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ARTICLE

India-Japan civil nuclear cooperation: Scenario analysis of nuclear energy systems and role of the QUAD framework

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In this policy-oriented paper, the authors have studied the exercise-based scenario analysis of nuclear energy systems, including the innovative nuclear technological development highlighting the role of the QUAD framework in India-Japan civil nuclear cooperation and focusing on clean energy partnerships. This research aims to showcase the importance of bilateral and multilateral civilian nuclear cooperation from the viewpoint of collaborative innovation-oriented nuclear technological development as well as existing nuclear energy systems. The scenario analysis is based on IAEA's INPRO KIND-ET methodology. KIND-ET means "Key Indicators for Innovative Nuclear Energy Systems-Evaluation Tool". KIND-ET is a quantitative approach based on multi-attribute value theory. The significant parameters in this scenario analysis are; economics, safety, nuclear non-proliferation, social acceptance, security, safeguards, environmental aspects, nuclear waste, and so on. This research emphasizes India-Japan civil nuclear cooperation and how the QUAD framework plays a role through the scenario analysis-based study. To explore the existing and innovative nuclear energy systems under bilateral or multilateral civilian nuclear cooperation, a comprehensive analysis is required to understand the complexities of nuclear energy systems. Thus, the KIND-ET methodology is implemented to examine the nuclear energy systems. While developing nuclear energy systems, a holistic approach becomes essential in designing the decision-making strategy for finalizing nuclear power generation projects. Through this scenario development, international collaborations in civilian nuclear energy have a greater possibility of successful implementation. Furthermore, this research can propose policy recommendations to the stakeholders in nuclear decision-making.

Keywords: India-Japan civil nuclear cooperation; QUAD; KIND-ET; nuclear energy systems

1. Introduction

The bilateral and multilateral civilian nuclear collaborations are the key pillars to establish safer nuclear power programs around the world. In this direction, the authors have studied the exercise-based scenario analysis of nuclear energy systems, including the new nuclear technological development and impact of Fukushima Dai-ichi nuclear power plant accident as well as highlighting the role of the QUAD framework [1] in India-Japan civil nuclear cooperation [2]. The role of QUAD framework comes as brief overview towards the extension of civilian nuclear cooperation from bilateral to multilateral levels. And, in this direction, India-Japan civil nuclear cooperation is considered as an example, because, India and Japan both countries are the members of QUAD framework along with USA and Australia and how these QUAD members can collaborate together in nuclear energy sector. To empower this QUAD framework, authors would like to make the policy recommendations towards the inclusion of India in Japan-USA fast reactor collaboration, as Indian fast reactor programme is quite progressive and advanced. The authors have demonstrated the implementation of IAEA's INPRO KIND-ET methodology [3]. KIND-ET is a quantitative approach based on multi-attribute value theory. Thus, in section 2, objective and in section 3, methodology are explained. The section 4 of the paper covers the background and timeline of India-Japan civil nuclear cooperation. Scenario analysis is implemented in the section 5 of the paper. QUAD's framework and its role are presented in section 6. Summary of results and conclusion are explained in section 7. The originality of this research is twofold; firstly, the authors have created a quantitative base for the comparative study of NESs under the framework of India-Japan civil nuclear cooperation as a case study which can be extended for other bilateral/ multilateral civilian nuclear cooperation as the benchmark study. Secondly, based on KIND-ET methodology [3], a mechanism of "Mutual Offerings" is established in bilateral/multilateral civilian nuclear cooperation which is derived from the comparative analysis of NESs. Other

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Nomenclature

QUAD	Quadrilateral Security Dialogue	ECON	Economics
LCOE	Levelized Cost of Electricity	WM	Waste Management
KIND-ET	Key Indicators for Innovative Nuclear Energy Systems-Evaluation Tool	PR	Proliferation Resistance
		ENV	Environment
IAEA	International Atomic Energy Agency	SN	Safe Operations of Nuclear Power Plants
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles	MT	Maturity of Technology
		TMI	Three Mile Island
NES	Nuclear Energy System	SMR	Small Modular Reactor
NPP	Nuclear Power Plant		

studies [4,5], such as Mexico's long-term nuclear energy planning scenario [4] and second one was conducted for Bulgaria [5]. Thus, from the policy research viewpoint, it is observed that both studies [4,5] conducted the NES analysis using KIND-ET methodology within the single country framework. But, in this research, the authors have implemented KIND-ET for the India-Japan bilateral civilian nuclear cooperation where Indian and Japanese nuclear energy systems are compared as a case study and further derivations of "Mutual Offerings" from the comparative analysis results of India and Japan case study are presented.

2. Objective

The chief objective of the research is to highlight the importance of bilateral and multilateral civilian nuclear cooperation to solve the complexities of nuclear energy systems through the "Mutual Offerings" The authors emphasize on "Mutual Offerings" as the key findings in this research. The Mutual Offerings are derived from the comparative study of Indian and Japanese nuclear energy systems implementing the IAEA INPRO KIND-ET methodology. INPRO's full form is "International Project on Innovative Nuclear Reactors and Fuel Cycles". It was established in 2000 [3]. KIND-ET means "Key Indicators for Innovative Nuclear Energy Systems-Evaluation Tool [3]". Through, this IAEA INPRO KIND-ET methodology based comparative study, authors have identified the strong points and weak points of both nations' nuclear energy systems. Moreover, to overcome the weak points, how India and Japan can strengthen each other's nuclear energy systems through the "Mutual Offerings" is the central analysis of this paper. Thus, "Mutual Offerings" play a vital role to empower the bilateral civilian nuclear cooperation and India-Japan civil nuclear cooperation is applied as the case study in this paper. Secondly, to further extend the cooperation in nuclear energy from bilateral to multilateral, QUAD framework is chosen as an example to enhance the multilateral approaches in civilian nuclear cooperation. And, this proposal is backed with the newly collaboration between the USA and Japan in fast reactor program and a policy recommendation is offered through the involvement of India due to its progressive fast reactor program.

3. Methodology

It is evident that nuclear is a complex system to deal with, and civilian nuclear cooperation plays a vital role by implementing best nuclear practices worldwide. To achieve the defined objective, the authors have chosen IAEA's INPRO KIND-ET methodology [3]. In this direction, as a case study, the authors have evaluated the Indian and Japanese nuclear energy systems applying the KIND-ET methodology. In nuclear energy systems, decision-making is crucial, and KIND-ET [3] offers a holistic approach for comparative analysis, scenario analysis, and sensitivity analysis among the various types of nuclear energy systems. Following the KIND-ET methodology's instruction manual, Indian and Japanese nuclear energy systems have examined. In brief, Indian NES scenario focuses on the development of new nuclear builds. Secondly, Japanese NES scenario highlights the impact of Fukushima Dai-ichi nuclear power plant accident. The authors have investigated the qualitative aspects such as economics of nuclear power, NES performance and acceptance of the NES through KIND-ET quantitative methodology.

KIND-ET is a quantitative approach based on multi-attribute value theory (MAVT). Following the KIND-ET approach [3], in this paper, performance framework is designed and performance framework broadly covers main objective titles, evaluation area titles, key parameter titles, key parameter abbreviations, min & max scores, and selections of scores of Indian and Japanese NESs. As shown in **Table 1** [3], in this paper, main objective titles are NES cost, NES performance, and NES acceptability. The evaluation area titles are economics, waste management, proliferation risk, environment, safe operations of NPPs, and maturity of technology. The key parameter titles are LCOE, research related cost factors, radioactive waste inventory, spent nuclear fuel, long-term radioactivity, nuclear material attractiveness, technology attractiveness, safeguards by design, bilateral/multilateral civilian nuclear cooperation aspects, impact of NES on environment, release prevention, design-based safety properties, early release and core damage, source term, NPP accident management, maturity of technology at design stage, technology maturity time period, nuclear regulatory aspects, and socioeconomic impact. With the reference of KIND-ET method, in this research, the minimum score is 1 and maximum score is 10 and based on this score range, scenario analysis is examined with respect to the weight factor analysis as explained in **Table 2** [3]. The value function and scores are described in **Table 4** [3].

Table 1. Performance framework.

NES Cost	NES Performance				NES Acceptability
Economics 1.LCOE (1ECON) 2.Research related cost factors (2ECON)	Waste Management 1.Radioactive waste inventory (1WM) 2.Spent nuclear fuel (2WM) 3.Long-term radioactivity (3WM)	Proliferation Resistance 1.Nuclear material attractiveness (1PR) 2.Technology attractiveness (2PR) 3.Safeguards by design (3PR) 4.Bilateral/multilateral civilian nuclear cooperation aspects (4PR)	Environment 1.Impact of NES on environment (1ENV)	Safe Operations of NPPs 1.Release prevention (1SN) 2.Design-based safety properties (2SN) 3.Early release and core damage (3SN) 4.Source term (4SN) 5.NPP accident management (5SN)	Maturity of Technology 1.Maturity of technology at design stage (1MT) 2.Technology maturity time period (2MT) 3.Nuclear regulatory aspects (3MT) 4.Socioeconomic impact (4MT)

Table 2. Weight factor description.

Main Objective	Main Objective Weight	Evaluation Area Title	Evaluation Area Weight	Key Indicator Abbreviation	Key Indicator Weight	Final Weight
NES Cost	0.333	Economics	1	1ECON	0.5	0.167
NES Cost	0.333	Economics	1	2ECON	0.5	0.167
NES Performance	0.333	Waste Management	0.25	1WM	0.333	0.028
NES Performance	0.333	Waste Management	0.25	2WM	0.333	0.028
NES Performance	0.333	Waste Management	0.25	3WM	0.333	0.028
NES Performance	0.333	Proliferation Resistance	0.25	1PR	0.250	0.021
NES Performance	0.333	Proliferation Resistance	0.25	2PR	0.250	0.021
NES Performance	0.333	Proliferation Resistance	0.25	3PR	0.250	0.021
NES Performance	0.333	Proliferation Resistance	0.25	4PR	0.250	0.021
NES Performance	0.333	Environment	0.25	1ENV	1	0.083
NES Performance	0.333	Safe Operations of NPPs	0.25	1SN	0.2	0.017
NES Performance	0.333	Safe Operations of NPPs	0.25	2SN	0.2	0.017
NES Performance	0.333	Safe Operations of NPPs	0.25	3SN	0.2	0.017
NES Performance	0.333	Safe Operations of NPPs	0.25	4SN	0.2	0.017
NES Performance	0.333	Safe Operations of NPPs	0.25	5SN	0.2	0.017
NES Acceptability	0.333	Maturity of Technology	1	1MT	0.25	0.083
NES Acceptability	0.333	Maturity of Technology	1	2MT	0.25	0.083
NES Acceptability	0.333	Maturity of Technology	1	3MT	0.25	0.083
NES Acceptability	0.333	Maturity of Technology	1	4MT	0.25	0.083

4. India-Japan civil nuclear cooperation

The current research background lies in the India-Japan civil nuclear cooperation [2] to enhance the bilateral and multilateral approaches in nuclear energy. This research is an effort to propose a quantitative policy oriented model focusing on nuclear decision-making to resolve the complexities of nuclear by considering multiple criteria such as cost, safety, nuclear non-proliferation, societal aspects, waste management, and other linked factors. The timeline of India-Japan civil nuclear cooperation is shown in **Figure 1**. It is shown in Figure 1 that the bilateral negotiations started in 2010. In 2016, the agreement was signed and entered into the force in 2017. From both Indian and Japanese governments' side a working group was established and first two meetings of the working group were held in Mumbai in 2018. And, in 2020, third meeting was held in Tokyo. This section provides time-wise information of the India-Japan civil nuclear cooperation

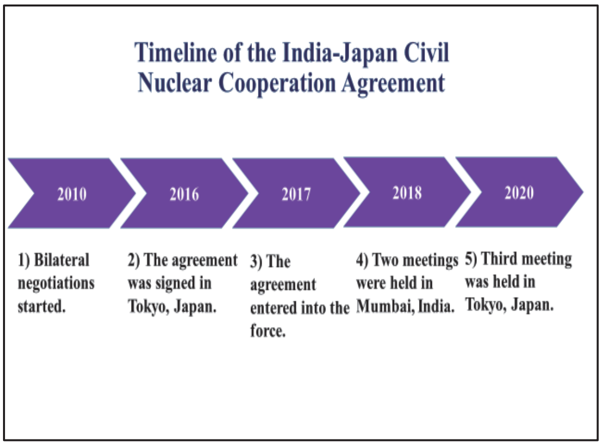

Figure 1. Timeline of India-Japan civil nuclear cooperation [6,7].

for the readers and reflect that how rigorous process has to be completed to accomplish a bilateral agreement between India and Japan. To optimize the extensive time resource, bilateral framework becomes even more important to achieve its goal. Moreover, in this direction, this present research plays an important role to propose the policy recommendations in the nuclear decision-making based on "Mutual Offerings" mechanism as the outcome of the research in the next sections of this paper.

5. Scenario analysis

Scenario analysis is designed on the basis of India-Japan civilian nuclear cooperation agreement such as waste management, nuclear non-proliferation, safety, technology transfer, nuclear fuel cycles, and so on. The authors have observed the exercise-based scenarios from the lens of India-Japan civilian nuclear cooperation.

Following the treaty Articles [2], the authors evaluated the Indian and Japanese nuclear energy systems using the KIND-ET methodology [3] considering economics [8], waste management, safe operation of NPPs, maturity of technology, proliferation resistance, and others. Furthermore, the scenario analysis provides the output in terms of "Mutual Offerings", which means that what both countries India and Japan can offer to each other mutually. Below Table 2 [3] explains the weights of main objectives, key parameters, indicators, and final weight. As per the MAVT, selection of weight factors plays an important role in the scores. The total sum of weights is always equal or less than 1.

Goal is key factor while designing the performance framework and value function. Thus, **Table 3** [3] explains the goal of three main objectives for which the current scenario analysis is conducted. As it can be observed that NES cost should be minimum to strengthen the economics of nuclear power towards the further development of new NPPs. Secondly, NES performance's goal is maximum because overall performance factor of a NES should be maximum while handling with waste management, proliferation resistance, environmental aspects, safety aspects of NPPs, and maturity of technology. NES acceptability is a complex parameter due to the multiple parameters to be considered such as social, technological, economics, safety, security, safeguards, political, regulatory, and nuclear accident related aspects of the NES. Thus, NES acceptability is assigned maximum goal to achieve for the peaceful uses of nuclear energy.

To achieve the above-mentioned goals in Table 3 [3], **Figure 2**, **Figure 3**, and **Figure 4** have explained the results. Table 4 [3] highlights the scores as the combination of value function with respect to the goal selection and assigned weight factors.

Figure 2 shows, main objective scores namely; NES cost, NES performance, and NES acceptability, for Indian and Japanese nuclear energy systems following the KIND-ET methodology instructions [3]. For Indian NES, it is noticed that due to the huge investment in the future new nuclear power plants-the NES cost score is on the higher side with the goal of cost minimization. For the Japanese NES, due to the impact of Fukushima Dai-ichi nuclear power plant accident, NES cost-based score is

Table 3. Goal information.

Main Objective	Goal
NES Cost	Minimum (Min)
NES Performance	Maximum (Max)
NES Acceptability	Maximum (Max)

Table 4. Value function and score.

Factor	Indian NES	Japanese NES
Value Function	0.471	0.332
Score of Main Objective		
NES Cost	0.167	0.167
NES Performance	0.138	0.082
NES Acceptability	0.167	0.083
Score of Evaluation Area		
Economics	0.167	0.167
Waste management	0.000	0.028
Proliferation resistance	0.021	0.021
Environment	0.083	0.000
Safe operations of NPPs	0.033	0.033
Maturity of technology	0.167	0.083

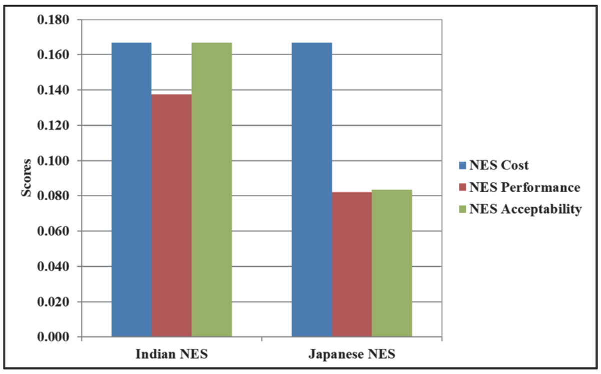

Figure 2. Main objectives' scores.

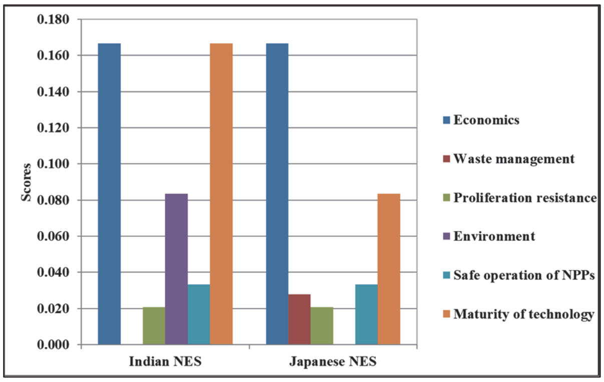

Figure 3. Evaluation areas' scores.

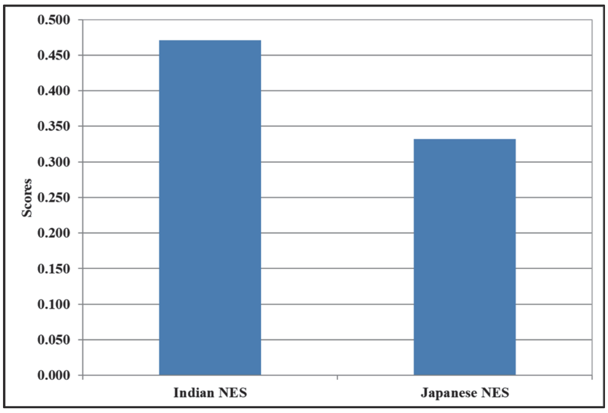

Figure 4. Overall score of multi-attribute value function

higher as decommissioning cost of nuclear power plants are extremely high as well as advanced review-based cost analysis of Japanese nuclear power plants. As shown in Figure 3, Indian NES is having higher scores in environment and maturity of technology parameters and Japanese NES has waste management related challenges as the consequence of multiple decommissioning. In Figure 4, the overall score is shown and it is clear that due to the significant number of incoming new nuclear power projects in India, Indian NES is having higher score.

6. Role of the QUAD

To enhance bilateral and multilateral civilian nuclear cooperation, the authors are interested in opening up the field for QUAD's nuclear framework. Therefore, to start with, as well as for the future work, the authors have undertaken the India-Japan civil nuclear cooperation as the benchmark in this paper to brief the QUAD's perspective. QUAD is a group of four countries: Australia, India, Japan, and the United States of America. As nuclear is a clean energy option, thus, the authors would like to propose possible collaboration among the QUAD nations under their clean energy partnerships initiatives.

Under the QUAD framework, Japan and the USA can work together on how to rejuvenate nuclear energy faster in Japan after Fukushima Dai-ichi nuclear power plant accident following the USA's lessons learned after TMI nuclear accident. Secondly, the USA can have potential to collaborate with Japanese nuclear sector through the inclusion of SMRs in Japanese nuclear energy systems to gain the speedy momentum. As the "Mutual Offering", India and Japan can work together for fast reactor cooperation or India can join the USA-Japan fast reactor program. Broadly, in this paper, QUAD's role is to strengthen and speed-up the bilateral cooperation progress as well as establish multilateral nuclear approaches among the countries. This paper can support as the policy proposal in the establishment of QUAD's nuclear working group to further build up the multilateral framework.

7. Summary of results and conclusion

While developing nuclear energy systems, a holistic approach becomes essential in designing the decision-making strategy for finalizing nuclear power generation projects. Through this scenario development for Indian and Japanese nuclear energy systems, international collaborations in civilian nuclear energy have a greater possibility of successful implementation. From the viewpoints of "Mutual Offerings", under the India-Japan civil nuclear cooperation, following the KIND-ET methodology-based evaluation results of the exercise, both countries can offer mutually beneficial agendas and cooperation strategies to work together, highlighting the importance of bilateral or multilateral civilian nuclear cooperation. On the ground of proven Japanese nuclear technology and as shown in the scenario analysis result that overall score of Indian NES is 0.471 and overall score of Japanese NES is 0.332, thus, India-Japan civil nuclear cooperation can become a strong pillar to further strengthen the Japanese nuclear enterprises which were suffered due to Fukushima accident and it can be considered as the major "Mutual Offering" through the involvement in new nuclear builds in India. Based on the presented results, the clear conclusion of present research is that KIND-ET methodology has established a quantitative study base and fulfilled the objective of present research to highlight the advantages of bilateral civilian nuclear cooperation, "Mutual Offerings" and further its extension in multilateral framework where India-Japan civil nuclear cooperation considered as a case study as well as importance of multilateral approach was examined through the QUAD. In addition, Indian and Japanese nuclear energy systems have significant potential to collaborate and advanced their respective nuclear power programs towards the promotion of peaceful uses of nuclear energy through India-Japan civil nuclear cooperation agreement. In the future work, the results of the present research would be helpful towards the development of regional civilian nuclear cooperation in Asia in the leadership of India and Japan. The regional civilian nuclear cooperation in Asia would facilitate the regional nuclear power growth for the peaceful uses and further would assure the nuclear fuel supply to the member countries.

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