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Designing research strategy and technology innovation for sustainability by adopting "imaginary future generations"—A case study using metallurgy

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Abstract

To mobilize science and technology for sustainability, it is essential to develop a method for explicitly considering the needs and preferences of future generations in designing research strategies and technology innovations. In this study, we conducted a participatory deliberation experiment on research strategy design of hydrothermal reactions and slag, to analyze whether the adoption of imaginary future generations (IFGs), which is a social system that has been proven to be effective for overcoming shortsightedness and activating futurability of people and society in pursuit of sustainability, could change the direction of research and development (R&D) and thereby innovation. A questionnaire survey was administered to the participants after each deliberation session to verify whether treatments, such as analyzing past R&D initiatives and adopting IFGs in deliberations, would change participants' perceptions about criteria related to designing R&D programs. The results of the deliberation experiment showed that the contents and ideas of research strategies, such as research visions, methodologies and anticipated benefits, were changed by the adoption of IFGs. The criteria used for designing R&D also altered according to changes in research strategy. The findings showed that adopting IFGs and examining issues from the viewpoint of "futurability" could shift the direction of research agendas and technological innovation. Furthermore, the findings could provide insights into how to design R&D strategies and generate innovations in pursuit of sustainability by reflecting upon the needs of and benefits to future generations.

KEYWORDS

imaginary future generations, innovation strategy, metallurgy, participatory assessment, research design

1 | INTRODUCTION

Sustainability problems, such as climate change, pose serious threats to our society. Rockström et al. (2009) demonstrated that the thresholds of planetary boundaries have been breached in several environmental domains, such as climate. Given the emergence of such sustainability problems, sustainability science has received considerable interest in recent decades as attempts are made to synthesize various disciplines to tackle complex issues (Clark & Dickson, 2003; Komiyama & Takeuchi, 2006). Mobilizing science and technology plays an important role in the realization of a sustainable society (Anadon et al., 2016; Cash et al., 2003), and it is essential to identify the research elements and technology seeds that are required to build a sustainable society and to formulate a research and development (R&D) strategy to foster the development and diffusion of promising technology seeds in society.

Various methods and approaches have been proposed to forecast and research technological developments (Hussain et al., 2017; Rau et al., 2018; Zhang et al., 2016). For strategic planning of visions and the exploration of technological developments with a view to realizing a sustainable future society, participatory scenario planning, backcasting, and other methods have been proposed (Hara et al., 2016; Kishita et al., 2016; Mander et al., 2008; Quist & Vergragt, 2006; Reed et al., 2013; Robinson et al., 2011). A variety of methods and techniques to incorporate foresight into governmental institutions have also been proposed (Kim & Dator, 1999). In addition, research and technology assessments, including ones following a participatory approach, have also been developed (Fuldauer et al., 2019; Hornsby et al., 2017; Kaplan et al., 2021; Reed et al., 2021; Tavella, 2016; van Oudheusden et al., 2015). Furthermore, constructive technology assessment (Schot & Rip, 1997) and technology assessment for responsible innovation (Grunwald, 2014) have been proposed and practiced. Empirical studies have shown that apart from curiosity-driven research, the social issues and needs that arise at different times have been a driving force for technological innovation (Fischer et al., 2003; Popp, 2005; Yabar et al., 2013).

To mobilize science and technology for sustainability, a long-term perspective is indispensable and the impact of the social implementation of technology seeds on future societies and generations needs to be considered. However, we argue that in existing approaches, such as those mentioned above, the exploration of research themes and the assessment of social implementations of research and technology seeds have not addressed the needs and preferences of future generations, as well as possible intergenerational conflicts and tradeoffs, in an explicit manner (Hara et al., 2019; Kuroda et al., 2021), despite the importance of these issues in the pursuit of sustainability. It is therefore considered important to identify approaches and assessment methods that can be used to identify the direction of innovations by reflecting on the needs of future generations and the impacts of research, development, and technological innovation on a future society.

It is argued that human characteristics, such as impulses (Sapolsky, 2012) and optimism for the future (Sharot, 2011), as well as current societal systems, such as markets, are the main reasons for not being able to consider the preferences of future generations in the decision-making process of society at present, leading to future failure (Saijo, 2018). It is therefore indispensable to design social systems that enable us to consider the needs of and benefits to future generations in the present. Shaping a sustainable society requires innovations that consider both the needs of future generations and the impact of social implementation of the research and technology seeds on future generations; however, no systematic methodology has been developed to achieve this goal.

Recently, the concept of Future Design, which is the design and praxis of social systems and devices to generate futurability of individuals and society, has been studied to deal with intergenerational conflicts by avoiding shortsighted decision-making (Saijo, 2018). A person exhibits futurability when he or she experiences an increase in happiness as a result of deciding and acting to forego current gains to enrich future generations (Saijo, 2020). One of the promising methods for generating futurability is to introduce "imaginary future generations" (IFGs) as stakeholders who are tasked with representing future generations by putting themselves in the shoes of those future generations. Studies involving economic experiments and participatory deliberations have clearly demonstrated that IFGs can help facilitate sustainable decision-making and reconcile intergenerational conflicts through the activation of futurability (Hara et al., 2019; Kamijo et al., 2017; Saijo, 2020). Furthermore, the introduction of IFGs has been so far conducted in a variety of policy fields, such as in the water environment, renewable energy, and urban planning (Hara et al., 2019, 2021; Kuroda et al., 2021; Nakagawa et al., 2019; Uwasu et al., 2020). Although the introduction of IFGs has been attempted in these studies with public policy-related themes, no studies have been conducted on identifying research agendas, development, and technological innovation using the case of academic research to date.

Previous studies have shown that ideas and decision-making by IFGs are more innovative than those made by current generations, assumingly due to overcoming shortsightedness and activation of futurability (Hara et al., 2019; Saijo, 2020). Based on the results of previous research adopting IFGs, we hypothesize that applying the mechanism of IFGs could lead to identifying new directions of research, development, and technological innovation from the perspective of futurability.

In this study, we focus on the seeds of research in the field of materials engineering as a case study and propose an innovative method for R&D design by considering the needs of future generations. Specifically, we apply the concept of IFGs to participatory deliberations aimed at R&D on specific research themes for targeted materials and verify the effectiveness of the method. The findings of previous studies have led us to hypothesize that applying the IFGs approach makes it possible to derive new directions of innovation from the perspectives of futurability and sustainability. In this study, we aimed to test this hypothesis.

As a case study, we focused on "slag" and "hydrothermal reactions," which are important research subjects for the future of manufacturing in terms of resource utilization and energy recycling.

As we describe below (Section 2.2), from the viewpoints of resource utilization and energy recycling, advances in studies on slag and hydrothermal reactions are expected to be important research and technology seeds in future manufacturing processes. However, there are challenges in terms of social implementation. For example, additional energy is needed to perform hydrothermal reactions using slag and waste glass, for pulverizing the slag, and for heating water, which has a high specific heat. Accordingly, implementing future research designs for slag and hydrothermal reactions is very important. Simply thinking in terms of current research and technology seeds limits our capacity to overcome known issues and hurdles and to arrive at research breakthroughs. Therefore, new methodologies and practices that facilitate innovation are required.

For this study, we conducted a series of participatory deliberation experiments (workshops) in which researchers and university students discussed the visions of society and manufacturing in 2050 and "research design" as it relates to slag and hydrothermal reactions. Here we define "research design" as the design of a research vision, concept, or a design framework, consisting of a methodology and methods. Using the data from discussions among participants, we identified the commonalities and differences between research designs from the viewpoint of current generations and those from the viewpoint of IFGs, in terms of the visions of a future society in 2050, images of manufacturing in 2050, and direction of future research design. In doing so, we verified the effectiveness of IFGs as a mechanism for defining research agendas and the direction of technological innovation from the viewpoint of futurability. In between the deliberations as current generations and IFGs, we also conducted a session in which participants evaluated the relevant R&D strategies in the past from a long-term perspective, which can also be considered effective for activating futurability (Nakagawa et al., 2019). Accordingly, we developed a method for evaluation using a database based on relevant previous studies. We then conducted questionnaire surveys of all the discussion participants before the workshop and after each of the three workshop sessions, to analyze how the relative priorities of their concerns in defining R&D themes were affected by adopting the perspective of IFGs over the course of the workshop. The results showed that examining research design from the perspective of future generations influences the content and direction of research design and the focus of R&D.

We argue that this study presents a new approach for identifying research design from the perspective of "futurability," which helps to establish a foundation for developing new methods and systems to induce innovation and realizing the goals of a sustainable society.

2 | METHODS

2.1 | Incorporating the viewpoints of future generations

To avoid future failure, it is important to design and implement social systems or social devices that facilitate sustainable decision-making that considers the benefits to future generations. As one of the approaches, the concept of Future Design has been proposed, which is the design and praxis of a society generating futurability (Saijo, 2018). Studies have been conducted on the generation of futurability and it has been found that one of the promising methods to overcome the shortsightedness and activate futurability is the introduction of "IFGs" who are tasked with representing future generations in decision-making or negotiations by adopting the perspective of future generations (Hara et al., 2019; Kamijo et al., 2017; Saijo, 2018). The effectiveness of introducing IFGs has been demonstrated increasingly through experiments, field experiments, questionnaire surveys, and actual practice (Hara et al., 2019, 2021; Kamijo et al., 2017; Nakagawa et al., 2019; Saijo, 2020). For example, the first practice session adopting IFGs, which was held in the town of Yahaba in Iwate Prefecture, Japan, demonstrated that the ideas and policies proposed by groups of IFGs were in stark contrast with those of current generations groups (Hara et al., 2019). In particular, the IFG groups demonstrated more creativity in their vision design and in identifying policy measures. The values and normativity that these IFGs emphasized differed from current generations groups in that they placed greater emphasis on values unique to the town, such as local resources (Hara et al., 2019; Hiromitsu et al., 2021). It was also found that IFGs developed more holistic and overarching views of current and future generations (Hara et al., 2021; Nakagawa et al., 2017), which we argue might have to do with the activation of futurability. It has also been demonstrated that having a retrospective perspective would be helpful to gain the perspectives of future generations or to generate "futurability." For example, Nakagawa et al. (2019) reported that looking back over the past and sending messages to the past were effective for obtaining future generations' perspectives. In Hara et al. (2019), through a Future Design experiment on regional revitalization, an assessment of socioeconomic and land-use changes from past to present was conducted before considering the perspectives of IFGs.

The methodology of IFGs has been applied to a variety of fields, including urban planning, environmental planning, and water environmental management (Hara et al., 2021, 2019; Hiromitsu et al., 2021; Kuroda et al., 2021). Recently, it has also been applied to backcasting methods (Kishita et al., 2023; Uwasu et al., 2020). However, few studies have attempted to apply the mechanism to research, development and technology innovation. We hypothesize that, based on the findings of the above previous studies, exploring research themes and technology development from the perspectives of futurability could lead us to identify new directions for innovation and ideas. To test this hypothesis, we conducted deliberative experiments (Future Design Workshop) as explained in Section 2.3.

2.2 | Discussion theme—slag and hydrothermal reactions

Steel and glass materials are indispensable to modern society, finding widespread use as structural materials for buildings and other structures, as well as for machine parts. However, over the whole life cycle of these materials, from manufacturing, to consumption and disposal after use, steel slag and waste glass, which are multicomponent oxides consisting mainly of SiO_2, are generated as by-products. Steel slag and waste glass are both generated in large quantities. In Japan, for example, 40 million tons of steel slag are generated each year from the production of 100 million tons of crude steel (Nippon Slag Association, 2022). Japan also generates 6 million tons of waste glass annually (Ministry of Environment, Government of Japan, 2022). As by-products, these oxide materials were recognized to offer little added value, and it is difficult to reuse them as functional materials. In terms of exergy, an indicator of the added value of a substance or a physical state, oxide is regarded as lower exergy than metal because metal is generally obtained by the reduction of oxide which requires energy. In addition, a mixture is regarded as a lower exergy state than pure substance because a mixture has a higher entropy than a pure substance. Consequently, steel slag and waste glass are both generally ranked very low, due to both being mixtures of multicomponent oxides. However, despite being multicomponent oxides, slag and waste glass can be converted into high-value-added materials if their exergy is increased through the incorporation of interfaces. Specifically, if microporous materials are produced from slag or waste glass, for example, they can be utilized as functional materials, such as thermal insulators and filters for removing impurities (Suzuki et al., 2014). Consequently, attempts have been made to discover a compositional design method to generate phase separation from multicomponent glasses, and then to create microporous materials by dissolving one of the glass phases with an acid solution (Suzuki & Tanaka, 2008).

However, it is desirable for interfaces to be able to be introduced into these waste materials in a way that has a minimal environmental impact, for example, at low energy loads without using any harmful substances. Various studies have examined the hydrothermal treatment of slag and waste glass as a method for introducing interfaces into the materials for the purpose of creating high-value-added products (Nakamoto et al., 2005; Suzuki et al., 2013; Yamamoto et al., 2012; Yoshikawa et al., 2008). Hydrothermal reactions are recognized as chemical reactions that are mediated by water at high temperature and pressure. Compared with conventional methods for processing slag and waste glass, which rely on high-temperature sintering, hydrothermal reactions are more energy efficient as they require significantly lower processing temperatures, and they have lower environmental impacts because they use only water as a solvent.

2.3 | Workshop design

In this study, we held participatory deliberations to investigate what kind of changes occur when IFGs as a new mechanism to consider from the perspective of futurability is applied to R&D and relevant decision-making. The workshop participants consisted of 21 members, including 17 students (D2: 1, M2: 5, M1: 5, B4: 6, including 3 females and 14 males) and four faculty members from the Interface Science and Technology Area of the Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University. The 21 participants were divided into four groups. Three discussion sessions were held on different dates, each lasting about 3 h. The group members remained fixed for all three sessions. All sessions were held on the Osaka University campus. The group members were selected so that each group had a similar composition in terms of age, academic grade, and gender.

Examples of R&D on the production of porous materials using both hydrothermal reactions and waste glass are very limited, so it is difficult to directly perform analysis and assessment of the past R&D on this subject, but this was attempted in Session 2 as described below. On the other hand, since adequate information can be found on R&D related to hydrothermal reactions and the utilization of waste glass or slag, separately, independent analyses of past R&D can be performed. In this study, we examined the above subjects separately to identify requirements for the sustainable utilization of the discussion themes in a future society, and finally to confirm the benefit of porous materials production. Accordingly, two of the four groups discussed the topic of “hydrothermal reactions”; the other two groups discussed “slag.” Over the three workshop sessions, the group discussions aimed at deciding “the most important research themes to be undertaken within the next five years” based on the group's vision of the state of society and manufacturing in 2050.

Figure 1 presents the framework of the workshop (Sessions 1–3). In Session 1 (December 17, 2019), each group discussed the assigned theme from the perspective of the current generations, taking an approach that looks out into the future of 2050 from the present time as current generations. In Session 2 (January 7, 2020), the groups conducted an analysis and assessment of the historical trend in R&D on the relevant research themes looking back from the present. In Session 3 (January 14, 2020), all participants adopted the viewpoint of IFGs to discuss the same topic as Session 1 from the perspective of the future generations living in 2050. The entire workshop was designed to compare the R&D ideas, strategies, perspectives, and decision criteria of Session 1, when the discussion was conducted as current generations, and Session 3, when the discussion was conducted from the viewpoint of IFGs. Note that we included the second session, on analyzing the past research development, based on findings from previous studies and our own hypothesis that looking back over the past is effective for acquiring the perspective of future generations (Nakagawa et al., 2019) and that the degree of social transformation can be clearly understood by analyzing what had changed in the past (Hara et al., 2019).

The groups were asked to write down the contents of their discussions in all three sessions on large poster-sized sheets of paper, which we used for analysis after the workshop. We also administered questionnaires to all the participants on four occasions—once before the start of the workshop and then at the end of each of the three sessions—to analyze changes in the decision-making criteria and contents emphasized by participants resulting from the discussion treatments we applied at each session (see Section 2.4 for details).

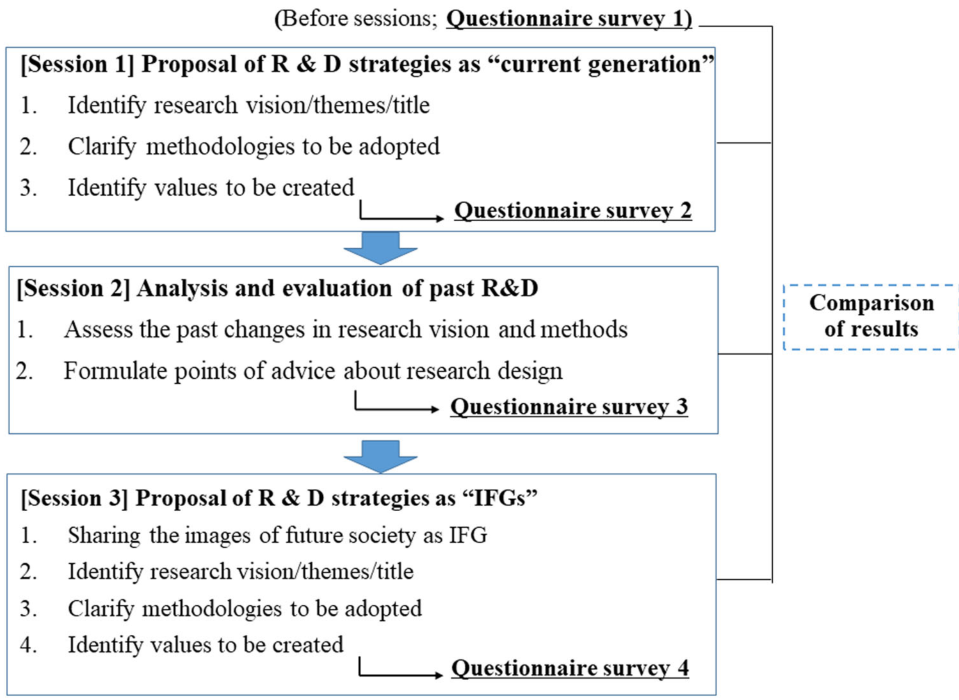

FIGURE 1 Scheme and flow of Future Design workshop.

A detailed outline and the conditions of the three workshop sessions are given below.

Session 1

Session 1, held on December 17, 2019, was conducted as follows. First, the workshop organizers (the authors) provided some basic background information about hydrothermal science, the general subject of discussion. Referring to this information, the groups then held discussions aimed at deciding the most important research themes to be undertaken within the next 5 years, from 2020 on by their laboratory, in light of the need to realize a sustainable society in the decades ahead. More specifically, the participants were asked to develop a written presentation in three steps: (1) Propose a research vision and a research project title that embodies it; (2) Propose a methodology and methods to realize the research vision and concept proposed in (1); and (3) Specify the precise reasons for the proposals made in (1) and (2), explaining how the proposals lead to value creation.

Session 2

In Session 2, held on January 7, 2020, the participants assessed past developments and strategies of their research theme based on information about the historical development of R&D relating to hydrothermal reaction and slag recycling up to the present, which was created by the method explained in Section 2.4. They were asked to express their analysis and assessment of the past in the form of advice to send to researchers engaged in historical research in the relevant field. Details of how we presented the historical development of the fields of study and created a case method are given in Section 2.4.

The discussions in Session 2 were conducted in two parts. First, in Part 1, the participants were asked to look back on the historical development of R&D in their assigned field up to the present and consider how they would assess the changes in research vision and methods, particularly in light of the current social situation and research trends. Then, based on the results of their assessment in Part 1, the participants were asked in Part 2 to formulate points of advice about research design to convey to all the researchers who worked on the research in that field in the past, from the standpoint of present-day researchers.

Session 3

In Session 3 of the workshop, held on January 14, 2020, participants assumed the perspective of IFGs living in the year 2050. First, they defined the state of society in 2050 from the perspective of IFGs, and then, from that same future perspective, they held discussions to decide the most important research themes for their laboratory to pursue within the next 5 years (from 2020). The participants were asked to propose their ideas in the form of advice to the generations of 2020. These two parts are explained in greater detail below.

Before they assumed the role of IFGs, the participants were provided with information. This information included the fact that various kinds of long-term sustainability issues have come to the forefront, such as climate change, and the possible reasons behind these sustainability issues. Then, IFGs, as an effective method to activate futurability, were introduced using some examples based on previous studies (Hara et al., 2019; Saijo, 2018). Participants were then instructed as follows: "Imagine that you travel 30 years into the future in a time machine, to the world in 2050, without aging. You live in that world of 2050 and continue to work on materials science in some way." (Hara et al., 2019).

After receiving these instructions, the participants were first asked to describe and share their vision of the world that they would be living in as IFGs in 2050. They were specifically asked to discuss the following three topics: (1) Living and lifestyle conditions in 2050; (2) Socially shared values and trends of 2050; and (3) What kind of vision and thinking by the manufacturing industry helped to shape the world of 2050. The participants were then asked to discuss the same topics that they discussed in Session 1, but this time from the perspective of the IFGs living in 2050, as they had just defined it. Namely, for the purpose of formulating a research design to undertake within 5 years (from 2020), they were asked to develop a written presentation in three steps: Step (1) Propose a research vision and concept; Step (2) Propose a methodology and methods to realize the research vision and concept proposed in (1); and Step (3) Specify the precise reasons for the proposals made in Steps (1) and (2), taking particular care to explain how the proposals lead to value creation. They were then asked to formulate their proposals as advice to the past generation of 2020 assuming their lab members.

It is important that the final discussion topics at Sessions 1 and 3 of the workshop were the same. The only difference between the two discussions was in the perspective taken (i.e., that of current generations vs. IFGs), so that the effectiveness of adopting IFGs could be evaluated.

2.4 | Methods to develop information materials for the analysis of past R&D

Here, we describe the method and procedure to prepare information on the historical development of R&D in the relevant research themes, which was used for analyzing and assessing the past R&D in Session 2. Specifically, we used the procedure described below to create Figure 2, which was presented to the participants in Session 2.

First, we collected information from previously published research papers related to hydrothermal reactions and slag recycling by searching the available literature. For our web-based search, we used the keywords "hydrothermal reaction" and "blast furnace slag." For the search period, we used 1980–2019, which corresponds to the years that return results for papers related to hydrothermal reaction. As a result of our keyword search, we identified 60 papers from the following journals, including both Japanese and international journals. These were: Technical Reports of NICHIAS Corporation; Journal of Ceramic Society of Japan; *Tetsu-to-Hagane*; Waste management research; Journal of Material Science Letters; Journal of High Temperature Society; Current Opinion in Chemical Engineering; Journal of the Japan Institute of Metals and Materials; ISIJ International; Journal of the European Ceramic Society; Journal of Smart Processing for Materials; Environment and Energy; Ceramics International; Master's thesis (2008) and doctoral thesis (2009) at Osaka University (2008); Materials Transactions; Reports of Ceramic Research Center of Nagasaki for the year 2009; Molecules 2019; Journal of Noncrystalline Solids; The Clay Science Society of Japan; Journal of the Society of Inorganic Materials, Japan; The Review of High Pressure Science and Technology; Journal of the Ceramic Association, Japan; Journal of Japan Society for Safety Engineering; Journal of the Mining and Materials Processing Institute of Japan.

Next, to construct our database, we analyzed all 60 of the collected papers based on the method above for information relating to the following eight items: "title," "research purpose and vision," "methods," "findings obtained," "applications," "needs," "age," and "challenges." Then, based on this database, we compiled a presentation on the historical development of hydrothermal- and slag-related R&D in the form of a timeline, organized according to meta-level categories such as "social backgrounds," "research visions," and "features of technology/research," as shown in Figure 2. This figure was created to offer the participants a "big picture" view of transformation through the decades, showing how social conditions have changed; how the contents, visions, and methodologies of research and relevant technologies have changed in the past; and how these factors have interacted with each other as they have been transformed. Information on historical trends could be effectively used for the session on the analyses of past R&D (Session 2).

2.5 | Questionnaire survey

To objectively analyze the changes in the thinking and decision-making of workshop participants through the course of discussions (i.e., Sessions 1–3), we conducted questionnaire surveys, one before the start of the workshop and one after each of the three workshop sessions (i.e., four times in total).

For the questionnaire form, we developed a list of 17 items relating to the discussion topics in terms of the importance when considering research design as listed in Table 1. Participants were asked three questions about these 17 items. In Question 1 (Q1), they rated the importance of each item on a scale of 1 (not very important) to 5 (very important). They were also allowed to propose different items than the 17 items listed in Table 1, if necessary. In Question 2 (Q2) they selected and ranked the five most important items from Q1. To investigate the changes in the thinking of the participants through the workshop, we asked them to answer the same questions four times.

3 | RESULTS

3.1 | Discussion results

Here, we show the discussion results and features of the four groups at each of the three workshop sessions. We analyzed changes in discussion focal points and ideas over the course of the workshop using the records of the discussion contents written up by each group on a large poster-sized sheet of paper.

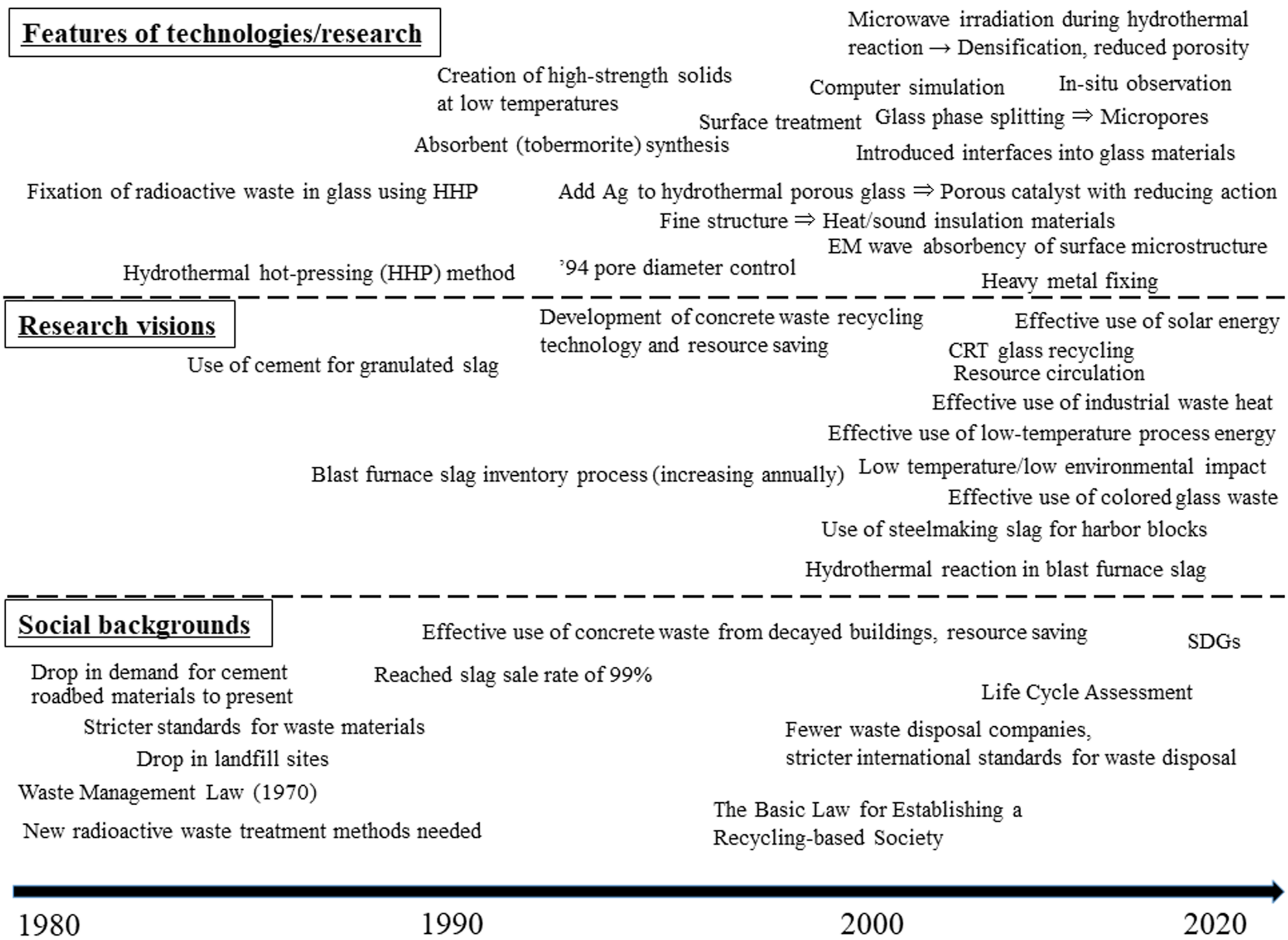

FIGURE 2 Historical development in hydrothermal- and slag-related research and development (R&D).

TABLE 1 Items in terms of importance when considering research design.

1	Novelty and originality	7	Needs of current society	13	The tradition of laboratory
2	Low environmental loads	8	Future needs of society	14	Likelihood of winning awards
3	Burden (cost) of research activities	9	Contributing to the global environment	15	Contribution to the performance of laboratory
4	Following a schedule strictly	10	The potential for expanding a technology to other applications	16	How interesting you find the research
5	Solving current social problems	11	Increasing utility and importance for a future society	17	New adoption of technology seeds
6	Solving future social problems	12	The policy of laboratory		

3.1.1 | Workshop session 1 (as current generations)

Table 2 presents an overview of each group's proposals for the research theme they proposed, which should be undertaken within 5 years. For each of the groups listed in the leftmost column (two hydrothermal groups and two slag groups), the table shows the "research theme" decided by the group, the vision on which the research theme proposal was based, and the methodology or methods that were employed to realize the proposed research theme.

The prevailing view expressed in the discussions after Session 1, shared by all groups, aimed at solving current social issues, improving on existing technologies, and proposing the development of new technologies. A look at the differences between the two themes revealed that both hydrothermal groups proposed the development of new applications for hydrothermal reaction technology as well as the development of new processes to replace existing technology. For example, "Study a new method of extracting rare earth elements using hydrothermal reactions" proposes a new process for the

TABLE 2 Discussion results of workshop Session 1 (as current generations).

	Research theme	Research vision	Methodology
Hydrothermal Group (1)	Investigate heat-dissipating materials made by coating the surface of hydrothermal porous glass with metal	Develop new applications of hydrothermal porous glass	Process hydrated glass by saturation with metal oxide, plating, and vapor deposition
Hydrothermal Group (1)	Investigate materials transmissible to visible light that do not react with supercritical water	Implement in situ observation of hydrothermal reactions	Analyze samples before and after they are maintained under hydrothermal reactions with supercritical water
Hydrothermal Group (2)	New extraction method for rare earth elements using hydrothermal reactions	Contribute to a more stable supply of rare earth elements and a more sustainable society	Hydrothermally treat calcium phosphate solid solution mined from seabed to extract rare earth elements
Slag Group (1)	Measure properties of slag in high-temperature states	Improve steel operation yield and increase the purity of iron	In situ observation of interfacial reactions using a container-less flotation method
Slag Group (1)	Study the creation of high-value-added slag by making its structure porous	Effective use and recycling of slag	Study porous structures using hydrothermal and reduction reactions
Slag Group (2)	"Treasure from waste"—creating new materials from slag	Reuse massive quantities of slag as a structural material Add new value as a functional material	Reduce weight (make porous structure), control ion conductor composition, stabilized spheroidizing technology, control melting and solidification processes

hydrothermal treatment of minerals mined from the seabed (containing solid solutions of rare earth elements in calcium phosphate). The slag groups proposed research aimed at recycling surplus slag, which is not being effectively utilized at present, specifically by using a chemical treatment to enhance functionality, and thereby, to add value.

3.1.2 | Workshop session 2 (retrospective analysis of past R&D)

In Session 2, the group was assigned the task of assessing the historical development of slag- and hydrothermal reaction-related research up to 2019 from a present-day standpoint based on the information shown in Figure 2, and formulating advice to the researchers of the past. The contents of the discussions of each group are shown in Supporting Information: Appendix A.

The hydrothermal groups engaged in lively discussion, not just from a technical perspective, that included the important question of how to implement hydrothermal reactions in society, recognizing that social needs and circumstances are constantly changing over time. For example, in response to the changes in R&D over the past decades, Hydrothermal Group (1) expressed the view that research should have been conducted with greater awareness about commercialization from a large-scale production perspective. In the slag groups, on the other hand, a participant who was familiar with how research used to be done commented that research on reducing slag emissions had been driven more by intentions to cut costs, demonstrate social responsibility, and avoid releasing harmful substances than to reduce the environmental impact. Another participant suggested that research in the past was driven principally from the viewpoint of selling products and not for addressing concerns about environmental impacts.

A common feature of all the groups was that seeing a "big picture" view of the history of R&D from the standpoint of the present enabled them to discuss issues from a broader perspective, quite removed from the perspective of the Session 1 discussions, which tended to focus on existing research and technology seeds. For example, they tended to give more consideration to social implementation and the need for utilizing secondary resources. Compared with the first session, the process of analyzing and assessing past R&D tended to stimulate viewpoints that went beyond scientific considerations, to recognizing the relationship between social reality and research and technology. Studies have shown that looking over the past by sending messages is an effective way of acquiring the perspectives of future generations (see, e.g., Nakagawa et al., 2019), but the findings here suggest that discussing issues from a perspective of sustainability, including the concept of time, also enlarged the perspective of participants.

3.1.3 | Workshop session 3 (as IFGs)

In Session 3, all of the participants engaged in discussions to decide important research themes that they felt should be undertaken within 5 years (from 2020), just as they did in Session 1, but this time from the standpoint of IFGs living in the year 2050. As explained in Section 2.3, they first considered the images of society in 2050 from the following viewpoints: (1) Living and lifestyle conditions; (2) Socially important values and trends; and (3) What kind of the manufacturing industries that shape the world of 2050 are created, and under what kind of vision and thinking manufacturing is operated. The results of the discussion are summarized in Supporting Information: Appendix B.

Although all the groups envisioned a society in which advanced artificial intelligence (AI) has become highly integrated, the details of discussions varied quite dramatically between groups. For example, Slag Group (2) imagined the occurrence of a Nankai Trough Mega Earthquake before 2050, which would cause a change in attitude toward manufacturing, leading to a renewed emphasis on the importance of creating things with human hands. By assuming the perspective of IFGs, the group managed to envision a distinctly unique society.

Next, each group formulated advice for the generation of 2020 about the research theme they need to tackle within 5 years from 2020, based on their perspective as IFGs living in the 2050 world they envisioned. Table 3 summarizes the results of each group's discussion.

All of the groups proposed distinctive themes that they considered to be essential for meeting the needs, and connecting with the values, of their envisioned society of 2050. For example, Slag Group 1 suggested the need for a theoretical framework to explain traditional technology, based on an emerging sense of nostalgia for skills performed by human hand (artisanship). Slag Group 2 reasoned that the experience of a Nankai Trough Mega Earthquake before 2050, as mentioned above, would lead to a manufacturing industry in 2050 in which it was necessary to expect that things will break. The group therefore advocated the pursuit of fundamental and practical research based on this approach to manufacturing assuming that things will break. In its discussion in Session 1, the group could not have imagined coming up with a research theme based on such a style of manufacturing. For their research vision, Hydrothermal Group 2 decided on the realization of hydrogen extraction as an energy source, while Hydrothermal Group 1 proposed research on the separation of salt in the form of ionic crystals, for the purpose of resolving shortages of drinking water.

All these proposals can be considered to be unique products of adopting the perspective of IFGs that sees social, economic, and technological changes from a long-term perspective with a clear awareness of changing social conditions and values in connection to the goal of achieving a sustainable society. Earlier studies have shown that when people examine issues from the standpoint of IFGs, their discussions become more sensitive to the possibilities of social and technological change (see, e.g., Hara et al., 2019), which is consistent with the findings of this study.

3.2 | Analysis of IFGs discussions and the effect of treatments

Comparing the results of the discussions from Session 1, which were based on the perspective of the current generations, with the discussions of Session 3, which were based on the perspective of IFGs of 2050, reveals major changes in the ideas and direction of the "research theme that needs to be tackled within five years" decided by each group. That is, these findings suggest that the treatments

TABLE 3 Discussion results of workshop Session 3 (as IFGs).

Group	Theme	Research vision	Methodology
Hydrothermal Group (1)	Unlimited purification of drinking water using hydrothermal reactions	Separation of salt in the form of ionic crystals, by reducing the dielectric constant of water → Solution to drinking water shortages	Use the decrease in the dielectric constant of water in hydrothermal reactions to separate salt in the form of ionic crystals
Hydrothermal Group (2)	Clarification of the properties of supercritical water	Realize hydrogen extraction as an energy source → Contribute to a sustainable society	Theoretical clarification of the properties of supercritical water
Slag Group (1)	(1) Development of materials for the development of biological machines and cyborgs (2) Theoretical clarification of traditional craft techniques	(1) Development of biomaterials using simulation design (2) → Contribute to the development of biological machines and cyborgs, which are cutting-edge technologies in 2050 (3) Address the needs of 2050, when the special appeal of "human hands" will be highly valued.	(1) Realize highly biocompatible materials with simulation design (2) Simulation design × iron/ceramics data = theoretical clarification of workmanship
Slag Group (2)	Decomposition process for biodegradable porous metals	Realization of resource recycling (manufacturing that assumes products will be broken) Achievement of the strengths of recyclability and structural strength	Assessment of interfacial phenomena by combining thermodynamics and kinetics, machine learning, and in-situ observations

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applied at the workshop sessions were effective in causing a shift in the direction of R&D and the approach to considering innovation. This change can be attributed specifically to the impact of two treatments: the analysis and assessment of the past R&D conducted in Session 2 and the adoption of the perspective of IFGs in Session 3.

To examine the effects of the two treatments—the analysis and assessment of the past, and the adoption of IFGs—and the features of the resulting discussions in greater detail, we analyzed our findings based on the discussion results of each group from the following four perspectives.

(1) Perspectives gained from the process of analysis and assessment of the past (Session 2)
(2) Characteristic perspectives as IFGs (Session 3), specifically the following three perspectives:

(2)-a: Ideas generated by utilizing perspectives acquired through analysis and assessment of the past (Session 2)
(2)-b: Ideas with universal significance, independent of viewpoint acquisition
(2)-c: New and original ideas that were not generated when assuming a present-day perspective in Session 1

(3) Conditions and needs of the society in 2050, envisioned as IFGs
(4) Technological requirements and research needs that should be considered in 2020 from the perspective of IFGs

Supporting Information: Appendix C offers a summary of related elements based on the discussion results. Several implications could be drawn from the summary shown in Supporting Information: Appendix C, as follows.

(1) Perspectives gained from the process of analysis and assessment of the past (Session 2).

First, the analysis and assessment of the past enabled the participants to realize how important it is to consider the social implementation of research and technology seeds, and also how little consideration has been given to potential environmental problems and environmental impacts (e.g., climate change, global water shortages) in past R&D policymaking. There is also a suggestion that, through the process of analyzing and assessing the past, the participants were able to appreciate the importance of capturing a broad, "big picture" view of the relationship between technology and society, by connecting research and technological development to social issues and needs, as opposed to simply conceiving research themes from the technological seeds of the moment.

(2)-a: Ideas generated by utilizing perspectives acquired through analysis and assessment of the past (Session 2)

Next, having adopted the viewpoint of IFGs in 2050, in terms of (2)-a, the perspective obtained through analysis and assessment of the past can be utilized by discussing the relationship between technological development and social conditions (issues and needs), rather than setting out to merely examine research and technology seeds. This also relates to the creative viewpoint offered by the IFGs, characterized by the fact that the conditions for technological development are defined with a spatial expansion—for example, utilization of underground resources—probably influenced by a greater appreciation for the importance of examining the requirements for technological development and social implementation with an expanded sense of space and time, acquired through the treatment of analyzing the past.

(2)-b: Ideas with universal significance, independent of viewpoint acquisition

We also note that in terms of (2)-b, the emphasis on recycling and environmental impact reduction as universal values which are independent of viewpoint acquisition. These factors were seen as important regardless of the perspective (current generations or IFGs).

(2)-c: New and original ideas that were not generated in Session 1.

With regard to (2)-c, as a characteristic viewpoint of the IFGs, we see a large degree of originality and character in spatial expansion, for example, in the use of the moon and underground resources, as well as the use of underground space to address climate change. Another notable characteristic of the IFG perspectives is a focus on manufacturing that is adapted to disasters and environmental changes, based on the assumption of a Nankai Trough Earthquake before 2050 and a worsening of climate change and other environmental problems.

(3) Conditions and needs of the society in 2050, envisioned as IFGs

The thinking of the IFGs of 2050 in most groups took for granted the development of advanced automation and AI. On the other hand, it is interesting how they also envision a growing appreciation for human skills (artisanship), in contrast to the total penetration of automation, which they assume to be obvious. Another distinctive feature of the future visions, aside from these viewpoints, are the assumptions related to global environmental problems like climate change and water shortages, and disasters such as earthquakes. This is also reflected in the assumptions that manufacturing will be based on an expectation that products will break and that underground spaces will expand.

(4) Technological requirements and research needs that should be considered in 2020 from the perspective of IFGs

In summary, the IFGs offer four main points of advice about R&D to the generation of 2020, based on their visions (images) of society in 2050. (1) The first one is to focus on research and technological development to deal with global environmental problems that are presumed to worsen, including climate change and water shortages, which are highly probable in the

TABLE 4 Mean and standard deviation of scores for each item in questionnaire survey (Q1).

Item number	Before start of WS		End of Session 1 (Current generations)		End of Session 2 (Analysis of past)		End of Session 3 (IFGs)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
(1)	4.57	0.53	4.48	0.44	3.95	1.15	4.10	1.09
(2)	3.90	0.47	4.24	0.28	4.20	0.26	3.95	0.95
(3)	3.10	0.75	2.76	0.75	3.30	0.71	2.90	0.59
(4)	3.00	0.67	2.76	0.75	2.95	0.35	2.80	0.56
(5)	4.38	0.43	4.48	0.34	4.10	0.29	3.70	1.01
(6)	4.24	0.37	4.24	0.47	4.40	0.44	4.50	0.25
(7)	4.24	0.47	4.48	0.25	4.20	0.56	3.60	0.74
(8)	4.19	0.54	4.10	0.28	4.60	0.34	4.45	0.35
(9)	4.00	0.57	4.24	0.37	4.25	0.29	4.20	0.46
(10)	3.48	0.73	3.62	1.19	3.90	0.59	4.00	0.70
(11)	3.86	0.60	3.86	0.50	4.65	0.33	4.50	0.45
(12)	3.24	0.94	3.10	0.66	2.65	0.63	2.95	1.05
(13)	3.00	0.67	2.86	0.79	2.45	0.65	2.60	0.94
(14)	2.95	0.43	2.29	0.68	2.55	0.85	2.30	0.81
(15)	3.05	0.90	2.57	1.01	2.90	1.29	2.75	0.79
(16)	3.90	1.32	4.05	0.81	3.80	1.16	4.10	0.89
(17)	3.57	0.72	3.90	0.47	3.85	0.53	3.65	0.63

future. (2) The second point is that the conditions for research and technological development and social implementation are different from those of the current generations' perspective, for example, substantial use of underground resources. (3) The third point of advice about R&D policy is to aim not just at technology, but also at processes. (4) The fourth point of advice gives importance not only to specific technologies but also to information technology, based on the assumption that automation and AI will be dominant in the society of 2050, and also to develop a theoretical framework of human experience and tacit knowledge, in light of the fact that human skills and experience will be valued more highly in the future. The above four points are characteristic of the discussions of the IFGs; that is, they are quite distinct to the focal points of the discussions conducted from the perspective of the current generations. We argue that these characteristics are consistent with previous studies testing the effectiveness of IFGs in public policy fields. For example, the adoption of IFGs helps increase "a sense of crisis about the future (Hara et al., 2022)," which is related to the first point above. It could also increase the sensitivity to the likely changes of technology in the future (Hara et al., 2019), which has to do with the second point. Furthermore, it could also lead to an awareness of eternal values, regardless of time and generations (Hiromitsu et al., 2021), which is related to the fourth point.

The notable focal points of the proposals formulated by the IFGs, such as the points that "human thinking and experience are considered to be important" precisely because of the dominance of automation in daily life, that resources are harvested from the moon and underground, and that "manufacturing will assume that products will break," which arose from the experience of a Nankai Trough Earthquake, are all new perspectives that could never have been conceived by just extrapolating or expanding on the R&D themes of the current generations. This finding suggests that acquiring a long-term perspective by adopting a mechanism to activate "futurability" leads to a clear change in the direction of R&D and innovation.

3.3 | Questionnaire analysis

Table 4 shows the results of our analysis of data obtained from the questionnaires administered to the participants before the start of the workshop and after each of the three workshop sessions. We calculated the mean and standard deviation of the responses for each item based on the responses to Q1 (ranking items on a scale of 1–5 in terms of their importance to discussing and deciding a research theme).

Table 4 shows that we can broadly divide the items into three types; those that become less important as the workshop progresses, those that become more important, and those whose importance does not change significantly. Items 1, 2, 5, and 7 decreased in importance, while items 6, 8, 10, and 11 increased in importance.

The item with the highest mean score before the workshop was item 1, "Novelty and originality," which means this point was considered to be very important. However, its importance decreased after each of the treatments of Session 2 (analysis of the past) and Session 3 (IFGs). Interestingly, the discussion results reveal that, while discussion from the perspective of IFGs generated highly original ideas, as opposed to extrapolations of current thinking, the participants rated the importance of novelty and originality in R&D design as being less important as the workshop progressed.

Along with item 1, the two items ranked most important after Session 1 of the workshop were item 5, "Solving current social problems" and item 7, "Needs of current society," but the importance of these items decreased after each of the next two sessions.

On the other hand, item 6, "Solving future social problems"; item 8, "Future needs of society"; item 10, "The potential for expanding a technology to other applications"; and item 11, "Increasing utility and importance for a future society" were all rated as being increasingly important after Sessions 2 and 3. Most notably, after Session 2, item 11 was ranked the most important point (highest mean score). After Session 3, in which discussions were based on the viewpoint of IFGs, items 6 and 11 were rated the most important. The interesting point here is that the importance of these items increased after analysis of the past in Session 2. Items 5, 8, and 11 all contain the word "future," but the fact that their importance ratings increased after Session 2 suggests that the treatment of analyzing the past (Session 2) may be effective in acquiring a perspective on change over time, that is, on the needs and the interests of future generations, which in turn implies that the step of analyzing the past is effective, to some degree, in enhancing "futurability." Moreover, the results obtained for item 10, "The potential for expanding a technology to other applications" are also compatible with findings obtained by analysis of the discussion content, that treatments of analyzing the past and acquiring an IFGs viewpoint lead to the adoption of a broader perspective, beyond the discussion of technology alone (Hara et al., 2019, 2021).

Next, we analyze the results of the second question of the questionnaire. In Q2, we asked participants which of the five items from Q1 they considered to be most important. For this, we defined an indicator to measure importance. To calculate the importance indicator, the item ranked first was assigned a score of 5, the second item a score of 4, the third item 3, fourth item 2, and the fifth ranked item was assigned a score of 1. We then calculated the relative importance of each item from each questionnaire by totaling the points for each item, dividing the total by the number of participants, and then multiplying by 100 to get a percentage. Figure 3 shows how the value of the importance indicator of each of the 17 items changed over the course of the workshop. The horizontal axis lists the 17 items listed in Question 1, and the vertical axis shows the degree of importance of each item, as ranked by the participants.

$$\text{Importance} = \frac{\text{Total of importance ranking scores}}{\text{Number of participants}} \times 100(\%).$$

As shown in Figure 3, the importance of items 3, 4, 12, 13, 14, and 15 remained low throughout the workshop sessions. Below, we list the items whose importance particularly changed over the course of the workshop. Supporting Information: Appendix D describes the significance of changes for the following items as well as implications.

- Item 1 "Novelty and originality."
- Item 5 "Solving current social problems."
- Item 6 "Solving future social problems."
- Item 7 "Needs of current society."
- Item 8 "Future needs of society."
- Item 11 "Increasing utility and importance for a future society."

The analysis in Supporting Information: Appendix D shows that in terms of multiple items, each of the treatments produced a clear

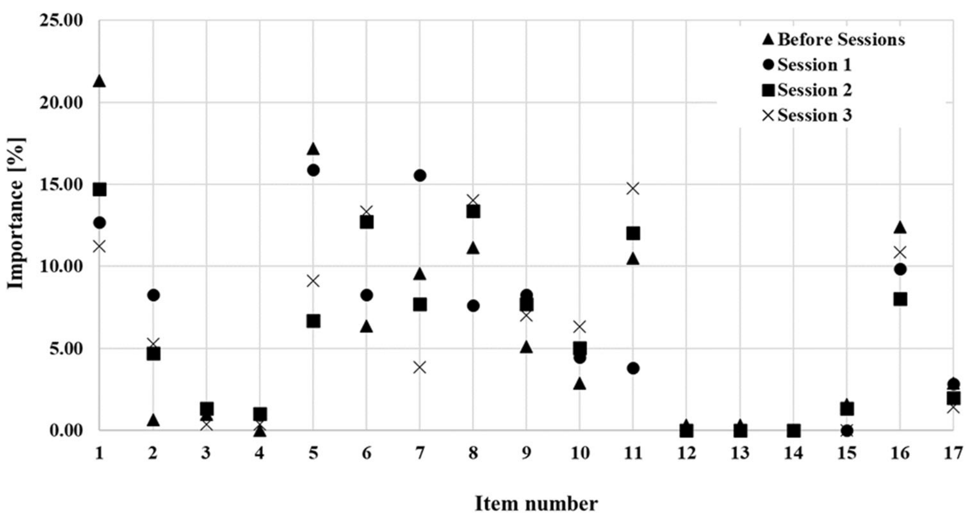

FIGURE 3 Trend in importance scores of discussion items, as ranked using Q2 of questionnaire survey.

change in perspective. We saw that the change was particularly large between Session 1, which examined a future society from the standpoint of the current generations, and Session 2, which focused on analyzing and assessing the past and enabled participants to develop a more objective view of current society by recognizing various social, economic, and technological changes of the past through the generations. A similar shift in the perception of importance can be observed for multiple items between Sessions 2 and 3, which focused on the perspective of future generations. In other words, the treatment of analyzing and assessing the past and the treatment of IFGs seem to have a common impact. Thus, the results of this study align with those of previous studies which empirically demonstrated that a retrospective perspective is useful for acquiring the perspective of future generations (see, e.g., Nakagawa et al., 2019).

The above observations show that (1) the treatment of analysis of the past has important value in acquiring the perspective of future generations; and (2) that there is a clear difference in the perception of the future depending on whether discussions are conducted from the perspective of the current generations or that of IFGs. These points support the conclusion that adopting the viewpoint of a future generation when examining questions of R&D and technological innovation, based on the theory of Future Design, is effective and valuable.

Coupled with the analysis of discussion results in Session 2.3, we argue that activation of futurability by adopting IFGs enables us to overcome shortsightedness, leading to a sustainable decision-making while taking into account the preferences of future generations. As a result, it becomes possible to consider and assess new research strategies and technology innovations based on new criteria. This point is demonstrated in the results of the questionnaire survey, in which the relative weights of items (indicators) were shifted by adopting IFGs.

4 | CONCLUSIONS

In this study, we conducted a participatory deliberation experiment on the academic aspects of hydrothermal reactions and slag, to analyze whether the mechanism of IFGs could be employed to change the direction of R&D and innovation. We also conducted a questionnaire survey of the experimental participants to verify whether the treatments of analyzing the past and adopting IFGs are capable of changing perceptions about the items related to the criteria of designing R&D.

The results of this deliberation experiment showed a significant difference in the contents and ideas of discussions, depending on whether they were approached from a contemporary perspective (Session 1) or from the perspective of IFGs (Session 3). The salient features of the research designs developed by the IFGs were: 1) Advocating the use of research and technological development to address worsening global environmental challenges, such as climate change and water shortages, which are highly likely to occur in the future; 2) The assumption of major changes in the conditions for research and technological development and social implementation compared with current perspectives, for example, utilization of underground resources and mining on the moon; 3) Proposal of R&D policies focused on processes rather than just technology; and 4) Awareness of the growing importance of information technology and the special value of human skills and experience, in view of the envisioned dominance of automation and AI in the future society. Notably, these are points that have rarely come up in discussions just from the perspective of the current generations (Session 1). Based on the results, we have effectively demonstrated that adopting IFGs and examining issues from a viewpoint of "futurability" have the potential to induce a new direction of research agendas and technological innovation.

The results of this study also suggest that the use of case studies to analyze and assess past R&D can have an impact on discussions by IFGs. In particular, we demonstrated the effectiveness of retrospective assessment using case studies based on the historical academic papers and relevant database. This helped to give participants a greater awareness of both time on a long-term scale and of major shifts in social and economic situations. Participants also realized that, in addition to pursuing development from the starting point of technology seeds, it is vital to consider the importance of the relationship between social issues and needs and the perspective of social implementation, as well as the importance of R&D initiatives that consider the various environmental problems that may occur in the future. Therefore, we showed the effectiveness of treatments for analyzing and assessing the past from a "big picture" perspective.

In addition, we learned that the criteria and focal points of discussions about R&D varied depending on viewpoint acquisition treatments. It became clear that applying a mechanism for generating "futurability" can affect the weight given to technology assessment frameworks and items, in conjunction with changes in the contents and ideas of discussions, compared with the results of assessments conducted from the perspective of the current generations. This suggests the necessity and potential for designing new technology assessment and innovation frameworks with long-term perspectives. Our results indicate the significance and necessity of a new research policy to facilitate research design from the perspectives of both current and future generations. The basic design of technology innovations that incorporate "futurability" is a vital future research topic. Constructing assessment systems to measure the impact and effectiveness of technology innovation on future societies is an important research theme for the design of a sustainable future society, so further research and case studies need to be conducted from this perspective. In addition, how to institutionalize the assessment systems that incorporate futurability will be an important issue to examine. In this regard, a feasibility study (Ahn, 2017) can be a good reference to address this issue in the future.

Looking ahead, we see a need to verify the effectiveness of adopting the viewpoint of IFGs in greater detail, for example by gathering more information, such as the attributes and orientation of discussion participants, and analyzing how these attributes relate to the acquisition of future generation viewpoints in a large-scale survey. In addition, conditions necessary to adopt IFGs in participatory workshops, such as how to provide information, should be further studied to effectively activate futurability in participants while controlling possible biases.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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