and assessment, mechanisms for licensing and authorizations, emergency response mechanisms, and inspection and enforcement protocols. PNRA has made a noticeable presence at both the national and international levels. Its collaboration with the IAEA and participation in conventions in the areas related to nuclear safety, nuclear accidents and radiological emergencies, and physical protection, as well as effective contribution in different committees and forums at the international level, reflect Pakistan's commitment to international nuclear governance.

Pakistan's policymakers and diplomats should keep advocating the rights and needs of developing countries for robust scientific knowledge, expertise, and infrastructure to pursue socioeconomic development. PNRA should keep navigating the complex international system by exploring frameworks and agreements to engage in international cooperation. It should leverage the IAEA Technical Cooperation Program for capacity-building activities. It needs to establish more partnerships with other regulatory bodies, particularly those RBs that are new in this field. PNRA can establish bilateral agreements with regulatory bodies to facilitate cooperation and knowledge sharing, particularly in areas of its specialized expertise, like nuclear safety, radiation protection, review and assessment, regulatory framework, inspection and enforcement, licensing and authorization, physical protection, and regulatory body human resource development. While advocating for more inclusive partnerships through multilateral forums, PNRA should keep its active engagement in international forums to enhance Pakistan's credibility as a responsible nuclear state. By addressing obstacles in global collaboration and leveraging opportunities, PNRA should keep pursuing international cooperation for strengthening global efforts aiming to further strengthen nuclear safety, radiation protection, and nuclear security in the country.

Assessment of Nuclear Safety and Security Regime of Pakistan

Tariq Majeed*

Abstract

As global interest in nuclear energy grows, particularly for low-carbon power generation, medical innovation, and agricultural resilience, establishing a robust nuclear safety and security regime is essential for ensuring the peaceful and responsible use of nuclear technology. This paper offers a comprehensive assessment of Pakistan's nuclear safety and security regime within the broader context of its peaceful nuclear program. A founding member of the International Atomic Energy Agency (IAEA) and an early supporter of the "Atoms for Peace" initiative, Pakistan has consistently demonstrated its commitment to the peaceful use of nuclear technology by developing a dual-focused regulatory framework that separately addresses nuclear safety and nuclear security. This study analyzes the evolution, legal foundations, institutional mechanisms, and regulatory infrastructure of Pakistan's national regime, highlighting its adherence to IAEA safety standards, international legal instruments, and voluntary codes of conduct. Drawing from Pakistan's practical experience, the paper examines the peaceful applications of nuclear technology across five key sectors: energy, healthcare, research and education, agriculture, and industry. It further explores the role of the Pakistan Nuclear Regulatory Authority (PNRA), the structure and enforcement of licensing and oversight mechanisms, and the integration of safety and security culture. Special attention is given to human capacity building, radioactive waste management, transport safety, emergency preparedness, and international cooperation— a *key dimension that shape Pakistan's proactive engagement with global nuclear governance. The analysis concludes by positioning Pakistan's nuclear safety and security regime as a responsible, transparent, and internationally aligned framework that contributes not only to national development but also to the strengthening of global nuclear norms.*

Keywords: Nuclear Safety, Nuclear Security, Pakistan, IAEA, PNRA, PAEC.

Introduction

The peaceful application of nuclear technology is an important contributor to the modern global challenges such as sustainable energy production, improved healthcare, food security and scientific progress. Since Pakistan had realized the potential of nuclear energy in enhancing the socioeconomic development of the country, it applied the peaceful use of nuclear energy in a well-developed legal, institutional and regulatory framework. As one of the initial supporters of the "Atoms for Peace program"[1] and the signatory of the IAEA in 1957, Pakistan has been showing compliance to the international norms and safety standards.

Pakistan's nuclear program has developed into a complex system which has applications in various sectors including energy, medicine, agriculture, industry and environmental management. The global events in the aftermath of 9/11 led to a fundamental change in the nuclear governance, which was caused by the rapidly changing dynamics of the global processes. This development separated the wider nuclear safety concept into two distinct areas of "nuclear safety" and "nuclear security." Nuclear safety encompasses measures, practices and regulations that are aimed at guaranteeing safe functioning of nuclear facilities, and protecting the environment and population against the adverse impact of ionizing

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[1] Rubio Varas, "D.3.6 Validated Short Country Reports," *Unavarra.es*, 2019, https://academica-e.unavarra.es/entities/publication/09b9eb69-3d58-432d-afd0-2f4f7a3cf435

radiations, particularly in the event of accidents or malfunctions.[2] Conversely, Nuclear Security is the application of measures that prevent, detect, and mitigate acts of theft, sabotage, unauthorized access, or unauthorized movement of nuclear or radioactive material and the facilities related to them.[3]

Pakistan emerged as a proactive actor through its advanced nuclear security infrastructure, complemented by its long-standing adherence to nuclear safety. Moreover, Pakistan implemented a dual-focus regulatory framework to prevent accidents (nuclear safety) and counter intentional threats (nuclear security). This progress was reflected in Pakistan's adherence to several legally binding and non-binding commitments, and voluntary measures. All these efforts have created a strong and two-pronged nuclear regulatory regime in Pakistan which continues to evolve in compliance with the international standards.

Pakistan has steadily advanced its commitment to utilizing nuclear technology for peaceful purposes, while maintaining compliance with nuclear safety and security frameworks. This adherence has led to the establishment of a well-coordinated national system that focuses on both aspects - nuclear safety and nuclear security. This article discusses the basic structure of nuclear safety and security regime in Pakistan, its evolution, structure, and operational dynamics. It discusses the regulatory role of the PNRA, implementation of the IAEA-based nuclear safety and security standards and institutionalization of a national safety and security culture. Furthermore, it covers the peaceful applications of nuclear technology in five core sectors. These include healthcare, power generation, research and education, agriculture, and industry. Alongside, it highlights Pakistan's contributions to the international nuclear governance in terms of cooperation, capacity-building and adherence to international instruments.

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[2] International Atomic Energy Agency (IAEA), IAEA Nuclear Safety and Security Glossary (Vienna: IAEA, 2022), https://www-pub.iaea.org/MTCD/Publications/PDF/IAEA-NSS-GLOweb.pdf

[3] IAEA, Nuclear Safety and Security Glossary.

Moreover, the paper highlights the national framework in Pakistan that has been developed in accordance with the international best practice and is comprised of five main pillars: Independent Nuclear Regulatory Authority, Comprehensive Legal and Regulatory Infrastructure, Robust Nuclear Security Architecture, Strong International Engagement, and Deep-Rooted Safety and Security Culture. This article is organized into three parts. The first part describes nuclear technology's applications in different sectors of Pakistan. The second part briefly discusses the history of international nuclear safety and security regime. Whereas the last part offers a thorough examination of the national regime in Pakistan which encompasses the five main pillars of Pakistan's national framework. This paper aims at evaluating Pakistan's role as a responsible nuclear state and its contribution to the international nuclear safety and security by analyzing the effectiveness, flexibility and international alignment of its regulatory infrastructure.

Peaceful Applications of Nuclear Technology in Pakistan

Pakistan is one of many countries utilizing nuclear technology for peaceful purposes. This utilization is aimed at benefiting humanity and advancing socio-economic development. Being a responsible nuclear power and a signatory of the IAEA, Pakistan has always ensured that its nuclear activities follow international standards of safety, security and peaceful use. The peaceful nuclear program in Pakistan is diverse and covers five primary areas, namely energy, research and education, healthcare, agriculture, and industry. Each of these sectors has played its own distinct role in Pakistan's development. Moreover, peaceful applications of nuclear technology are widespread which not only fulfill the domestic requirements of Pakistan but also underscores the positive role of Pakistan in IAEA-led activities and technical cooperation programs. Based on the regulatory regime of Pakistan and its dual responsibilities of ensuring nuclear safety and security, this section explores the practical manifestation of Pakistan's commitments in the domain of peaceful uses of nuclear technology.

Nuclear Energy for Climate-Resilience

Pakistan views nuclear and renewable energy as key components of its energy mix to support socio-economic development and mitigate the impacts of climate change. Pakistan remains highly vulnerable to climate change,[4] regardless of its minimal contributions to greenhouse gas emissions. The Government of Pakistan Vision 2030 states, "Nuclear energy is becoming attractive again, and so is renewable energy. We will expand our existing knowledge base in nuclear power and build up the same in renewables to meet a growing part of our energy needs in this century."[5] Under its Energy Security Plan 2005-2030, Pakistan aims to achieve 8800 MWe of nuclear capacity by 2030, including recent additions such as the K-2 and K-3 Pressurized Water Reactors (PWRs) with a power capacity of 1100 Mwe, each at the Karachi Coast.

A total of six nuclear power plants – PWR-type reactors - are currently operational in Pakistan, comprising four Chashma Nuclear Power Generating Stations (CNPGS) and two Karachi Nuclear Power Generating Stations (KNPGS), with a combined electricity generation capacity of 3,256 MWe, contributing significantly to the country's energy requirements. One nuclear plant - a Canada Deuterium Uranium (CANDU)-type Pressurized Heavy Water Reactor (PHWR) was shut down permanently for decommissioning in August 2021, following nearly six decades of service to the nation.

Research and Education

"Pakistan Institute of Nuclear Science and Technology (PINSTECH)" is one of the main research and development (R&D) facilities for nuclear science, radiopharmaceuticals, radiation safety, and nuclear physics.

[4] Rabia Maqsood and K. Abbas, "Climate Change and Fisheries: A Global Perspective," *Progress in Aqua Farming and Marine Biology* 2024, no. 1 (July 16, 2024): 180033, https://academicstrive.com/PAFMB/PAFMB180033.pdf

[5] Planning Commission, Pakistan 2030: Vision for the Future (Islamabad: Government of Pakistan, 2007), 66, https://file.pide.org.pk/pdf/vision-2030.pdf.

Enormous contributions are being made to environmental protection, food security, biotechnology, development of climate resilient crops, sustainable agriculture and scientific education by several institutes in Pakistan. These institutions are "Nuclear Institute for Agriculture (NIA)," "National Institute for Biotechnology and Genetic Engineering (NIBGE)," "Nuclear Institute for Food and Agriculture (NIFA)," and "Nuclear Institute for Agriculture and Biology (NIAB)." A comprehensive nuclear safety and security regime in Pakistan ensures the use of nuclear and radioactive materials safely and securely by following national regulations of PNRA, developed according to international standards set by the IAEA.

Significant contributions are made by nuclear medical centers in Pakistan to the research work on the development of radiopharmaceuticals, treatment planning, radiotherapy, cancer imaging and diagnosis, radiation oncology, and biomarker research. Clinical fellowships are also offered by these medical centers to physicians and technologists, a significant contribution to human resource development in this field.

Human Health

Currently, PINSTECH, under the supervision of Pakistan Atomic Energy Commission (PAEC), operates two research reactors - Pakistan Atomic Research Reactor (PARR 1&2), for research, development, education, and training purposes. PARR-1 is a 10 MW pool-type research reactor, supplied by the USA in 1965 under the "Atoms for Peace" program. PARR-2 is an indigenous 30kW miniature neutron source reactor (MNSR). Operational since 1974, this reactor uses highly enriched uranium (HEU) fuel and is based on the Chinese design.[6] Additionally, PARR-1 supports the Molybdenum production facility, which fulfills the national demand for radiopharmaceuticals and supplies to all nuclear medical centers across the country for both diagnostic and therapeutic applications.

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[6] Pakistan Nuclear Regulatory Authority (PNRA), "Research Reactors," *PNRA*, https://www.pnra.org/r-reactors.html

Currently, nineteen nuclear medical centers (Cancer hospitals) are being operated by PAEC, treating nearly one million patients annually.[7] One nuclear medical center – Nuclear Medicine, Oncology and Radiotherapy Institute (NORI), Islamabad, has been designated as an Anchor Center under the flagship initiative of the IAEA "Rays of Hope" and will support regional countries in expanding access to cancer treatment. Additionally, 21 full-fledged medical centers, 6,237 Diagnostic X-ray centers, 8 radiotherapy centers, 12 nuclear cardiology centers, 6 irradiators (blood), 14 isotope production & PET/CT (Cyclotron), and 10 Radioimmunoassay (RIA) labs are supporting this goal in the private and public sectors.[8]

Food and Agriculture

Four agriculture and biotech institutes (NIAB, NIBGE, NIFA, and NIA), owned by PAEC, have introduced 150 different crop varieties and treated millions of acres through Integrated Pest Management (IMP). Equipped with advanced facilities such as gamma irradiators, Polymerase Chain Reaction (PCR) systems, and mass spectrometers, these institutes also offer national and international training and academic programs through Pakistan Institute of Engineering and Applied Sciences (PIEAS). In the realm of food safety, Pakistan has established its first ISO/IEC 17025-accredited veterinary drug residue laboratory at the NIAB, enabling the analysis of export–bound meat and training hundreds of professionals and farmers. Addressing climate change challenges, Pakistan has adopted Climate Smart Agriculture practices with IAEA support, utilizing isotopic techniques to optimize fertilizer use, manage soil salinity, and reduce greenhouse gas emissions. These achievements have enhanced national food security and agricultural resilience. Food and agriculture institutes are licensed by PNRA

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[7] International Atomic Energy Agency (IAEA), *Pakistan Partnering with IAEA for Strengthening South-South Cooperation* (Vienna: IAEA, 2023), https://www.iaea.org/newscenter/news/pakistan-and-iaea-accelerate-nuclear-cooperation-to-address-climate-food-and-health

[8] Pakistan Nuclear Regulatory Authority (PNRA), *Annual Report 2023* (Islamabad: PNRA, 2023), https://www.pnra.org/upload/pnrarpt/PNRA%20Annual%20Report%202023.pdf

to allow them the use of radiotracers and irradiators for nuclear techniques such as radiation processing, isotope tracer studies, and mutation breeding.

Industrial Applications

Nuclear and radiation technologies have several applications in industrial sectors. These applications include Non-Destructive Testing (NDT) of materials and welds, industrial radiography, gauging and process control (e.g., moisture/density gauges, process control), radiation sterilization of medical devices and packaging, and nuclear gauges for mining and mineral exploration. Since these applications involve the use of sealed radioactive sources, accelerators, and radiation-producing devices, they require stringent regulatory oversight. In this regard, PNRA ensures that operators and workers handling radioactive sources are well-trained and well-qualified experts.

Furthermore, other industrial applications of radiation sources include well logging in oil exploration, non-destructive testing for material inspection, food irradiation, and the sterilization of food and other products. PNRA has licensed 243 industrial facilities for these purposes. Licensees are bound to comply with all regulations and standards, such as PNRA's regulation PAK/926[9] on "Security of Radioactive Sources" and IAEA's "code of conduct on the Safety and Security of Radioactive Sources." Safe and secure use of radioactive sources ensures a safe environment that improves quality of life, health, education, equality, and sustainability, demonstrating how nuclear technology can support not just energy or health, but industrial modernization as well.

Global Nuclear Safety and Security Regime

The Global Nuclear Safety Regime is a set of international legal, institutional and technical systems that guarantee safe operation of nuclear

[9] Pakistan Nuclear Regulatory Authority (PNRA), *Management of Nuclear Security Events Involving Radioactive Sources: Pakistan Nuclear Regulatory Authority Regulatory Guide* (Islamabad: PNRA, 2023), https://www.pnra.org/upload/guidelines/PNRA-RG-926.02.pdf

facilities.[10] Whereas, the Nuclear Security Regime, defined by the IAEA is as "the legislative and regulatory framework and administrative systems and measures governing the security of nuclear material, other radioactive material, associated facilities, and associated activities; the institutions and organizations within the State responsible for ensuring the implementation of the legislative and regulatory framework and administrative systems of nuclear security; and nuclear security systems for the prevention and detection of and response to nuclear security events."[11]

The global nuclear safety and security regime is based on a range of instruments, conventions, and protocols. These include binding agreements, non-binding protocols, and voluntary commitments to govern the safe and secure utilization of nuclear technologies, materials, and installations. This regime relies on national efforts within a country's jurisdiction. The regime is supported by the relevant national and international institutions, intergovernmental organizations, and multinational regulators' as well as operators' networks. Since 1986, the IAEA has held a central position in advancing global nuclear safety and security by acting as the secretariat for multiple international legal frameworks - both binding and non-binding. Notable among these are the "1986 Convention on Early Notification of a Nuclear Accident (ENCA),"[12] the "1987 Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE),"[13] and the "Convention on the Physical Protection of Nuclear Material

[10] International Nuclear Safety Advisory Group (INSAG), *INSAG-21: Strengthening the Global Nuclear Safety Regime* (Vienna: International Atomic Energy Agency, 2006), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1277_web.pdf

[11] International Atomic Energy Agency (IAEA), *Objective and Essential Elements of a State's Nuclear Security Regime* (Vienna: IAEA, 2013), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1590_web.pdf

[12] International Atomic Energy Agency (IAEA), *Convention on Early Notification of a Nuclear Accident and Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, Legal Series No. 14 (Vienna: IAEA, 1986), https://www.iaea.org/sites/default/files/infcirc335.pdf

[13] International Atomic Energy Agency (IAEA), *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, INFCIRC/336 (Vienna: IAEA, 1986), https://www.iaea.org/sites/default/files/infcirc336.pdf

(CPPNM)," originally adopted in 1987 and extended in scope in 2005.[14] Furthermore, Pakistan is a party to the "1994 Convention on Nuclear Safety (CNS)"[15] and the "2001 Joint Convention on the Safety of Spent Fuel Management and on the safety of Radioactive Waste Management."[16] It has expressed political commitment to the IAEA's "2003 Code of Conduct on the Safety and Security of Radioactive Sources,"[17] and follows IAEA guidance outlined in the "2006 Code of Conduct on the Safety of Research Reactors."[18]

IAEA Safety Standards and Security recommendations represent a central part of the international nuclear governance framework. They provide technical requirements, practical guidance and good practices to facilitate harmonized approaches for the safe operation and regulation of facilities and activities involving nuclear and radiological materials.

The fundamental framework of the Global Nuclear Safety Regime has been established very well and it operates in a way that complements the national nuclear infrastructure of individual nations. The regime, despite its existing structure, still holds the potential for gradual reforms that may lead to the improvement of international safety standards. The "International Nuclear Safety Advisory Group (INSAG)," a group of internationally recognized experts convened by the IAEA, gives authoritative advice on nuclear safety principles and policies, emphasizing that high levels of safety at nuclear

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[14] International Atomic Energy Agency (IAEA), *Convention on the Physical Protection of Nuclear Material*, INFCIRC/274/Rev.1 (Vienna: IAEA, 1979), https://www.iaea.org/sites/default/files/infcirc274.pdf

[15] International Atomic Energy Agency (IAEA), *Convention on Nuclear Safety* (Vienna: IAEA, 1994), https://www.iaea.org/sites/default/files/infcirc449.pdf

[16] International Atomic Energy Agency (IAEA), *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, INFCIRC/546 (Vienna: IAEA, 2001), https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste

[17] International Atomic Energy Agency (IAEA), *Code of Conduct on the Safety and Security of Radioactive Sources* (Vienna: IAEA, 2003), https://www-pub.iaea.org/MTCD/publications/PDF/Code-2004_web.pdf

[18] International Atomic Energy Agency (IAEA), *Code of Conduct on the Safety of Research Reactors* (Vienna: IAEA, 2006), https://www-pub.iaea.org/MTCD/publications/PDF/CODEOC-RR_web.pdf

facilities can be realized through effective application of frameworks based on the Global Nuclear Safety Regime. The Group underlines that the recommendations provided in its reports are not only achievable, but they should be followed by all nuclear stakeholders on a regular basis.[19]

Key Aspects of Pakistan's Nuclear Safety and Security Regime

Pakistan, a founding member of the IAEA, has served the Chairmanship of the Board of Governors of the IAEA three times.[20] Pakistan is a party to many international instruments that seek to reinforce the national as well as international nuclear security infrastructure. The next section addresses the main features of Pakistan's nuclear safety and security regime.

Independent Regulator

The regulatory and operational nuclear industry of Pakistan is structured in various institutions and legislations. In this regard, the PNRA is mandated to offer "radiation protection," "nuclear safety" and "physical protection of nuclear materials and installations,"[21] but the PAEC is mandated to facilitate peaceful uses of nuclear energy and to manage the activities of nuclear installations. The "National Safety Policy (NP-02/2020)" was issued in 2020, which also contributes to the work of Pakistan to attain nuclear safety and radiation protection. Pakistan has established a robust and sustainable regulatory framework that has safety and security as the top priority.

Pakistan has evolved its nuclear regulatory system. This started with the establishment of "Pakistan Nuclear Safety Committee" in 1964 and subsequent establishment of "Pakistan Nuclear Regulatory Board" in 1994.

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[19] International Nuclear Safety Advisory Group (INSAG), *INSAG-21: Strengthening the Global Nuclear Safety Regime* (Vienna: International Atomic Energy Agency, 2006), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1277_web.pdf

[20] International Atomic Energy Agency (IAEA), "Previous Board Chair: 1957 to Present," *IAEA*, January 30, 2015, https://www.iaea.org/about/policy/board/previous-chair-1957-to-present

[21] International Atomic Energy Agency (IAEA), *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5)*, Nuclear Security Series No. 13 (Vienna: IAEA, 2011), https://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf

PNRA is a nuclear regulatory authority which was enacted under the PNRA Ordinance, 2001. The primary goal of this institution was to separate the regulator of the nuclear power generation and the agency that oversees it. PNRAs structure comprises one chairman, two permanent members, and seven serving on a part-time basis.

PNRA holds complete authority to perform all regulatory functions and procedures related to radiation protection, nuclear safety, and nuclear security. Moreover, this institution supervises the import, export, transit, transport and disposal of radioactive material. PNRA issues relevant certificates such as No Objection Certificates and Radiation Free Certificates. PNRA ensures due compliance with its legislative and regulatory framework with the help of well-defined enforcement mechanism. This enforcing mechanism is further facilitated by PNRA "Enforcement Regulations- (PAK/950)."

Additionally, PNRA serves as the national contact point for all relevant international agreements that deal with nuclear and radiological emergencies. PNRA also plays an important role in inter-agency coordination, generating public awareness, and performing safety related research in case a nuclear or radiological emergency occurs. The organization's priorities are enhancing regulatory effectiveness through capacity-building and institutional development. PNRA has adequate skilled human resources, access to knowledge and technical as well as financial resources to support effective and efficient work of the organization.

As part of its commitment to maintaining regulatory effectiveness, PNRA employs a comprehensive monitoring and assessment framework that includes both internal and external evaluation mechanisms. Internally, the latest PNRA report (2023) indicates satisfactory performance, evaluated through ten well-defined strategic performance indicators. Externally, PNRA reinforced its commitment to transparency and international best practices by hosting a full-scope IAEA "Integrated Regulatory Review Service (IRRS)" mission in April 2014. IAEA conducted a follow-up IRRS mission in February-March 2022 which confirmed that all recommendations from the initial review, had been successfully implemented by Pakistan. A significant advancement in national-level regulatory infrastructure of Pakistan was also reported with a focus on efficiency and effectiveness.

Comprehensive Regulatory Framework

A comprehensive regulatory framework has been established by PNRA for all operational nuclear facilities, radiation facilities, research reactors and associated activities in Pakistan. The PNRA regulatory system is based on a holistic paradigm to monitor the radioactive material in its entire life cycle, from "Cradle to Grave." This paradigm covers the systematic tracking of all stages in the lifecycle of a nuclear or radioactive substance, including its origin, which is the initial production stage, to its final disposal. This approach is used to ensure continuous accountability and safety of nuclear and radioactive materials throughout their lifecycle. There is another set of rules that regulate the control of nuclear radiation facilities which incorporates all the phases of the facility, site selection, construction to operation, decommissioning once the facility stops operating, and the final release of the sites out of the regulatory control.

Nuclear Power Plants

Pakistan has shown a strong determination to uphold highest standards of nuclear safety by ensuring safe operation of Karachi Nuclear Power Plant (KANUPP) since its inception in 1971. Pakistan signed the CNS on 20 September 1994 and ratified on 30 September 1997, to be in line with the international standards to facilitate its peaceful nuclear energy program.

Moreover, since the creation of PNRA in 2001, it has issued 23 regulations, nearly 20 of which relate directly or indirectly to the safety of nuclear power plants. These regulations have special provisions which deal with "licensing and safety requirements" of site selection, design and operational characteristics of nuclear power plants. These rules are based on the IAEA Safety Standards and are also complemented by a set of IAEA regulatory guidelines. Other international or national industrial standards and codes, where applicable, are also recommended by PNRA to cover regulation and be in line with international best practices.

The PNRA regulations are regularly updated and changed as and when it is needed to address the changes in technology and safety needs. To maintain transparency and participation of stakeholders, these regulations are posted on the PNRA website.[22] The fact that Pakistan has a very good record in the safety of its nuclear power plants is an indication of a good safety culture. Also, the presence of a strong regulatory authority- PNRA, and a leadership that is deeply interested in upholding the best safety standards confirm that Pakistan is a responsible nuclear power. The accident of Fukushima presented numerous lessons that reinforced the emphasis of Pakistan on the vigilance of regulation and continuous enhancement.

In addition, PNRA requires a gradual licensing process. This process involves granting a site license, construction license, operating license, and a decommissioning license. To facilitate transparency and community participation, every stage of this process involves an in-depth Environmental Impact Assessment (EIA), submission of a Safety Analysis Report (SAR), and consultation with the community. PNRA conducts regular checks and audits to guarantee high-level of safety and security. It also incorporates the input of operational experience, promotes a strong safety culture, develops cybersecurity standards and prepares to react to emergencies.

[22] www.pnra.org

Research Reactors

An effective regulatory system is necessary to ensure safe and secure operations of research reactors since they use nuclear and radioactive materials in their operations. To this end, PNRA has established stringent national policies that are compliant with international standards. Its regulatory system is consistent with the key IAEA safety publications, including "IAEA SSR-3, "SSG-20, and INFCIRC/225/Rev.5." It is worth noting that PNRA has developed some regulations known as "Regulations on the Safety of Research Reactors (PAK/932)" that encompass all the concerns related to research reactor safety. Pakistan, in accordance with the IAEA "Code of Conduct on the Safety of Research Reactors, is particularly concerned with the problem of equipment obsolescence, and it is well aware of the necessity of regular maintenance, timely replacement of components and strict adherence to technical specifications to ensure the integrity of operations.

Simultaneously, PNRA facilitates the development and implementation of quality assurance programs even in low-power reactors that reflects the compliance of Pakistan with the best practices worldwide, despite the historical exemptions. In Pakistan, licensing of research reactors is a staged and stringent procedure, and it has adopted a model similar to that of nuclear power plants. PNRA also ensures the safety of its staff, the general population and the environment at all levels and the use and storage of nuclear materials. PNRA allows safe scientific advancement with strict regulatory oversight and compliance with the needs of licensees, without undermining Pakistan's non-proliferation commitments or nuclear safety obligations.

Radiation Facilities

PNRA has a detailed licensing and regulatory system of the facilities that utilize ionizing radiation which is in line with its regulatory framework. These are "PAK/908 (Rev.1)," Regulations of the Licensing of Radiation

Facilities Other than Nuclear Installation(s)," and "PAK/904" which describes the Radiation Protection Regulations. The safe use of radiation sources in non-nuclear facilities is based on these rules, which increase occupational and population safety. These regulations ensure that all the activities that involve radiation are undertaken in a safe way with the priority being given to the protection of human health and the environment. PNRA takes a graded approach in regulating such radiation facilities. In addition, the facilities are categorized based on the radiation hazards and safety significance that they possess.

In the licensing process, PNRA duly evaluates the required submissions that include SARs, Physical Protection Plans (PPPs), Emergency Preparedness Plans (EPPs), and Radiation Protection Programs (RPPs). In this regard, a national database for occupational exposure as specified by "PAK/908," has been developed and maintained by PNRA. By 2023, records for 14,800 radiation workers were maintained. Over 97.1% of workers received below 5mSv per annum, indicating effective implementation of "ALARA (As Low as Reasonably Achievable)" principles.

Transport of Radioactive Material

Safe and effective use of nuclear technology requires a cross-cutting component of transporting radioactive material. Most radioactive materials, except those produced domestically as radiopharmaceuticals used to treat cancer, are imported to Pakistan; international and domestic radioactive material shipments are controlled by the "Regulations for the Safe Transport of Radioactive Material (PAK/916)" of the PNRA. These rules are based on the "SSR-6 (2018 Edition)" of the IAEA and are aimed at establishing safety in all modes of transport. The PNRA is the regulatory body that has the mandate of regulating Class 7 radioactive materials and operates in close cooperation with national transport agencies to ensure that there is harmonization of regulatory application and maintenance of safety standards during the transport process.

Radioactive Waste Management, Spent Fuel Management, and Decommissioning

The safe, secure, and sustainable management of radioactive waste is an important element of nuclear governance in the modern world. All radioactive facilities and nuclear plants in Pakistan handle radioactive waste in complete adherence to the internationally accepted principles and best practices. The Government of Pakistan has institutionalized its commitment to this field by issuing a national policy document titled "National Policy on Safe Management of Radioactive Waste, Decommissioning, and Spent Nuclear Fuel in the Islamic Republic of Pakistan (RWP-01/2018)." The policy offers a long-term strategic direction of responsible management of radioactive waste, which is environmentally friendly, safe for the population, and in line with international standards.[23] This policy sets goals, requirements, and responsibilities of different stakeholders, allowing for safe management of disused radioactive sources which could not be returned to the main supplier in other country, along with orphan sources, and ownerless radioactive waste in the national radioactive waste storage or disposal facilities, operated by PAEC and licensed by PNRA. The policy also ensures the availability of funds for these purposes. Moreover, to implement the policy, PAEC has established strategies for radioactive waste management, spent fuel management, and decommissioning.

For the last six decades, spent nuclear fuel generated by the operation of nuclear power plants and research reactors is considered an asset by the Government of Pakistan. Therefore, it is being stored at spent fuel storage facilities operated by PAEC and licensed by PNRA. The first dry spent fuel storage facility to safely manage spent fuel of CANDU reactor is KANUPP Spent Fuel Dry Storage Facility (KSFDF). It is currently operational, and a second one is under construction at Chashma to safely manage PWR-type spent fuel.

[23] Pakistan Nuclear Regulatory Authority (PNRA), "Regulations," *PNRA*, https://www.pnra.org/regulations.html

Pakistan has not yet acceded to the "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management." This convention entered into force in 2001. While Pakistan is not a part of the Joint Convention, it has developed a comprehensive national regulatory framework for spent fuel management, radioactive waste management, and decommissioning of nuclear facilities.[24] These regulations place the primary responsibility for safety on licensed operators, requiring them to implement robust waste management programs, conduct regular safety assessments, and ensure long-term containment and control. Sustainability of the basic safety principles is ensured across all stages of spent fuel management and radioactive waste management by the implementation of this regulatory framework.

Emergency Preparedness and Response

In 1989, Pakistan signed two significant IAEA Conventions, ENCA and CACNARE. PNRA is at the center of emergency preparedness and response to all nuclear and radiological incidents at the national level. It has been well-stated in "National Radiation Emergency Plan (NREP) on nuclear and radiological emergencies." PNRA offers technical assistance to the concerned government agencies at any level. PNRA has established elaborate regulations (PAK/914) in accordance with international best practices and lessons learnt, which require all facilities to include emergency communications, response to contaminated persons, protective measure taking, provision of containment measures, and long-term safety measures in their emergency planning procedures. PNRA ensures that the concerned organizations formulate emergency plans in the event of radiological incidents and that the plans are coordinated properly with the organizations involved. PNRA as the national competent authority of Pakistan, coordinates with IAEA and other states in events of radiological

[24] *The Gazette of Pakistan*, "S.R.O. 1236(I)/2018," August 15, 2018, https://www.pnra.org/upload/policies/National%20Policy%20on%20Safe%20Management%20of%20Radioactive%20Waste,%20Decommissioning%20and%20Spent%20Nuclear%20Fuel%20in%20Islamic%20Republic%20of%20Pakistan-_RWP-012018_.pdf

emergencies, as per the obligations of the "International Conventions on Early Notification and Assistance."

The National Radiation Emergency Coordination Centre (NRECC) is the national point of contact in radiation emergency under the direction of PNRA. It has the responsibility of informing and liaising with national and international stakeholders, assessing radiological incidents using in-house tools and specialized Radiation Monitoring Teams (RMTs), and giving advice to the government and other relevant parties on appropriate response measures. NRECC is important in making sure that there is timely communication, good decision making and coordinated emergency preparedness and response at the national level.

Environmental Safety

As per the Ordinance 2001- Section 39 "Environmental surveillance and radiation emergency plans," PNRA is responsible for implementing and coordinating a national environmental monitoring program to detect any build-up of radioactivity that could pose a risk to public health. PNRA conducts regular environmental monitoring around nuclear power plants, research reactors, and industrial sites to ensure safe levels of radioactivity. It independently verifies data submitted by nuclear operators and uses high and low volume air samplers for the detection of airborne radioactive substances.

In 2023, monitoring near CNPGS and KNPGS showed no radiological risk to the public. PNRA also assessed Naturally Occurring Radioactive Material (NORM) in industrial sectors like oil, coal, gas, and phosphate, with results showing activity levels well below regulatory limits. Additionally, PNRA issues radiation analysis certificates for exported edible and non-edible items. In this regard, 381 samples were analyzed by PNRA by 2023. PNRA also provides dosimetry services for the protection of occupational workers by monitoring their radiation exposure and ensuring that enforcement actions are taken if radiation exposure exceeds the safety limits. Calibration labs to ensure the accuracy of radiation monitoring equipment, being used across nuclear and radiation facilities, have been established by PNRA in Islamabad and Kundian.

Pillars of Nuclear Safety and Security Regime in Pakistan

All sensitive installations, including nuclear installations of Pakistan, are under custodial control. The nuclear security regime in Pakistan aims at a layered defense approach that attempts to address numerous threats, such as hostile external forces, internal corruption, and cyberattacks. The security regime, inter alia, includes physical protection, material control and accounting, emergency preparedness to radiological incidents, and border security measures. In addition, the primary aim of nuclear safety and security is to protect individuals, societal structures, and the environment from the harmful effects of radiation. Therefore, basic principles overlap, whereas the implementation might differ. Actions and measures taken in one domain also carry implications for the other. The Nuclear Security Regime in Pakistan is anchored on three key interrelated pillars. First is "Legislative and Regulatory Framework," second is "Physical Protection and Security Measures" and the third pillar is "Institutional Coordination and Capacity Building." These pillars contribute collectively to Pakistan' s strong and robust nuclear security stance.

The first pillar consists of a comprehensive and structured legal and regulatory framework that governs nuclear security for materials, facilities, and associated activities involving radioactive substances. The legislative framework encompasses the "National Command Authority (NCA) Act (2010),"[25] "Pakistan Nuclear Regulatory Authority Ordinance (2001),"

[25] Pakistan Nuclear Regulatory Authority (PNRA), *Regulations on Radioactive Waste Management (PAK/915) (Rev.1)* (Islamabad: PNRA, 2019), https://www.pnra.org/upload/regs/PAK-915.pdf. Pakistan Nuclear Regulatory Authority (PNRA), *Regulations for the Safe Management of Spent Nuclear Fuel (PAK/918)* (Islamabad: PNRA, 2020), https://www.pnra.org/upload/regs/PAK-918.pdf.Pakistan Nuclear Regulatory Authority (PNRA), *Regulations on Decommissioning of Facilities Using Radioactive Material (PAK/930)* (Islamabad: PNRA, 2016), https://www.pnra.org/upload/regs/PAK-930.pdf

"Pakistan Strategic Export Control Act (2004),"[26] and "Pakistan Atomic Energy Commission Ordinance (1965)." Over time, this legal and regulatory framework has undergone gradual development. This development introduced the "Pakistan Nuclear Safety and Radiation Protection (PNSRP)" Regulations in 1990, marking its initial milestone. These regulations outlined the core provisions for ensuring the physical security of the nuclear materials and those facilities that are associated with them. Additionally, Pakistan incorporated IAEA "INFCIRC/225/Rev.4" to regulate physical protection measures at nuclear facilities, aligning them with the provisions of the CPPNM framework.

The "Physical Protection of Nuclear Material and Nuclear Installations regulation (PAK/925)" was introduced by Pakistan in 2019 to set standards consistent with international practices and to strengthen its nuclear security framework. These provisions, following a graded approach, cover the protection of nuclear facilities and materials during operational use, storage phases, and transportation. Furthermore, requirements for security measures regarding insider threat mitigation and prevention of cyberattacks were also established. These regulatory measures draw from the IAEA's nuclear security guidance "INFCIRC/225/Rev.5" and are structured to comply with the provisions of the CPPNM and its 2005 Amendment.

The "Security of Radioactive Sources regulation (PAK/926)" was similarly enacted to ensure protection of such materials during their manufacture, application, transit, and storage. Consistency is maintained between these regulations and the provisions of the "Code of Conduct on radioactive source safety and security," including its two supplementary guides. They mandate graded security measures that encompass detection, delay, response, and comprehensive management of radioactive sources.[27]

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[26] *National Command Authority Act, 2010*, Government of Pakistan, published in *The Gazette of Pakistan*, December 20, 2010, https://na.gov.pk/uploads/documents/1300934282_934.pdf
[27] *The Pakistan Strategic Export Control Act, 2004*, Government of Pakistan, https://fas.org/nuke/guide/pakistan/export-control.pdf

The second pillar is the organizations and institutions, which are the responsible authorities in this field. Under the NCA Act, authority over the management of Pakistan's nuclear assets and the protection of its nuclear program is vested in the NCA. PNRA oversees the physical safety of nuclear assets and is tasked with ensuring their secure and responsible use. "Strategic Export Control Division (SECDIV)," which was created through legislation, has been appointed as the key body that is supposed to oversee the rules and regulations governing export and import of sensitive materials, and dual-use equipment and technologies. PAEC is the promotional body overseeing nuclear applications in all sectors of Pakistan.

The third pillar encompasses a multi-layered array of systems and measures, designed to ensure effective implementation of nuclear safety and security. This primarily includes the implementation of physical protection systems, nuclear material accounting and control, as well as detection and response mechanisms. Radiation detection systems, including portal monitors and handheld devices, have been installed at Pakistan's border checkpoints under the NNDA to address cross-border trafficking of nuclear and radioactive materials. Additionally, an Integrated Cargo Container Control system has been operating since 2007 at Port Qasim near Karachi. These are operated by the officials of Pakistan Customs as Front-Line Officers (FLOs).

To assist FLOs, Radiological Assistance Groups (RAGs) and technical support units have been constituted to provide on-the-spot support for a range of critical functions, including identifying unknown radioactive sources, conducting checks for surface contamination, undertaking extensive searches and recovery operations for radioactive materials that are not under regulatory control. The amendments in the "Customs Act 1969 (IV of 1969)" have included NCA and PNRA to enhance oversight of the import and export of nuclear and radioactive materials. Relevant offences and penalties have been defined to criminalize malicious acts involving these materials.[28] "Nuclear Material Accounting and Control (NMAC)" mechanism exist as part of physical protection regime and efforts are being made to establish modern training facility to enhance capabilities of professionals on advanced techniques of NMAC. In fulfillment of its national and international commitments, Pakistan has established these systems and measures as the main pillar of its nuclear security regime. These systems and measures are designed to provide detection, delay and response to potential nuclear security threats including the physical protection, and robust cyber security protocols to prevent attacks on nuclear installations and radiation facilities, all of which are informed by regular threat assessments to ensure their effectiveness.

This harmonious interplay of legislative, institutional, and technical components enables Pakistan to maintain a vigilant and proactive approach to nuclear security. In its "Nuclear Security Index 2020," the US based nuclear threat initiative (NTI), which assesses countries' progress on nuclear security, categorized Pakistan as most improved country for its nuclear security measures, being quoted as "Most improved among countries with materials in 2020 is Pakistan, which was credited with adopting new on-site physical protection and cybersecurity regulations, improving insider threat prevention measures, and more." [29]

Human Capacity Building

The development of human capacity is a fundamental pillar of developing a robust nuclear safety and security regime in any nation. In Pakistan, the dire shortage of skilled human resources in this field has been overcome by the creation of several reputable institutions, most of which are operated

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[28] Ministry of Foreign Affairs, *Pakistan's Overview of Nuclear Security Regime* (Islamabad: Ministry of Foreign Affairs, Government of Pakistan, 2024), https://mofa.gov.pk/nuclear-safety-security

[29] Government of Pakistan, *The Customs Act, 1969 (IV of 1969)* (Islamabad: Printing & Publication Customs Budget, FBR, 2024), https://bwcimplementation.org/sites/default/files/resource/Customs%20Act%201969%20as%20of%202024.pdf

under the supervision of the PAEC. The most notable of these is the PIEAS which also supervises a chain of affiliated institutions. PIEAS has a varied academic program that offers Bachelor's, Master's, and doctoral degrees. In addition, PIEAS also offers professional development courses and research opportunities in many scientific and engineering fields. It is worth noting that PIEAS has been recognized as an IAEA Collaborating Centre in Nuclear Engineering, which indicates its international status and contribution to nuclear education and training in the world.

PNRA has also established the "National Institute of Safety and Security (NISAS)" to fulfill the essential requirements of developing human resources in nuclear safety and security field. NISAS offers dedicated training courses along with refresher courses related to nuclear security, radiation detection systems, physical protection systems, which are used for security of nuclear and radioactive materials and related facilities, emergency preparedness, and detection of nuclear and radioactive materials out of regulatory control for professionals from various national and international organizations. NISAS also serves as a collaborating center for the IAEA for the nuclear security discipline.

Another important institution that plays a significant role in human resource development in nuclear safety and security is "Pakistan Centre of Excellence in Nuclear Security (PCENS)." [30] PCENS also provides a variety of training courses, including specialized courses in the fields of nuclear security and physical protection systems to facilitate the best practices in nuclear security. It is an internationally recognized facility for both domestic and international participants. In March 2016, PCENS organized an annual meeting of the "International Network of Nuclear Security Support Centers (NSSC)." It was the first meeting of this Network, which was held outside of the IAEA Headquarters.

[30] Nuclear Threat Initiative (NTI), "The 2020 NTI Nuclear Security Index," *The Nuclear Threat Initiative*, February 22, 2022, https://www.nti.org/analysis/articles/2020-nti-nuclear-security-index/

Extended International Cooperation

PNRA has greatly emphasized the pivotal role of international collaboration in enhancing the effectiveness of regulatory systems and the reinforcement of global nuclear safety and security frameworks. In this regard, PNRA has established good partnerships with IAEA and the regulatory bodies of several other nations in order to support the exchange of regulatory experiences, knowledge sharing and other initiatives for capacity-building. Pakistan maintains an active participation in all IAEA Safety Standard Committees, including the "Nuclear Security Guidance Committee (NSGC)," "Radiation Safety Standards Committee (RASSC)," "Nuclear Safety Standards Committee (NUSSC)," "Waste Safety Standards Committee (WASSC)," "Transport Safety Standards Committee (TRANSCC)," "Commission on Safety Standards (CSS)," and "Global Nuclear Safety and Security Network (GNSSN)." Additionally, PNRA also maintains coordination with several IAEA forums like the "Incident Reporting System (IRS)," "Illicit Trafficking Database (ITDB)," "International Nuclear and Radiological Event Scale (INES)," "Regulatory Cooperation Forum (RCF)," "Response and Assistance Network (RANE)," "International Generic Ageing Lessons Learned (IGALL)," "United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)," and "Radiation Safety Information Management System (RASIMS)."

In addition to participation, PNRA facilitates the IAEA with expert support for conducting "International Physical Protection Advisory Service (IPPAS)" missions, "Integrated Regulatory Review Service (IRRS)" missions, developing training materials and safety standards, and conducting workshops and training courses in Member States. PNRA also participates in various IAEA Technical Cooperation Programs intended for enhancement of the capabilities of its regulatory personnel, resulting in consolidation of Pakistan's regulatory infrastructure. Pakistan also serves as a designated point of contact for the IPPAS Good Practices Database,[31] maintained by the IAEA since 2016. The main purpose of this database is to share the lessons learnt from IAEA IPPAS missions with the international nuclear security community.

PNRA has also forged bilateral cooperation agreements with several international organizations, like "China's Nuclear Safety and Radiation Protection Center (NSC)," "China Nuclear Power Operations Technology Corporation Ltd. (CNPO)," and "China's National Nuclear Safety Administration (NNSA)." The main objectives of these agreements are to promote professional development, facilitate assistance in regulatory matters, and exchange regulatory experiences. Additionally, a Memorandum of Understanding (MoU) has been signed by PNRA with Nigerian Nuclear Regulatory Authority (NNRA) to facilitate capacity building of NNRA through scientific visits and fellowships under the sponsorship of the IAEA.

Pakistan's longstanding and constructive engagement with the IAEA was duly recognized by the IAEA Director General, Rafael Mariano Grossi, during his visit to Pakistan in February 2025. He also asserted the IAEA's commitment, in the same spirit, for sustained collaboration with Pakistan. Grossi also described Pakistan's nuclear power generation program as one of the most globally successful programs, by highlighting the country's substantial progress in nuclear power generation, healthcare, agricultural advancements, and industrial development, all leading to its socio-economic growth. Notably, in recognition of Pakistan's sustained dedication to nuclear safety, Chairman PNRA, Faizan Mansoor, was unanimously elected as President of the Tenth Review Meeting of CNS in September 2024, with the meeting scheduled to continue through April 2026.

[31] International Atomic Energy Agency (IAEA), "Nuclear Security Commitments and Actions," *IAEA Bulletin* 57, no. 4 (2016), https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull/bull574_nuclearsecurity.pdf

Related to Nuclear Security, Pakistan is dedicated to strengthening its nuclear security by ratifying several key international instruments. Pakistan became a state party to the CPPNM in 2000 and its 2005 amendment in 2016, which seeks to "physically protect nuclear facilities and materials utilized for peaceful purposes in domestic use, storage, and transport." It also involves the criminalization of certain offences related to nuclear material. Additionally, Pakistan has adopted the IAEA "2004 Code of Conduct on Safety and Security of Radioactive Sources," its "supplementary Guidance on the Import and Export of Radioactive Sources, and Management of Disused Radioactive Sources."

Pakistan is fully committed to implementing the obligations outlined United Nations Security Council Resolutions (UNSCRs) 1373, 1540, and 1887, which focuses on the prevention of nuclear weapon proliferation, combating terrorism, and promoting nuclear security and non-proliferation. Pakistan has been presenting implementation reports to UNSCRs committees, as necessary, in pursuance of the objectives of these UNSCRs. The active cooperation of Pakistan with international partners and agencies, compliance with international instruments, and institutional approach is evidence of the utmost importance of a strong nuclear safety and security regime in Pakistan.

Highly Valued Safety and Security Culture

PNRA encourages the existence of safety and security culture in organizations which are involved in nuclear activities. These are operators, regulators and designers. The global nuclear community has significantly focused on the incorporation of safety culture in regulatory agencies following the Fukushima accident. To align with this worldwide trend, PNRA has undertaken a Safety Culture-Self Assessment (SCSA) initiative to enable the evaluation and improvement of the role of safety culture through leadership practices and in the organizational processes.

Data collection was done through a number of approaches at all levels of the organization. This involves interviews, surveys, focus groups, document analysis and observations. The primary goal of this program was to encourage open communication, increase safety awareness and build a common vision of safety objectives. The SCSA results were used to design safety culture improvement activities, strengthening the strong areas and working on the improvement of weak areas. By undertaking this self-assessment, PNRA not only reinforced its position as a leader in nuclear safety regulations but also demonstrated its commitment to continuous safety culture enhancement, a cornerstone of its leadership and regulatory strategy. PNRA has established regulations that emphasize the role of leadership in safety and the commitment to creating a safety-conscious organizational culture.

Similarly, a strong security culture among professionals and nuclear organizations plays a critical role in strengthening the security regime in a country. Being vigilant of this fact, all responsible organizations related to nuclear security are making efforts to guarantee a strong nuclear security culture. In 2018, PNRA conducted an international workshop focused on the practical application of nuclear security culture. The event aimed to deepen understanding of its core principles and practices. PNRA, through its regulatory processes, promotes a safety and security culture among its licensees. They have also introduced a nuclear security culture assessment procedure (a survey) among scientists and engineers as per IAEA guidelines.

Conclusion

The nuclear safety and security regime in Pakistan is robust, mature, as well as fully aligned with the international nuclear governance framework. Pakistan has demonstrated a consistent commitment to maintaining the exemplary standards of nuclear safety and nuclear security which places its regulatory infrastructure at par with those of technologically advanced countries. All components of the national nuclear regulatory framework are clearly defined, actively implemented, and continuously enhanced. PNRA's regulations fully cover the comprehensive regulatory sectors such as licensing and inspection, physical protection, radioactive waste management, emergency preparedness and occupational and public safety. Significant efforts are made to strengthen the capacity of the regulator, promote a strong safety and security culture in the country, and contribute to global nuclear knowledge-sharing platforms.

This was also acknowledged by the DG IAEA during his visit to Pakistan in February 2025. Through close cooperation with the IAEA, along with active participation in regional and international forums, Pakistan not only upholds its own safety and security responsibilities but also supports other countries embarking on peaceful nuclear programs. This cooperative spirit reinforces Pakistan's image as a responsible country in the nuclear sector. It also projects Pakistan as a proactive partner in promoting nuclear safety and security. Lastly, Pakistan's nuclear regulatory regime reflects Pakistan's steadfastness to ensuring nuclear safety, international obligations, and peaceful development. Through continuous improvement, transparency, and international cooperation, Pakistan maintains a robust and responsible nuclear infrastructure to ensure environmental stewardship and scientific advancement for its socio-economic development.

Book Reviews

Nuclear Law: The Global Debate

International Atomic Energy Agency, *Vienna, Austria* (T.M.C Asser Press, 2022), 341

The book *Nuclear Law: The Global Debate* is a significant and timely addition to the literature on nuclear governance. Rooted in the discussions of the International Atomic Energy Agency's (IAEA) First International Conference on Nuclear Law in 2022, this edited volume, compiled by the IAEA, is thematically organized to underscore the agency's pivotal role and the multifaceted nature of the legal frameworks governing nuclear activities worldwide. The book presents a thoughtfully assembled collection of essays that explore the current and future challenges of nuclear law in a rapidly evolving technological and geopolitical context.

The IAEA, since its founding in 1957, has remained central to the development and variety of challenges associated with technological advances in nuclear technology. IAEA Director General, Rafael Marianno Grossi emphasizes the importance of the agency's role in shaping international nuclear law, particularly its four core pillars: safety, security, safeguards, and liability.

The book offers detailed insights into the legal, policy, and technical aspects of domestic and international nuclear law, while also addressing developments related to broader themes like climate change, technological innovation, and sustainable development.

The widespread potential of nuclear energy has evolved beyond the traditional role of power generation, encompassing technological solutions in clean energy, poverty, climate change, and the broader range of the United Nations' Sustainable Development Goals (UNSDGs). However, it is inherently a dual-use technology, and robust and adaptive legal and regulatory frameworks are essential to ensure its safe, secure, and peaceful utility. The book highlights the importance of nuclear science and technology as essential to global efforts in fostering equitable, resilient, and sustainable development trajectories.

The global nuclear legal framework is comprised of a mix of legally binding and non-binding treaties and instruments. Its evolution is reflective of developments within the IAEA and countries with developments in nuclear technology, leading to the need for standards in areas ranging from nuclear safety, security, liability, and governance. However, as countries continue to engage in expanding their nuclear energy infrastructure, there is an active need for greater transparency and active stakeholder engagement between technical experts and regulators, with legal experts for sustainable solutions.

The rising interest in nuclear energy as a low-carbon energy source against the growing challenges of climate change has necessitated a greater focus on nuclear safety. The nuclear industry must remain constantly vigilant against the possibility of a serious accident due to the threat of radiation exposure to people, the environment, and infrastructure. The 2011 Fukushima incident in Japan provides a glaring example for national governance structures to reinforce nuclear safety through a robust and vigilant oversight framework. The international legal framework reinforces continuous IAEA inspections with the target of increased transparency and a harmonized approach to the implementation of nuclear safety standards.

The widening impact of climate change worldwide has highlighted the importance of nuclear energy in achieving Net Zero emissions targets. The book reflects on the potential of nuclear energy for a reliable solution for a low greenhouse gas footprint and a need for energy system transformation by countries, reiterating the need for timely decisions and planning. However, any future planning for investment in nuclear technology pre-requires a strong national legal governance mechanism and commitment to international standards, laid down by IAEA regulations and treaties governing the use of this technology.

Nuclear liability continues to evolve with ongoing deliberations, including issues like interpretation of cost and responsibility for the adverse effects of radiation harm in any untoward eventuality or lapses in weakened systems. Similarly, nuclear security remains intrinsic to the historical evolution of international legal architecture.

The book discusses the Convention on the Physical Protection of Nuclear Material and its Amendment (A/CPPNM) and relates its development from 1980 to the present as a reflection of technological developments like small modular reactors (SMRs) and floating platforms, especially in countries like Russia and the United Kingdom (UK). Nonetheless, this technological change has implicated new dimensions in revision and changes to regulations and standards by legal experts, national experts, regional partners, and the IAEA. The book emphasizes the need for the adoption of a balanced international legal framework clearly defining responsibilities between supplier and host countries in the case of SMRs. These adaptations are needed to address the unique characteristics of SMRs, which provide time-efficient and cost-effective energy solutions vis-à-vis the standard large nuclear power reactors.

Nuclear law, while adopted by different countries of the world, translates into the requirement and understanding of the limitation of its political, technical, and administrative capacity. National nuclear laws and legal governance mechanisms focus on identifying a clear blend of global standards and selective approaches, made achievable through commitment, regional and bilateral partnerships guided and supplemented with the IAEA's expertise and leadership in the nuclear domain.

IAEA provides the historical foundation, continuously evolving along with its member states in dealings with the entire breadth of issues and challenges that form the landscape of global nuclear law. The IAEA safeguards system involves mutually agreed-upon agreements that form an intrinsic part of nuclear governance in all its member states. These safeguards have changed over the years in response to both technical and political changes. It offers standardized arrangements for countries' comprehensive, facility-specific (in nuclear weapons states), research-based, and safeguards for small quantities. IAEA has retained its leadership in spearheading its role in nuclear technology governance and remains central to developing new solutions to any legal interpretation, whether led by technological developments or international security implications for the nuclear sector.

The case study of the UAE's (United Arab Emirates) nuclear program is presented as a learning opportunity to understand the dynamics involved in a specific country in formulating comprehensive legal, regulatory, and institutional frameworks of a peaceful nuclear power program. This history provides the key information in political, technical, and specifically international partnerships involved in the achievements of operational, regulatory, and legal setups for a national nuclear energy program under the auspices and support of the IAEA.

Similarly, the case study of Morocco highlights its almost six decades of efforts in the development of nuclear and radiological infrastructure. Morocco's example illustrates the integration of its national nuclear agency, the Moroccan Agency for Nuclear and Radiological Safety and Security (AMSSNuR), its regulatory mechanism, and infrastructure in adherence to international nuclear legal standards in safety and security.

This book offers a unique insight into the historical understanding of international nuclear law, while simultaneously addressing the new and evolving debates for its implementation in the future. It includes a diverse range of contributions from legal, political, and technical experts from different Member States of the IAEA. This multiplicity of perspectives enhances the analytical depth of the information in the book and attempts to provide a well-rounded understanding of the global nuclear legal landscape. The inclusion of national case studies adds substantial value, offering concrete illustrations of how different countries address the legal, regulatory, and institutional aspects of nuclear energy governance while dealing with ongoing technological advancements. By addressing both theoretical and applied dimensions of nuclear law, the book fills an important gap in existing literature.

Reviewed by Maryam Siddiq Baba, Senior International Relations Officer, Pakistan Atomic Energy Commission (PAEC), Islamabad.

The Technological and Economic Future of Nuclear Power

Reinhard Haas, Lutz Mez, Amela Ajanovic (Springer, 2019), 382

This book is edited by Reinhard Haas, Lutz Mez, and Amela Ajanovic, with contributions from various researchers and analysts in the areas of the economics of nuclear power, the legal and political aspects of sustainable energy, climate policies, and technical challenges. The book provides a comprehensive discussion and analysis of the technical and economic factors hindering the renaissance of nuclear power. It is divided into seven themes, covering a range of aspects that include nuclear power history, economics, legislation, technical issues, nuclear waste and proliferation, major accidents, and alternatives.

In the chapter titled *From Military to Early Civilian Applications*, Rosaria Di Nucci examines the transfer of nuclear technology from military institutions to civilian atomic agencies following the advocacy of "Atoms for Peace" program. She discusses the gradual development of nuclear frameworks that facilitate the legitimization of nuclear power and industry. Di Nucci highlights that Light Water Reactors (LWR) originated as by-products of research conducted for military submarines, particularly in the United States (US), the United Kingdom (UK), and France. Furthermore, she elaborates on the proliferation of LWR technologies through licensing agreements, such as the collaboration between Framatome and Westinghouse in 1958. Additionally, Di Nucci addresses the promotion of nuclear energy, which is strengthened by several factors such as the availability of enriched uranium, turn-key packages for plant construction, and government subsidies.

In the chapter *The Current Status of the World Nuclear Industry*, M. Scheinder and A. Froggatt correlate nuclear power with heat (temperature rise) and water in the context of climate impact. They highlight the ongoing struggles of the global nuclear industry, geographic trends, challenges being faced by new reactor builds, economic viability, and future sustainability of nuclear power. They highlight that the global nuclear energy industry is experiencing stagnation with 32 units in Long Term Outage (LTO) as of July 2018, in the 'big five' nuclear generating countries, such as the US, the UK, France, and South Korea, except China. The authors mention that renewables and cheaper alternatives, efficient energy sources, e.g., natural gas combined cycle projects working in Egypt with 60% efficiency, rising costs, and political opposition, are changing the landscape of nuclear energy. Long construction timelines due to significant delays, budget overruns, or abandonment and aging reactor fleets turn nuclear power into an 'endangered species.

Aviel Verbruggen and Yuliya Yurchenko, in the chapter *The Collision of Atomic and Flow Renewable Power in Decarbonization of Electricity Supply,* critically analyzed the shift from nuclear to renewable energy in global climate policy, criticizing the Paris Agreement for allowing wealthy states to continue emissions under a 'rights to emit' framework. They argue that nuclear and renewable energy are incompatible in fully decarbonized systems due to their differing technical, economic, and systemic needs. They call for a transition to sustainable renewables supported by a stronger, binding, and equitable international governance framework beyond the current limitations of the Paris Agreement.

R. Haas et al., in the chapter *The Historical Development of the Costs of Nuclear Power*, describe the historical trajectory of nuclear power costs, focusing on investment and construction expenses and considering the actual investment cost rather than overnight costs (ONC). Once viewed as a low-cost option, nuclear power now faces rising expenses due to underestimated budgets, government subsidies, extended construction timelines (e.g., extreme cost overruns of projects Hinkley Point C, Olkiluoto-3, and Flamanville-3), increasing interest rates, rising raw material and labor costs, safety requirements, and pre-construction forecasts. They conclude that nuclear power is no longer an inexpensive energy source and is not economically viable compared to renewable technologies like wind and solar.

In the chapter *Renewable Energies versus Nuclear Power Comparison of Financial Support Exemplified at the Case of Hinkley Point C*, Gustav Resch and Demet Suna evaluate the cost-effectiveness and financial support schemes for renewable and nuclear energy through both static and dynamic analyses. They underscore Hinkley Point C's cost escalation from €19 billion in 2013 to €43 billion in 2014, criticizing its financial model and comparing it to the European Union's (EU) renewable energy support, which resulted in a 40% increase in the deployment of renewable energies. The authors in this chapter reveal that renewable energy offers greater environmental and economic advantages, concluding that the UK could save up to 8.4% by selecting renewable energy over nuclear energy.

Wolfgang Irrek, in the chapter *Financing Nuclear Decommissioning*, analyzes the growing financial challenges of dismantling aging nuclear power plants. He discusses the complexities and risks involved, the polluter pays principle, and long-term liabilities. The chapter highlights the need for accurate cost estimates and strong regulatory frameworks. The author emphasizes that uncertainty can be minimized through transparent, well-governed financing models with segregated funds and regular contributions to ensure sufficient resources for decommissioning.

The chapter, *Nuclear Policy in the EU from a Legal and Institutional Point of View* by Dörte Fouquet, highlights the legal and institutional aspects of nuclear regulation in the EU. It focuses on the founding treaty establishing the European Atomic Energy Community i.e., treaty of EURATOM, its limited scope, challenges, and power struggles, its relationship with EU laws, and its conflicts with EU energy market goals. The author reveals the structural weaknesses in the EURATOM treaty and argues for its revision or replacement with a more effective regulatory framework to address current market conditions instead of relying on its outdated subterfuge.

In the chapter *Economic Management of Future Nuclear Accidents*, Tomas Karberger argues that the financial burden of seven nuclear accidents falls on victims and taxpayers due to hidden subsidies enabled by international liability frameworks. Using car accident analogies, he critiques the Price-Anderson Act (1957) and international conventions for shielding the nuclear industry from full liability. Citing approximately 10 major incidents over 17,000 reactor-years, the author highlights underestimated risks and costs and proposes a compulsory catastrophe bond system to ensure operator accountability and shift cost assessments from political to market-based mechanisms.

In the chapter *Corporate Policies of the Nuclear Vendors*, Stephen D. Thomas analyzes the global nuclear reactor supply industry as a risky niche market in some states. He discusses the financial struggles of major Western vendors such as Westinghouse, GE, Siemens, Framatome, Hitachi, and Toshiba, many of which have shifted to service roles or exited the market. He notes the rising dominance of Russian and Chinese firms but points to challenges such as limited Western regulatory reviews, China's restricted exports, and financial constraints. The author concludes that the future of the industry hinges more on political and economic support than on commercial viability.

David Reinberger et al., in the chapter *The Technological Evolution of Different Generations and Reactor* explores the technological evolution of nuclear reactors from Generation I to emerging Generation IV designs. They discuss improvements in safety and performance, construction delays, and rising costs in Gen III+, along with the potential of SMRs and Gen IV technologies. However, they highlight persistent challenges such as economic uncertainty, material limitations, and fissile control. The authors conclude that even with substantial public investment, nuclear research is unlikely to resolve issues related to nuclear power, climate change, and energy security.

Ben Wealer et al., in the chapter *Decommissioning of Nuclear Power Plants and Storage of Nuclear Waste: Experiences from Germany, France, and the UK,* explore the technical and financial challenges, national strategies, and funding sources involved in the decommissioning of large nuclear power plants and the storage of nuclear waste in Germany, France, and the UK. They note that France and the UK are postponing the decommissioning of the legacy fleets well into the next century, using internally segregated funds in France and taxpayer costs over the next 100 years in the UK. They argue that uncertainties in financial estimates for decommissioning, a lack of visible scale effects, public trust issues, and long-term waste disposal represent significant challenges.

In the chapter *Future Prospects on Coping with Nuclear Waste*, Gordon MacKerron investigates the global challenges of managing high-level nuclear waste, addressing technological, political, ethical, and economic dimensions. He also explores issues like Geological Disposal (DGD), the 'polluter pays' principle, public distrust, and centralized decision-making. The author contends that enhanced public trust and participatory approaches observed in Sweden and Finland are essential for advancing nuclear waste management while ensuring ethical responsibility and public acceptance.

M. V. Ramana, in the chapter, *The Changing Picture in China and the Global Future of Nuclear Power*, evaluates China's ambitious targets in nuclear power, the evolving landscape of nuclear energy within the country, and its implications for global nuclear expansion. The chapter highlights China's nuclear policy and goals, its nuclear growth, the economic and technical challenges limiting that expansion, and export restrictions. The author argues that China's nuclear program—once perceived as a potential savior for global nuclear expansion—is unlikely to reverse the overall decline of nuclear power.

In the chapter *The Reality after Fukushima in Japan Actual Damage to Local People*, Tadahiro Katsuta describes the human impact of the Fukushima Daiichi nuclear disaster, highlighting the suffering of nearly

99,000 evacuees and the inadequate government response. The author discusses TEPCO's bankruptcy, massive compensation costs, and the political use of science to downplay risks. The chapter also notes a rise in thyroid cancer, especially among children, and criticizes Japan's renewed focus on nuclear energy policy, arguing it comes at the expense of victim welfare and public health.

In the chapter titled *Three Decades after Chernobyl: Technical or Human Causes?* Nikolaus Muellner provides a thorough reassessment of the Chernobyl disaster, referencing INSAG reports (A report by the International Nuclear Safety Advisory Group) and expert evaluations. The author emphasizes the underlying deficiencies in the RBMK (Reaktor Bolshoy Moshchnosty Kanalny) reactor design, including flawed control rods, prevailing safety misconceptions, and breaches of operational protocols. He contends that the disaster resulted from a combination of design vulnerabilities and procedural shortcomings, suggesting that any crew in a similar situation might have made comparable errors. Furthermore, Muellner cautions that Western reactors could also be at significant risk if existing design flaws are overlooked or if safety warnings are disregarded.

Eri Kanamori and Tomas Kåberger assess costs to manage the consequences of the Fukushima-Daiichi nuclear disaster in the chapter 'Distributing the Costs of Nuclear Core Melts: Japan's Experience after 7 Years.' They describe the financial burden of managing the Fukushima-Daiichi disaster, the escalation of an initial estimate of €25 billion in 2012 to €215 billion by 2017, and continuously changing TEPCO's (Tokyo Electric Power Company) business plans. They also discuss the complex financial mechanisms devised by TEPCO, such as government contribution, special bonds, transmission charges, and contributions from all nuclear operators, and distributing liabilities across consumers and taxpayers. Authors evaluate that Japan's nuclear cost management approach is unsustainable in a competitive market and suggest that nuclear operating countries prepare financial strategies for future nuclear accidents.

The last chapter of the book, *On New Thinking and Designs of Electricity Markets Heading towards Democratic and Sustainable Electricity Systems*, Reinhard Haas and Hans Auer examine how the increasing shares of variable renewables are reshaping electricity markets. They trace the market's historical evolution, review the reliance on capacity payments for underutilized plants, and propose a decentralized, bidirectional system featuring innovative technologies and active consumer participation. The authors advocate shifting away from rigid, centralized models toward a more flexible, competitive, and sustainable market design that integrates high levels of renewables without depending on government subsidies.

This book presents a thorough and critical examination of the ongoing debate surrounding nuclear energy. Through comprehensive case studies and comparative analyses, it elucidates the economic, political, and technical challenges that currently confront the nuclear power sector. The authors highlight these issues by juxtaposing them with the swift advancements in renewable energy sources and their economic viability. Furthermore, the contributors compellingly question established perceptions regarding the potential of nuclear energy. This volume serves as essential reading for stakeholders engaged in formulating future energy policies and addressing the risks associated with climate change.

Reviewed by Khalil ur Rahman, PhD, Principal Engineer at National Institute of Safety and Security, Pakistan Nuclear Regulatory Authority (PNRA), Islamabad.

Sabre Rattling in Space: A South Asian Perspective

Ahmad Khan and Eligar Sadeh. (Singapore: Springer, 2024), 250

The importance of outer space needs no emphasis, as it is discernible from competition amongst space powers. Meanwhile, the weaponization of global commons, especially outer space, vis-à-vis space securitization, is now debated in space policy discourse. Furthermore, space securitization is viewed through the prism of “Access to Space,” which is critical to the military and economic security of the “Nation States.” In this domain, *Sabre-rattling in Space: A South Asian Perspective,* co-authored by Ahmad Khan and Eligar Sadeh, is a timely book that articulates various subjects relevant to regional and global security. Khan has completed his PhD from the Department of Strategic Studies, National Defence University (NDU), Islamabad. Sadeh is a former space scientist at National Aeronautics and Space Administration (NASA). He has also served at the United States (US) Air Force Academy, Lockheed Martin, and the University of Colorado, US. This joint academic endeavor is the first-ever book written by a Pakistani and an American scholar on a highly important subject. This book is published by the Springer and comprises nine chapters and a conclusion.

The book’s central theme indicates that states have followed a path from space militarization to weaponization. Notably, it explores how the bonhomie between the US-led West and India is evident in obtaining exceptional waivers for niche technologies to develop anti-satellite (ASAT) weapons, endangering space operations. In addition, the book offers a comparative analysis of India’s and Pakistan’s space policies, suggesting that Pakistan’s space ambitions are entirely peaceful and aimed at socio-economic development of the country. Whereas India’s space ambitions are focused on weaponizing space. In this book, following key space security aspects are covered from a South Asian perspective.

Schools of Thought on Space Security

Space is a congested, contested, and competitive domain. Major space powers, including the US and China, have invested vital national resources into exploring, exploiting, and using space. However, without understanding the behavior of states, it is naive to map their paths toward space weaponization. No state has accepted that it has deployed space weapons in outer space. However, specific behaviors exhibited by spacefaring states demonstrate that space has been weaponized.

The book discusses four schools of thought on state behavior for this purpose: space nationalism, technological determinism, global institutionalism, and social interactionism. To map counterspace capabilities, the authors have noted that space weapons have been deployed while major powers focus on doctrines including sanctuary, survivability, and high ground and space control. Based on this theoretical framework, the authors conclude that space weapons may continue to exist without being disarmed, and states will continue to possess these weapons. However, no major power will declare that it has deployed weapons in outer space as it would compel other states to follow suit. Since there is no defence against satellites or space objects, any deployment of space weapons by any major power will not ensure their effective employment. Therefore, the survivability doctrine will prevail over the sanctuary, high-ground, and space control doctrine. This means that space weapons will be used for assured space deterrence, and any armed conflict will erode it if not actively pursued.

Contextualizing Space Security

Security for what, security for whom, and security to what extent are key questions explored in this book. Space security is unlike other domains such as land, air, and sea. These domains have witnessed many armed conflicts where one party was the victor while the other was being defeated. However, space warfare is relatively new, and no major war has been fought in this domain. Hence, contextualizing space security is difficult. Nevertheless, the authors reviewed space security using theoretical perspectives such as Balance of Power (BoP), Regional Security Complex Theory (RSCT), and Revolution in Military Affairs (RMA).

Space Doctrines, Policies and Strategies: US, China, India, and Pakistan

The authors analyze the space doctrines, policies, and strategies of the US, China, India, and Pakistan. The US space doctrine follows the Five Ds: deception, disruption, denial, degradation, or destruction, to deter threats to its space assets, prioritizing "Freedom of Action in space" and "Denying Space for Others." The Chinese doctrine remains unpublished, although its White Papers emphasize technological progress, with future rivalry with the US possible due to misperceptions. India has opted to weaponize space and has tested an ASAT missile in outer space. The Indian Armed Forces Joint Doctrine (IAFJD) 2017 and Land Warfare Doctrine (LWD) 2018 highlights space as a fourth medium of warfare. Pakistan has not demonstrated any behavior or capability that indicated its intent to weaponize space; its 2002 policy advocates peaceful use and national security.

Counterspace Capabilities: US, China, India, and Pakistan

The authors examine the counterspace capabilities of the US, China, India, and Pakistan. Of 7,560 operational satellites, the US operates 5,184 satellites, China 628, Russia 181 satellites, and India has 63 operational satellites, and 27 of these satellites are for military purposes, including navigation, communication, remote sensing, and intelligence, reconnaissance, surveillance (ISR) purposes. Satellites are dual-use objects and are usually considered as space militarization capabilities. However, space weaponization capabilities include missiles, directed energy weapons (DEWs), and co-orbital missiles. The US leads space situational awareness and plans to use Lagrange Points for military outposts to counter future threats.

On the other hand, China is also pursuing advanced space militarization and weaponization capabilities, triggered by misperceptions and misunderstandings between the US and China. More recently, the successful re-entry of the China-launched Fractional Orbital Bombardment System (FOBS) has astonished the US and led to plans for a co-orbital defense system to counter China's FOBS in the future.

Regarding India, the book gives insights into India’s interexchange ability of space and missile technologies to build its long-range ballistic missile program from its space launch vehicle technologies. The utilization of space technologies to build long-range ballistic missile programs remains clandestine. India has explored space launch vehicle cooperation with the US, the former Soviet Union, Germany, and France to build its Space Launch Vehicle (SLV) program. However, this has imprints on its Intercontinental Ballistic Missiles (ICBMs) as well. Likewise, India also built its ASAT missile from its BMD and ICBM programs. The authors question India’s need for ICBMs, capable of striking long-distance targets such as London, Paris, and New York when medium-range missiles can already target Pakistan. It suggests that India’s development of ICBMs is aimed at countering China.

Pakistan, on the other hand, has neither shown any intent nor demonstrated any space weaponization capabilities that can verify that it has the potential to build and test counterspace capabilities. While it has the technological foundation to develop SLVs and potentially ASATs, the authors conclude that Pakistan has no interest in pursuing space weapons for its military objectives.

Emerging Space Order

The authors highlight the emerging global and regional space order, noting that the US holds preeminence in space. Presently, the operational satellites of the US are 5184, 4771 for civil/commercial use, 167 for federal government use, and 246 are used for military purposes. On the other hand, China ranks second globally with 628 satellites for civil and military purposes, while India leads regionally with 63 satellites. The authors argue that the combined effect of global and regional space capabilities and intentions of major spacefaring states forms a rule-based global, regional, and sub-regional space order. States with advanced space militarization and weaponization capabilities can influence these rule-based orders. India has attempted to establish a sub-regional space order, but Pakistan has declined to join due to security concerns.

Space Security Trilemma in South Asia

There is an exclusive chapter on the space security trilemma in South Asia. By applying RSCT, the authors consider South Asia a superregional complex with a pattern of enmity and amity. India and Pakistan have enmity relations, and India and China also have similar relations. In contrast, Pakistan and China's relationship is based on amity.

On top of that, China and the US have adversarial relations. Interestingly, the misperception and misunderstanding dynamics between China and the US exist in space. Consequently, China views US measures in space as offensive and vice versa. This also stirs India-China relations. Finally, Pakistan comes to the end of the space chain. It produces a space security trilemma between China, India, and Pakistan, with the US's external influence affecting South Asian security.

Challenges to International Space Governance

Overall, the authors emphasize that no legally binding treaty can restrict the arms race in outer space. While the 1967 Outer Space Treaty bans the detonation of weapons of mass destruction in space, it does not prohibit the conventional weaponization of space, leaving a legal gap. In addition, writers also note that major spacefaring states are increasingly interested in lunar exploration, with over 50 countries, including India, joining the US-led Artemis Accords to explore, exploit, and use lunar resources. Meanwhile, Russia and China lead the International Lunar Research Station (ILRS) program, which includes Pakistan as a partner state. This emerging bloc formation in space has created profound challenges to international space governance.

The book offers new insights concerning space security, doctrines, policies, and strategies of major spacefaring states, including the US, China, India, and Pakistan. The authors believe the US will continue dominating space order due to its overwhelming capabilities. Conversely, China is attempting to catch up but remains behind, while India prioritizes space as a key political agenda. Pakistan is an emerging space power with modest space capabilities and is expanding its space program to meet its objectives under its Space Vision 2047. However, it still lacks adequate domestic legislation, as seen in the delay in licensing Starlink due to missing regulations for Low Earth Orbit (LEO) internet services. Pakistan does not currently have an SLV but plans to develop complete space transportation systems to meet its space objectives for the country's socio-economic development.

It is pertinent to note that in the realms of nuclear deterrence and space security, jargons play a vital role in understanding deterrence relationships, postures, doctrines, policies, and strategies. Some analysts add China to the India-Pakistan dyads from the lens of the US-China dyad, thereby hindering the independent deterrence equation in South Asia. Moreover, some analysts also project South Asia as Southern Asia to include China in the regional equation. This is methodologically incorrect as it does not project historical and strategic trajectories of South Asia. Such conceptual blending may impede the prospects of arms control in the nuclear and space domains. The book concludes that space conflict is inevitable as states will keep building counter-space capabilities to preserve their national interests in space. Despite the absence of a consensus among states on negotiating a legally-binding treaty to prevent an Arms Race in Outer Space, the desire to negotiate such an agreement under the Prevention of an Arms Race in Outer Space (PAROS) still exists.

Reviewed by Anum A. Khan, Associate Director Research, at the Center for International Strategic Studies (CISS), Islamabad.

Nuclear Arms Control in South Asia: Politics, Postures, and Practices
Zafar Nawaz Jaspal (Paramount Books, Pakistan, 2025), 416

The book "Nuclear Arms Control in South Asia: Politics, Postures, and Practices," authored by Zafar Nawaz Jaspal, PhD, is a scholarly study of the complicated dynamics of nuclear arms control in South Asia. The author is a Professor and Dean of the School of Politics and International Relations (SPIR) at Quaid-i-Azam University (QAU), Islamabad. The book is organized into three sections, i.e., Politics, Postures, and Practices. The structured approach deployed in this volume provides a comprehensive framework for analyzing the intricate interplay of political motivations, strategic postures, and practical measures within the theoretical context that shapes South Asia's nuclear environment.

The first section of the book, titled *Politics*, discusses the philosophical constructs of nuclear arms control in South Asia from a realist perspective. It explains in detail how the realist perspective has influenced the strategic thinkers in South Asia and how they consider that the security dilemma has encouraged Pakistan and India to acquire nuclear weapons. The author has analyzed the dynamics of the India-Pakistan relationship through the lens of offensive and defensive realism. He opines that officials dealing with Pakistan seek to obtain Credible Minimum Deterrence (CMD), akin to the defensive realist's point of view. While applying the perspectives of nuclear optimists and pessimists on South Asia, the author emphasized that nuclear pessimism has struggled to gain importance in the region due to the perception that nuclear weapons have effectively deterred conventional wars between India and Pakistan. This perception is particularly evident in key events such as the Kargil conflict in 1999, the India-Pakistan military standoff in 2001-2002, and the 2019 Pulwama-Balakot crisis. These incidents underscore the role of nuclear deterrence in maintaining strategic stability in the region.

There is discussion about the transitioning trends in contemporary nuclear order, dominated by the strategic competition between the nuclear-armed states. At the global level, there has been a rift between the United States and Russia, and China and North Korea. Additionally, competition exists between France and Russia, India and China, and India and Pakistan. Due to constantly growing rifts and competition, states are modernizing their nuclear arsenals and conventional forces, marking a new era of force modernization and military growth. The author discusses how the Indian and Pakistani applications to the Nuclear Suppliers Group (NSG) have sparked a debate about the international expansion of the Export Control Regimes. The author believes that the reliance on nuclear weapons for security purposes is unlikely to decrease. Moreover, the absence of tangible initiatives for denuclearization may push a few more latent states to develop nuclear weapons capabilities.

Section II of the book, *Postures*, applies the concepts of deterrence and compellence to India and Pakistan. It also identifies the doctrines and postures related to nuclear weapons, with a special focus on India and Pakistan. The author observes that compellence is often employed in coercive diplomacy. Compellence involves threatening to inflict harm on another state until it complies with an explicit set of demands; in contrast, deterrence uses conditional threats to prevent an adversary from taking undesirable actions and disrupting the status quo. The author argues that compellence is inherently an offensive strategy, frequently employed by India against Pakistan. This approach includes options such as war, which can destabilize nuclear deterrence. Conversely, deterrence is primarily defensive and has been Pakistan's preferred strategy to prevent regional war. In South Asia, nuclear deterrence plays a more significant role by influencing an adversary's decision-making process rather than eliminating its strategic options.

This section also provides a comprehensive account of the acquisition of nuclear weapons by the US, the Union of Soviet Socialist Republics (USSR), the United Kingdom (UK), France, China, North Korea, and Israel. The available data on nuclear policies and postures of the above states is listed in the book. While discussing India's Nuclear Doctrine and Posture, the author notes that India's current nuclear force posture aligns with a nuclear first use (FU) policy designed to counter Pakistan's tactical nuclear weapons (TNWs). India has modernized its nuclear arsenal to maintain credible nuclear deterrence. There is substantive data available on the development of India's nuclear forces, delivery systems, strategic bombers, ballistic missile systems, and nuclear-powered submarines.

While discussing Pakistan's nuclear doctrine and posture, the author explains that the debate regarding Pakistan's nuclear posture requires a fresh examination. Pakistan does not follow a no-first-use (NFU) nuclear policy backed by capabilities, delivery systems, and centralized command and control (C2). Pakistan's strategic defense policy is to: a) maintain a robust conventional military, capable of addressing conventional and sub-conventional threats; b) implement a full-spectrum nuclear deterrence doctrine and force posture; c) ensure an adequate stockpile of nuclear weapons and reliable delivery systems for assured second-strike capability; and; d) develop a survivable strategic force alongside a robust National Command Authority (NCA) for centralized control of nuclear weapons.

Section III of the book, *Practices*, explains the theoretical foundations of nuclear arms control and the Nuclear Non-Proliferation Regime (NPR). It discusses the underlying principles that have historically guided efforts to curb both vertical and horizontal proliferation. The author has further focused on how the NPR has traditionally functioned to prevent the unchecked spread of nuclear weapons while promoting peaceful uses of nuclear technology. Moreover, the author discusses how India rhetorically supports the NPR without practically embracing the norms. Indian diplomats, on international forums, often take a moral high ground on disarmament issues and use terms like "nuclear apartheid" as a shield to hide their vertical proliferation. India's arrogant attitude towards Pakistan and its lack of reciprocity to the proposed arms control initiatives, are major contributing factors to the nuclear arms race in South Asia.

On the other hand, Pakistan's engagement with the NPR is more constructive and pragmatic. The author highlights Pakistan's commitment to responsible nuclear stewardship and its emphasis on regional strategic stability. Islamabad advocates for non-discriminatory frameworks that address its legitimate security concerns and promote equity in nuclear non-proliferation efforts. This approach emphasizes Pakistan's willingness to engage meaningfully with the NPR, despite facing significant challenges and international scrutiny.

The author also discusses the impact of emerging technologies on arms control and nuclear postures in South Asia. It focuses on how emerging technologies, including hypersonic weapons, missile defense systems, cyber capabilities, and Artificial Intelligence (AI) are reshaping the strategic landscape. These technologies not only create opportunities for strategic coercion but also encourage risk-taking behaviors among nuclear-armed states. The author identifies that India's incorporation of these emerging technologies into its surgical strike doctrine poses significant challenges to regional stability.

This book is thoroughly researched, well-written, and engaging, making it accessible to scholars, policymakers, and students of strategic and nuclear studies. The clear and concise writing style ensures that it reaches a wide audience and serves as a valuable textbook on nuclear arms control in South Asia. The book has numerous key strengths, providing an academic perspective and adopting a textbook format to benefit Pakistani students. The separate chapters dedicated to Pakistan and India provide a detailed comparison of their nuclear policies, forces, postures, missiles, and missile defense systems. This book is particularly valuable given the dynamic nature of these doctrines and the limited public information available.

This book has particularly identified India's nuclear posture as of FU, supported by examining the history of various strategic events in the region. The primary focus of the book is that nuclear politics remains a significant genre, central to the strategic discourse; however, there have been few studies of this subject, especially by Pakistani authors. While much of the existing literature on South Asian nuclear issues is dominated by Indian perspectives, this book incorporates Pakistani perspectives and narratives, offering a more balanced and nuanced understanding of the regional security dynamics.

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List of Acronyms

AAL	Average Annual Losses
Ac-225	Actinium-225
ADSec	Advisory Group on Nuclear Security
AECHs	Atomic Energy Cancer Hospitals
AEMC	Atomic Energy Medical Centre
AI	Artificial Intelligence
ALARA	As Low as Reasonably Achievable
APSCO	Asia-Pacific Space Cooperation Organization
AR6	Sixth Assessment Report
ASA	Arid and Semi-Arid regions
BNCT	Boron Neutron Capture Therapy
CACNARE	Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency
CANDU	Canada Deuterium Uranium
CCA	Climate Change adaptation
CCs	Collaborating Centers
CENNA	Convention on Early Notification of a Nuclear Accident
CIRT	Carbon ion radiotherapy
CITA	Communication and Information Technology Authority
Co-60	Cobalt-60
CNNs	Convolutional Neural Networks
CPs	Contracting Parties
CPPNM	Conventions on Physical Protection of Nuclear Materials
CNPGS	Chashma Nuclear Power Generating Stations

CNPO	China Nuclear Power Operations Technology Corporation Ltd
CNSA	China National Space Administration
CNSC	Canadian Nuclear Safety Commission
CNS	Convention on Nuclear Safety
CRPs	Coordinated Research Projects
CSS	Commission on Safety Standards
CT	Computed Tomography
DL	Deep Learning
DCI	Directorate of International Cooperation
DIRAC	Directory of Radiotherapy Centers
DNSRP	Directorate of Nuclear Safety and Radiation Protection
DoS	Denials of Shipment of Radioactive Material
DRR	Disaster Risk Reduction
EBRT	External Beam Radiation Therapy
EIA	Environmental Impact Assessment
EIGE	European Institute for Gender Equality
EO	Earth Observation
EPPs	Emergency Preparedness Plans
EPReSC	Emergency Preparedness and Response Standards Committee
FEWS	Flood Early Warning Systems
FLOs	Front-Line Officers
GDP	Gross Domestic Product
GEO	Geostationary Orbit Satellites
GINUM	Gujranwala Institute of Nuclear Medicine and Radiotherapy
GIS	Geographic Information Systems

List of Acronyms

GIT	Geo-Information Technologies
GNSSN	Global Nuclear Safety and Security Network
GPS	Global Positioning System
HPC	High-Performance Computing HPC
IAEA	International Atomic Energy Agency
ICONS	International Conference on Nuclear Security
ICTs	Information and Communication Technologies
IGALL	International Generic Ageing Lessons Learned
IGRT	Image-Guided Radiation Therapy
IMP	Integrated Pest Management
IMRT	Intensity-Modulated Radiation Therapy
INMOL	Institute of Nuclear Medicine and Oncology
INSAG	International Nuclear Safety Advisory Group
INSEN	International Nuclear Security Education Network
INES	International Nuclear and Radiological Event Scale
INSSC	International Network of Nuclear Security Support Centers
IPCC	Intergovernmental Panel on Climate Change's
IPPAS	International Physical Protection Advisory Service
IRNUM	Institute of Radiotherapy and Nuclear Medicine
IRRS	Integrated Regulatory Review Service
IRS	Incident Reporting System

IRSRR	Incident Reporting System for Research Reactors
ISA	Iranian Space Agency
ITDB	Incident and Trafficking Database
IMAGINE	IAEA's Medical Imaging and Nuclear Medicine Global Resources Database
JAMA	Journal of the American Medical Association
JPMC	Jinnah Postgraduate Medical Center
KANUPP	Karachi Nuclear Power Plant
KIRAN	Karachi Institute of Radiotherapy and Nuclear Medicine
KNPGS	Karachi Nuclear Power Generating Stations
KPK	Khyber Pakhtunkhwa
KSFDF	KANUPP Spent Fuel Dry Storage Facility
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LINACs	Linear Accelerators
LMP	Lise Meitner Programme
MHVRA	Multi-Hazard Vulnerability and Risk Assessment System
ML	Machine Learning
MNSR	Miniature Neutron Source Reactor
Mo-Tc	Molybdenum-Technetium
MoUs	Memoranda of Understanding
MRI	Magnetic Resonance Imaging
MSCFP	Marie Sklodowska-Curie Fellowship Programme
NASA	National Aeronautics and Space Administration

List of Acronyms

Nat-Cat model	Natural Catastrophe Modelling
NCA	National Command Authority
(NCDs)	Non-Communicable Diseases
NDMA	National Disaster Management Authority
NDRMF	National Disaster Risk Management Fund
NDT	Non-Destructive Testing
NEA	Nuclear Energy Agency
NEOC	National Emergencies Operation Center
NIA	Nuclear Institute for Agriculture
NIAB	Nuclear Institute for Agriculture and Biology
NIBGE	National Institute for Biotechnology and Genetic Engineering
NIFA	Nuclear Institute for Food and Agriculture
NIMRA	Nuclear Institute of Medicine and Radiotherapy
NISAS	National Institute of Safety and Security
NMAC	Nuclear Material Accounting and Control
NNRA	Nigerian Nuclear Regulatory Authority
NNSA	National Nuclear Safety Administration
NNDA	National Nuclear Detection Architecture
NORI	Nuclear Medicine, Oncology, and Radiotherapy Institute
NORM	Naturally Occurring Radioactive Material
NPPs	Nuclear Power Plants
NPT	Non-Proliferation of Nuclear Weapons
NRA	Nuclear Regulatory Authority
NRECC	National Radiation Emergency Coordination Centre
NREP	National Radiation Emergency Plan

List of Acronyms

NSC	Nuclear Safety and Radiation Protection Centre
NSGC	Nuclear Security Guidance Committee
NSSC	National Nuclear Security Support Centre
NUSSC	Nuclear Safety Standards Committee
NTI	Nuclear Threat Initiative
OECD-NEA	Nuclear Energy Agency Organization for Economic Cooperation and Development
PAEC	Pakistan Atomic Energy Commission
PARR	Pakistan Atomic Research Reactor
PCENS	Pakistan Centre of Excellence in Nuclear Security
PCR	Polymerase Chain Reaction
PINUM	Cancer Hospital Faisalabad
PNRA	Pakistan Nuclear Regulatory Authority
PRSC-EO	Pakistan Remote Sensing Satellite - Earth Observation 1
PRSS-1	Pakistan Remote Sensing Satellite-1
PRSC-EO1	Pakistan indigenous Electro-Optical Satellite
PakSat-1R	Pakistan communication satellites
PET	Positron Emission Tomography scans
PWRs	Pressurized Water Reactors
PHWR	Pressurized Heavy Water Reactor
PPPs	Physical Protection Plans
PINSTECH	Pakistan Institute of Nuclear Science and Technology
PNSRP	Pakistan Nuclear Safety and Radiation Protection Regulations
PRSC-EO	Pakistan Remote Sensing Satellite - Earth Observation 1

List of Acronyms

QA	Quality Assurance
QC	Quality Control
Ra	Radium
R&Ds	Research and Development Facilities
RASSC	Radiation Safety Standards Committee
RAGs	Radiological Assistance Groups
RANET	Response and Assistance Network
RASIMS	Radiation Safety Information Management System
RASSC	Radiation Safety Standards Committee
RBs	Regulatory Bodies
RCF	Regulatory Cooperation Forum
RNTs	Radionuclide Therapies
RPPs	Radiation Protection Programs
RSS	Remote Sensing Satellite System
RMTs	Radiation Monitoring Teams
SACRED	Space Application Center for Response in Emergency and Disaster
SAR	Synthetic-Aperture Radar Satellites
SAR	Safety Analysis Report
SBRT	Stereotactic Body Radiation Therapy
SCSA	Safety Culture-Self Assessment
SDGs	Sustainable Development Goals
SECDIV	Strategic Export Control Division
SMRs	Small Modular Reactors
SPECT/CT	Single Photon Emission Computed Tomography–Computed Tomography
SPECT	Single-Photon Emission Computed Tomography

SRS	Stereotactic Radiosurgery
SRS	Satellite Remote Sensing
STEM	Science, Technology, Engineering, and Mathematics
SUPARCO	Space and Upper Atmosphere Research Commission
TCP	Technical Cooperation Program
TPNW	Treaty on the Prohibition of Nuclear Weapons
TRANSCC	Transport Safety Standards Committee
TSA	Turkish Space Agency
TSOF	Technical Support Organization Forum
UAVs	Unmanned Aerial Vehicles
UNIDIR	United Nations Institute for Disarmament Research
USD	United States Dollar
UNSCR	United Nations Security Council Resolutions
UNSDG	United Nations Sustainable Development Goal
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VMAT	Volumetric-Modulated Arc Therapy
WASSC	Waste Safety Standards Committee
WiN	Women in Nuclear
Y-90	Yttrium-90