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.

*Huma Rehman is a Former Fellow Center for Non-Proliferation Studies (CNS)-US and SIC-US Research Project Consultant.

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

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[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.

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[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

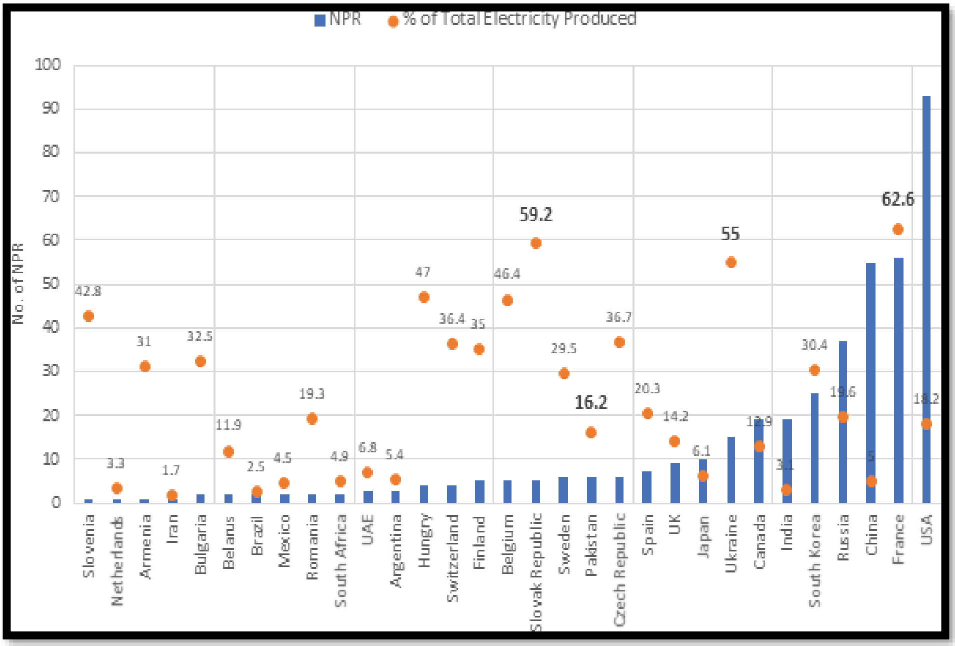

Figure 1: World Nuclear Power Capacity
Source: The IAEA Database on Nuclear Power Reactors[18]

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]

[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.

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[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]

[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

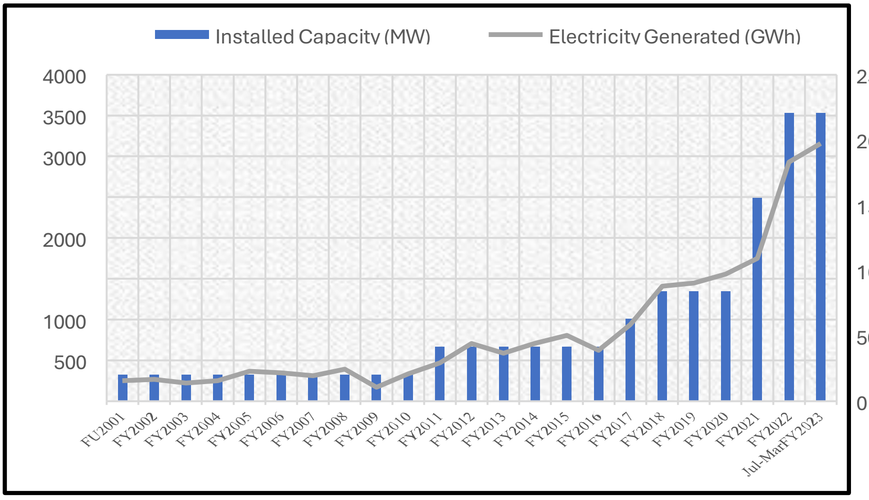

Figure 3: Pakistan Nuclear Power
Source: NTDC Power System Statistics, 47th Edition, 2022, and GOP, 2023.

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]

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[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

[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.

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[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

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[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.