

Restructuring of Nuclear and Radiation Education under the 2022 Revised Curriculum in the Era of Carbon Neutrality

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1. Introduction

As the global energy paradigm shifts toward low-carbon and carbon-free energy sources in response to the climate crisis, nuclear energy is once again attracting attention as a major means of achieving carbon neutrality, owing to its high energy density and stability as a baseload power source [1]. More recently, as geopolitical risks and instability in energy supply chains have intensified, the strategic importance of nuclear energy has become even more pronounced from the perspectives of national energy security and self-reliance. These changes make the role of public education increasingly important in helping future generations understand the characteristics and limitations of major energy sources on the basis of scientific evidence.

Nevertheless, continuous review is needed to determine whether the Korean public education system adequately reflects, in a balanced manner, the scientific principles, quantitative evidence, and technological applications of nuclear energy and radiation. When sufficient scientific understanding of energy technologies is not established through schooling, students' perceptions are more likely to be shaped by social discourse or fragmentary information than by objective data. This underscores the need for educational review, given that such perceptions may ultimately influence social judgments regarding energy policy and the public acceptance of science and technology.

Domestic research on nuclear and radiation education has expanded to include curriculum development, instructional material development, learner perceptions, and analyses of curricula and textbooks. Lee et al. [2] and Han et al. [3] highlighted the need for systematic school education through the development of school-level curricula and textbooks. Park [4] showed that adolescents' perceptions of radiation are strongly influenced by social events and risk perception. In addition, Lee and Shin [5-8], through analyses of research trends, the SAQ (Socially Acute Questions) perspective, cross-national comparisons, and domestic and international school education, argued that nuclear education should encompass not only scientific understanding but also socially contentious issues and civic decision-making.

These prior studies are significant in that they demonstrate both the necessity of nuclear and radiation education and its potential for expansion. However, previous studies have mainly focused on curriculum development, instructional material development, perception surveys, cross-national comparisons, and the exploration of socially acute questions. Accordingly, studies that comprehensively analyze the arrangement of content across school levels and the structural limitations of nuclear and radiation education by linking the 2022 revised national curriculum documents with actual textbook descriptions remain limited. In particular, a simultaneous analysis of curriculum documents and textbooks is essential for identifying the actual status and limitations of nuclear and radiation education.

Although the 2022 revised national curriculum emphasizes expanded learner choice, competency-based education, sustainability, and convergence education [9], there is still insufficient systematic analysis of how nuclear- and radiation-related content is organized in terms of hierarchy and articulation across school levels and subjects. In contrast, new and renewable energy is presented in curricula and textbooks from elementary through high school with hierarchy, continuity, and articulation, and is structured as one major pillar of energy transition education [10–12]. Nuclear energy, however, is reflected relatively limitedly within this inter-school-level structure, and even in textbooks, its scientific principles and application contexts tend not to be presented in a sufficiently hierarchical manner [10–12]. This difference may constrain students' ability to compare and understand the characteristics and limitations of different energy sources in a balanced manner.

Accordingly, this study investigated the current status and structural limitations of nuclear energy and radiation education in Korea through an analysis of the 2022 revised curriculum documents, related textbooks, relevant literature, and case literature on nuclear energy and radiation education from major advanced countries and international organizations. Based on a comparison with new and renewable energy education, the study comprehensively examined the hierarchy and continuity of nuclear energy- and radiation-related content across school levels, intersubject articulation, the extent to which major concepts are reflected, and the balance of

content and descriptions concerning safety, environmental aspects, and applications. In particular, it focused on the range and level at which content on new and renewable energy, as well as nuclear energy and radiation, is presented across school levels and subjects, and on whether elements related to safety, environmental aspects, applications, and technological development are reflected in a balanced manner. Drawing on these findings, the study sought to suggest directions for restructuring nuclear energy and radiation education and to present policy implications appropriate for the carbon-neutral era.

2. Materials and Methods

This study employed qualitative document analysis and comparative policy analysis to identify the structural characteristics and limitations of nuclear and radiation education under the 2022 revised curriculum. The materials analyzed were as follows. First, curriculum documents for the science curriculum, practical arts (technology and home economics)/informatics curriculum, and middle school elective subjects under the 2022 revised curriculum were examined [10–12]. Second, the analysis included descriptions related to energy, nuclear energy, and radiation in elementary, middle, and high school textbooks developed on the basis of the 2022 revised curriculum. Third, quantitative data used to compare the environmental and safety characteristics of energy sources were reviewed, including life-cycle greenhouse gas emissions and mortality rates per unit of electricity generation by energy source [13,14]. Fourth, international educational cases and materials related to advanced nuclear technologies were examined [15,16], including those presented by CEA/INSTN in France, the American Nuclear Society (ANS), the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, and the International Atomic Energy Agency (IAEA) [17–36].

By combining curriculum document analysis with textbook analysis, this study comprehensively examined how learning elements presented in the national curriculum are reflected in textbook descriptions used in actual school settings. Particular attention was given to the extent and level to which new and renewable energy and nuclear- and radiation-related content are presented across school levels and subject areas, as well as to whether elements related to safety, environmental impacts, practical applications, and technological development are addressed in a balanced manner.

The analysis was conducted by focusing on five criteria, as presented in Table I. First, it examined the extent to which core concepts related to nuclear energy and radiation across school levels and subjects were organized and reflected with hierarchy, continuity, and articulation in the curriculum content framework, achievement standards, and textbook descriptions [10–12]. Second, it analyzed whether the safety and environmental aspects of nuclear energy were presented

in a balanced manner in the curriculum and textbooks, together with quantitative comparative data, rather than being limited to descriptions centered on accident cases [13,14]. Third, it reviewed how next-generation nuclear technologies and their potential future industrial applications were reflected in the educational content [15,16]. Fourth, it analyzed whether radiation was described in a balanced manner in the curriculum and textbooks, not only in relation to natural radiation but also with regard to its applications in the medical, industrial, agricultural, and environmental fields [17–19]. Fifth, it analyzed cases of nuclear energy and radiation education in major advanced countries and international organizations [20–36].

Table I: Research materials and analytical framework

Category	Source	Focus of Analysis	References
Curriculum and textbooks	Science curriculum, Practical Arts (Technology and Home Economics)/Informatics curriculum, Elective curriculum for middle school	Analysis of the content framework and achievement standards related to new and renewable energy, nuclear energy, and radiation by school level	[10]-[12]
	Relevant elementary, middle, and high school textbooks (Science, Technology and Home Economics, Integrated Science, Physics, Environment, etc)	Analysis of key concepts and textbook descriptions related to new and renewable energy, nuclear energy, and radiation	Textbooks
Quantitative data	Data from Our World in Data (2020), etc.	Analysis of the incorporation of environmental and safety data for different energy sources (life-cycle greenhouse gas emissions and deaths per unit of electricity generated)	[13], [14]
International cases	Materials from the IAEA, etc.	Analysis of the incorporation of next-generation nuclear technologies	[15], [16]
	Materials from the IAEA, WHO, etc.	Analysis of the incorporation of natural radiation, fundamental radiation concepts, and radiation technologies	[17]-[19]
	Materials from the IAEA, CEA/INSTN, ANS, MEXT, etc.	Analysis of overseas educational cases	[20]-[36]

3. Results

3.1 Lack of Hierarchical Progression and Limitations in the Continuity of Nuclear Energy and Radiation Learning in the Curriculum

A comprehensive review of the 2022 revised curriculum for science, practical arts (technology and home economics)/informatics, middle school elective subjects, and related textbooks shows that new and renewable energy is introduced and progressively expanded across the entire K–12 curriculum. In the second semester of Grade 6 science, students investigate different types of renewable energy and develop interest in sustainable energy use, thereby establishing foundational concepts. At the middle school level, Technology and Home Economics 1 addresses the characteristics and applications of eco-friendly energy resources, while the elective subject

Environment guides students to explore issues related to the use of new and renewable energy and resource circulation and to analyze interactions among relevant factors. In high school, Integrated Science II further deepens this learning by examining the use of new and renewable energy technologies in the context of sustainable development and environmental problem-solving. Textbooks likewise present these topics in a repetitive and expanding manner across school levels, suggesting that content related to new and renewable energy is organized in a relatively hierarchical and continuous way throughout the curriculum.

In contrast, nuclear energy is not addressed in the elementary school curriculum or textbooks and is presented only in a limited manner at the middle school level, mainly in the elective subject Environment within the context of nuclear power use and related environmental issues. Nuclear energy appears more explicitly only at the high school level, where Integrated Science II introduces it as one of the heat sources for power generation. However, key concepts necessary for understanding the scientific principles of nuclear energy, such as mass-energy equivalence ($E = mc^2$), nuclear fission, and nuclear reactions, are mainly covered in elective physics courses. As a result, these concepts cannot be regarded as part of a common learning experience for all students. Rather than forming a hierarchical structure in which nuclear energy concepts are introduced in earlier school years and deepened at later stages, the current curriculum tends to concentrate them in specific school levels and subjects. This indicates that learning about nuclear energy does not develop through cumulative and continuous experiences across school levels.

A similar pattern is observed for radiation. Radiation is absent from the elementary school curriculum and textbooks and is addressed only in a limited way in middle school, primarily in the elective subject Environment in connection with environmental issues such as radioactive leakage from nuclear power plant accidents. It is only at the high school level that Integrated Science II addresses radiation and radioactive waste generated during nuclear power generation as potential threats to human health and the environment. Thus, radiation-related content is presented largely within the specific context of nuclear power generation and environmental risk, rather than through a hierarchical learning structure in which foundational concepts are progressively developed into more advanced ones across school levels. Consequently, radiation is not organized as an independent learning topic with curricular continuity, but is instead presented in a limited and fragmented manner.

Taken together, while new and renewable energy forms a relatively systematic learning structure that is progressively expanded and deepened from elementary through high school, nuclear energy and radiation are excluded at the elementary level, only minimally addressed in middle school, and only partially developed at the high school level. This suggests that

key concepts related to nuclear energy and radiation fail to secure sufficient hierarchical progression and continuity within the current curriculum.

Under this structure, students are more likely to encounter nuclear energy and radiation in a fragmented manner in particular grades and subjects rather than developing these concepts cumulatively and systematically. Nuclear energy, despite being one of the major energy sources in discussions of energy transition and carbon neutrality, is not given sufficient curricular space for comparison and understanding alongside other energy sources. Likewise, radiation is presented primarily in risk-related contexts rather than in a way that encompasses its scientific principles, safety management, and social applications. This reveals structural limitations in the current curriculum and textbook organization for supporting systematic learning of nuclear energy and radiation.

Meanwhile, the applications of radiation continue to expand into fields such as precision medicine, space exploration, and advanced manufacturing, and radiation plays an increasingly important role in science- and technology-based industries. Nevertheless, the current curriculum does not sufficiently address basic concepts related to natural radiation present in everyday surroundings, including rocks, soil, food, and water. In particular, middle school Environment textbooks and high school Integrated Science II textbooks under the 2022 revised curriculum tend to describe radiation primarily in the context of environmental issues, such as radioactive leakage from nuclear power plants.

Such a narrative structure may hinder the development of a balanced understanding of the scientific principles of radiation and its social value and applications. When students encounter radiation mainly through risk-centered examples, they are more likely to form perceptions in which risk is emphasized over its technological usefulness and everyday presence. Therefore, foundational concepts regarding the everyday existence and natural origins of radiation should be introduced progressively from the elementary and middle school levels, and diverse applications in medicine, industry, agriculture, and environmental fields should be incorporated in a hierarchical and continuous manner across school levels.

3.2 Absence of Quantitative Comparison of Energy Sources in Terms of Safety and Environmental Impact

As a result of analyzing textbook descriptions related to nuclear energy, it was found that in the middle school elective Environment and high school Integrated Science II, nuclear energy is presented primarily through risk-centered cases such as nuclear power plant accidents, radioactive waste, and safety issues, whereas quantitative information comparing its safety and environmental impact with those of other energy sources is not provided. Moreover, even in textbooks that include nuclear energy-related content, explanations centered on accident cases or associated

controversies are more prominent than those offering quantitative comparisons of environmental impact and safety. Although these issues constitute important components of nuclear energy education, an overemphasis on specific risk cases may make it difficult for students to develop a balanced understanding of the environmental impact and safety of different energy sources.

For example, in terms of environmental performance, greenhouse gas emissions by energy source can be compared using Life Cycle Assessment (LCA), as shown in Fig. 1. The IPCC presents median values for life-cycle greenhouse gas emissions for different electricity sources. According to these estimates, nuclear energy has a life-cycle greenhouse gas emission level of approximately 12 gCO₂-eq/kWh, which is comparable to wind power and lower than that of solar power. More specifically, the representative values presented in IPCC AR5 Annex III are 12 gCO₂-eq/kWh for nuclear power, 11 gCO₂-eq/kWh for onshore wind, and 48 gCO₂-eq/kWh for utility-scale solar photovoltaics.

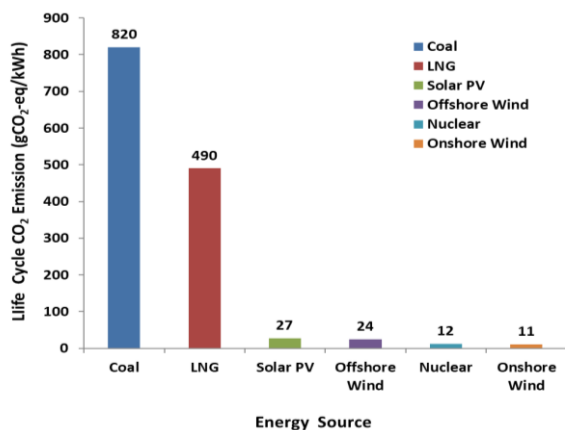


Fig. 1. Life-cycle greenhouse gas emissions by energy source (g CO₂-eq/kWh). Data adapted from IPCC (2022) [13]. Values represent median life-cycle emissions

Quantitative comparison is also possible with respect to safety. Fig. 2 presents a comparison of deaths caused by accidents and air pollution per 1 TWh of electricity generation. Comparative datasets show that nuclear power has a very low mortality rate, whereas coal exhibits a markedly higher rate. In a representative comparison compiled by Our World in Data, coal is reported to account for approximately 25 deaths/TWh, whereas nuclear power accounts for approximately 0.03–0.04 deaths/TWh, indicating that nuclear power involves a substantially lower level of risk than coal.

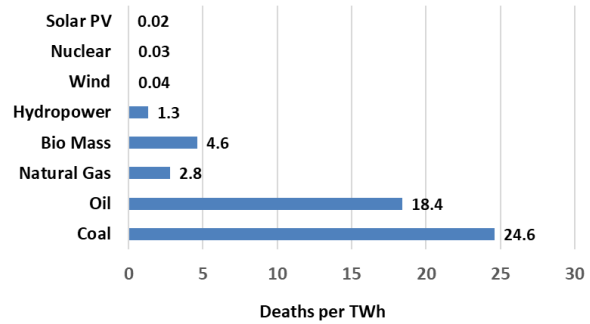


Fig. 2. Mortality rates per TWh of electricity generation by energy source. Data adapted from Our World in Data (2020) [14]. Mortality includes accident-related and air pollution-related deaths.

Quantitative comparative data of this kind can provide an important educational basis for understanding nuclear energy in a balanced manner within the context of climate crisis response and energy security. However, such data are not sufficiently reflected in the current curriculum and textbooks. As a result, students may be more likely to perceive nuclear energy through a risk-centered image rather than to compare and understand it objectively in relation to other energy sources. Therefore, educational content on the safety and environmental performance of energy sources should be supplemented not only with descriptions of accidents and risk cases, but also with comparable quantitative data such as greenhouse gas emissions by energy source, deaths per unit of electricity generated, supply stability, and resource characteristics.

3.3 Limitations in the Reflection of Advanced Nuclear Technologies and Their Future Industrial Applications

Recently, the field of nuclear energy has been rapidly expanding its technological and industrial scope to include small modular reactors (SMRs), spent fuel management technologies, and space nuclear power. Nevertheless, these advanced nuclear technologies and their potential future industrial applications are not adequately reflected in the current curriculum and textbooks [15]. In particular, discussions have increasingly focused on SMRs in terms of their safety, economic feasibility, and potential use as distributed power sources [15,16]. These technologies go beyond simple improvements in power generation efficiency and offer new possibilities for enhanced safety, the development of distributed energy systems, and convergence with future industries.

However, in the current curriculum and textbooks, nuclear energy continues to be presented largely within the limited framework of conventional commercial nuclear power plants. As a result, students may perceive nuclear energy as a legacy industrial technology or a controversial energy source, and may not have sufficient opportunities to understand it as an area of

present and future technological innovation. This may limit their understanding of the contemporary significance and broader potential of nuclear technology and constrain a comprehensive appreciation of the role of nuclear energy amid ongoing changes in energy technologies.

Accordingly, advanced nuclear technologies and their potential future industrial applications need to be selectively incorporated into educational content in consideration of school level and curricular sequence.

3.4 Limitations in the Incorporation of the Everyday Presence and Practical Value of Radiation into Educational Content

Radiation is used in a wide range of fields, including medicine, industry, agriculture, food, and the environment, and constitutes an important element of the scientific and technological foundation of modern society [16–19]. For example, radiation is applied in medical fields such as diagnostic imaging and cancer treatment, in industrial fields such as sterilization and non-destructive testing, in agricultural and food-related fields including food irradiation and mutation breeding, and in environmental fields such as tracing and contamination analysis [16–19]. These examples demonstrate that radiation is not merely an object of risk but also a technology with substantial social utility.

Nevertheless, in the curriculum and textbooks, radiation tends to be presented mainly in the context of risk factors or environmental issues associated with nuclear power generation [10–12]. In addition, although humans are routinely exposed to naturally occurring radiation from sources such as soil, rocks, water, food, and cosmic rays, the existence of natural radiation, everyday radiation exposure, and the medical and industrial applications of radiation are not given sufficient emphasis in textbooks [17,19]. As a result, the basis for students to develop a balanced understanding of radiation as a science and technology encompassing both risks and practical applications appears to be relatively weak.

This mode of presentation may reinforce vague anxiety or risk perception rather than promote a scientific understanding of radiation. Accordingly, radiation education needs to be restructured so that, while addressing risks and the need for safety management, it also presents the existence of natural radiation and its diverse social applications in a balanced manner.

4. Analysis of Educational Cases in Major Advanced Countries and International Organizations

France is a country in which nuclear power occupies a substantial share of electricity generation, accounting for approximately 67% of total electricity production in 2024 [20]. This national energy structure is reflected in school education, where nuclear and radiation education is addressed not simply as the acquisition of scientific

concepts, but within the broader contexts of energy choice, environmental impact, and social decision-making [21–23]. According to the curriculum of the French Ministry of National Education and Youth and Eduscol materials, at the elementary level, cycle 3 (approximately ages 9–11), nuclear energy is introduced as part of the exploration of different energy sources and their environmental consequences, with uranium presented as one example of a non-renewable energy source [21]. At the middle school level, cycle 4 (approximately ages 11–15), learning related to the atom, the atomic nucleus, and radioactivity is developed in greater depth [22]. At the high school level, within the scientific education curriculum, students are expected to analyze the use of nuclear energy from both technical and social perspectives [23]. Furthermore, public institutions such as the CEA and INSTN provide scientific culture and specialized educational resources that complement the formal curriculum, thereby broadening nuclear and radiation education beyond risk-centered narratives into the domains of science and technology, industry, and citizenship [24,25].

The United States has developed nuclear education as an important component of STEM (Science, Technology, Engineering, and Mathematics) education, integrating topics that range from the basic concepts of nuclear science to engineering applications and future technological possibilities [26–29]. Within the U.S. public education system, nuclear-related content is introduced indirectly at the elementary level (K–5) through broad topics such as forms of energy and the structure of matter, while at the middle and high school levels it is addressed more explicitly through concepts related to atomic structure, energy transformation, radioactivity, nuclear fission, and nuclear fusion in accordance with the Next Generation Science Standards (NGSS) [26]. In particular, HS-PS1-8, a high school Physical Science performance expectation in the NGSS, requires students to develop models that illustrate changes in nuclear composition and energy release during the processes of fission, fusion, and radioactive decay, demonstrating that nuclear science content is explicitly incorporated into the formal science curriculum [26]. In addition, radiation education in the United States is not confined to understanding nuclear power generation alone. The U.S. Nuclear Regulatory Commission (NRC) provides instructional units and activity materials for educators that are designed to help students understand both the benefits and risks of radiation, covering topics such as the uses of radiation, reactor-generated electricity, radioactive waste, and the transportation of radioactive materials [27]. Furthermore, the U.S. Department of Energy (DOE) and the American Nuclear Society (ANS) provide online STEM resources, virtual field learning opportunities, digital instructional materials, project-based activities, and career exploration resources, thereby helping students understand nuclear energy and radiation not as fixed technologies of the past, but as innovative technologies for responding to the climate

crisis and advancing the future energy transition [28,29]. This approach is educationally significant in that it goes beyond the mere transmission of knowledge and motivates students to explore future careers in the energy industry and radiation-related fields [28,29].

Japan has promoted nuclear energy and radiation education under the Course of Study established by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in a manner that cultivates both scientific understanding and social decision-making competence. In particular, it adopts a structure in which scientific concepts are progressively deepened across the elementary, lower secondary, and upper secondary school levels. Following the Fukushima nuclear accident, the scope of this education has been expanded to encompass not only scientific understanding of radiation but also risk communication and disaster response competencies [30–33]. The fact that the 2024 revised MEXT supplementary readers on radiation are provided separately for elementary school students and for lower and upper secondary school students indicates that Japan is systematically strengthening radiation literacy in accordance with students' developmental stages.

At the elementary school level, learning is not centered on an independent unit devoted specifically to nuclear energy; rather, emphasis is placed on building the foundation for later learning of nuclear energy- and radiation-related concepts through basic study of energy and matter. The MEXT commentary on the elementary school Course of Study places importance on the structuring of content across the elementary, lower secondary, and upper secondary levels, as well as articulation according to developmental stages. In this sense, the elementary level can be understood as being responsible for foundational learning that helps students understand natural phenomena and their relationship with science and technology [30].

At the lower secondary school level, radiation-related content is introduced more explicitly on the basis of this foundation. The MEXT commentary on the lower secondary Course of Study is organized on the premise of the gradual deepening of scientific concepts and calls for radiation to be addressed within the context of the use of science and technology and the conservation of the natural environment [31]. In addition, MEXT's supplementary readers and instructional materials on radiation present the properties and uses of radiation as core content at the lower secondary level and encourage visual understanding of radiation through inquiry activities such as cloud chamber observation [32]. This shows that radiation education in Japan is not confined to mere risk awareness, but rather incorporates both conceptual scientific understanding and learning about practical applications.

At the upper secondary school level, content related to radiation and nuclear energy is treated in greater depth, primarily within science subjects. According to the commentary on the upper secondary Course of Study, the physics domain addresses the uses of

radiation and nuclear energy, nuclear decay, half-life, nuclear fission, nuclear fusion, and the equivalence of mass and energy, while also presenting activities such as radiation measurement and cloud chamber observation [33]. This content structure demonstrates a hierarchical progression in which radiation-related concepts introduced at the lower secondary level are extended at the upper secondary level into more sophisticated physical concepts and applications.

Thus, nuclear energy and radiation education in Japan exhibits a hierarchical and continuous structure in which the elementary school level lays the foundation of basic scientific concepts, the lower secondary level engages students more fully in learning about the properties and uses of radiation through inquiry activities, and the upper secondary level expands this learning toward the uses and safety of nuclear energy as well as judgment related to energy issues. Particularly since Fukushima, there has been a clear tendency to strengthen radiation literacy not only as the ability to understand scientific facts about radiation, but also as the ability to critically interpret related information and make rational judgments in disaster situations [32]. In this respect, the Japanese case demonstrates that nuclear energy and radiation education can be designed not as fragmented descriptions centered solely on risk, but as an educational approach that cultivates both scientific understanding and public judgment.

Meanwhile, the International Atomic Energy Agency (IAEA) approaches nuclear energy not merely as a power-generation technology, but in an integrated manner linked to diverse fields such as health, agriculture and food, industry, and education and training [34–36]. The IAEA provides scientific advice, education and training, technical documents, and nuclear data so that nuclear science and technology can contribute to sustainable development and improvements in quality of life in its Member States, thereby supporting a broader understanding of the wide-ranging applications of nuclear energy and radiation [34]. In particular, in the health sector, the Rays of Hope initiative supports the strengthening of capacities in medical imaging, nuclear medicine, and radiotherapy, demonstrating that radiation technology plays an important role in the medical field, including cancer diagnosis and treatment [35]. In addition, in the agriculture and food sector, the Atoms4Food initiative supports the enhancement of food security, improvement of agricultural and livestock productivity, assurance of food safety, improvement of nutrition, adaptation to climate change, and management of natural resources through the use of nuclear and isotopic techniques [36]. This approach provides important educational implications in that it frames nuclear energy and radiation not as technologies confined to the power sector, but as multipurpose science and technologies that contribute to sustainable development and the improvement of human quality of life.

These international cases commonly demonstrate that nuclear energy and radiation education should not remain at the level of fragmented knowledge transmission within a single subject, but rather needs to be designed as a structure encompassing energy transition, scientific and technological innovation, applications in health, agriculture, and industry, and even social decision-making. This suggests that the Korean curriculum and textbooks also need to further strengthen the hierarchy, continuity, balance, and contemporaneity of nuclear energy and radiation education.

5. Strategic Directions for Reconstructing the Curriculum to Enhance Nuclear Energy and Radiation Education

5.1 Basic Principles of Curriculum Reconstruction

The preceding analysis showed that, in the current curriculum and textbooks, content related to nuclear energy and radiation is not sufficiently systematized in terms of hierarchy, continuity, and articulation across school levels, and that its content organization is also limited by an overemphasis on risk-centered descriptions. Accordingly, this chapter proposes the basic principles and specific directions for curriculum reconstruction aimed at addressing these limitations and strengthening the substance of nuclear energy and radiation education.

Above all, the basic principles of curriculum reconstruction should be to ensure hierarchy, continuity, articulation, balance, and modernity simultaneously. In other words, learning elements related to nuclear energy and radiation should be organized hierarchically so that they deepen progressively across school levels, while continuity should be secured so that what is learned at one stage naturally leads to learning at the next. In addition, the curriculum should be structured so that scientific concepts and their social significance can be understood in an integrated manner through articulation across subjects. Furthermore, educational content should be developed in a balanced way so as to reflect not only safety and risk, but also environmental impact, applicability, and the potential for technological innovation, thereby avoiding excessive emphasis on any single perspective. Moreover, given the rapid development of advanced nuclear technologies and radiation applications, educational content also needs to appropriately reflect changes in contemporary science and technology.

5.2 Hierarchical Organization and Continuity of Nuclear Energy Concept Learning

The curriculum structure needs to be improved so that core concepts related to nuclear energy can be learned progressively with hierarchy, continuity, and articulation across school levels. The current 2022 revised curriculum and related textbook descriptions

provide a gradual and connected learning pathway for new and renewable energy from elementary through high school; however, they do not provide sufficient opportunities for concept formation and contextual learning about nuclear energy before the high school level. Under the current structure, in which nuclear energy first appears in earnest only at the high school stage, it is difficult to secure continuity and cumulative conceptual development.

Accordingly, the curriculum should be reconstructed so that nuclear energy is introduced at the elementary level as one type of energy source, addressed in middle school in an overview of its characteristics and role within the context of energy transition and environmental issues, and studied more deeply in high school with respect to nuclear fission, energy conversion processes, safety, and environmental impact. Such a structure can contribute to improving curricular balance by enabling students to compare and understand nuclear energy on an equal educational footing with other major energy sources, while also establishing a learning pathway in which content expands and deepens naturally without interruption as students progress through school levels.

5.3 Incorporating Quantitative Comparative Data on Safety and Environmental Impact

Educational content on the safety and environmental impact of nuclear energy needs to be supplemented by moving beyond accident- and risk-centered descriptions to include quantitative comparative data. Textbook descriptions to date have tended to emphasize social issues such as nuclear accidents, radioactive waste, and safety concerns. However, such an approach alone makes it difficult for students to compare and evaluate the characteristics of energy sources objectively.

Therefore, it is necessary to present comparable data such as life-cycle greenhouse gas emissions by power source, deaths per unit of electricity generated, supply stability, and resource characteristics, so that students can understand nuclear energy in a balanced way alongside other energy sources. This is important not because it promotes a one-sidedly positive or negative view of nuclear energy, but because it establishes a learning structure in which students judge its relative characteristics and limitations on the basis of scientific data. In addition, when such comparative learning is organized so that it develops across school levels from basic numerical understanding to more sophisticated data interpretation and critical judgment, both continuity and the potential for deeper learning can be secured.

5.4 Reflecting Advanced Nuclear Technologies and Future Industrial Applications

Advanced nuclear technologies and their potential future industrial applications need to be reflected in educational content. Today, nuclear technology is no longer confined to conventional large commercial

nuclear power plants, but is expanding in various directions, including small modular reactors (SMRs), spent fuel management technologies, space nuclear power, and medical radiation technologies. These changes demonstrate that nuclear energy is no longer merely a legacy industrial technology, but is being reconstituted as part of future energy systems and advanced science and technology industries.

Accordingly, the curriculum should incorporate examples of advanced technologies and industrial applications, in ways suited to school level and educational objectives, so that students can understand nuclear energy and radiation as fields connected to technological innovation in present and future society. Such content should not be presented as a one-time topic at a particular school level, but should instead be organized continuously so that students' understanding of future technologies expands progressively across elementary, middle, and high school. This is also meaningful in that it broadens students' understanding of future science and technology fields and provides opportunities for career exploration.

5.5 Balancing Radiation Education Content and Systematizing It Across School Levels

Educational content should be strengthened so that it reflects the everyday presence of radiation and its diverse applications in a balanced manner. In current school education, radiation tends to be presented mainly in limited contexts associated with nuclear power generation or environmental issues. In reality, however, radiation is widely used in many fields, including medical imaging and cancer treatment, industrial nondestructive testing, food irradiation, agriculture, and environmental analysis. In addition, although human beings live daily within a natural radiation environment, this fact is not adequately addressed in textbooks.

Therefore, future curricula need to improve the content framework so that it includes not only the risks of radiation and principles of safety management, but also the existence of natural radiation, everyday exposure to radiation, and examples of its use in medicine, industry, agriculture, and environmental fields in a balanced way. This can help students understand and judge radiation rationally on the basis of scientific facts, rather than perceiving it merely as an object of vague anxiety or fear. Furthermore, such content should also be presented continuously across school levels, so that understanding develops from familiarity grounded in everyday experience to an understanding of scientific principles and social applications.

At the same time, radiation education itself also needs to be organized hierarchically and continuously across school levels. In elementary school, basic familiarity can be developed by focusing on the existence of natural radiation and examples of radiation encountered in everyday life. In middle school, foundational knowledge can be built around the

concepts of radioactive materials, radioactivity, and radiation, along with basic units. In high school, it is desirable to address more systematically the types and characteristics of radiation, the principles of exposure and shielding, applications in medicine and industry, and the principles of radiation protection and safety. Such a hierarchical and continuous structure is important because it prevents radiation education from remaining at the level of fragmented information and instead creates a framework in which learning at one stage naturally leads to conceptual understanding and recognition of social applications at the next. Through this, an educational system can be established in which understanding of scientific concepts and awareness of social applications deepen together.

6. Conclusion and Implications

This study examined the current status and structural limitations of nuclear energy and radiation education in Korea through an analysis of the 2022 revised curriculum documents, related textbooks, and domestic and international cases. The analysis found that, whereas new and renewable energy is presented in a relatively hierarchical and continuous manner from elementary through high school in the current curriculum, content related to nuclear energy is effectively absent at the elementary and middle school levels and is introduced only in high school, specifically in Integrated Science II and the science-track elective Physics. This indicates that the introduction of nuclear energy concepts occurs excessively late. Under such a structure, it is difficult to establish a hierarchical learning sequence in which nuclear energy concepts are progressively deepened and expanded across school levels, and continuity and cumulative development in concept formation are likewise difficult to ensure. Radiation is also not addressed at the elementary level; in middle school, it is presented only in a limited manner in the elective subject Environment, mainly in the context of environmental issues related to radioactive leakage; and in high school Integrated Science II, content is centered on the potential threats of radiation and radioactive waste to human health and the environment. This shows that content related to nuclear energy and radiation is not organized in a way that enables progressive understanding within a hierarchical and continuous learning framework across school levels, but is instead presented only in limited grades and specific contexts. As a result, students are more likely to acquire fragmented and restricted understandings of nuclear energy and radiation than to develop a comprehensive understanding in terms of scientific principles, energy transition, quantitative comparison, industrial applications, and technological innovation.

Meanwhile, cases from France, the United States, Japan, and the International Atomic Energy Agency (IAEA) demonstrate that nuclear energy and radiation education need not remain at the level of fragmented knowledge transmission or risk-centered narratives.

Rather, such education can address scientific principles, energy choices, social decision-making, and industrial applications in an integrated manner within a structure that ensures hierarchy and continuity across school levels. These findings suggest that nuclear energy and radiation education should be reconstructed not merely as a subject of simple pro- or anti-nuclear debate, but as an educational theme connected to energy transition, climate crisis response, scientific and technological innovation, and civic judgment.

Taken together, the central conclusion of this study is that, compared with new and renewable energy education, nuclear energy and radiation education in the current Korean curriculum remains structurally insufficient in terms of hierarchy, continuity, and balance, and therefore does not adequately support students' balanced concept formation and comprehensive understanding. Accordingly, future nuclear energy and radiation education should be reconstructed in ways that strengthen hierarchy and continuity across school levels and articulation across subjects, while also incorporating quantitative comparisons of safety and environmental impact, advanced technologies, and the everyday presence and social value of radiation in a balanced manner. This task goes beyond simply supplementing content; rather, it involves redefining the framework of civic education on energy and science and technology. At a time when carbon neutrality and energy transition have emerged as major societal challenges, it is an important responsibility of public education to help students understand the characteristics and limitations of major energy sources on the basis of scientific facts and data and to make rational judgments about the diverse issues surrounding nuclear energy and radiation.

However, this study has several limitations. Because it was conducted primarily through document analysis of curriculum materials and textbooks, it was not able to directly reflect actual classroom implementation or students' learning experiences in school settings, nor did it empirically verify the perceptions of students, teachers, and parents or the educational effects of such content. In addition, the international case analysis was limited to selected countries and institutions, and further examination that takes into account Korea's own educational environment and policy context is necessary before applying these cases directly to curriculum reform.

Therefore, in order to achieve the substantive inclusion of nuclear energy and radiation education in the next curriculum, systematic and comprehensive follow-up research is required. First, based on a detailed analysis of the content structure and modes of description in the current curriculum and textbooks, it is necessary to specify the timing and level of introduction of nuclear energy- and radiation-related learning elements at each school level. Next, empirical investigations of perceptions and educational demand among students, teachers, and parents are needed to confirm the necessity of curricular inclusion and the

possibility of social acceptance. Building on this, achievement standards and content elements for each school level should be developed, followed by the systematic development and validation of textbook descriptions, teaching and learning materials, inquiry activities, and assessment items. Ultimately, these research outcomes should be accompanied by efforts to secure the policy validity and educational necessity of incorporating nuclear energy and radiation education into the curriculum.

With such follow-up research and policy efforts in place, nuclear energy and radiation education can, in balance with new and renewable energy education, become a core educational domain for fostering the scientific citizenship and energy literacy required by future society.

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