Designing Technology Diffusion Roadmaps of Thermoelectric Generators Toward a Carbon-Neutral Society

Yusuke Kishita, Shun Kashima, Kotaro Kawajiri, Yukihiro Isoda, and Yoshikazu Shinohara

Abstract—Thermoelectric generators (TEGs) have the potential to contribute significantly to the realization of a carbon-neutral society by recovering electrical energy from various types of waste heat. Potential applications include wireless sensors, automobiles, and wearable devices. Despite their promise, however, TEGs have not been widely diffused due to their currently high cost and low energy conversion efficiency. This article aims to design technology diffusion roadmaps in order to clarify the gap between market needs and technological development, and discusses ways to bridge this gap. Drawing on the backcasting-based roadmap design method developed previously by the authors, TEG roadmaps were prototyped using online interviews with two companies that are developing and marketing their own TEGs for specific applications. Based on the responses, a roadmap design process consisting of five steps—problem setting, preparation, information gathering, structuring and analyzing the results, and feedback—was developed. To demonstrate the proposed method, a case study in which various digital platforms and tools were utilized to efficiently exploit the knowledge and opinions of participating experts was conducted online. Results revealed a pathway by which TEGs could be effectively diffused to meet both social and market needs over the next 30 years. Internet of Things sensors and automobiles were identified as promising applications for the near term, while, for the longer term, the need to develop new solutions and surrounding technologies in order to expand future demand for TEGs was made evident.

Index Terms—Carbon neutrality, competing technology, roadmap, technology diffusion, thermoelectric generator (TEG).

I. INTRODUCTION

THERMOELECTRIC generators (TEGs) hold the promise of reducing greenhouse gas emissions and contributing to the realization of a carbon-neutral society by recovering waste heat from sources such as manufacturing plants and internal combustion engines [1], [2]. The advantages of TEGs include the ability to extract usable electricity from lower-temperature heat (200°–300° Celsius) while being virtually maintenance-free. However, TEGs have not yet been widely diffused in society because of their relatively high production costs and low conversion efficiency. In support of technology planning for TEGs, a number of scholars and organizations have proposed possible roadmaps [3]–[5]. For example, the roadmap developed for Thermoelectrics of Japan [3], which is based on the knowledge and opinions of experts in the field, focuses on forecasting performance (e.g., conversion efficiency) and production costs through 2040. Freer and Powell [5] developed a roadmap based on a literature review, where performance improvement is projected with potential applications through 2040.

While most existing TEG roadmaps focus on technological aspects, relatively little research has dealt with the question of what conditions need to be satisfied for the future diffusion of TEGs, taking into account changes in social and market needs and potential competing technologies. To address this broader question, we discuss the design of a suitable technology diffusion roadmap, with a particular focus on TEGs. In this article, a “technology diffusion roadmap” refers to a graphical representation describing the dynamic interactions between social and market needs, technological development, and technology diffusion that is actualized in the form of products and services. Drawing on our previous work [6], we took an experimental approach to developing a method for designing technology diffusion roadmaps. Specifically, we prototyped two TEG roadmaps using online interviews with two TEG-involved companies and developed a five-step roadmap design process (see Section III) based on the interview responses we received. By combining the design process with an online workshop that included several qualified experts in the field, a technology diffusion roadmap of TEGs was developed, with a time horizon of 2020–2050.

The rest of this article is organized as follows. Section II is a literature review of TEG applications and existing studies related to roadmapping. Section III describes the proposed method for designing a technology diffusion roadmap based on two prototyped roadmaps and interviews with industry members. Section IV presents a case study to illustrate the application of the proposed method. Section V discusses the advantages and limitations of the method. Finally, Section VI concludes this article.
TABLE I
EXAMPLES OF TEG APPLICATIONS

| Field of application          | Heat source              | Competing technologies                      | Target year for commercial use | References |
|-------------------------------|--------------------------|---------------------------------------------|-------------------------------|------------|
| Aerospace                     | Radioactive ray          | Solar cell                                  | 1960                          | [4][5][7]  |
| Watch                         | Body heat                | Button battery                              | 1998                          | [8]        |
| IoT sensor                    | Exhaust heat             | Button battery, solar cell                  | 2020-2035                     | [5]        |
| Biomedical hearing aid        | Body heat                | Button battery                              | 2025                          | [2][5]     |
| Large industry waste heat recovery | Exhaust heat               | n/a                                         | 2025-2030                     | [3][5]     |
| Wearable device               | Body heat                | Button battery                              | 2030                          | [4][5]     |
| Automobile                    | Exhaust heat             | Battery                                     | 2022-2030                     | [4][5][7][9][10] |
| Thermal power station         | Exhaust heat             | n/a                                         | 2030                          | [3]        |
| Airplane                      | Exhaust heat             | Battery                                     | 2040                          | [3]        |
| Large-scale thermoelectric generation | Various            | n/a                                         | 2040                          | [3]        |

*For demonstration phase.*

II. LITERATURE REVIEW

A. Overview of TEGs and their Applications

TEGs are based on a physical phenomenon called the thermelectric effect, which enables the direct conversion of temperature differences to electric voltages [1]. Theoretically, the conversion efficiency increases as the temperature difference between the heat source and heat sink becomes larger. The performance of TEGs is usually evaluated using the thermelectric figure-of-merit ($Z$), defined as

$$Z = \frac{S^2 \sigma}{\kappa}$$  \hspace{1cm} (1)

where $S$ is the Seebeck coefficient (V/K), $\sigma$ is the electrical conductivity (Ω m$^{-1}$), $\kappa$ is the thermal conductivity (W/(m K)), and $T$ is the absolute temperature (K). The $Z$ shows an energy conversion efficiency at a certain temperature under the ideal conditions that there is no Peltier effect or Joule heat. The maximum conversion efficiency $\eta_{\text{max}}$ is given by

$$\eta_{\text{max}} = \frac{T_H - T_L}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_L}{T_H}}$$  \hspace{1cm} (2)

where $T_H$ and $T_L$ are the absolute temperatures of the heat source and the heat sink, respectively, and $\bar{T}$ is the average of $T_H$ and $T_L$. The $\eta_{\text{max}}$ increases with $Z$. While the $\eta_{\text{max}}$ is currently in the neighborhood of 7% at $T_H = 280K$ and $T_L = 30K$, it is projected to increase to 20–30% by 2030–2040 according to available technology roadmaps [3][5][7]. TEGs are generally maintenance-free, have a long life, and are quiet, as they have no moving parts, and do not require large-scale systems.

Although researchers continue to work on improving the performance of TEGs by creating new thermoelectric materials, TEGs have not yet been successfully introduced into the marketplace. Nevertheless, there are a wide range of possible applications, including Internet of Things (IoT) sensors, wearable devices, and internal combustion engine vehicles (see Table I). A variety of formats [11]. Technology roadmapping is useful for supporting technology planning and product development in commercial organizations [12], as well as in science, technology, and innovation policy-making within government agencies [13].

In the roadmap development process, workshops are frequently used to share and generate ideas among stakeholders. In combination with such workshops, a number of roadmap development processes have been proposed. For example, the T-Plan proposed by Phaal et al. [14] aims to fast-start the roadmap implementation process to support product planning. Daim and Oliver [15] provided a technology planning method based on case studies of technology roadmaps in the energy service sector. Others have applied digital technologies to assist technology roadmapping [16], [17].

B. Technology Roadmapping

Roadmapping is a time-based, structured, and graphical method for representing the dynamic linkages between technologies, market needs, and products and services [11]. A roadmap often consists of multiple layers (e.g., market, product and service, and technology layers) and can be presented in a variety of formats [11]. Technology roadmapping is useful for supporting technology planning and product development in commercial organizations [12], as well as in science, technology, and innovation policy-making within government agencies [13].

In the roadmap development process, workshops are frequently used to share and generate ideas among stakeholders. In combination with such workshops, a number of roadmap development processes have been proposed. For example, the T-Plan proposed by Phaal et al. [14] aims to fast-start the roadmap implementation process to support product planning. Daim and Oliver [15] provided a technology planning method based on case studies of technology roadmaps in the energy service sector. Others have applied digital technologies to assist technology roadmapping [16], [17].

C. Backcasting-Based Roadmap Design Method

Seeking to address the question of how to fill the gap between a sustainable vision and the present, Okada et al. [6] developed a backcasting-based roadmap design method, as illustrated in Fig. 1. The idea here is to integrate backcasting and forecasting approaches into the roadmap design process, creating a sustainable vision using backcasting, developing a baseline scenario using forecasting, and identifying the gap between the vision and the baseline scenario with the intention of finding effective ways to fill the gap. The proposed method was originally designed to address sustainability issues (e.g., carbon neutrality) with a relatively long-time horizon (e.g., 2050) in mind.
D. Problems Addressed

With existing TEG technology roadmaps focused largely on the technological aspects of performance and cost [3]–[5], the conditions for TEG diffusion have remained unclear. From a methodological viewpoint, requirements for designing an appropriate technology diffusion roadmap should include:

1) Representing the dynamic interactions between social/market needs, technological seeds, and technology diffusion over time.
2) Helping to fill the gap between a future vision and the present by identifying driving and inhibiting factors for technology diffusion.

Indeed, the graphical representation of technology roadmapping has the potential to satisfy both of the abovementioned requirements. However, to the best of our knowledge, little guidance is available regarding the process of designing proper technology diffusion roadmaps.

III. METHODOLOGY

A. Approach

In this article, the roadmap template (see Fig. 1) developed by Okada et al. [6] was applied in order to gain insights into how technology diffusion roadmaps are designed. Taking an experimental approach, we sought to develop the design process by prototyping TEG diffusion roadmaps through online interviews with two industry members. Based on the prototyped roadmaps and the development process observed at the participating companies, we produced a representation scheme and design process for appropriate technology diffusion roadmaps. To verify the effectiveness of the model, we conducted an online workshop in which three experts were asked to help design a TEG diffusion roadmap.

B. Prototyping Roadmaps Using Company Interviews

We arranged two semistructured online interviews with Companies A and B, each of which is developing and marketing its own TEGs for specific applications. The duration of the interviews was approximately two hours per interview. The list of questions used in the interviews was developed in advance based on our previous work [9]. The list included questions on current technologies and applications, current production and sales amounts, driving factors for future diffusion, competing technologies, and the future prospects of market needs and the company’s business.

Based on the interview results (audio data), we compiled detailed minutes of each interview. After careful analysis of the minutes, we then described our technology diffusion roadmaps using the roadmap canvas shown in Fig. 1. Finally, we asked each of the companies to review the respective roadmaps in order to determine whether the proposed roadmap was consistent with their intentions.

Although the detailed contents of the developed TEG roadmaps cannot be disclosed for confidentiality reasons, we found a common pattern (see Fig. 2). In each case, the roadmap consisted of five elements: 1) current technology, 2) product development and related information (including specific applications using TEGs), 3) potential needs (e.g., environmental policies and regulations), 4) challenges and solutions, and 5) further expansion of applications and full-scale diffusion. In (4), technologies competing with TEGs and specific areas of application were cited. It should be noted that, in (5), delineating a future vision for the two companies was difficult, although we had originally intended to apply a backcasting approach. The implication is that it may be easier for companies to develop their roadmaps using a forecasting approach rather than a backcasting approach, as companies are likely to already have a concrete business plan for the near-term, while the longer term (e.g., through 2050) is far more uncertain.

C. Method for Developing Technology Diffusion Roadmaps

Based on the results of the prototyped roadmaps and our experience in producing them, we gained valuable insights into how best to develop effective technology diffusion roadmaps. These insights are summarized as follows.

First, from our analysis, the following information was included in the content of the prototyped TEG roadmaps:

1) current level of performance of the target technology (i.e., TEGs) and its future prospects;

Fig. 2. Structure identified based on the two prototyped roadmaps.
To better understand the roadmap content listed previously, we developed the representation scheme shown in Fig. 3, wherein we proposed representing the roadmap using the following three aspects.

1) Applying PEST (political, economic, social, and technological) analysis to differentiate the variety of factors that could influence technology diffusion.
2) Dividing the entire roadmap into baseline, pathway, and vision to distinguish the different types of futures.
3) Defining three link types (causality, detail, and competing) to indicate the different types of connections. While causality is the most frequently used in roadmapping in general, we additionally defined detail and competing, using detail to represent the features of the product and potential applications, and competing to represent competing technologies.

Second, we developed the roadmap design process illustrated in Fig. 4 by generalizing the two prototyping cases. Assuming that there are two types of actors (roadmap designers and participants), the design process consists of the following five steps.

1) Problem setting: The designers define the objective of roadmap design, the target technology, and the scope and time horizon of interest.
2) Preparation: Prior to conducting interviews and workshops, the designers gather necessary information (e.g., products and applications related to the target technology) and prepare a list of questions. The designers then arrange and conduct the interviews and workshops.
3) Idea generation: The designers invite participants (e.g., experts) to the interviews and workshops in which the participants generate various ideas related to technology diffusion on the roadmap canvas (see Fig. 1), mainly using a forecasting approach, stepping from baseline and pathway to vision.
4) Structuring and analyzing the results: The designers sort out the information obtained from Step 3, revise, structure, and analyze the roadmap.
5) Feedback: Steps 3 and 4 are iterated until consensus among the participants is reached and the predetermined objective is met.

It should be noted that the main feedback loop extends to Step 3, but possibly to Step 1 or 2 depending on the progress made during the roadmap design process.

IV. CASE STUDY

An online workshop involving three experts and the five-step process described in Section III was conducted as a case study of the efficacy of the proposed TEG diffusion roadmap design procedure.

A. Problem Settings

Two of the authors served as the roadmap designers. The objective was to design a TEG diffusion roadmap consisting of a future vision for 2050 and a pathway to that future vision from the present. The time horizon was assumed to be 2020 to 2050.

B. Preparation

The designers invited three experts from the industry to participate in an idea-generating online workshop. The online format was chosen out of concern that a face-to-face workshop would be untenable due to the covid pandemic. The duration of the workshop was approximately two hours, limited primarily by the participants’ availability. In preparation for the workshop, the designers developed a list of questions that would be put to the workshop participants. The questions were divided into three sections: the current situation of TEGs, obstacles to TEG diffusion, and the future vision and prospects of TEGs. The online workshop environment, in which a web conference system and online whiteboard were used, is shown in Fig. 5.

C. Idea Generation

The designers encouraged the participants to generate a variety of ideas related to TEG diffusion. One of the designers facilitated the workshop using the prepared questions; the other designer focused on technical assistance, posting digital sticky notes on the online whiteboard based on the ongoing discussions and sorting them using PEST analysis. By the end of the workshop, a total of 63 ideas (political: 7; economic: 3; social: 16; technological: 37) were posted on the roadmap.
TABLE II
BREAKDOWN OF THE COLLECTED IDEAS

|        | Political | Economic | Social | Technological | Total     |
|--------|-----------|----------|--------|---------------|-----------|
| Baseline | 3(5%)     | 3(5%)    | 5(8%)  | 18(28%)       | 29(45%)   |
| Pathway  | 4(6%)     | 3(5%)    | 8(12%) | 8(12%)        | 23(35%)   |
| Vision   | 2(3%)     | 2(3%)    | 7(11%) | 2(3%)         | 13(20%)   |
| Total    | 9(14%)    | 8(12%)   | 20(31%)| 28(43%)       | 65(100%)  |

D. Structuring and Analyzing the Results

Following the workshop, the designers updated portions of the roadmap based on the recorded audio data, structuring it according to the representation scheme shown in Fig. 3. The final output is given in Fig. 6 and Table II. Our analysis showed that the same structure that appeared in the prototyped roadmaps (see Fig. 2) was evident in Fig. 6.

The storyline of the design roadmap is as follows: Based on the current technological development of TEGs, TEG development for automotive and IoT sensor applications will progress through 2025 or so. This will further accelerate the technological advancement of TEGs in general. Combining TEGs with appropriate services as part of an integrated system will lead to a monetized business model. Taking into account the high durability of TEGs and the existence of competing technologies (e.g., batteries), new ways of using TEGs will be explored to increase people’s convenience, where policy options such as subsidies and tax credits could be made available to support diffusion of the technology. By 2030 and beyond, TEGs could be used as electricity sources when disasters occur or in dangerous areas where people cannot be easily served. In this way, TEGs will be widely diffused as one of the key technologies in the quest to achieve carbon neutrality by 2050.

As described in Table II, the ideas collected in the workshop were distributed across all three sections (baseline, pathway, and vision) of the roadmap. The baseline accounted for the largest portion (45%), which was to be expected as the participants were from the industry and very knowledgeable about current and short-term technological developments and business practices. According to our PEST analysis, technological ideas accounted for the largest share (43%), more than half of which were placed in the baseline. Social ideas (31%) included social goals to be achieved, social and market needs, and consumer awareness of TEGs. Political ideas (14%) included policies and regulations related to energy and the environment, while economic ideas (12%) were concerned primarily with cost and business models.

E. Feedback

The three workshop participants were subsequently asked to review the designed roadmap and provide feedback on both the roadmap and the workshop. For this purpose, the designers sent the final version of the roadmap (see Fig. 6) by email, along with a brief questionnaire. The questionnaire consisted of five questions concerning methodological validity, understanding of the workshop process, validity and usefulness of the designed roadmap, critical driving and inhibiting factors for TEG diffusion, and any other feedback on the roadmap’s content.

Most of the feedback received from the participants was positive. One of the participants noted that the roadmap workshop was efficient even given the limited time (two hours) because of the separation of its two principal components—discussions among the participants and the designers’ real-time roadmap design in a digital format. In the end, this workflow worked well, contributing to less misunderstanding during the workshop. However, one participant noted the lack of time for interactive discussion. Although the designers were able to efficiently collect many ideas from the participants using the prepared questions, the interactive discussions were somewhat constrained by the time limitation and digital environment. Another comment related to the roadmap’s content, suggesting that the group’s knowledge of state-of-the-art material development would be enhanced by inviting academic experts and noting that the three industry participants were highly knowledgeable about business practices but not about academic research and the prospects of future technologies.

V. DISCUSSION

Based on our exploration of TEG roadmap design, a number of key findings and methodological insights emerged.

A. Key Findings From the Designed Roadmap

From our analysis of the final roadmap (see Fig. 6), we confirmed that the two requirements predefined in Section II were satisfied insofar as several solutions for supporting TEG diffusion were obtained based on social/market needs, technological development, competing technologies, and their interrelationships during the period 2020–2050. Our findings from the designed roadmap can be summarized as follows.

1) Short term (up to 2025 or so): Taking into account technological feasibility, exhaust heat from automobiles and IoT
sensors are possible TEG applications. The CO2 emission regulations in Europe could be a driving factor for automotive applications; however, it will be necessary to reduce cost, increase reliability, and ensure relative advantages over batteries as a competing technology. Insofar as TEG applications in IoT sensors may compete with solar cells, the usability of TEGs in places where solar cells are infeasible or ineffective (e.g., an indoor or dark environment) could provide a constructive focus.

2) Long term (2030 and beyond): It is important to explore new ways of using TEGs by taking advantage of their strengths, such as their low maintenance requirement and high durability. One promising approach is to increase people’s convenience by, for example, installing TEGs in hard-to-reach locations where maintenance is difficult or utilizing TEGs as electricity sources when disasters and emergencies occur. Development of ancillary technologies and software is also needed in order to expand the ways in which TEGs can be used. Additionally, as long-lasting efforts, increasing general awareness of TEGs and engaging in increased lobbying activities aimed at promoting supportive government policies (e.g., subsidies) are important to TEG diffusion. Full-scale diffusion of TEGs for a wide range of applications should be viewed as a potentially significant contributor to carbon neutrality by 2050.

As such, the method employed in this article was helpful for suggesting the future directions of TEG diffusion based on social/market needs and technological requirements. These suggestions could be used to develop new business models. However, in order to clarify the conditions for widespread TEG diffusion, more detailed analyses need to be undertaken. For example, with respect to automotive applications, a comparative assessment of TEGs versus batteries should be conducted quantitatively from both an economic and environmental perspective. For this purpose, market analysis [9] and life cycle analysis [10] could be combined with our roadmap design method. One other shortcoming of the approach employed in our study was the somewhat limited range of information available during the workshop discussions, as was pointed out by one of the participants (see Section IV-E). Engaging participants from more diverse fields in order to make the roadmap more comprehensive is an issue that will need to be addressed.

B. Methodological Contributions

As described in the previous section, the proposed method was effective in designing technology diffusion roadmaps using the five-step process described in Section III. Importantly, while the focus of this paper is on TEGs, the method is applicable to any technology. Based on the case study results and feedback from the participants, we found three advantages in our method.
First, the representation scheme of the proposed method provides a better understanding of the designed roadmap by visualizing the relationship between social/market needs, technological development, and possible solutions for technology diffusion over time. It facilitates communication among participants and stimulates a discussion of technology diffusion based on such questions as: What are the targets of technological development in terms of performance and cost? What are the potential areas in which the technology could be used to meet social needs while gaining advantages relative to competing technologies? How should the technology be used in these areas by providing new services and business models? Who should be involved in enabling or accelerating technology diffusion?

Second, the method enables an efficient workflow of workshop-based roadmap design. In the case study, we were able to design the TEG diffusion roadmap by means of a two-hour workshop. Finishing one cycle of roadmap design in a limited time is important, as the experts from industry and academia needed for a productive workshop are often too busy to attend a longer session (e.g., a half-day or one-day workshop). One advantage of our method is that participants generate a variety of ideas under a strict time constraint, with an eye on bridging the gap between social needs and technological seeds and the gap between a sustainable vision (in this case, carbon neutrality by 2050) and the present. Nevertheless, running multiple cycles of roadmap design by organizing a second or third workshop would be desirable in order to collect more ideas, produce a comprehensive roadmap, and evaluate the content of the developed roadmap. In this regard, the proposed method could be positioned as a very early phase of the roadmap design process in the context of technology diffusion.

Third, we showcased a roadmap design workshop using a digital environment. Such an environment offers the opportunity to invite experts living in distant locations to participate, which, in turn, should help improve roadmap design at a relatively low cost. Furthermore, combining this with other digital technologies and techniques (e.g., text mining) provides a promising approach to making the roadmap design process more efficient and effective. This trend will likely to be accelerated in the field of futures and foresight, including technology roadmapping [18].

C. Limitations

The proposed method has several limitations. First, the effectiveness and validity of the method has yet to be investigated beyond the single case study described in this article. Conducting additional industrial case studies is clearly necessary. Second, the possible integration of the proposed method with simulation models to further support decision making by companies and governments needs to be considered. Examples of such models include demand estimation using market simulation techniques (e.g., logit models [19] and conjoint analysis [20]) and environmental impact evaluation using life cycle assessment [21]. Third, developing a computational system by implementing the proposed method in a way that enables other researchers and practitioners to more easily design technology diffusion roadmaps would be highly desirable. In particular, combining digital platforms with such a system would provide opportunities for direct communication among stakeholders in the online workshops. We intend to pursue each of these areas in our future work.

VI. Conclusion

In this article, we designed technology diffusion roadmaps for TEGs to determine the conditions (e.g., technology development goals) for future diffusion. We produced prototype TEG roadmaps using online interviews with representatives from two companies. Based on the results, we developed a representational scheme for technology diffusion roadmaps. We also implemented a roadmap design process consisting of five steps—problem setting, preparation, information gathering, structuring and analyzing results, and feedback. One advantage of our approach is that it helped workshop participants generate a variety of ideas under a strict time constraint in order to bridge the gap between social needs and technological seeds, and between a sustainable vision and the present.

To demonstrate the proposed method, we conducted a case study in which several industry experts engaged in an online workshop using digital platforms. The results suggested possible ways for TEG diffusion to bridge the gap between social/market needs and technological development for a time horizon of 2020–2050. In the shorter term, IoT sensors and automobile applications appear promising. For the longer term, it will be necessary to develop new solutions and surrounding technologies in order to expand the demand for TEGs. Future work includes conducting more industrial case studies to further test the validity of the proposed method.

ACKNOWLEDGMENT

The authors would like to thank the three experts who participated in the workshop for providing their very fruitful and constructive inputs to design the roadmap.

REFERENCES

[1] G. J. Snyder and E. S. Toberer, “Complex thermoelectric materials,” Nature Mater., vol. 7, 2008, Art. no. 105e114.
[2] N. Jaziri, A. Boughamoura, J. Müller, B. Mezghani, F. Tounsi, and M. Ismail, “A comprehensive review of thermoelectric generators: Technologies and common applications,” Energy Rep., vol. 6, pp. 264–287, 2020.
[3] Thermoelectric Society of Japan, “Thermoelectrics academic roadmap,” (in Japanese) 2011, Accessed: Sep. 12, 2021. [Online]. Available: http://www.thermoelectrics.jp/zata/RoadMap(c).pdf
[4] EPSRC Termoelectric Network U.K., “Thermoelectric roadmap: Energy harvesting from waste heat,” R. Freer and A. V. Powell, Eds., 2018.
[5] R. Freer and A. V. Powell, “Realising the potential of thermoelectric technology: A roadmap,” J. Mater. Chem. C, vol. 8, pp. 441–463, 2020.
[6] Y. Okada, Y. Kishita, Y. Nomaguchi, T. Yano, and K. Ohtomi, “Backcasting-based method for designing roadmaps to achieve a sustainable future,” IEEE Trans. Eng. Manage., vol. 69, no. 1, pp. 168–178, Feb. 2022.
[7] D. Champier, “Thermoelectric generators: A review of applications,” Energy Convers. Manage., vol. 140, pp. 167–181, 2017.
[8] National Institute for Materials Science (NIMS), “Thermoelectricity,” (in Japanese) Survey Analysis Lab., NIMS, Tsukuba, Ibaraki, Japan, Tech. Rep. NIMS-RAO-FY2014-2, 2014.
[9] Y. Kishita, K. Kawajiri, and Y. Shinohara, “Describing diffusion scenarios of thermoelectric generators: An exploratory study,” in Proc. 13th Biennial Int. Conf. EcoBalance, 2018, p. 153.

[10] Y. Kishita, Y. Ohishi, M. Uwasu, M. Kuroda, H. Takeda, and K. Hara, “Evaluating the life cycle CO$_2$ emissions and costs of thermoelectric generators for passenger automobiles: A scenario analysis,” J. Cleaner Prod., vol. 126, pp. 607–619, 2016.

[11] R. Phaal, R. C. J. P. Farrukh, and D. R. Probert, “Technology roadmapping: A planning framework for evolution and revolution,” Technological Forecasting Social Change, vol. 71, pp. 5–26, 2004.

[12] C. H. Willyard and C. W. McClees, “Motorola’s technology roadmap process,” Res. Manage., vol. 30, pp. 13–19, 1987.

[13] Y. Yasunaga, M. Watanabe, and M. Korenaga, “Application of technology roadmaps to governmental innovation policy for promoting technology convergence,” Technological Forecasting Social Change, vol. 76, pp. 61–79, 2009.

[14] R. Phaal, C. Farrukh, R. Mitchell, and D. Probert, “Starting-up roadmapping fast,” Res.-Technol. Manage., vol. 42, pp. 52–58, 2003.

[15] T. U. Daim and T. Oliver, “Implementing technology roadmap process in the energy services sector: A case study of a government agency,” Technological Forecasting Social Change, vol. 75, pp. 687–720, 2008.

[16] A. Nazarenko, K. Vishnevskiy, D. Meissner, and T. Daim, “Applying digital technologies in technology roadmapping to overcome individual biased assessments,” Technovation, 2021, Art. no. 102364, doi: 10.1016/j.technovation.2021.102364.

[17] S. Ozcan, A. Homayounfard, C. Simms, and J. Wasim, “Technology roadmapping using text mining: A foresight study for the retail industry,” IEEE Trans. Eng. Manage., vol. 69, no. 1, pp. 228–244, Feb. 2022.

[18] Y. Kishita, “Foresight and roadmapping methodology: Trends and outlook,” Foresight STI Governance, vol. 15, no. 2, pp. 5–11, 2021.

[19] V. K. Borooah, Logit and Probit: Ordered and Multinomial Models. London, U.K.: Sage, 2001.

[20] A. Gustafsson, A. Herrmann, and F. Huber, Conjoint Measurement: Methods and Applications. Berlin, Germany: Springer, 2003.

[21] M. Hauschild, R. K. Rosenbaum, and S. Olsen, Life Cycle Assessment: Theory and Practice. Berlin, Germany: Springer, 2018.