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Assessing future potentiality of technologies from the perspective of "imaginary future generations" – A case study of hydrothermal technology

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ABSTRACT

To guide technological innovation for sustainability, it is essential to develop a methodology for assessing the future potentiality of a technology from a long-term perspective. In this study, we propose an innovative method for assessing the future potentiality of technology from the perspective of imaginary future generations (IFGs) using a case study of hydrothermal technology and verify the effectiveness of the method. We conducted participatory deliberation experiments adopting the method and studied its effect on the formulation of scenarios for the adoption of hydrothermal technology in society in the year 2040, and on the assessment of the future potentiality and innovation of technology. Using deliberation experiments and questionnaires administered to the participants, we confirmed that IFGs had a significant effect on the adoption of technology in future scenarios and on the assessment results, with concomitant shifts in the relative weights of assessment indicators. We also found that the adoption of IFGs could lead to relativizing the value and positioning of a technology, and to shifting the requirements for the development and adoption of a technology. The results provide insights into the methodology to assess future potentiality of technologies and guide technology innovation from the viewpoint of futurability.

1. Introduction

Various challenges associated with resources, energy and the environment have emerged as factors that threaten the realization of a sustainable society (Steffen et al., 2015). Since technological innovation is set to play a central role in resolving these issues and in pursuing sustainability (Cash et al., 2003; Anadon et al., 2016), consistently implementing technologies backed by basic research is considered to be vital. It is particularly important to examine policy, direction, and strategy relating to research and development (R&D), and to assess the potentiality of research and technologies with a clear vision of the future that we wish to live in.

Within the context of a future society, various methods and approaches for practically affecting the adoption of basic research and technologies and forecasting technological development have been studied. One such method is the scenario approach, which includes participatory methods (Mao et al., 2020; Hussain et al., 2017; Kishita et al., 2016; Robinson et al., 2011). The challenges of linking promising technologies to the realization of macro-level visions, such as a carbon-neutral or recycling-based society have also been examined (Hara et al., 2012). However, these existing approaches have several issues and limitations, particularly in terms of overcoming intergenerational conflicts that arise because these future scenarios have been designed from the standpoints of current generations (Kuroda et al., 2021; Hara et al., 2019).

An equally important consideration is to assess the future potentiality of technologies and the various impacts associated with their adoption from a long-term perspective. Numerous studies have been conducted on technology assessments, including participatory approaches, and a variety of sustainability assessment methods have been proposed (Kaplan et al., 2021; Farrukh and Holgado, 2020; Ren et al., 2017; Smits and Leyten, 1988; Attri et al., 2022; Schot and Rip, 1997). However, studying impact assessments that include the viewpoint of future generations has been difficult, even though the adoption of technology in society is expected to have marked impacts on future societies and generations.

It is therefore important to develop assessment methods that explicitly incorporate the prospects of a technology from the perspective of future generations. With these issues in mind, the goal of this study was to develop a foundation for a methodology that could be used to

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assess and examine innovation in a way that incorporates the perspective of future generations and to define a pathway for the adoption of technologies. To this end, we employed the method of "Future Design." In recent years, studies have been undertaken that focus on designing social systems for guiding sustainable decision-making in ways that incorporate the perspectives of future generations to overcome human characteristics, such as impulses (Sapolsky, 2012) and optimism for the future (Sharot, 2011), and to avoid future failure (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; Future Design is thus the praxis of generating futurability of individuals and society through designing social systems (Saijo, 2020). As a promising approach, the method of employing "imaginary future generations" (IFGs), who are tasked with representing future generations in decision-making and negotiations, has been demonstrated to be effective for incorporating the perspectives of future generations in decision-making and generating futurability (Kamijo et al., 2017; Hara et al., 2021; Hara et al., 2019; Saijo, 2020). Indeed, the method has been effectively applied to policymaking in a variety of fields, and these Future Design practices have demonstrated the effectiveness of IFGs for visioning and decision-making in ways that attempt to overcome shortsightedness and consider the preferences of future generations (Hara et al., 2021; Hara et al., 2019; Hiromitsu et al., 2021; Uwasu et al., 2020; Nishimura et al., 2020; Nakagawa et al., 2019). To date, however, research in the fields of technology assessment and innovation with the adoption of IFGs has been limited.

In this study, we applied this approach to develop a methodology for guiding new directions for R&D and technological innovation from the viewpoint of future generations. We analyzed the effectiveness of the methodology for assessing the future potentiality of technologies by focusing on the use of IFGs and discussed the importance of incorporating a time dimension and the perspectives of future generations. Previous studies demonstrated that, compared with the viewpoints of the current generation, new and innovative ideas can be generated by employing the IFG approach (Hara et al., 2019; Saijo, 2020). We therefore hypothesize that applying IFGs to technology development and assessment could steer research, development, and technological innovation in new directions from the viewpoint of futurability.

To demonstrate this point, we conducted a participatory deliberation experiment involving students and researchers in the field of materials research and applied the concept of IFGs in the discussions. In the experiment, we explored the topic of hydrothermal reactions as a case study for a technology with the potential to resolve possible resource and energy issues. More specifically, we examined the adoption of hydrothermally produced porous glass, which is a porous glass that is obtained by a reaction that utilizes subcritical water or vapor as a medium. We took up this technology because, although it is considered environmentally friendly due to enabling a much lower powder reaction temperature than conventional methods (Suzuki et al., 2014), it has short-term issues related to its adoption, as explained in Section 2.1. Consequently, adopting this technology requires a long-term outlook to overcome these potential issues before a pathway for future adoption can be formulated. Through this experiment, we examined the trade-offs related to the widespread adoption of hydrothermal technology from the perspective of future generations. We also examined the relative importance of indicators for assessing the future potentiality of the technology and how this can be affected by the adoption of IFGs. Based on a detailed analysis of participants' discussions and responses to questionnaire surveys, we show that the concept of IFGs is effective for assessing and examining the development and adoption of technologies, and also for guiding the direction of new technological innovations.

The remainder of the manuscript is organized as follows. The subsequent section, Section 2, describes the methods, focusing particularly on the design of a deliberation experiment and questionnaire survey for the assessment of the future potentiality of a technology. Section 3 summarizes the discussion and assessment results, focusing on the differences between those based on the perspective of current generations and those of IFGs. Section 4 discusses the main findings and implications, followed by conclusions.

2. Methods

2.1. Case study topic – Hydrothermally produced porous glass and issues with its adoption

This study examined hydrothermally produced porous glass, which is fabricated using hydrothermal reactions, as a theme (case study) for discussion by the participants of a participatory deliberation workshop. Hydrothermally produced porous glass is a porous glass material formed by the hydrothermal treatment of waste glass. The glass is infused with a large quantity of H_2O during hydrothermal treatment. Then, by reheating at atmospheric pressure, the H_2O in the glass volatilizes and desorbs, resulting in spontaneous expansion of the glass. Nakamoto et al. (2005) reported that this hydrothermal reaction enables glass containing SiO_2 and B_2O_3 to store large quantities of H_2O. Yoshikawa et al. (2008) found that borosilicate glass infused with H_2O softens at a much lower temperature than non-hydrated glass, making the production of porous glass relatively straightforward. Furthermore, Suzuki et al. (2019) used a spectroscopic method to investigate the morphology of hydroxyl groups in porous glass, and discussed the mechanism by which the porous structure is formed.

In terms of applications of hydrothermally produced porous glass, attempts have been made to use the porous glass as a catalyst support by the application of catalytically active silver nanoparticles (Yoshikawa et al., 2011), and to fabricate porous glass with a porous surface comprised of a tobermorite compound with the ability to adsorb and remove heavy metal ions from aqueous solutions (Suzuki et al., 2013). The above-mentioned method aims to reuse waste materials containing multicomponent oxides, such as waste glass and slag, and to develop new applications. Hydrothermally produced porous glass can be produced using waste glass, water, and waste heat. In addition to filters for removing impurities, it can be used as a heat-insulating material for buildings, due to its excellent thermal insulation that its porous structure confers. In addition, hydrothermally produced porous glass has attracted considerable interest, because it can also be recycled repeatedly as a raw material for fabricating new porous glass.

On the other hand, the adoption of hydrothermally produced porous glass technology has faced several problems. For example, the waste glass that is used as a raw material needs to be pulverized in order to promote hydrothermal reactions, resulting in an additional energy requirement. Other problems include the requirement for energy to heat the water, which has a high specific heat, as well as the cost of transporting the waste heat from other industries, and other technical issues (Fig. 1). From a Life Cycle Assessment standpoint, the additional energy that is required to manufacture hydrothermally produced porous glass is a major disadvantage (Muralikrishna and Manickam, 2017). As this example shows, viewing technological development and its adoption as an extension of current circumstances presents a variety of hurdles and challenges. In terms of materials production that places a priority on sustainability and resource recycling—a challenge that humanity must look to address—R&D and methods to promote adoption need to be examined strategically. To examine the direction of new innovations, from basic research and R&D to adoption, it is therefore necessary to consider the perspective of future generations comprehensively.

2.2. Adoption of IFGs – Rationale behind the workshop design

Previous studies have demonstrated the effectiveness of adopting IFGs in decision-making to generate futurability (Kamijo et al., 2017; Saijo, 2020; Hara et al., 2019). The first practice of Future Design was conducted in 2015 in the town of Yahaba, Iwate Prefecture, Japan (Hara et al., 2019). Residents of the town participated in a series of workshops

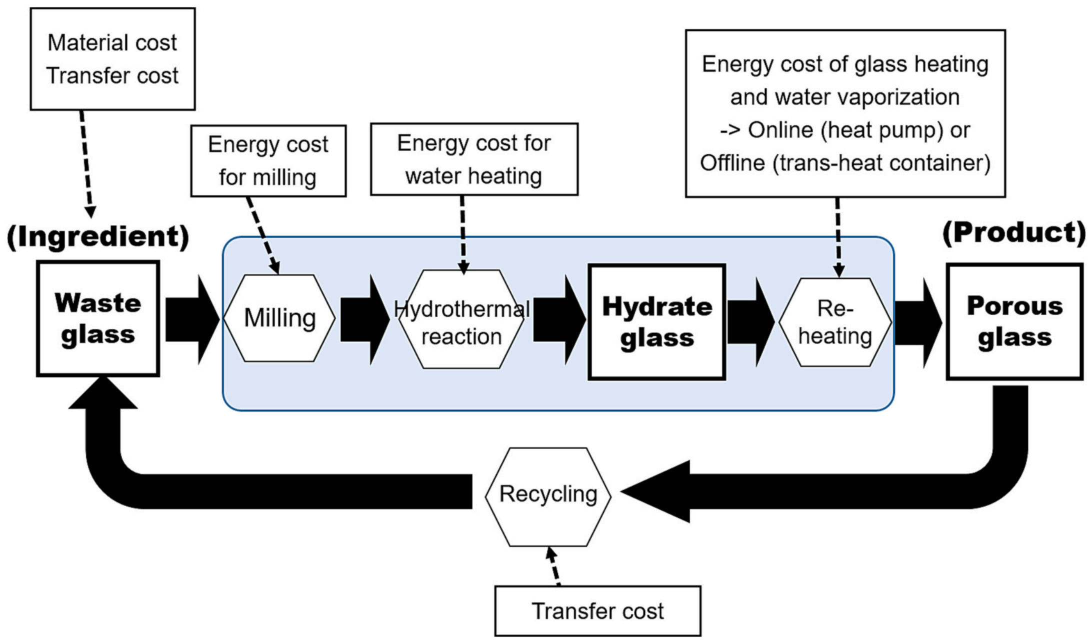


Fig. 1. Processes of manufacturing using hydrothermal technology.

over a period of six months to design a local development plan with a target year of 2060, and to identify the policy measures that needed to be implemented in order to realize the plan. Participants were divided into four groups, i.e., two groups representing IFGs and two groups representing the current generation. After each group had devised plans and policy measures, the current-generation groups and the IFG groups were paired to build consensus between their proposals. The findings showed that the ideas and proposals of the IFG groups were considerably more creative than those of the current-generation groups, as the former placed more emphasis on utilizing local resources and the positive aspects of the town while latter focused more on problem solving-type solutions. The IFG groups were more concerned about the values of future generations (Hara et al., 2019). This tendency of the IFGs to prioritize different normative values considering the benefits of the future generation and sustainability were demonstrated in a variety of subsequent Future Design practices (Hara et al., 2021; Hiromitsu et al., 2021; Uwasu et al., 2020; Nishimura et al., 2020; Kuroda et al., 2021). We argue that the new perspectives and creativity demonstrated by IFGs is related to the activation of futurability (Saijo, 2018).

In this study, we refer to the method of using IFGs (Hara et al., 2021), which is based on Shahrier et al. (2017). In this method, participants shift their viewpoints from the current generations to future generations. The method has been applied to various Future Design practices and has been demonstrated to be effective for generating futurability.

The effectiveness of a retrospective perspective, i.e., of "looking back" over the past and sending messages to the past, was also proven to be effective for activating "futurability" (Nakagawa et al., 2019). Hara et al. (2019) analyzed the socioeconomic and land use changes between the past and present before adopting IFGs. We argue that analyzing the past can be used to provide insights into how to generate future generations' perspectives and to understand long-term viewpoints.

By referring to the aforementioned studies, the present study aims to demonstrate our hypothesis that the adoption of IFGs can shift the direction of technology innovation and assessments of the future potentiality of technology from the viewpoints of futurability and sustainability by overcoming shortsightedness. The following section explains the methods used based on previous studies to prove this hypothesis.

2.3. *Outline of workshop*

2.3.1. *Settings*

For this study, four participatory deliberation sessions were held to investigate the adoption and future potentiality of hydrothermally produced porous glass. A total of 23 people participated in the deliberations; 18 undergraduate and graduate students and five faculty members from the Interface Science and Technology Area, Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University. For the discussions, which were held over four sessions, the participants were divided into four groups. In forming multiple groups for the discussion experiments, we hoped to obtain sufficient knowledge to identify common effects of the treatments that we applied to condition the discussions, while keeping the discussion contents diverse. The group members were selected so that each group had a similar age, academic level, and gender composition, and groups remained fixed for all four sessions. Each group consisted of 5 or 6 members. The four groups recorded the contents of their discussions by writing them down on poster-sized sheets of paper during the course of the discussions. After each discussion session, we administered a questionnaire survey of all participants, as described in Section 2.4.

2.3.2. *Workshop design*

The four discussion sessions were held as follows: Session 1 (Oct. 5, 2020), Session 2 (Oct. 17, 2020), Session 3 (Oct. 26, 2020), and Session 4 (Nov. 2, 2020). Each discussion session, which was held in rooms on the Osaka University campus, lasted about 3 h.

The discussion process described below was designed based on findings from earlier studies on Future Design that aimed to activate futurability, as described in Section 2.2. In Session 1, the participants looked ahead to the future from the perspective of current generations, to first examine the effects and challenges of practically implementing hydrothermal technology. They then discussed the social and manufacturing scenarios in 2040, as well as scenarios for the adoption of hydrothermal technology to realize their vision of society in 2040. In Session 2, the participants analyzed and assessed case studies of past R&D projects that were related to hydrothermal technology in Japan and worked to redesign these previous R&D projects. In Session 3, all of the participants adopted the perspective of an imaginary future generation of 2040 to discuss and describe a vision of society and manufacturing in 2040, just as they did in Session 1. Maintaining the perspective of IFGs, in Session 4, they described a scenario for the adoption of hydrothermal technology in 2040 based on the state of society and manufacturing in 2040 that they described in Session 3. Note that the study of the scenario for the adoption of hydrothermal technology was centered mainly on Japan, but the participants were permitted to consider case studies from other countries, as necessary.

The workshop was designed to enable participants to examine the state of society and manufacturing in 2040, as well as adoption scenarios for hydrothermal technology in 2040 from the viewpoint of the current generation (Session 1), and from the viewpoint of the IFGs of 2040 (Sessions 3 and 4). This enabled us to compare the discussion contents and the commonalities and differences in the ideas between the two viewpoints (i.e., current generations and IFGs) and to examine the effects of treatments adopted in the study. In this way, we analyzed how the adoption of IFGs affects the way that a future society is depicted, the scenarios affecting the adoption of a particular technology, and the direction of R&D and technological innovation. The inclusion of the discussion process of Session 2 was based on earlier studies, which showed that the process of evaluating the past is also effective for acquiring the perspective of future generations (Nakagawa et al., 2019). Fig. 2 shows the flow of the workshop.

In addition to writing up their discussion contents and remarks during each session on poster-sized sheets of paper, participants also made audio recordings of all discussions. Consequently, everything expressed by the groups was recorded and used in the analysis of the discussion contents and results. At the end of each discussion, each group made a presentation of the contents of their discussion, so information was shared between the groups. Table 1 overviews discussion contents and steps of the workshop. A detailed description of the discussions held in each session is given below.

Table 1
Discussions and steps in each session.

	Discussion contents
Session 1: Discussion as current generations	• Information provisions and basic orientation on hydrothermal technology • Part 1: Study the effects and challenges of implementing hydrothermal technology • Part 2: Address potential changes in social conditions (social values) and the state of manufacturing and industry in 2040 • Part 3: Depict scenarios for hydrothermal technology implementation through to 2040 • Part 4: Discuss indices (items) for evaluating the future potentiality of hydrothermal technology
Session 2: Analysis/redesign of past projects	• Information on past projects on hydrothermal technology • Part 1: Review and assess past case studies/projects • Part 2: Analyze past trends and review current status • Part 3: Redesign past projects and R&D case studies
Session 3: Discussion as IFGs	• Part 1: Review Sessions 1 and 2 • Explanation of Future Design • Part 2: Depict 2040 society and manufacturing practices as IFGs • Part 3: Create a timeline of historical development as IFGs and revise vision of society in 2040
Session 4: Discussion as IFGs	• Part 1: Review discussion of previous session • Part 2: Depict implementation and state of R&D of hydrothermal technology in 2040 • Part 3 Discuss evaluation indexes used for comprehensively assessing the future potentiality of hydrothermal technology

- Session 1 (October 5, 2020): Discussion as current generations

In Part 1, we first provided basic information about hydrothermal technology. Specifically, we presented information on the theory of hydrothermal reactions, strengths of hydrothermal technology (e.g., ability to react at low temperatures, short reaction times, use of resources with low environmental impact, etc.), challenges (e.g., problems in life cycle assessment such as cost and energy issues for technology diffusion, technical constraints, etc.), and manufacturing processes using hydrothermal technology, as shown in Fig. 1. Then, the

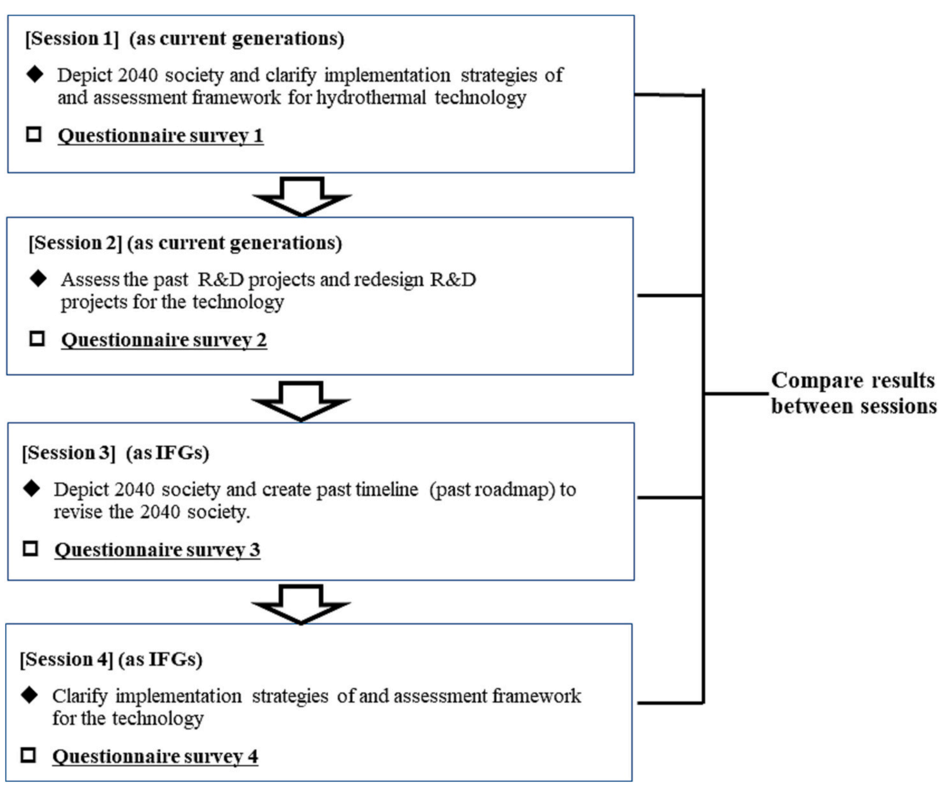


Fig. 2. Flow of workshop.

participants were divided into four groups and held their discussions in four parts, as described below.

In Part 1, the groups discussed the effects and advantages for society of implementing hydrothermal technology in the future, as well as the hurdles and challenges facing the implementation and diffusion of the technology, and they shared their views with the other groups.

In Part 2, the participants discussed changes in social circumstances and the state of manufacturing and industry in 2040. Specifically, they used worksheets to list events that might affect the values of society by 2040 and examined scenarios based on how each of the events might impact the values of society, the state of industry, human life, and the state of manufacturing. Finally, from the results of their discussions, the groups summarized the state of society in 2040 (i.e., envisioning the society in 2040).

In Part 3, the participants discussed the implementation scenarios for 2040 that they envisioned in Part 2, focusing on the value of hydrothermal technology and how it would be utilized in society. Furthermore, they examined whether there would be any hurdles or challenges to the implementation of hydrothermal technology in 2040.

In Part 4, the participants were asked to list indicators for evaluating the future potentiality of hydrothermal technology with a view to the society of 2040. As examples of indicators, they were presented with the indicators used in the questions of the questionnaire forms, as shown in Section 2.4 (Table 2). They then discussed their priorities (weighting) of these indicators and whether there were any other indicators that needed to be added in order to enable a comprehensive assessment.

- Session 2 (October 17, 2020): Analysis, assessment, and redesign of the past

In Session 2, the groups analyzed and assessed previous R&D projects related to the technology in question and engaged in a redesign process to explore alternatives to the projects that were actually implemented. To begin, as an example of a relevant R&D project undertaken in the past, the authors presented participants with an outline of the Hyogo Eco-Town project, along with some details of relevant issues that were prevalent at the time. The Eco-Town project concept was a zero-emissions initiative introduced by the Japanese government in 1997 to promote both environment-friendly urban development and the revitalization of local industries. As part of this project, hydrothermal technology was deployed in Hyogo Eco-Town as part of a slag recycling system, beginning in 2006. At this workshop session, we presented facts and information about the hydrothermal reaction experiments, the slag recycling process, economic data relating to implementation of the technology, and the issues associated with implementation that became known due to this project. The implementation issues included additional costs for pulverizing material, additional energy for heating water, and technical issues associated with waste heat transportation. These issues were all explained using concrete data based on the Hyogo Eco-Town project in which one of the authors was involved.

Based on the above information, in Part 1 of the session, the participants exchanged opinions on the hydrothermal R&D characteristics and implementation issues in the Hyogo Eco-Town project case study within each group. In Part 2, through the following three steps and using a worksheet, the groups examined the historical development of hydrothermal technology from 2006, when the Hyogo Eco-Town project began, to the present (2020).

1) Identify previous social phenomena and events that impacted social values and industrial systems (manufacturing), and analyze their impacts and effects on society or on the shaping of social values.
2) Based on the information provided, examine whether any changes or developments occurred in R&D or technology requirements associated with hydrothermal technology.
3) Compare the current situation in 2020 with that in the early 2000s, when the project began, characterize the situation in 2020 in terms of two points: (1) social values and the state of manufacturing, and (2) the development of hydrothermal technology.

In Part 3, the groups used the historical development and current (2020) characteristics (in Japan or overseas) discussed in Part 2 as a basis for "redesigning the past", by formulating alternative directions in R&D and adoption different to those that actually occurred in this project, from the standpoint of the present year 2020. More specifically, they discussed what might have happened and what situation might have developed in 2020 with regard to the pathways of hydrothermal technology R&D and implementation if other alternatives had been realized at previous time points in this project.

- Session 3 (October 26, 2020): Discussion as IFGs

In Sessions 3 and 4, all participants adopted the perspective of the future generation of 2040 to examine the issues in question from the standpoint of IFGs. In Part 1 of Session 3, the authors gave a presentation on Future Design. In accordance with the findings of previous studies, the presentation explained meaning and the value of adopting the perspectives of future generations, together with information on the actual practices adopting IFGs (Saijo, 2018; Hara et al., 2019). Then, to help the participants step into the shoes of IFGs, we told them the following: "Imagine time-traveling 20 years into the future, to the world of 2040, but remaining the same age, and imagine what it is like to live in that world. Imagine that in that world of 2040, you are still a student or researcher who is eagerly involved in R&D on materials engineering and the realization of a sustainable society." This instruction is basically the same as that employed in other Future Design workshops that have been conducted (Hara et al., 2021; Hara et al., 2019; Hiromitsu et al., 2021; Uwasu et al., 2020).

In Part 2, the groups discussed and formulated images of society and manufacturing practices in 2040 from the perspective of the IFGs of 2040. They specifically discussed 1) social values and trends in 2040, and 2) what kinds of practices and technological developments are prevalent in what kinds of manufacturing industry of 2040, in accordance with such social values.

In Part 3, the participants used a worksheet to create a timeline showing the historical course of events that occurred before 2040 (i.e., historical roadmap before 2040). Based on the worksheet, they revised and updated the images of 2040 society they formulated in Part 2. The groups created this historical timeline by deepening their discussions of the following points: a) What significant social events and phenomena (including policy trends in national and international organizations) occurred between 2000 and 2040? b) What kinds of social values and trends were shaped by these processes? c) As a result, in the manufacturing industry of 2040, what kinds of practices and R&D were pursued, and what kind of values were they based on? Next, based on the historical timeline, the groups revised and redefined the shared images of 2040 society.

- Session 4 (November 2, 2020): Discussion as IFGs

In Session 4 of the workshop, the participants were asked to continue the discussion of Session 3 from the same perspective; i.e., that of the

Table 2
Questionnaire items.

Item No.	Items (type of indicators)
(1)	Resource recycling and reuse
(2)	Reducing environmental impact
(3)	Effective energy utilization
(4)	Implementation costs (initial and running costs)
(5)	Resource and energy burdens of implementation
(6)	Social acceptability
(7)	Technological innovation

IFGs of 2040. After reviewing the previous discussion in Part 1, in Part 2 the groups imagined how hydrothermal technology could be used in society based on the current state of society and manufacturing industry in 2040. They did this according to the following three-step process:

(1) Examine how hydrothermal technology is being applied or utilized in the context of the state of the world, social values, and manufacturing practices of 2040. Examine the state of R&D on hydrothermal technology.
(2) Examine what kind of value hydrothermal technology can offer in 2040, based on the results of discussions in step (1).
(3) Examine the challenges in applying or implementing hydrothermal technology (or in hydrothermal R&D) in 2040.

Finally, based on the above, the groups summarized the state of hydrothermal technology utilization in 2040. For this task as IFGs, they were asked to imagine that they were sending a message to people in 2020.

Retaining their viewpoint as IFGs, in Part 3 of the session the groups discussed evaluation indicators and relative importance among them for comprehensively examining the future potentiality of hydrothermal technology. We specifically advised them as follows: "Now that you all know the state of the application of hydrothermal technology in 2040, what advice would you send to researchers and engineers who are considering the future potentiality of hydrothermal technology in 2020?" The participants prepared a message for the generations of 2020 from their perspective as IFGs in 2040.

2.4. Questionnaire surveys

After each workshop session, we administered a questionnaire to the participants, asking them to rate the degree of importance of different indicators for assessing the future potentiality, in terms of the adoption of hydrothermal technology. The same questionnaire was administered after each of the four sessions, to analyze the changes in responses over the course of the workshop. The questionnaire was completed by individuals after the discussion.

In advance, we selected seven possible indicators to comprehensively assess the future potentiality of hydrothermal technology and its adoption, based on exchanges of opinions with hydrothermal technology researchers and essential issues identified by referring to Fig. 1 (See Table 2). Question 1 (Q1) of the questionnaire asks the workshop participants to rank the importance of each of the seven indicators on a scale of 1 (not very important) to 5 (very important). In Question 2 (Q2), they had to rank the three most important indicators from Q1 in order of importance. Then in Question 3 (Q3), the participants were asked to provide reasons for their choices in Q2 in descriptive form. As described below, the third and fourth questionnaires were administered immediately following discussions conducted from the viewpoint of IFGs, so the participants (respondents) were instructed to maintain that perspective while answering the questionnaire. Using the data collected from the questionnaires, we analyzed how the importance of different indicators changed over the course of workshop sessions.

3. Results

3.1. Analysis of discussion contents

Appendix 1 summarizes the essential points and discussions in each session by group. Based on Appendix 1, the main points of the discussions of each group in each session are summarized below. In particular, we show the changes in discussion results as a result of adopted treatments, such as IFGs.

- Group A
- Workshop Session 1 (As the current generation)

The society of 2040 envisioned by this group, from the viewpoint of the present, was characterized by increased automation and remote working, with manufacturing distributed in remote locations rather than centered in one place. At the same time, the group imagined that due to a failure to satisfactorily implement the SDGs by 2030, a new set of common goals for humanity, known as the Post-SDGs, are imposed. Thus, the group envisioned the society of 2040 in which the values of aiming for a sustainable society are universally shared based on the reflections of the SDGs.

In this society, hydrothermal technology is used as a heat-insulating material for houses and buildings in rural areas, which are increasing due to the acceleration of remote working and living. Key technical issues to be addressed in 2040 are the energy cost of hydrothermal reactions, and solutions to finding an alternative material to boron and to recovering boron.

In light of the above, the group concluded that the most important indicators for technology assessment were "Resource recycling and reuse" and "Reducing environmental impact". It is suggested that the emphasis on these two indicators is related to the fact that in this group's vision of 2040, sustainability has become a universal value.

- Workshop Session 2 (Analysis and redesign of the past)

Through its analysis and assessment of the past, this group confirmed the emergence of "doubts regarding living safety" as a major social concern, as well as the emergence of a new way of thinking about energy after the nuclear accident that occurred following the Great East Japan earthquake of 2011, specifically, with greater emphasis on processing and clean energy.

The group confirmed that, by the time the technology was proposed in the Hyogo Eco-Town, the ability to capture heavy metals using the tobermorite hydrate crystals generated by hydrothermal treatment of blast furnace slag had already been clearly demonstrated; only its mechanism remained unclear. In addition, although there was little motivation or concern about improving water quality at the time, by 2020, awareness about improving water quality was high, so the pursuit of R&D was proposed as the theme of redesign, taking account of this goal. Also, since competing calcium silicate materials offer a cost advantage, it was important to create alternative products with high added value. From this viewpoint, heavy metal recovery should have been promoted. Summarizing the above, the group redesigned the R&D at the start of the Hyogo Eco-Town project to place greater focus on recovery and adsorption of heavy metals.

- Workshop Sessions 3 and 4 (As IFGs)

Adopting the perspective of IFGs in the year 2040, the group envisioned a world in which renewable energy is prevalent. In 2040, hydrogen power generation is mainstream in high-latitude regions, while solar power is the mainstream at low latitudes. The oil and fossil fuel industries are in decline. On the other hand, the destruction of nature (deforestation) due to the proliferation of renewable energy plants has become a problem. The vision also foresees social problems stemming from economic strife in oil-producing countries and a widening disparity between rich and poor.

In the 2040 society that they envisioned in Session 3, the group saw hydrothermal technology used widely to recover heavy metals and to increase thermal insulation performance through porous structure control. Hydrothermal technology was helping to recycle the huge quantities of waste window glass resulting from the decline in use of office buildings due to the diffusion of remote working. At the same time, the group viewed hydrothermal technology's continued lack of appeal in 2040 as a serious issue. Applications of hydrothermal technology are still limited, and its lower cost and energy savings are not sufficient to make the technology attractive. Therefore, technological innovation is important for improving the appeal of the technology. As an example of potential innovation, the group proposed research combining materials informatics with porosity control, to improve the thermal insulation of products.

In accordance with the above discussion results, the group ranked the indicators for future potentiality of this technology, in order of most to least important, as “Technological innovation”, “Social acceptability”, “Resource recycling and reuse”, and “Reducing environmental impact”.

- Group B
- Workshop Session 1 (As the current generation)

In their vision of society of 2040 from the current generation’s perspective, the group imagined a world in which environmental values are being stimulated by weather patterns changes and increasingly frequent natural disasters. They also envisioned that recycling technology would mature and that the practice of social distancing, which started after COVID-19, would persist after 2020, thereby reducing opportunities for human contact. In the field of manufacturing, factories are more distributed and remote, advanced recycling is the norm, and the recovery of rare metals is actively practiced.

In the group’s vision of the world in 2040, hydrothermal technology has not yet been used in any substantial way, despite some attempts to apply it in urban mining for rare metal recovery and for waste treatment. The key challenges for the technology are developing a clearer understanding of how it works through in-situ observations and explaining clearly what kind of processes can only be achieved by hydrothermal technology (i.e., making added value clearer).

The group concluded from the above discussion that “Technological innovation” was the most important indicator for assessing the future potentiality of this technology. It also proposed “Comparison with other technologies” as a new indicator.

- Workshop Session 2 (Analysis and redesign of the past)

The group shared various observations from its analysis and assessment of the past. In terms of changes in social values, it noted that the importance of sustainability has begun to be recognized and that values related to rationality have been fostered. In connection to this, it also noted the trend towards shorter working hours and other work-style reforms. In its redesign of the Eco-Town project, the group suggested that use of geothermal power generation be adopted in highly volcanic regions (e.g., *Kyushu*) as a heat source for hydrothermal technology. In other words, by analyzing and redesigning past policies, the group may have revised its view of the scope and concept of “place” as a condition for applying and socially implementing technology, leading to the emergence of a new perspective.

- Workshop Sessions 3 and 4 (As IFGs)

In their perception of the world in 2040, from the viewpoint of IFGs, renewable energy is prevalent, global warming has slowed somewhat, but worldwide carbon emissions are still rising due to development in Africa, social distancing has become normalized, and Internet literacy has improved as Internet behavior is monitored.

As for manufacturing fields in this society, the group imagined the completion of a lunar base in the late 2030s, followed by the commencement of steel production on the Moon in the early 2040s, the mining of methane hydrate from beneath the ocean, as well as the rise of 3D printers and the ubiquity of made-to-order manufacturing.

In the world envisioned by the group in 2040, research and applications of hydrothermal technology are focused on reducing environmental impacts, based on the social value of “Labor-saving”. Research on the use of hydrothermal conditions on the seabed and applied research aimed at implementing this technology for rare metal recovery and other applications is progressing. At the same time, the safety of supercritical water and a lack of clarity about hydrothermal reaction mechanisms remain issues.

In response to these discussions, the group added a new indicator for assessing the future potentiality of hydrothermal technology: “Labor-saving”, in the sense of promoting the elimination of any kinds of effort. As the workshop progressed, the group placed increasing importance on the indicators “Reducing environmental impact” and “Effective energy utilization”, and decreased importance on “Technological innovation” and “Social acceptability”.

- Group C
- Workshop Session 1 (As the current generation)

In its vision of the world in 2040 from the perspective of current generations, the group anticipated that the social distancing that began in 2020 would continue, with people commuting shorter distances due to the prevalence of IT-based remote work, as well as accelerating parameterization from various viewpoints and the use of advanced digital IT. From these results, a prevalence of 3D printers and accelerating parameterization would enable successful porous structure control in hydrothermal technology, facilitating considerable freedom in glass-shaping. Furthermore, “4D printing” technology based on a hydrothermal sintering function would be used as a forming technology. (The extra dimension, or “D”, relative to 3D printing means that design drawings can be sent to a remote location, even overseas, for local production.)

On the other hand, the group saw that developing new applications for the technology remained a significant challenge. In accordance with the group’s discussions, the future potentiality indicators it considered most important were “Technological innovation”, “Social acceptability”, and “Resource recycling and reuse”.

- Workshop Session 2 (Analysis and redesign of the past)

In the process of analyzing and assessing the past, the group identified and shared several lessons. For example, it pointed out that various past incidents (e.g., accidents) led to increased safety consciousness and that the Great East Japan earthquake reshaped peoples’ thinking about energy and raised awareness about safety. In R&D, the group confirmed that neural networks came into use in the early 2000s, that a digital information revolution occurred, and that manufacturing systems were designed with recycling in mind from the outset. In its redesign of past projects, the group suggested that the past generations should have anticipated the rise of advanced IT by the research combining machine learning with hydrothermal technology. The group also proposed data collection and optimization of hydrothermal conditions and optimized steelmaking process incorporating slag reuse, and based on these ideas, it drafted an alternative plan that would have enabled a faster and more optimal hydrothermal process.

- Workshop Sessions 3 and 4 (As IFGs)

In the world of 2040 envisioned by the group from the viewpoint of IFGs, sustainability has become a widespread and important social value, manufacturing has advanced to the point of reaching zero waste generation (all waste becomes recycled material), and a resource recycling system has been established. In this society, the perception “Waste = Recycled material” is natural, and all manufacturing involves a complete cycling of resources within the country or region.

In the group’s perception of 2040 in this session, hydrothermal technology is used as one of several potential technologies supporting the established recycling system, generating value by contributing to resource and energy recycling. The group also proposes the idea of recycling energy in the process of producing porous glass by blowing hydrated glass using hydrothermal energy. In other words, it shared the concept of “Energy circulation” as a new requirement for technological development. However, the group considered that the challenge of developing technologies and systems to circulate energy was difficult, with a lack of accumulated data for optimization.

In its rating of indicators for assessing the future potentiality of technologies, the group stressed the importance of the positioning of individual technologies, particularly for a society with a highly integrated resource and energy circulation system. It therefore ranked "Technological originality" as the most important indicator. Given that resource recycling is incorporated into society, the group discussed the importance of accurately grasping the relative strengths and weaknesses of specific characteristics, rather than just evaluating technologies as superior or inferior.

- Group D
- Workshop Session 1 (As the current generation)

The group's vision of 2040 from the perspective of current generations is of a world that emphasizes sustainability where people are willing to pay money to help solve environmental problems. The group also assumed that manufacturing in 2040 would feature fully automated and decarbonized production processes.

In this kind of society in 2040, the group envisioned hydrothermal technology as being used for the manufacturing of highly recyclable consumables, thereby creating value in terms of recyclability.

In its ranking of indicators for assessing the future potentiality of the technology, the group saw "Reducing environmental impact" as an important indicator from the viewpoint of creating products from waste, and it also gave importance to "Technological innovation", in light of the fact that the technology represents a new way of using a highly familiar substance, water. At the same time, the group saw "Implementation costs" and "Resource and energy burdens of implementation" as relatively unimportant, because it envisioned major advances in the miniaturization of equipment capable of withstanding high pressure, as well as lower costs for transportation and the creation of high-pressure environments.

- Workshop Session 2 (Analysis and redesign of the past)

In its analysis and assessment of the past, the group perceived a lack of concrete policies for addressing environmental issues, as well as a change in consumer consciousness about energy (especially the safety aspect), triggered by the Great East Japan earthquake. On hydrothermal reaction technology, the group commented that even though Hyogo Eco-Town promoted waste heat utilization, it would have been better from the standpoint of 2020 to focus on a production process that does not emit CO_2. Consequently, the group suggested that there was a need for R&D to make the energy required for a clean production process (decarbonized).

In its redesign of the past project, the groups formulated an alternative scenario of the past, in which a breakthrough in waste glass powderization technology, which was an issue in Eco-Town, enabled greater implementation of hydrothermal technology.

- Workshop Sessions 3 and 4 (As IFGs)

In its view of 2040 society from the perspective of IFGs, the group saw innovations in renewable energy facilitate abundant use of clean, decarbonized energy. In the field of manufacturing, the promotion of high-mix low-volume production and decarbonization processes are essential, and products that emit CO_2 are subjected to environmental taxes, thereby cultivating a widely shared perception that the cost of environmental conservation is a social cost. The group also envisioned that the acquisition of natural resources from the moon and the oceans is well established.

In its vision of the world in 2040, the group considered that hydrothermal technology can be implemented anywhere, thanks to advances in high-temperature and high-pressure technologies (adding value to small-scale production and made-to-order products). There have also been significant cost reductions due to breakthroughs in waste glass powderization technology. Carbon-free manufacturing is now taken for granted and hydrothermal technology has demonstrated its value in CO_2 emission-free production processes. Furthermore, the social value placed on paying for the real cost of resource use and in trying to recycle waste materials boosts the use of hydrothermal technology. On the other hand, the group sees challenges, including a need to expand applications beyond building materials and to develop high value-added products.

In accordance with the above discussions, the group considered the most important indicators for evaluating the future potentiality of the technology as "Reducing environmental impact", as well as a new indicator it proposed itself, "Expandability of applications". The latter indicator was considered especially important, given that developments in hydrothermal technology have enabled increasing product diversity boosting demand for the technology.

3.2. Analysis of questionnaires

3.2.1. Changes in scores by group

We present the results of Q1 to show the change in the relative importance of indicators by the treatments, such as retrospective analysis and IFGs. Figs. 3–6 below show the mean ratings (scores) of each group (average score of group members) for each of the seven evaluation indicators of Q1 in the questionnaire, for each of the four workshop sessions, in the form of radar charts. Appendix 2 shows the scores related to Figs. 3–6. The following discusses the results of analysis in relation to the deliberation results summarized in Subsection 3.1, and demonstrates that the assessment results could change in response to the adopted treatments.

- Group A

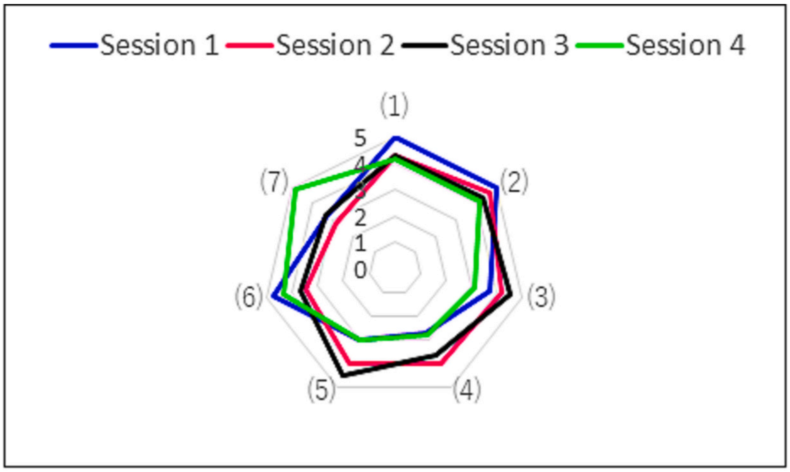
As shown in Fig. 3, a visible characteristic of Group A was a sharp increase in the rating of the indicator (7) "Technological innovation" after Session 4 (all members gave a rating of 5) compared to Session 1. There is also a notable increase in importance at the end of Sessions 2 and 3 of the indicators (3) "Effective energy utilization", (4) "Implementation costs (initial and running costs)", and (5) "Resource and energy burdens of implementation".

In Session 1, the group discussed how hydrothermal technology for recycling multicomponent oxides would be utilized in 2040, in a framework of extrapolating from existing technology. In 2040, it saw hydrothermal technology used as a heat-insulating material (hydrothermally produced porous glass) in a growing number of houses in rural areas. Assuming that in 2040, universal values aimed at a sustainable society under the framework of the "post-SDGs" after 2030 would have a great impact on society, the group placed particular importance on the indicators (1) "Resource recycling and reuse" and (2) "Reducing environmental impact".

On the other hand, in Session 4, in its discussion from the perspective of IFGs, the group realized that to successfully implement hydrothermal technology in 2040, there was a need for technological innovation to increase the technology's appeal and to clarify the reasoning for its use. For this reason, the group sharply increased its rating of the importance of "Technological innovation". Assuming that the indicators (1) "Resource recycling and reuse" and (2) "Reducing environmental impact" would be satisfied, the group's discussions led them to realize that it was important to make hydrothermal technology more attractive by giving more importance to the indicator (7) "Technological innovation".

- Group B

In the case of Group B, the results for which are shown in Fig. 4, a



Item No.	Items (type of indicators)
(1)	Resource recycling and reuse
(2)	Reducing environmental impact
(3)	Effective energy utilization
(4)	Implementation costs (initial and running costs)
(5)	Resource and energy burdens of implementation
(6)	Social acceptability
(7)	Technological innovation

Fig. 3. Results of responses to Question 1 (Group A).

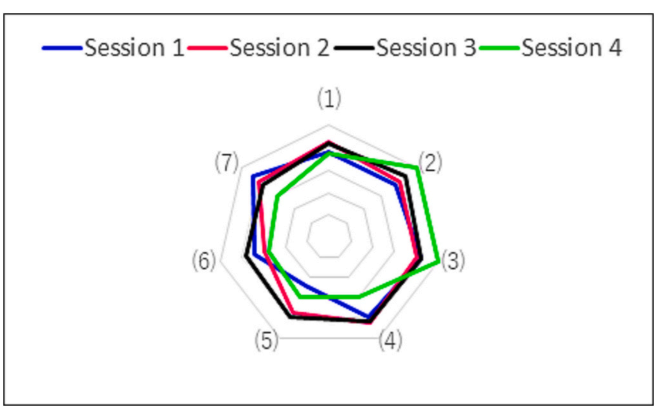


Fig. 4. Results of responses to Question 1 (Group B).

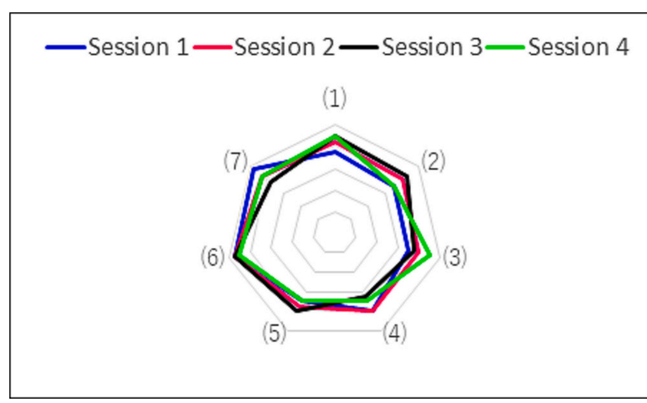


Fig. 5. Results of responses to Question 1 (Group C).

comparison of the responses after Sessions 1 and 4 reveal a marked rise in the importance rating of the indicators (2) "Reducing environmental impact" and (3) "Effective energy utilization", and a marked drop in the importance ratings of the indicators (4) "Implementation costs (initial and running costs)" and (7) "Technological innovation". Indicators (2) and (3) were considered particularly important in Session 4.

In the society of 2040 envisioned in Session 1, the group was unable to clearly discern the merits of hydrothermal technology implementation, imagining that although research on rare metal recovery had advanced, hydrothermal technology had not found substantial utilization. With this scenario in mind, the group rated the indicator (7) "Technological innovation" as the most important indicator for assessing the future potentiality of the technology. The group also put forward a new indicator, "Comparison with other technologies", to help fulfill the future potentiality of hydrothermal technology by identifying functions, features, applications, etc., that are exclusive to hydrothermal technology.

In Session 2, the group redesigned an alternative to the past implementation of hydrothermal technology, proposing the use of the technology in places where natural hydrothermal environments such as volcanoes can be harnessed. The lesson learned here helped to overcome the limitations of physical constraints, such as place as implementation

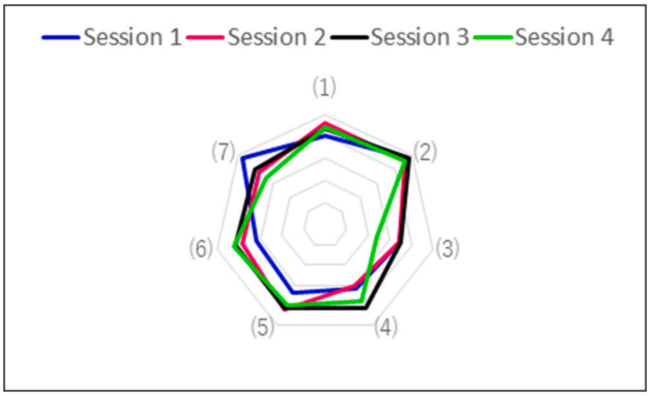


Fig. 6. Results of responses to Question 1 (Group D).

requirements, and to think with an expanded sense of space. The group also learned the lesson of rationality as a form of value formation. In Session 3, utilizing the lessons it learned in Session 2, the group eliminated all physical limitations by depicting a world that produces steel on the moon and mines methane hydrate from the ocean floor. Even as global carbon emissions are still rising due to the development of Africa, it considered "Labor-saving" as a social value, representing the idea of rationally eliminating all kinds of useless effort by using natural resources and forces in creative ways.

In Session 4, the group's image of 2040 featured increasing global carbon emissions. With this in mind, the group rated the indicators (2) "Reducing environmental impact" and (3) "Effective energy utilization" as being the most important for assessing the future potentiality of hydrothermal technology. The group also proposed "Labor-saving" as a new evaluation indicator.

- Group C

In the case of Group C (Fig. 5), a comparison of the group's responses between Sessions 1 and 4 indicated a significant rise in the importance of the indicators (1) "Resource recycling and reuse" and (3) "Effective energy utilization". At the same time, however, the importance of the indicators (4) "Implementation costs (initial and running costs)" and (7) "Technological innovation" decreased. The group also rated the indicator (6) "Social acceptability" as very important throughout the four sessions. At the end of Session 4, the group also introduced its own new indicator, "Technological originality".

In Session 1, the group envisioned a future (2040) in which the microporous structure of hydrothermally produced porous glass could be successfully controlled due to advances in digital IT technology, and implementation of hydrothermal technology featuring the application of a sintering mechanism to hydrothermal synthesis. This suggests why the indicator (7) "Technological innovation" was rated the most important indicator at the end of Session 1.

In Session 3, the group's perception of 2040 society as IFGs is characterized by a shared commitment to shaping a sustainable society and a resource recycling system that is fully integrated into society. The concept of waste does not exist in this society, because all waste is considered a resource material. In Session 4, hydrothermal technology is viewed as one of the component technologies of this 2040 society's fully integrated resource recycling system. Since the group positioned hydrothermal technology as one element supporting an entire system, it proposed a new evaluation indicator, "Technological originality". This points to the fact that the value and positioning of individual technologies can be relativized and redefined. Given that a fully integrated resource recycling system is now a prerequisite for implementing any technology, it is unsurprising to note that the importance of the indicator (1) "Resource recycling and reuse" increased after this session. Furthermore, the group floated the idea of circulating energy in hydrothermally produced porous glass fabrication processes, which is likely why the group assigned increased importance to the indicator (3) "Effective energy utilization" after this session.

- Group D

In the case of Group D (Fig. 6), we can see dramatic increases in the importance attributed to the indicators (4) "Implementation costs", (5) "Resource and energy burdens of implementation", and (6) "Social acceptability" between Sessions 1 and 4. At the same time, we note significant decreases in the importance of the indicators (3) "Effective energy utilization" and (7) "Technological innovation". The indicator (2) "Reducing environmental impact" remained important in all of the questionnaires.

In Session 1, the group envisioned a 2040 society in which there is a social consensus that costs associated with realizing a sustainable society should be accepted, which is likely why it considered the indicator (4) "Implementation costs" as being relatively unimportant. On the other hand, since hydrothermal technology is powered by water, a highly familiar substance, the group considered the indicator (7) "Technological innovation" to be important. Anticipating the strong focus on decarbonization in 2020 to continue through to 2040, the group also considered the indicator (2) "Reducing environmental impact" as being important.

In Session 2, the group realized that powderization technology was a hurdle to the implementation of hydrothermal technology and that a breakthrough to overcome this hurdle was important. It also realized that demand for decarbonized clean energy was more important than waste heat utilization, so in its redesign of the past, the group shifted the direction of R&D policy towards the development of clean energy processes. In Session 3, the group built on the findings of its analysis of the past to share an image of society in 2040 as IFGs in which clean energy processes have been successfully developed. In a world in which clean energy can be used in abundance, R&D requirements naturally change. Thus, the relative importance of the indicators (3) "Effective energy utilization" and (7) "Technological innovation" declined. At the same time, since the group considered the creation of high value-added products and gaining broad public acceptance challenges, it proposed "Expandability of applications" as a new indicator and gave more importance to "Social acceptability". Throughout the four sessions, the group argued consistently for the importance of decarbonization and maintained a high rating for the indicator (2) "Reducing environmental impact".

3.2.2. *Implications of the analysis*

This section discusses the trends in the changes in scores across groups and their implications in terms of the effects of adopted treatments based on the results of the questionnaires (Appendix 2). Comparing the scores after Session 4 (Discussions as IFGs) and those after Session 1 (Discussions as the current generation), we found that the scores obtained for environment related-issues, such as (1) Resource recycling and reuse, (2) Reducing environmental impact, and (3) Effective energy utilization, could either increase or decrease depending on the images of society in 2040 and the characteristics of discussions. The primary motivation for the research and development of hydrothermal technology lies in the premise that it is environmentally friendly (e.g., the ability of hydrothermal technology to utilize waste heat). For example, the mean scores of both items (1) and (2) in Group A were 5.0 after Session 1 (as the current generation). However, the scores for items (1), (2) and (3) decreased after Session 4 (as IFGs). On the other hand, the scores for items (1), (2) and (3) tended to increase in other groups after Session 4. We argue that the direction of changes in scores have to do with both how the society, and technological adoption within the society, were envisioned in 2040. A previous Future Design practice in the industrial sector showed that indicators related to global environmental issues would be more prioritized as a criterion for R&D strategy when formulating considerations as IFGs (Hara et al., 2023a). However, we argue that the relative importance of such indicators could change depending on the envisioned images of future society and other conditions, such as the background and attributes of participants, when thinking as IFGs.

Item (5), i.e., "Resource and energy burdens of implementation", is related to implementation of hydrothermal technology in a real society. Notably, the scores obtained for the indicator increased between Sessions 1 and 4 in Groups B and D, and remained the same in Groups A and C, demonstrating that the participants noticed the importance of the item as the result of discussions as IFGs.

As for item (7), i.e., "Technological innovation", the scores for the item decreased for Groups B, C and D after Session 4, but the score increased in the case of Group A. Group A discussed the importance of technology innovation in view of its adoption in a specific context of future society, as illustrated in Section 3.2.1. However, we argue that the importance of the aspect of "Technological innovation" appeared to have decreased by examining the issues in the contest of implementation in future society from the perspective of future generations.

4. Discussion

4.1. Main findings and implications

The important findings and implications of this study are described below. In particular, there are some points that can be commonly observed in the discussions of all groups.

Firstly, it is clear that there can be a significant difference between the perspectives of current generations and IFGs when considering the state of society and manufacturing in 2040, or in scenarios related to the adoption of hydrothermal technology. It is also important to note that there was a marked difference among groups in terms of how the society in 2040 was envisioned. Several factors could have affected the resultant diversity in these perspectives, including the attributes of participants. It is known that the adoption of IFGs could enhance the perception about future risks (Hara et al., 2023b), while it could also lead to strengthening innovative ideas (Hara et al., 2019; Saijo, 2018). The possible effect of adopting IFGs could also be one of the reasons for the resultant diversity of the images of future society. The findings also showed that there was a shift in the frame of reference used to view technology development strategies and adoption requirements. We argue that this shift pertains to the activation of futurability by adopting IFGs (Saijo, 2018; Hara et al., 2021; Hara et al., 2019). Different scenarios for future society and technology adoption envisioned by the IFGs led to a major change in the conditions and prerequisites of technological development and adoption. This also indicates that considering research and development from the viewpoint of IFGs could lead to a change in the direction of innovation, due to the activation of futurability.

Secondly, in the process of analyzing and redesigning the past in Session 2, the participants acquired viewpoints and learned lessons about how social and economic conditions, as well as R&D and adoption requirements, change over time. The perspectives directed towards the past may contribute to the acquisition of new thoughts and ideas as IFGs. Studies on Future Design have shown that analyzing the past is effective for acquiring the perspective of future generations (Nakagawa et al., 2019). The results of this study are not only consistent with these findings, but also suggest that the process of analyzing the past can serve to generate ideas for thinking about things from the viewpoint of future generations.

Thirdly, the relative value of a particular technology and the conditions for its broad implementation change when a society is envisioned as IFGs. By extension, the indicators needed to assess the future potentiality of the technology and the relative importance assigned to them can also change accordingly. Whereas discussion from the viewpoint of the current generations focused on the technology, the future viewpoint enabled them to see the technology from different angles.

Usually, when indicators for evaluating technologies are selected, current conditions related to existing technologies are taken for granted. However, this study clarified that examining the same technology from the viewpoint of future generations naturally changes a variety of assumptions about the technology, such as its value, its position in society, and the requirements for R&D and social adoption. Furthermore, this shift in perspective can even change the framework for evaluating the future potentiality of the technology itself. In other words, these findings suggest that examining the direction of technological innovation from the viewpoint of futurability or sustainability tends to change the indicators and criteria that need to be given importance and their relative priority. The results are also consistent with the findings of a previous study (Hara et al., 2023a), which demonstrated the impact of the adoption of IFGs on the relative importance of indicators related to R&D strategy in industry. Examining issues from the perspective of IFGs can even lead to proposals of new indicators for evaluating the technology's future potentiality. In this study, three new indicators emerged: "Technological originality" (Group C), "Labor-saving" (Group B), and "Expandability of applications" (Group D).

From all the above results, we summarized the essential points obtained through the four sessions from the following viewpoints: "Shifting requirements of technological development and social adoption", "Shifting and relativizing the value and positioning of the technology", "Giving rise to new evaluation indicators for the technology's future potentiality", and "Gaining perspective by analyzing, assessing, and redesigning the past" (see Table 3). These interpretations should be further substantiated by the accumulation of case studies in the future.

These points indicate the effects of introducing the perspective of future generations into the technology assessment framework. To date, various methods and frameworks of technology assessment, including participatory approaches, have been developed and practiced (e.g., Kaplan et al., 2021;). Constructive technology assessment has prioritized dialogue among and interaction with actors (Schot and Rip, 1997). Technology assessment for responsible innovation has also been proposed and practiced (Grunwald, 2014). Participatory Technology Assessment has attempted to incorporate knowledge and values into the evaluation and policy-making associated with new technologies (Tavella, 2016). The assessment method also encompasses methods to incorporate social actors into science policy discussions (Joss and Bellucci, 2002; Kaplan et al., 2021).

However, these conventional approaches have not explicitly incorporated the important issue of intergenerational trade-offs and viewpoint of future generations. In this sense, the approach developed in this

Table 3
Effects of Future Design discussions.

Characteristic change in thinking	Specific discussion contents
1) Shifting and relativizing the value and positioning of the technology	• Increase the appeal of hydrothermal technology (Group A) • Hydrothermal technology within systems (Group C)
2) Shifting requirements of technological development and adoption	• Diffusion of renewable energy (Groups A, B, D) • Energy circulation (Group C) • Implementation of data science, digital IT (Groups A, B, C) • Use of clean energy (Group D)
3) Giving rise to new evaluation indicators for the technology's future potentiality	• Technological originality (Group C) • Labor-saving (Group B) • Expandability of applications (D)
4) Gaining suggestions and shifting the requirements for technological development by analyzing, assessing, and redesigning the past	• Issue of powderization technology (Group D) • Clean energy process (Group D) • Shift in physical places as an implementation requirement (Group B)

study is distinctive compared to the conventional approaches mentioned above. Notably, the findings demonstrate that the adoption of IFGs as a new institution to activate futurability could shift the perceptions of participants, leading to changes in assessment results and relativizing the value and positioning of the technology. Thus, the findings of this study could provide important insights into the direction and further development of methods and systems for technology assessment in view of sustainability of future society.

4.2. Future studies

There are several issues to be considered for future studies based on the results of present study. Firstly, we need to further investigate how the diversity and attributes of participants could affect discussions on future scenarios and technology assessments, both as members of the current generation and as IFGs. Previous studies attempted to explore the relationship between individual attributes of participants and activation of futurability by adopting IFGs (Hara et al., 2023b; Hara et al., 2021; Nakagawa et al., 2019; Kuroda et al., 2021; Hiromitsu et al., 2021). However, studies on this issue in the context of R&D strategy and technology innovation are still limited, and further study is needed.

Secondly, it is important to develop the effective frameworks and systems for technology assessment incorporating the viewpoint of futurability. In particular, it is essential to further investigate how to integrate the assessment results from the perspective of both the current generation and IFGs. The mechanism and theory required to institutionalize the assessment systems incorporating the viewpoint of futurability would also be an important issue to study. Feasibility studies, such as that proposed by Ahn (2017), could be a good reference for discussing how to formalize assessment systems that incorporate the viewpoint of futurability.

Thirdly, conditions and settings in participatory assessment need to be studied further in order to effectively generate futurability among discussion participants when making decisions as IFGs, particularly in terms of the way in which relevant information is provided to participants while controlling possible biases.

5. Conclusions

For this study, we set out to conduct a participatory deliberation experiment adopting the method of IFGs based on Future Design to verify the effect of IFGs on the formulation of scenarios for the adoption of hydrothermal technology in an imagined 2040 society, and also its effect on the relative importance of indicators for assessing the future potentiality of the technology. From the results of the discussions of the four groups and their responses to four questionnaires, we identified the commonalities and significant differences in the contents of discussions.

Specifically, the results clearly show that the adoption of IFGs leads to the following: 1) Shifting and relativizing the value and positioning of a technology; 2) Shifting the requirements for the development and adoption of a technology; and 3) Identifying essential indicators for assessing the future potentiality of a technology. The study results also demonstrate the effect and value of adopting a "perspective of future generations" when examining R&D strategies and technological innovation.

Looking ahead, we identify four further research challenges. The first is to build a foundation for an evaluation framework for use in technology assessment based on Future Design. Although this is a first step, we need to consider the construction of a systematic methodology for assessing technology in which the perspectives of future generations are integrated by accumulating more case studies. The second challenge is to verify a mechanism for guiding new technological innovations. Although the results of this study suggest that the direction of innovation can be changed, further case studies are needed to systematize methods and mechanisms for effectively guiding this reorientation process. The third challenge is to devise more effective ways to provide information. We need to think more about how to share information in ways that promote better understanding of the technology in question and effectively generate futurability while controlling biases. Lastly, case studies should be accumulated to further examine what kinds of indicators and decision criteria for technology innovation and R&D strategy should be employed by discussion participants, both as members of the current generation and as IFGs. In this study, the participants considered the relative importance of indicators based on a list of selected indicators, although they were allowed to propose new ones in the process of discussions. This setting was chosen in this study to effectively analyze the effects of adopting IFGs in accordance with the primary of objective of this study. Given that there is a possibility that different types of indicators could be proposed both by the current generation and IFGs, different kinds of settings need to be tested in the future.

CRediT authorship contribution statement

Keishiro Hara: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Iori Miura:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Masanori Suzuki:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Toshihiro Tanaka:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendices. Supplementary data

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