Roadmap of Energy Technologies for Envisioning Future Energy Systems

Michihisa Koyama, Takuya Hasegawa, and Yuya Kajikawa

Abstract Roadmaps, visions, and scenarios are different representations of certain aspects of thinking or perceptions of the future. Technology roadmaps have been used as a planning and management tool in industry and organizations. This book describes the current status of Japan's energy system and roadmaps of energy technologies. In this chapter, we elaborate on the background and concepts of roadmaps. We also discuss the function, potential risks, and usage of a technology roadmap.

Keywords Technology roadmap • Uncertainty • Risk • Future energy system

1 Aim of This Book

Energy functions a basis for modern human life. It supports daily living and industrial, economic, and social development. Energy is a matter of exploration across broad disciplines. New discoveries and inventions in energy and related technologies, such as turbines, nuclear power, and photovoltaic cells, have changed our ways of living. Exploration with intense curiosity has pioneered frontiers of science and established disciplines like thermodynamics and nuclear science and technology. The history of energy is also one of resource exploitation. Fossil fuels, which remain and will likely be a major energy resource, are regenerated little within human history and thus are defined as a nonrenewable resource. Such fuels

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Y. Kato et al. (eds.), *Energy Technology Roadmaps of Japan*,
DOI 10.1007/978-4-431-55951-1_2

have been exploited at increasing speeds during the last two centuries. Exploitation of energy resources has degraded local environments and led to global climatic change. International conflicts over limited access to resources have sometimes led to war. The importance of transformation into renewable energy systems and sustainable society is currently well recognized, but appears to have limited influence on social change through motivating stakeholders with a sense of urgency.

It is known that a single technology or social system will not solve current issues or bring about sustainable society; thus, it is mandatory to implement a number of technologies in society in an integrative manner, possibly with suitable support by policies or realization of new societal systems. Someone intending to draw a pathway to a future sustainable society may face difficulties in identifying feasible enabling technologies, which play key roles in realizing that society, from among a variety of options. Nowadays, we typically face difficulties in developing a comprehensive view of an issue while keeping the details reliable and neutral. Information infrastructure enables efficient access to information. However, this poses challenges, even for researchers who purport to have deeper knowledge of technology futures relative to other types of stakeholders, because disciplines are continually divided into many branches or subdisciplines because of the continuous accumulation of knowledge and development of academism.

This book is edited so as to help stakeholders envision a possible future society on the basis of feasible technology options, as well as to appropriately identify related technology in the big picture of a possible future society. By comparatively reading the thematic chapters, readers will find the mutual relationships of technology options, such as competitive, coexisting, and tightly coupled. This will facilitate fair discussion, ideally avoiding one biased toward a certain technology option or an a priori presumed conclusion. In this book, a future perspective is described in each chapter to the author's best knowledge. This will support comparison of technology options not limited to the present or near future, but also considering the temporal development of technology maturity or change of social systems. Such comparison will help identify related technology in the future society in a more objective manner, or help to envision that society in a more integrative and robust way.

The book is organized considering the present situation of Japan. Although editors are aware that the country's contribution to fossil resource savings and greenhouse gas (GHG) emission reduction is small in the global context, we believe the contents will be of great use in other countries. As pointed out by Dr. Komiyama, Japan is facing problems in advance of other countries. That is, many of its problems have emerged first or early relative to the rest of the world, whose countries will eventually face them. Energy presents a typical problem for Japan because of the country's scarce domestic resources. To conquer or counter problems that have emerged, the country has put a number of state-of-the-art technologies into practice, including light-emitting diode lighting, low-fuel-consuming vehicles with ultra-low harmful exhaust emission, residential fuel cell systems, hydrogen-fueled vehicles, and ultra-low GHG emission landfills for garbage treatment. We thus believe the present status and future prospects of technologies described in this book provide a useful showcase for many other countries.

In the subsequent parts of this book, the reader will find chapters describing the present status and future perspectives, as well as risks associated with technology penetration in the sector addressed. The authors of each chapter have an engineering background in their respective fields. Most have strong expertise in the technologies that will be important in the focused-on sector. This makes the book a compilation of state-of-the-art knowledge, covering a variety of sectors related to society. The editors acknowledge that the granularity and development phase of the described content depends on the chapter, i.e., sector. Some sectors adopt long-lived conventional technologies with continuous retrofitting of improvements, while others include alternatives to current technologies and unique and emerging directions to follow.

The editors also acknowledge that each author is not necessarily an expert in other technologies or sectors, even if the author is closely tied to the relevant sector. In other words, an author has expertise in a specific technology described in the chapter, but does not necessarily have comprehensive perspectives of competing technologies. Thus, the reader is encouraged to read chapters of interest followed by related chapters, irrespective of chapter order, to discover various ways of thinking, unexpected relationships, trade-offs, and potential discrepancies. More importantly, such a comparison may stimulate the reader to consider possible integration of technologies that are conventionally considered only for certain sectors.

For example, one will find as a current serious issue that intermittent outputs of photovoltaic and wind power generation systems are detrimental to the electrical grid, which must maintain a stable frequency. This situation may hinder the large-scale penetration of such renewable technologies by 2030 or beyond. One may also notice that a decrease in nuclear and increase in fossil-fuel-based thermal power plants is used to legitimate the need for large-scale penetration of photovoltaic and wind power generation systems in Japan, as a transition from a fossil-fuel-based to a low-carbon society. The chapters on nuclear systems guide the reader to appropriately understand the issue of nuclear waste, even if the country chooses a nuclear-free society in the future. The proposed concept of power generation from innovative waste treatment, matched with an intermittent renewable option, may suggest to readers its combination with secondary energy sources such as hydrogen, which affects the transportation and residential sectors.

As a unique aspect of this book, there is peer review of descriptions in subsequent chapters by researchers not only in the same field but also in other disciplines, such as life-cycle engineering, process engineering, and innovation management. Experts and peers in the same discipline have sometimes shared norms and opinions regarding their technology and its societal potential, which lack rigid logic and evidence. To best improve the neutrality and reliability of the descriptions, reviewers have commented from a wide range of aspects such as competition with other technologies, potential risks, self-consistency, and feasibility. Also, comments are geared toward understandability for readers in other disciplines while keeping expertise in the field.

2 Constructing the Roadmap with Uncertainty and Risks

A technology roadmap is a map illustrating the future direction of technological development. It aims to direct future paths of advancing technologies and foster understanding among stakeholders. One of the functions of the technology roadmap is to support understanding of focal technology by articulating technological development and plans. It is also used to visualize relationships between technology, products, service, systems, markets, plans, and required resources. Another objective is to accelerate research and development by enabling a concentration of effort toward technological options selected in the roadmap. Explicit statements regarding technology bottlenecks facilitate the overcoming of challenges and thereby accelerate development. In addition, a comprehensive view enables engineers and managers in product/service/system design to make decisions and form a consensus. An attractive future is expected to be realized if the development proceeds as illustrated in the roadmap, which would enhance positive expectations of that roadmap. This book illustrates each technology roadmap within the common framework shown in Fig. 1.

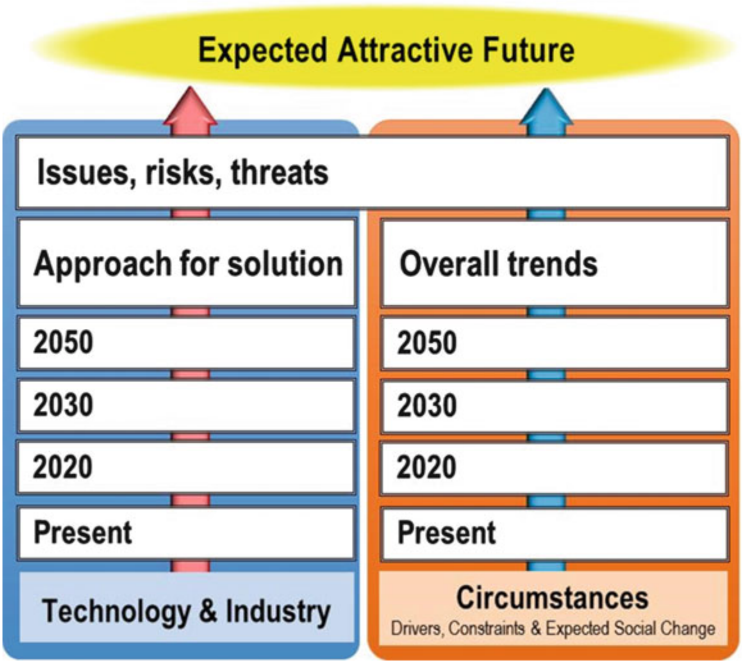

Fig. 1 Framework of the roadmap in this book

Technology roadmaps have been used to promote understanding among stakeholders, accelerate research and development, and support decision making. However, these roadmaps represent an opinion or plan rather than facts. Presently, there are a variety of roadmaps, visions, and scenarios. It is rare for different scenarios to be compared and assessed against each other. There are substantial discrepancies in their reliability and feasibility. It is sometimes difficult to judge whether a roadmap is based on solid mechanistic estimates, feasibility assessment and strategic planning, or simply a manifestation of an author's opinion and dream. Obviously, the future is uncertain; no one can fully predict it. Despite this, we should maximize our capability to envision the future. Although this does not mean that such a future is realized as imagined, that future will seldom be realized if not imagined. We must envision the future in not only attractive and salient ways but also in reliable, feasible, and legitimate ones.

For example, futures with artificial intelligence (AI) have been illustrated in a variety of movies including *2001: A Space Odyssey and Blade Runner*. But the future is still (and in principle) uncertain. It has positive and negative sides. AI can assist and improve our lives by machine translation and diagnose of diseases and as companions. AI might autonomously develop them and be out of our control by threatening our physical and psychological existence, privacy, jobs, lives, and society. A vision and technological breakthrough in AI have attracted imagination for future and investment in research and development, but it has accompanied decline of investment after bubbles. It also has provoked a sense of fear. Expectation and its control are essential means of future innovation and its management for orchestrating challenges and activities that address uncertainty. Expectation has a positive aspect in that it attempts to overcome a sense of crisis with respect to uncertainty, by encouraging the actions of others. Innovation accompanies risk, and its realization is uncertain. Despite the uncertain outlook, we bet on selected options and collect investment and resources for their development. Optimistic expectations enable collective and orchestrated efforts toward the selected option. However, expectation also has a negative aspect in that it can induce gambling investment and fever and cause unbalanced development through unrealistic expectations. The latter, termed hyper-expectations or hype, has been exemplified in various fields, including biotechnology, nanotechnology, information technology, and energy. It can be said that hype is a side effect of any technology roadmap and innovative advocacy.

It is not a rudimentary task to assess the reliability of statements on future perspectives and to avoid hype. As a challenge to our roadmapping process, we explicitly rate the reliability of statements within three ranks, solid mechanistic estimates, extrapolation of trends, and controversial values including personal perspectives (Table 1). The envisioned future has both objective and subjective bases. Some paths are depicted by forecasting past trends via solid mechanistic estimates; others are extrapolations of observed trends from the past; and still others are representations of author opinions and dreams, lacking justification.

Even when based on solid mechanistic estimates, the aforesaid descriptions inevitably include uncertainty, because they result from a projection of plausible

Table 1 Rating of author confidence level

Rating	Technology parameters
★★★	Solid mechanistic estimates
★★	Extrapolation of trends
★	Personal perspective, competition with existing technology (e.g., controversial value)

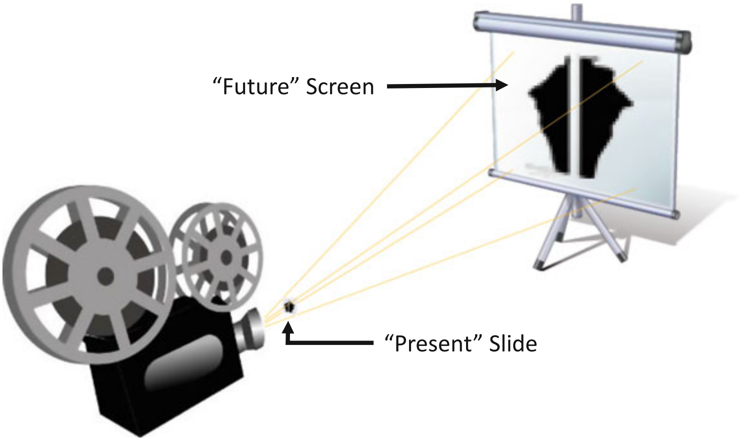

Fig. 2 Projecting to a screen (Published with kind permission of © Michihisa Koyama and Takuya Hasegawa 2015. All rights reserved)

futures based on past trajectories. As schematically illustrated in Fig. 2, the main objective of the projection is not to discern the exact future status but to project the potential future on a screen and provide directions on which we should act now. Although the rank itself and its criteria shown in Table 1 are not strict, we believe that it can help readers understand authors' assessment of the reliability and feasibility of their statements.

A technology roadmap is not a retrospective description of trends but a prospective plan and strategy. It is normative rather than descriptive or analytical. The goal reflects a norm and is shown as what is desirable to attain. Roadmap construction is not just a simple forecast from the present to the future, but also involves a backcasting process from the goal to present status. A roadmap lacking projection is not realistic or feasible. A roadmap depicting a future along the present trend will be realized with high probability, but is not attractive for posing technological challenges to overcome current limitations. Balance and iterative feedback between forecasting and backcasting are essential.

Along the time horizon, the roadmap must be scientifically informed and fact based, with additional efforts to describe what specific years (e.g., 2020, 2030, and 2050) mean. For example, 2030 can be 2020 + 10, 2030 ± 3, or 2030 ± 10, with background calculation that socioeconomically supports specific-year accuracy.

However, we admit that the authors in this book do not necessarily intend to give a specific year with accuracy. The authors cite years without such accuracy, just as with indexes of technological “difficulty” for each technology.

Authors show not only attractive futures beyond the paths illustrated in the roadmap but also issues, risks, and threats along every point in those paths. They include technological feasibility, uncertainty in research and development, safety of materials, scarcity and diversity of natural resources, manufacturing capability of products, development of competitive and complementary technologies and infrastructures, the market, and social acceptance.

To fully use the roadmap, we must take care during the first step, because otherwise we make our best efforts using the wrong combination of button and button hole if that step is not carefully examined (Fig. 3). Even when the logic of the second button from the top is coherent, there may be discrepancies between attractive technology of the future and associated risks, supply-side expectation and demand-side/social perceptions, planned development paths and their feasibility, hidden assumptions and a master equation, fact and data as represented fact, and dream and reality. In any case, there is room for learning and self-development by focusing on the above discrepancies or gaps. We hope that this book will be of assistance in the design of future energy systems, identification of the aforementioned gaps that are worthy of investigation and development, and realistic thinking and creative imagination.

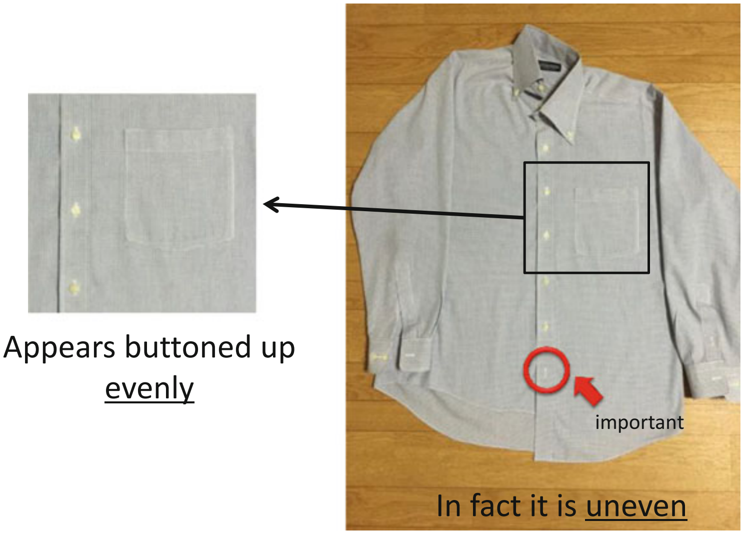

Fig. 3 Illustration of uneven buttoning (Published with kind permission of © Takuya Hasegawa 2015. All rights reserved)

http://www.springer.com/978-4-431-55949-8

Energy Technology Roadmaps of Japan
Future Energy Systems Based on Feasible Technologies Beyond 2030
Kato, Y.; Koyama, M.; Fukushima, Y.; Nakagaki, T. (Eds.)
2016, XIV, 573 p. 302 illus., 260 illus. in color., Hardcover
ISBN: 978-4-431-55949-8