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Original Article

Development and strengthening of the nuclear and radiation safety infrastructure for nuclear power program of Bangladesh

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ABSTRACT

Bangladesh, as a newcomer country, is expecting to start her nuclear power journey by 2022. Due to evident reasons, newcomer nuclear countries face several key challenges concerning the development of national nuclear safety infrastructure. The paper investigates the status of the 7 key safety infrastructure issues out of the 19 and readiness of the supportive organizations, laboratories, and workforces following the International Atomic energy Agency's status evaluation guide at milestone 3 and foreign countries' practice. Much progress has been achieved at phase 3 regarding the establishments of a few Acts, a regulator, and an operator. However, comprehensive regulatory frameworks, skilled workforces, establishments of a few supportive organizations, and laboratories for managing environmental radioactivity, radiological accidents, and radioactive wastes are yet to ready. Several suggestions are made for establishing and expediting radiation monitoring laboratories, a radiological emergency management center, a radioactive waste management company, and technical support organizations for the safety infrastructure. To avoid perceived risks, policymakers and competent authorities need to emphasize creating an optimized safety infrastructure before commissioning and operating the 1st nuclear power plant safely, securely, and cost-sustainably.

1. Introduction

Nuclear power is an inevitable option for Bangladesh to address the shortage of electricity. To fulfill the increasing electricity demand, the government of Bangladesh has undertaken the Rooppur Nuclear Power Plant (NPP) project for two units with a capacity of 1200MW$_e$ each [1]. Launching a nuclear power program is a major undertaking that requires careful planning, preparation, investment, and workforces. It can take 10–15 years from planning to commissioning of the 1st NPP and a commitment lifecycle for nearly 100-year [2]. To build the first NPP, each country needs to develop a national nuclear infrastructure for supporting a nuclear power program. In this connection, the International Atomic Energy Agency (IAEA) has developed the 'milestones approach' for the countries embarking on nuclear power programs to self-evaluate the nuclear infrastructure development status during construction phases [2]. Fig. 1 shows the IAEA milestones approach which is a phased extensive technique that helps a nation by providing pragmatic directions on developing the 19 infrastructure issues i.e. national position, nuclear safety, management, funding & financing, legislative framework, safeguards, regulatory framework, radiation protection, electrical grid, human resources development, stakeholders involvement, site and supporting facilities, environmental protection, emergency planning, security and physical protection, nuclear fuel cycle, radioactive waste, industrial involvement, and procurement. It consists of four phases and three milestones. The activities that are needed to be done in each phase is given in Fig. 1 as an example. Completion of the required actions for each phase represents the achievement of the associated milestone. According to the IAEA milestones approach, to reach milestone 3 (ready to commission and operate) and to complete the phase 3 (activities to contract, license, and construct) for the 1st NPP, each Member State has to ensure all the necessary competencies and capabilities to be able to control and manage the NPP safely, securely, and economically over its life span including the safe management of radioactive waste. A lot of infrastructure development and capital expenditure occurs during phase 3 and it is the longest phase (7–10 years) compared with phases 1 and 2 [3,4].

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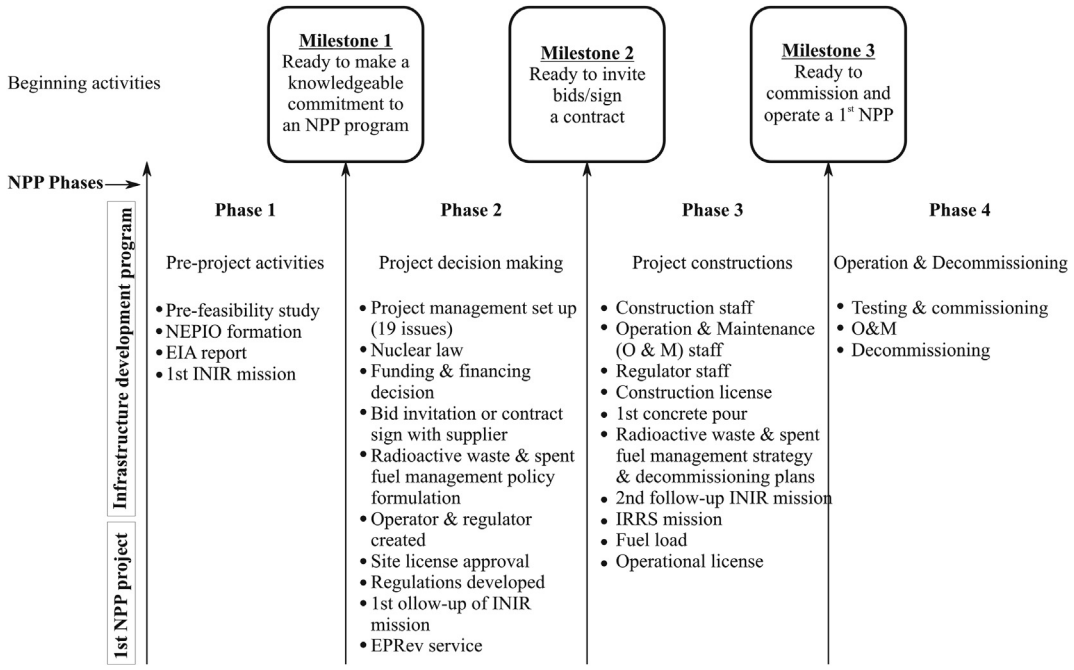

Fig. 1. IAEA milestones approach and phase-wise activities for the development of a national nuclear infrastructure [2].

Apart from the milestones and evaluation guides, IAEA provides review and advisory services in each phase to find weaknesses/gaps (Acts, license, organizations, workforces, laboratories, etc.) for the continuous improvement of the nuclear embarking countries [5].

Implementation of Bangladesh's nuclear power program is going to be materialized with the financial and technical assistance of the Russian Federation and the IAEA's technical cooperation program. Bangladesh follows the IAEA milestones approach for building the national nuclear infrastructure for its maiden reactor. In 2011, Bangladesh invited the IAEA integrated nuclear infrastructure review (INIR) mission for reviewing the 19 infrastructure issues for both phases 1 and 2. Subsequently, the 1st follow-up of INIR mission was also conducted in 2016 [1]. The 1st follow-up of INIR mission concluded that Bangladesh's nuclear power program, in general, has progressed into phase 2 and recommended strengthening the regulatory body in the areas of legal authority, independence, competency, resources, and budget [6]. Significant progress of the national nuclear infrastructure development program has been made during the last four years for fulfilling the recommendations and suggestions of the IAEA's 1st follow-up of INIR mission.

However, developing and maintaining a sustainable safety infrastructure is a complex and lengthy process. It is the most critical issue and overriding priority. The State's responsibility is to ensure the nuclear safety regime with the global standard. To protect people, properties, and the environment from the harmful effects of ionizing radiation is the ultimate goal of nuclear and radiation safety [4].

The fundamental safety objective applies to all nuclear and radiological facilities and activities from cradle-to-grave during planning, siting, manufacturing, construction, commissioning, operation, waste management, transport, decommissioning, and closure [7]. According to International Nuclear Safety Advisory Group-22, nuclear safety infrastructure is defined as –*"the set of institutional, organizational, and technical elements and conditions established in a Member State to provide a sound foundation for ensuring a sustainable high level of nuclear safety"* [7]. To develop a nuclear safety infrastructure, the essential elements include enacting proper nuclear legislation, the establishment of an independent regulatory body and licensing structure, and the establishment of an operating organization and structure [8]. More importantly, the reactor operator holds the sole responsibility for ensuring nuclear and radiation safety.

The works of Chakraborty et al. [9] mainly emphasized the review and analysis of the draft of Bangladesh Atomic Energy Regulatory (BAER) Act-2012 regarding its effectiveness to ensure the nuclear and radiation safety regime while considering nuclear power program. Karim et al. [10] showcased the necessity for the development of an independent and competent legal and regulatory body concerning nuclear energy development in Bangladesh. Based on public documents, no such independent studies or scholarly articles are available in the literature focused on evaluating the nuclear and radiation safety infrastructure status during the construction of 1st NPPs. To evaluate the nuclear and radiation safety infrastructure status following the phase-wise progress requirement, it is vitally important to do an independent assessment in finding lapses, in which will ultimately cause construction delays, cost overruns, and public distrust. 19 national nuclear infrastructure issues are directly and indirectly related to nuclear and radiation safety. However, to limit the volume of the article, 7 key infrastructure issues i.e. legislative and regulatory framework, radiation protection, human resources development, environmental protection, emergency planning, and radioactive waste management are considered high-priority nuclear safety infrastructure issues. Therefore, the objectives of this article are to evaluate the current status of the nuclear and radiation safety-related to 7 key infrastructure issues based on the IAEA evaluation documents [2–4], foreign countries' practice, and then finding gaps for the proper development of those issues, if any. These 7 key issues are the most critical safety infrastructure elements to protect citizens, neighboring countries, and the world. Maintaining a robust safety infrastructure will increase in building public

confidence locally, nationally, regionally, and internationally. Such an independent assessment is being done not only to find gaps but also to facilitate the learning by doing continuous improvement, and sharing experiences.

2. Nuclear power program development initiatives and activities

To promote the peaceful use of nuclear energy, the Bangladesh Atomic Energy Commission (BAEC) was established in 1973. Right from its inception, BAEC started research & development (R&D) works in the branches of physical science, bioscience, and engineering. Now, it is known as the largest scientific and technical research organization in Bangladesh [11]. One of the charter responsibilities of BAEC is to facilitate the construction of NPPs for solving the country's chronic power crisis.

In 1961, the first initiative for a site selection for building the NPPs was taken at Rooppur, Ishwardi in the Pabna district, 160 km away from the capital city of Dhaka. To build the Rooppur NPP project before 1971, four proposals were given by the USA, Sweden, the former USSR, and Belgium. A few initiatives were taken by BAEC to construct the Rooppur NPP project after independence in 1971 [1,12]. The National Energy Policy-1996 recommended the implementation of the Rooppur NPP project. According to the country's 'Power System Master Plan 2010', a 10% share of nuclear power was projected over the total power generation in 2020 and 2030 which are estimated to be 20000MW$_e$ and 60000MW$_e$ respectively [13]. Fig. 2 shows the phase-wise progress made of the Rooppur NPP project.

The activities at phase 1 are included, but are not limited to; the government approved the *'Bangladesh Nuclear Power Action Plan'* in 2000 [1]. Russia and Bangladesh signed a memorandum of understanding on May 13, 2009, for the exchange of nuclear technology. On May 21, 2010, Bangladesh-Russia signed a five-year cooperation agreement for building NPPs for peaceful use [1]. The government formed the nuclear energy program implementing organization (NEPIO) in 2010 as a result of firm political commitment [12].

Fig. 3 shows the country's NEPIO structure for the development of national nuclear infrastructure. NEPIO consists of a national committee, a technical committee, working groups, working subgroups, coordination committees, and sub-committees. BAEC works as a secretariat of the NEPIO with the assistance of the line ministry-Ministry of Science and Technology (MoST). It has no physical set-up. NEPIO provides necessary directives and policy decisions for the development of a national nuclear infrastructure for the nuclear power program. The main functions of the NEPIO are to select strategic nuclear partnerships, funding and financing

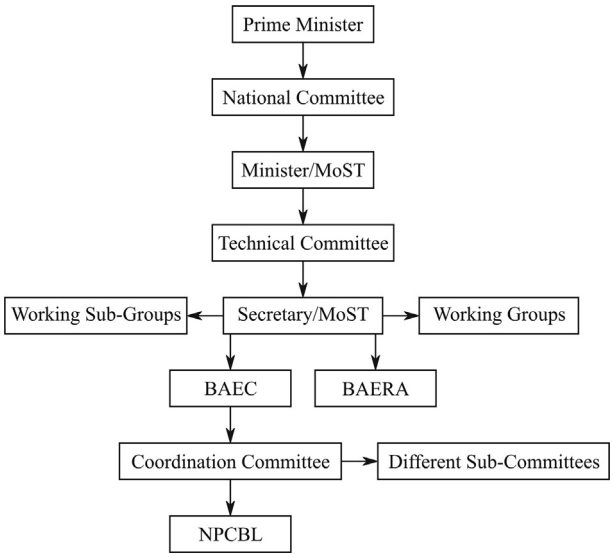

Fig. 3. The structure of NEPIO for development of a national nuclear infrastructure [12].

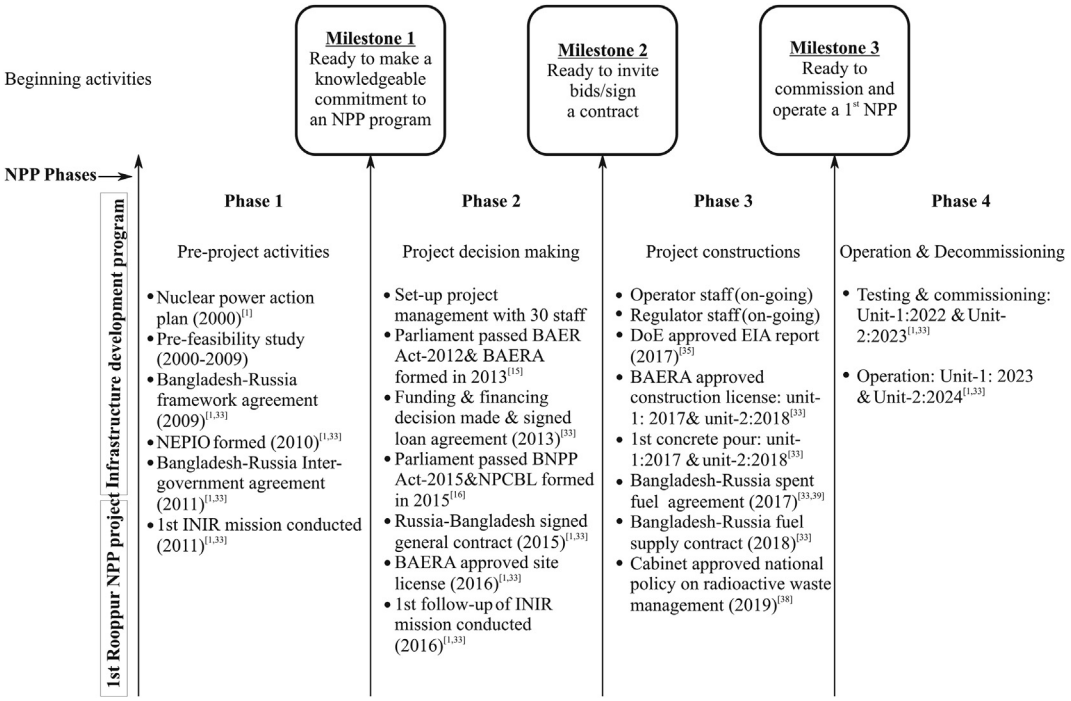

Fig. 2. Phase-wise development of Rooppur NPP project (Authors' compilation).

mechanisms, development of contract agreements, project management set-up, formulating legislative and regulatory frameworks, creation of regulator, owner/operator, and many more. A national committee has been formed by the government and is headed by the Prime Minister.

The functions of the national committee are to provide guidelines and proper monitoring of the Rooppur NPP project. A technical committee has also been formed and is headed by the Minister of the MoST. The secretary of the MoST is leading the different working groups and working sub-groups to coordinate the overall progress activities of the 19 infrastructure development issues involving relevant ministries/organizations. The technical committee, working groups, sub-groups, and coordination committee are coordinating all activities to the infrastructure issues, technical matters, and regular monitoring of the progress of the Rooppur NPP project activities [6,12]. For example, one of the working sub-groups under MoST is named as 'International obligations, legal and regulatory aspects, and nuclear safety and security'. This working sub-group will monitor the national position, nuclear safety, legislative framework, regulatory framework, radiation protection, emergency planning, safeguards, and security of the infrastructure issues for the development of a national infrastructure for nuclear power [14]. Their function includes;

- To finalize all the regulations and the statute and take initiative to establish legislation for the implementation of the Rooppur NPP project as required according to the BAER Act-2012.
- To identify and take proper initiatives for relevant international legal instruments are signed, ratified, and incorporated into national nuclear legislation.
- To take necessary steps for the formation of an effective, independent, and competent nuclear regulatory body.
- To take proper initiatives for the introduction to nuclear safety culture in regulating and operating organizations.
- To take proper initiatives to establish a physical protection system for installations related to NPP and transportation, warehousing, and storage of nuclear and radioactive materials.

An intergovernmental agreement was signed on November 2, 2011 between the government of Bangladesh and the Russian Federation to build the two VVER model reactors in the territory of Bangladesh [1]. The government of Bangladesh invited the IAEA INIR mission in 2011.

The activities at phase 2 are included, but are not limited to; The NEPIO formed a project management team with nearly 30 staff mostly hired from the BAEC. The funding decision was made and a financial contract was signed with the Russian Federation in 2013. Bangladesh atomic energy regulatory authority (BAERA) was formed in 2013 while the BAER Act was approved by the national assembly in 2012 [15]. Nuclear power company of Bangladesh Ltd. (NPCBL) was also formed in 2015 under the Bangladesh NPP Act-2015 [16]. Based on the site feasibility studies at Rooppur, the government has selected an AES-2006 model VVER-1200 generation III+ advanced twin reactors with 1200MW_e electric capacity each under the general contract in 2015 [17] and the engineering, procurement, and construction (EPC) contract was awarded to the Russian Federation. BAERA approved the site license in 2016 and the government again invited the 1st follow-up of IAEA INIR mission in 2016.

The activities at phase 3 are included, but are not limited to; the environment regulator approved the EIA report of the Rooppur project in 2017. BAERA approved the construction license of unit 1 and 2 in 2017 and 2018 respectively and the concrete pour dates of unit 1 and 2 were held in 2017 and 2018 respectively. Bangladesh-Russia signed a spent fuel take-back policy agreement in 2018 and the Bangladesh cabinet approved the national waste management policy in 2019. As of September 2020, the Rooppur NPP project is in phase 3 and will move forward to reach phase 4. It was reported that about 20% of construction work is complete as of December 12, 2019 [18]. To implement the country's first NPP, BAEC works as the owner organization of the NPCBL as well as a technical support organization (TSO). Table 1 shows the timeline of different events from fuel loading to online of the two units. As per the current schedule, the test operation of unit 1 and 2 will be performed by 2022 and 2023 respectively. In the following years, both units will undergo a full-power operation.

Table 1
Timeline of different events of unit1 and 2 of Rooppur NPP project [19].

Activities	Unit-1	Unit-2
Fuel loading	Oct. 2022	Oct. 2023
Power start-up	Dec. 2022	Dec. 2023
Provisional takeover	Oct. 2023	Oct. 2024
Final takeover	Oct. 2024	Oct. 2025

BAEC and BAERA operate under the MoST while the NPCBL operates under the BAEC. Being an operator of the Rooppur NPP, NPCBL holds the prime responsibility for ensuring nuclear and radiation safety during all stages of the plant (cradle-to-grave) according to the IAEA safety guide [20].

3. Methodology

The objective of this study can be reiterated here and it is to evaluate the current status of the nuclear and radiation safety-related to 7 key infrastructure issues and then finding out the impediments for proper development of those issues based on the IAEA self-evaluation document [3] and foreign countries' practice. IAEA self-evaluation document is used to identify weaknesses, prioritizing activities, and continuously improving works based on conditions, evidence, plans, and observations. Table 2 shows the evaluation process which is used to check the status of the phase 3 development activities of 7 national nuclear safety infrastructure issues. The evaluation covers the general safety requirements as per the IAEA safety standards.

Besides, cooperation, intergovernmental agreements, contracts, Acts, INIR missions' suggestions and recommendations, concrete pouring dates and operational schedule of the Rooppur NPP project are presented in chapter 2; current development status of the 7 key safety infrastructure issues are focused in chapter 4 and foreign countries' practices are presented in chapter 5. These constituents of the respective chapters are used as indicators of the phase 3 development activities of the Rooppur NPP project. Gap identifications (chapter 6) for establishing a homogeneous safety infrastructure in phase 3 are derived based on chapter 2, 4, and 5. Suggestions in the form of major actions needed are given in chapter 7 to improve the 7 safety infrastructure issues for completing the phase 3 activities to reach milestone 3. The judgment on whether the major activities are required or not is based on the work that still needs to be introduced or fulfilled to meet the conditions. Fig. 4 shows a process flow diagram of the gap identifications carried out for each issue.

4. Status of nuclear and radiation safety infrastructure development issues

4.1. Legislative framework and international legal instruments

People have the fundamental right to access electricity and the government has to ensure the safety of the people as per the

Table 2
Evaluation process.

Issues	Conditions	Basis for evaluation [2–4]
Legislative framework	- Comprehensive legislative supervision in the nation is to be set up	- Comprehensive legislative oversight established - Legislation maintained and amended as required - All activities to implementing the relevant international legal instruments ought to be finished
Regulatory framework	- A competent, independent regulatory body is to be set up	- All regulations, codes, and standards are made ready - Adequate regulatory staff recruitment is in place - Competence of workforce is maintained - Inspection and enforcement activities are in place - Open communications with appropriate stakeholders are established
Radiation protection	- All essential radiation monitoring and protection program are to be set up to rationalize the radiation exposure of the workers, the public, and environment	- Whether radiation monitoring equipment is set up and ready for both on-site and off-site - Completely materialized site environmental monitoring program - Performing off-site radiation monitoring program - Radiation dosimetry laboratory set up for workforces - Upgrading the radiation protection program to optimize radiation exposure during plant operation
Human resources development	- All human resources to regulate, commission, and operate the 1st NPP are to be set up - Education and training program for the ongoing flow of competent individuals has to be on track	- Fully staffed for regulatory, operation, maintenance, and technical support matters - Continuation and personnel development plan to maintain the competence of all areas of the national nuclear program - Improved educational opportunities to develop a continuing flow of qualified workforces - Enhanced training programs for the regulator, operator, owner, and TSOs - Integrated HRD plan established
Environmental protection	- Conformity with environmental laws and regulations are to be assured - Monitoring and assessment program is to be fully implemented under international standard	- Identification of specific environmental requirements and their inclusion in the licensing conditions for facility operation - Complete characterization of the site and its surroundings to create a baseline condition - Development and full implementation of environmental monitoring program with international standards
Emergency planning	- The groundwork for emergency planning is to be concluded and tested	- All plans have been concluded into compact programs and actions - The regulatory body has assessed and endorsed the emergency plans - Communication protocols and strategies among relevant organizations and neighboring countries are established - Emergency notification frameworks are set up and altogether tried - Challenges to sheltering and evacuation have been taken out - Emergency drills and exercises have been executed with the engagement of local and national organizations and demonstrations given to the regulatory body — to test and to ensure the efficacy of the emergency arrangements
Radioactive waste management	- Storages or disposal facilities of low and intermediate level waste (LILW) are to be fully arranged	- Existing, upgraded or new facilities for the storage or disposal of LILW are completely operational and ready to collect waste from the 1st NPP - The liable party and funding structure has been set up - Practice international efforts and progress toward final high level waste (HLW) disposal and modify state policy

constitution of Bangladesh [21]. The nuclear and radiation safety legislation and regulation are shown in Fig. 5 in a hierarchical order. BAERA is responsible for formulating safety rules regarding the safe use of atomic energy [6]. BAER Act-2012 [15] is the comprehensive legal framework for the regulation and monitoring of peaceful applications of atomic energy, which covers the issues of safety and radiation protection, environmental protection, control of the operation, security, non-proliferation, waste management, emergency preparedness, and response, transport of nuclear and radioactive material, nuclear liability, decommissioning and closure. It can be mentioned here that the *'Nuclear Safety and Radiation Control (NSRC) Act-1993'* is repealed now, as BAER Act-2012 is promulgated. The function of the NPCBL is to operate Rooppur NPP along with other future NPPs set-up under the Bangladesh NPP Act-2015 [16]. BAEC was formed in 1973 under the Presidential Order #15, repealed by BAEC Act-2017; it has given all mandates to atomic activities for peaceful use [22]. The ministry of environment, forest, and climate change has the responsibility to ensure public safety from harmful ionizing radiation arising from the nuclear industries and activities as per the environmental conservation

Fig. 4. Gap identification process for safety infrastructure issues.

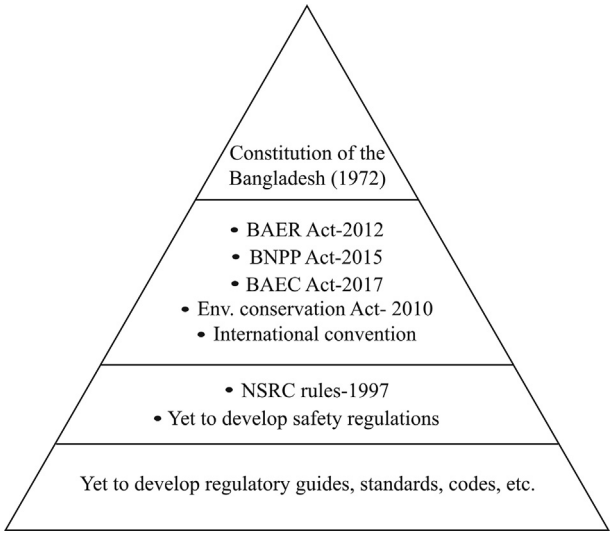

Fig. 5. Hierarchy of legislative framework for nuclear and radiation safety.

Table 3
Status of international safety instruments [1,24,25].

Title of the Instrument	Came into force	Status	Binding/ Non-Binding
Convention on Nuclear Safety	1996-10-24	Signature: 1995-09-21	Binding
Convention on Early Notification of a Nuclear Accident	1988-02-07	Accession: 1988-01-07	Binding
Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency	1988-02-07	Accession: 1988-01-07	Binding
The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	Not applicable	Non-Party	Binding
Vienna Convention on Civil Liability for Nuclear Damage	Not applicable	Non-Party	Binding
Protocol to Amend the 1963 Vienna Convention on Civil Liability for Nuclear Damage	Not applicable	Non-Party	Binding

Act-2010 [23]. Other than these Acts in Bangladesh, there is no separate law related to atomic or nuclear energy.

The process for creating any Act related to atomic energy in Bangladesh is initiated by the regulatory body or BAEC by making a draft following the international practices involving the experts from home and abroad. The draft Act is reviewed by the MoST. Before sending it to the cabinet, the MoST sends it to the law ministry for vetting. If the cabinet approves the draft Act, it is sent to the Parliament for final approval (refer to Fig. 6).

For maintaining additional safety measures, the government adopts relevant international legal safety instruments into national nuclear legislation for meeting the IAEA safety requirements and international standards. Table 3 shows the status of international safety instruments. As a signatory of the convention on nuclear safety, early notification in the case of an accident, and assistance in the case of a nuclear accident or radiological emergency, Bangladesh is obliged to respond and adhere to the safety principles. Being signatories of the three conventions, the country has been receiving IAEA technical assistance and cooperation.

'The Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management' [26] is the international legally binding instrument concerned with the safety of spent fuel and radioactive waste management. This joint convention obliges the State that national arrangements for spent fuel and radioactive waste management are adequate and meeting the international standards. Moreover, it provides avenues to receive assistance for those countries that have limited resources and budget. Bangladesh is not a signatory to this joint convention. Bangladesh is also not a signatory to the '*Vienna Convention on Civil Liability for Nuclear Damage*' [24,25]. Chapter VII of BAER Act-2012 states about nuclear liability and coverage that includes liability of a national/foreign operator and liability during transportation. Section 45 specifies the amount of liability *"The maximum amount of liability in respect of each nuclear incident/accident shall be Bangladeshi taka equivalent of three hundred million special drawing rights or the amount specified by the government by notification and the liability of an operator or foreign operator for each nuclear accident shall be prescribed by regulations"* [15].

4.2. Regulatory framework

The regulatory framework is based on the BAER Act-2012 and the subordinate legislation i.e. bylaw-the NSRC rules-1997, which is still enforced [27]. As shown in Fig. 5, nuclear and radiation safety regulations, safety guides, standards, and codes for design, construction, inspections, licensing reviews, and enforcement activities are yet to be developed. However, Bangladesh has made agreements with 'Global Centre for Nuclear Energy Partnership' under the department of atomic energy and atomic energy licensing board, India, and FSUE 'VO Safety', a TSO of Russian regulatory body Rostechnadzor for developing regulatory documents, reviewing safety analysis reports, exchanging experts for inspection of construction works and verification of design & drawing [28–30]. These two regulators have experiences in VVER-1000 and

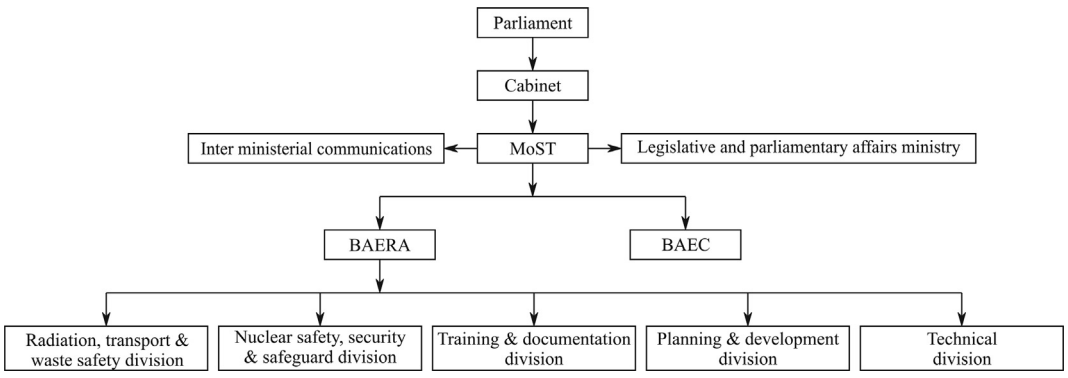

Fig. 6. Structure of national safety regulatory framework.

1200 model reactors' respectively similar with Rooppur NPP reactors.

Establishment of the regulatory authority, office premises, constitution, tenure of chairman and members, and responsibilities and functions of the authority is stated in Section 4, 5, 6, 7, and 11 of the BAER Act-2012 [15]. The prime responsibility of the regulatory authority is to regulate the safe use of atomic energy through authorization, inspection, and enforcement under the provision of Section 11 of the BAER Act-2012 and the nuclear safety and radiation control (NSRC) rules-1997. Within the existing structure of the government, as shown in Fig. 6, BAERA operates as an autonomous body under the MoST. BAERA has five divisions.

Among them, the nuclear safety, security & safeguard division is responsible for safety of nuclear activities while the radiation, transport & waste safety division is overseeing the safety of nuclear and radiological activities. The decision-making body of the regulatory authority consists of four members and a chairman. The chairman is the chief executive who works under the secretary and minister of the MoST. To create any regulatory documents such as regulations, rules, standards, guides, codes, etc., the regulatory authority has to take the proper initiative following the BAER Act-2012 and BAERA's administrative MoST is the responsible organization to approve them. If a new Act/law is to be developed or the amendment of BAER Act-2012 or NSRC rules-1997 is required, it will go to the concerned law ministry, cabinet, and then to the parliament for final approval. To acquire a license, the licensee should apply to the regulatory authority in filling out all prescribed forms by the regulatory requirements. In 2020, communication is being conducted by BAERA with the IAEA for integrated regulatory review service (IRRS) mission to identify the regulatory gaps, if any.

4.3. Radiation protection

Sections 30 and 31 of the BAER Act-2012 [15] deal with nuclear safety and radiation protection respectively. BAERA is the autonomous body to manage whether the arrangements identified with the radiation protection in its jurisdiction are appropriately conformed to or not. The fundamental regulatory document to endorse the prerequisite for radiation protection to both workers and the public is the NSRC rules-1997, which was formulated based on the IAEA basic safety standards no.115 [31]. It covers the radiation protection program, dose limits for different target groups, the requirements of radiation surveillance and its procedures, the obligations and duties of radiation control officers (RCOs). BAERA has a structured radiation monitoring, licensing and enforcement program. Individual dose monitoring and area monitoring are routine programs for radiation protection under the BAER Act-2012 and NSRC rules-1997. BAERA regularly conducts training programs for radiation protection workers, RCOs, and technicians of radiological practices in the medical and industrial sectors. The NPCBL is in charge to ensure radiation protection of NPPs' operation, transport, storage, and radioactive waste management as per the regulatory requirements. The health physics laboratories of the BAEC work for the implementation of the radiation protection program. It has manpower and equipment for radiation dose monitoring for the workers, the public, and the environment. A secondary standard dosimetry laboratory is maintained by BAEC. It provides calibration services to radiological equipment using medical, industrial, and research facilities.

4.4. Human resources development (HRD)

BAERA has a phased recruitment plan to strengthen the workforce up to 360 personnel by 2025. In 2020, BAERA has only 24 scientific and 6 technical employees with graduate and post-graduate degrees [6]. A total of 1660 workforce has been identified for the operation and maintenance of the two units of the Rooppur NPP. Among them, there is 1048 scientific and technical personnel [6,32,33]. Under the general agreement, continuing education and training for the operational and maintenance team of the Rooppur NPP project are being provided by the vendor Russia. Before NPCBL was established, about 30 employees worked at the Rooppur NPP project management unit. Among them, 18 personnel were from scientific backgrounds, mostly physics and the rest 12 were from different engineering disciplines. In 2020, the total workforces at NPCBL are 436 where the engineer and scientist ratio is 2.63:1. The country has an integrated national HRD plan for the nuclear power program [32,33]. Under this plan, about 70 students are currently studying at the Honor's and Master's level at Moscow Engineering Physics Institute (MEPhI) with Bangladesh and Russian Government scholarships. MEPhI takes 20 students every year. Till 2019, 29 students already graduated from MEPhI and most of them are working at NPCBL. This is the only international academic initiatives running in cooperation with the Russian Federation to develop nuclear knowledge induced workforces. Furthermore, nuclear engineering education is very new in this country. Two academic institutes with 65 intake students annually are presently offering nuclear engineering education at Honor's level with limited resources [33].

4.5. Environmental protection

The BAER Act-2012 and NSRC rules-1997 address the responsibilities relevant to environmental protection due to the nuclear or radiological hazards arising from the nuclear industry. There also exists the Bangladesh environmental conservation Act-1995 with amendment in 2010 and Bangladesh environmental conservation rules-1997 defining the regulatory requirements for environmental protection [23,34]. The department of environment (DoE) under the ministry of forest, environment, and climate change, possesses the responsibility of monitoring radioactivity along with the environmental impact assessment for nuclear and radiological facilities and activities [1,23,34]. The owner (BAEC) and the operator (NPCBL) prepared the environmental impact assessment (EIA) report of the Rooppur NPP project in collaboration with the vendor country and the DoE approved the EIA report before the pouring of concrete of unit 1 and 2 in 2017 [35]. Probable radiological effects on individuals and the environment are evaluated at the project site at different operating conditions of the Rooppur NPP, considering the atmospheric dispersion models, present, and likely future demographic distribution in the area. Installations of radiation portal equipment, radiation dosimetry laboratory, and other necessary infrastructures for environmental protection are underway with the help of the vendor country.

4.6. Emergency planning

For the prevention and mitigation of a wide range of natural and man-made calamities including nuclear and radiological emergencies, the government of Bangladesh has established the disaster management Act 2012 [36] and formed the national disaster management council (NDMC) headed by the Prime Minister. As per BAER Act-2012, BAERA will work as a coordinator with the relevant stakeholders in figuring national nuclear and radiological emergency assistance, plans, and for all exercises concerning the mitigation of emergencies. Section 40 of BAER Act-2012 is concerned about emergency preparedness, planning, and preventive and remedial measures which include on-site and off-site emergency plans. The draft national nuclear and radiological emergency preparedness and response (NNREPR) plan has been readied following

Table 4
Progress and practice of UAE, Belarus, and South Korea's safety infrastructure.

Issues	UAE (^{1st} NPP, Phase-3)	Belarus (^{1st} NPP, Phase-3)	South Korea (Nuclear developed)
Legislative and Regulatory Framework	- Federal authority for nuclear regulation (FANR) established in 2009 as a regulator with full legal competence and administrative independence from the promotional body of Emirates nuclear energy corporation - FANR operates under the UAE cabinet - FANR hired several int. TSOs and made agreements with KINS(Korea), NRC(USA), ASN(France), and STUK (Finland) - Planned for a local TSO [40]	- Formed Gosatomnadzor in 2016 as a regulator with full legal competence and administrative independence from the promotional body of directorate for nuclear power construction under the ministry of energy - Gosatomnadzor operates under the ministry for emergency situations - Institute for power and nuclear research (Sosny) under the national academy of sciences of Belarus works as TSO both regulator and operator [41]	- Established nuclear safety and security commission (NSSC) in 2011 as a regulator with full legal competence and administrative independence from the promotional body of the ministry of trade, industry, and energy - NSSC operates under the prime minister's office Established Korea institute of nuclear safety (KINS) as a TSO for a regulatory expert that works under the NSSC - Regulator, operator, and energy promoter are in separate ministries
International Instruments	- Joined IAEA agreements, conventions, etc. including joint convention and civil liability	- Joined IAEA agreements, conventions, etc. including joint convention and civil liability	- Joined IAEA agreements, conventions, etc. including joint convention and civil liability
Radiation Protection	- Secondary standard dosimetry laboratory established in 2017 by FANR -Developed certified dosimetry services for both internal and external dose measurements [40] - FANR assessed the operator's radiation protection technical training program	- Developed radiation monitoring equipment and dosimetry requirements and put in operation by the operator and environment regulator [42] -Maintained automated radiation monitoring systems in regions closer to NPP neighboring countries [42]	- Established a national safety management center and maintains a computerized database system to investigate and assess the occupational exposures and tracking of radiological workers' dose throughout the lifespan [43]
Human Resources Development	- As of August 2016, 200 staff work at FANR [40] - Arranged a national program on capacity building - Established a fully operational technical training center as well as a modern simulator training center [40] -Operator works with local universities for qualified workforce recruitment [40] -Initiated an inspector qualification program [40] - Approved nuclear R&D policy [40]	- Staff (82) at Gosatomnadzor almost recruited [41] - Operator & regulator work with local universities for qualified workforces -Arranged internships for teachers, researchers, and students at home and abroad [41] - Invited expatriate nuclear experts to work at the Belarusian NPP - Belarusian NPP training center is fully staffed and operational since 2016	- As of 2018, 17 universities offer major in nuclear engineering [44] - Maintains in-house training centers among Korean atomic energy research institute, KINS, and Korea hydro & nuclear power [44] - Formed nuclear education cooperation council involving industry, R&D, and academic stakeholders
Environmental Protection	- FANR established the environmental monitoring laboratory - Environment agency-Abu Dhabi (EAD) issued an environmental permit for construction activities based on the EIA report [40]	- Established env. radiation impact lab by the env. regulator for conducting regular sampling and testing during the operational phase of the NPP along with the operator's automated env. radiation monitoring system - Performed yearly radiation monitoring by the Sosny	- Apart from the operator, KINS performed environmental monitoring and managed central radiation monitoring station across the country - Adopted mobile environmental radiation monitoring capability during a massive earthquake and tsunami [43]
Emergency Planning	- Law specifies the responsibilities of authorities to formulate and implement onsite and offsite emergency plans, preparedness, and response measures - The regulator and operator completed a memorandum of understanding [40] -Established national emergency crisis and disaster management authority under the ministry of interior [40]	- Established a robust emergency preparedness and response systems during NPP construction through integrating into the national emergency response system [42] - Coordinated emergency response plan with neighboring countries within the precautionary action zone or the urgent protective action planning zone [42]	- NSSC formulates a national radiological emergency plan every five years and prepares a national radiological preparedness plan each year as well as establishes and operates the offsite emergency management center [44] - During radiological emergencies, NSSC works as a coordinator and communicates with the ministry of interior and safety for taking measures [44]
Radioactive Waste Management	- An initial decommissioning plan submitted and the regulator reviewed [40] - Spent nuclear fuel, radioactive waste policy and decommissioning trust fund resolution under cabinet approval [40] - Proposed a radioactive waste management company [40]	- Arrangement is in place for LILW at onsite and offsite and established the waste management organization - Planned to commission the 1st stage of the waste disposal facility no later than 2028 [41] - Plans for decommissioning available	- Korea radioactive waste management agency is set up under the radioactive waste management Act and this operates for LILW - Approved national policy on HLW management [45]

the IAEA safety standards [37]. The NNREPR plan is approved at a national level by incorporating its functions and obligations of related stakeholders and foundation of the hierarchy of leadership for emergency response management. The NNREPR plan reflects inter-organization connections and the concept of operation, which is vital with other emergency response plans of different agencies. Invitation of the IAEA emergency preparedness review (EPRev) mission for the evaluation of the nuclear and radiological emergency preparedness and response systems at phase-3 is pending.

4.7. Radioactive waste management

Bangladesh cabinet approved the national policy on radioactive waste and spent nuclear fuel management in 2019 which says that the management and disposal of radioactive wastes will be conducted by a state-owned waste management company [38]. The government will form a company named 'radioactive waste management company' under the Bangladesh company Act to manage the disposal of radioactive waste. The new company will be operated under BAEC and it will manage the nuclear and radiological waste of the country. BAEC has interim storage facilities at atomic energy research establishment, Savar, Dhaka to manage radioactive wastes of the country other than those that will be generated in the NPPs. Bangladesh has limited expertise in managing LILW. However, the HLW (i.e. spent nuclear fuel) from the Rooppur NPPs will be returned to the fuel supplier [33,39].

5. Foreign countries' practice

Since the first NPP is being constructed in Bangladesh, a

comparative study with the incumbent countries can be supportive for assessing the country's 1st NPP progress, gaps, and significant measures that are needed to develop a nuclear safety infrastructure. For this, the nuclear safety infrastructure development of the United Arab Emirates (UAE) and the Republic of Belarus are delineated, as they are newcomers in the nuclear arena. The construction progress of the Rooppur NPP project of Bangladesh is just a precedent of the UAE and Belarusian NPP projects. Furthermore, South Korea has achieved a high degree of technical, scientific, and industrial self-reliance in various fields of the national nuclear infrastructure, which is considered as a model country. Table 4 presents progress and practice status concerning 7 key safety infrastructure issues of the UAE, Belarus, and Soth Korea in light of IAEA INIR mission reports and countries' nuclear power profiles. In connection to these issues of the UAE and Belarus at phase 3 regarding the establishments of the independent regulator with sufficient regulatory frameworks, endorsement of all related international legal instruments, competent manpower, implementation of the national plan, development of relevant institutes, laboratories, and roles & responsibilities for radiation monitoring, radiological emergency management, and managing radioactive waste has been implemented following the IAEA safety requirements and nuclear-developed countries' strategy i.e. South Korea. These comparative studies are used in identifying the gaps to complete the phase-3 activities of the Rooppur NPP project.

6. Gap identification

Countries embarking on nuclear power program usually face several key challenges in developing national nuclear infrastructure such as, completing the national policy and strategy, developing legal frameworks, independent regulator, operator, incorporating international legal instruments into national legislation, project management set-up, building skilled workforces, and creating new organizations due to limited resources and budget [46]. Bangladesh has some tangible achievements and has also some challenges during the infrastructure development journey from phases 1 to 3. In the light of two newcomer nuclear countries' infrastructure development progresses, practices (refer to Table 4), and IAEA evaluation and safety guides' indicators, recommended actions, evidence, observations, and the present status of the 7 key safety infrastructure issues delineated in chapter 4, following gaps for each issue are identified.

6.1. Legislative, regulatory framework, and international legal instrument

BAERA deals with the shortage of regulations (radiation protection, environmental protection, waste management, nuclear safety etc.), competent manpower, proper training, and experiences in various regulatory fields. The challenges concerning the required regulations, guidelines, standards, and codes for properly supervising the Rooppur NPP project are perceptible. Given the fact that regulatory authority still operates under the same ministry, where the operator and the owner of the NPP work together, there remains incompleteness over the independence and sovereignty of the BAERA following the IAEA safety requirements and the international practices.

As of August 2020, Bangladesh is not a signatory of the *Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management*. Bangladesh is also not a party to the *Vienna Convention on Civil Liability for Nuclear Damage*. Besides, Bangladesh has no agreement with the neighboring countries regarding the trans-boundary effects of nuclear and radiological disasters. This shows that the national legal framework is inadequate as the two mentioned international agreements are not signed and incorporated into national nuclear legislation. Hence, the country may not receive international cooperation in the areas of spent fuel and radioactive waste management, nuclear accident management, and compensation deals.

6.2. Radiation protection

BAERA has an established radiation oversight program for its existing radiological facilities including regulatory dose limits for both workers and the public. However, to the stage of implementation of the nuclear power program in radiation protection activities, design specific radiological monitoring instruments and systems are not restructured by the BAERA and BAEC. Arrangements for dosimetry measurements, monitoring, and record-keeping during reactor operation, maintenance, and accidental situation are still not upgraded through staff recruitment, training, and procurement of equipment by establishing channels of communication with the NPCBL.

6.3. Human resources development (HRD)

Though an integrated national HRD plan exists for workforce development, it lacks linking with the academic institutes. No roadmap is found for faculty and laboratory developments in the integrated national HRD plan. No time-bound action plan is found for recruiting local nuclear engineering graduates at NPCBL, BAERA, and BAEC. About 100 nuclear engineering graduates remain unemployed as of August 2020. Coordination among academics, regulatory personnel, and owner/operator is absent for developing quality graduates, faculties, and joint research. Due to limited work opportunities and researches, it would be difficult to attract talented youths in nuclear engineering education. However, physical science and conventional engineering graduates (Electrical & Electronics, Mechanical, Civil, and Chemical) are getting more attracted due to more recruitment at BAERA, NPCBL, and BAEC. BAEC has a training institute with limited resources. BAERA has a training and documentation division but it lacks professional trainers and resources.

6.4. Environmental protection

The BAER Act-2012 and the environmental Act-2010 ensure the protection of people and the environment against radiological hazards. There is, thus, an overlap of responsibilities between the BAERA and the environmental regulator/DoE for radiological impacts on people and the environment. In the case of environmental protection, strategy in developing the coordination roadmap as well as the demarcation of roles and responsibilities among regulator, owner/operator, and DoE are still not found for environmental radioactivity monitoring arrangements.

6.5. Emergency planning and management

According to the approved NNREPR plan, the establishment of a nuclear and radiological emergency management organization i.e. NNREMC is yet to be readied. The absence of the NNREMC appears to be an obstacle to the development of safety infrastructure. There is no mechanism of emergency exercises or drills to implement the response plan and procedures in coordination with the local and regional governments, the NDMC, and the international level.

6.6. Radioactive waste management

Though the spent fuel produced from the Rooppur NPP is

Table 5
Major actions needed for strengthening the nuclear and radiation safety infrastructure at phase-3 of the Rooppur NPP project.

Infrastructure Issues	Responsible organizations	Major actions needed
Legislative and Regulatory framework	BAERA	-International instruments Joint conventions and civil liability endorsement -National instruments Development of regulations, technical guides, standards, and codes with the help of international TSOs i.e. vendor state as well as other experienced regulators -R&D capabilities Nuclear safety and radiation monitoring laboratory enhancement -Separation of regulator and operator from the nuclear power promoting organizations
Radiation protection	NPCBL/BAEC, BAERA	-BAEC and BAERA should have their radiation protection and environmental monitoring programs keeping independent from the operating organization -Readiness of radiation protection equipment up to the emergency planning zone by the health physics unit of BAEC for monitoring of areas, personnel, systems, effluents, exposure control, and exposure investigations during routine and accident operational cases -Establishment of radiation protection monitoring/Dosimetry lab by BAERA
Human resources development	BAERA, NPCBL/ BAEC	-BAERA Staff recruitment & development -NPCBL/BAEC Staff development for reactor operation & maintenance, radiation protection, waste management -Upgrading training center for regulator, operator, and owner -Nuclear education and research programs in line with industry demand -Linking academic institutions with industry and R&D organizations
Environmental protection	NPCBL/BAEC, BAERA, DoE BAERA	-Classification of clear roles and responsibilities among NPCBL/BAEC, BAERA, and DoE for environmental monitoring as per BAER Act-2012 and environmental conservation Act-2010 - Set up a central radiation monitoring station
Emergency planning	NPCBL/BAEC, BAERA, Offsite response organizations	-Founding of NNREMC based on approved NNREPR plan -Establish clear roles and responsibilities among BAERA, NPCBL, NNREMC, NDMC, and DoE -Perform emergency drill & exercise as per NNREPR plan -Coordinate with national, regional, local, and international emergency management organizations -Multilateral and bilateral agreements with neighboring countries for coordination of emergency preparedness and response measures
Radioactive waste management	NPCBL/BAEC, BAERA	-Establish a radioactive waste management company provided with the required facilities, manpower, and budget -Selection of waste management and disposal sites -Formulate a decommissioning plan
Others	BAERA, BAEC/	-Establish and develop national TSOs
•TSO	NPCBL	-The earlier trained competent workforce at home and abroad can be recruited in the national TSOs.
•Safety culture	NPCBL/BAEC, BAERA	- Human factors like trust, attitude, behavior, leadership, management, and cognitive redefinition are to be established as an institutional framework for safety culture [43]
•IAEA advisory services and missions	NPCBL/BAEC, BAERA	-Invite for IRRS mission, 2nd follow-up of INIR, and emergency preparedness review (EPRev) missions

supposed to be taken back to Russia via a separate agreement, the management of the LILW like conditioning, treatment, storage, transportation is to be carried out within the country by the State responsibilities. There is no development for the establishment of a national radioactive waste management company under the *'National Policy on Radioactive Waste and Spent Nuclear Fuel Management-2019'*. Also, the decision of disposal site and options e.g. surface, near-surface, underground, etc. for LILW are pending. The absence of regulation, guidelines, or plans regarding the management and disposal of radioactive waste is another safety concern.

6.7. Others

6.7.1. National TSO

The country has not yet developed its own TSO to deal with the insights of this complex nuclear technology. The owner of the NPCBL i.e., BAEC, is working as a TSO. For the development of BAERA's regulations, guides, licensing process, standards, codes, etc. Russia and India are working as the international TSOs. Developing national TSOs for the localization of a foreign technology, smooth operation and maintenance with the cost-sustainability of the NPP, and maintaining a robust nuclear and radiation safety regime with IAEA requirements and global standards, is yet to be readied.

6.7.2. Safety culture

Fostering a safety culture within the organization and its regular self-assessments on employees is the key to reach the organization's goals and expectations [47]. It needs to be established as an institutional framework. However, there are no such regulations, training or self-assessment exercises available in the management systems of the BAERA, NPCBL, and BAEC.

7. Suggestions

Based on gap identification in chapter 6, Table 5 shows what major actions to be needed and which organizations should take appropriate measures on 7 key infrastructure development issues for strengthening nuclear and radiation safety.

8. Conclusion

The government of Bangladesh has commenced the nuclear power program for its energy security and socio-economic development. Construction progress of the two units of VVER-1200 model generation III+ reactors along with the development of the 19 infrastructure issues is underway. Seven (7) safety-related predominant infrastructure issues are evaluated with regard to phase 3 activities of the national nuclear safety infrastructure development program. The study identifies several development

activities at phase 3 regarding the establishments of several Acts, a regulatory body, and an operator. Also the study finds a good practice that Bangladesh has logically selected the vendor country's regulator to have the regulatory assistance for developing regulations, codes, standards, guides, and human resources for the country's nuclear power program. To keep pace with the current progress and to reach milestone 3 (ready to commission and operate 1st NPP) by 2022, significant actions need to be taken by the regulator, operator, and owner. These include the ratification of joint conventions and civil liability, capacity building of the regulatory authority in terms of independence, workforce, regulations, technical guidance, standards, codes, R&D facilities, and establishment of clear roles and responsibilities between the regulator and related stakeholders. The operating organization should focus on competent staff recruitment and continuous training for the development of skilled workforces for oversight of the construction works and reactor operation. It is vitally important to make a bridge between academics and nuclear stakeholders for the continuous flow of quality graduates, faculties, and joint research in the areas of safety. Creating the NNREMC, waste management company, selecting waste disposal option & site, formulating a decommissioning plan, building national TSOs both for regulator & operator, and inviting the IAEA advisory services, are indispensable. In the management system, safety culture should be introduced in the regulator, operator, and owner to meet the organization's goals & objectives. Accomplishing all of the aforementioned actions will facilitate the successful completion of the phase 3 journey of the Rooppur NPP project to protect the people, society, and environment from the detrimental effects of ionizing radiation. This independent evaluation can be compared with the owner/operator's self-evaluation studies for a blind review. Such kind of independent evaluation can be extended to the 19 infrastructure issues. This article can also be beneficial for the emerging nuclear power countries for developing a nuclear and radiation safety infrastructure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acronym

ASN	French Nuclear Safety Authority
BAEC	Bangladesh Atomic Energy Commission
BAERA	Bangladesh Atomic Energy Regulatory Authority
DoE	Department of Environment
EIA	Environmental Impact Assessment
EPRev	Emergency Preparedness Review
FANR	Federal Authority for Nuclear Regulation
HRD	Human Resources Development
HLW	High Level Waste
IAEA	International Atomic Energy Agency
INIR	Integrated Nuclear Infrastructure Review
IRRS	Integrated Regulatory Review Service
KINS	Korea Institute of Nuclear Safety
LILW	Low and Intermediate Level Waste
MoST	Ministry of Science and Technology
NDMC	National Disaster Management Center
NPCBL	Nuclear Power Company of Bangladesh Ltd.
NPP	Nuclear Power Plant
NSSC	Nuclear Safety and Security Commission
NSRC	Nuclear Safety and Radiation Control
NEPIO	Nuclear Energy Program Implementing Organization
NNREPR	National Nuclear and Radiological Emergency Preparedness and Response
NNREMC	National Nuclear and Radiological Emergency Management Centre
NRC	Nuclear Regulatory Commission
O & M	Operation & Maintenance
RCO	Radiation Control Officer
R&D	Research and Development
STUK	Radiation and Nuclear Safety Authority
TSO	Technical Support Organization
UAE	United Arab Emirates

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