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REVIEW ARTICLE

Research needs and challenges faced in supporting scenario design in sustainability science: a literature review

Yusuke Kishita[1] · Keishiro Hara[1] · Michinori Uwasu[1] · Yasushi Umeda[2]

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Abstract A number of scenarios have been created to explore possible images of and transitions to a sustainable society, as famously represented by the IPCC's greenhouse gas emissions scenarios. These can be valuable as underlying information for policy makers making plans for a low-carbon society. Although many researchers have developed individual methods that can be used for designing scenarios, research agendas or challenges for supporting scenario design activities have not been sufficiently discussed. Based on an intensive literature review of existing studies, this paper aims to clarify requisites and challenges for supporting scenario design, particularly in the context of sustainability science. Given that the value of designing scenarios is to help generate and communicate various ideas about the future as argued by sustainability science literature, scenarios are often created with stakeholder participation, through iterative cycles that are composed of three steps: (a) idea generation, (b) idea integration and scenario description, and (c) scenario evaluation. The results of our literature review also show that, though a wide array of methods and tools are available to support some of the steps, there are research issues to be further addressed in supporting scenario design. They include (1) accumulating existing scenarios and simulators as a promising approach to structuring knowledge about sustainability science and (2) ensuring the transparency of the logic underlying scenarios to facilitate communication between participants. Addressing these points will enhance support for sustainability scenario design.

Keywords Scenario design · Stakeholder participation · Design support · Literature review · Research agenda · Knowledge structuring

Introduction

There is a strong need to establish a sustainable society by solving a wide array of environmental problems, such as climate change, resource depletion, and the deterioration of biodiversity. With a particular focus on the coexistence of human beings and the environment, sustainability science deals with complex challenges that we human beings face at multiple levels by exploring the complex interactions of various systems and providing visions that lead toward sustainable societies (Clark and Dickson 2003; Kates et al. 2001; Kates 2011; Komiyama and Takeuchi 2006; Spangenberg 2011). As both social and natural systems involve inertia, as seen in climate change problems, sustainability problems need to deal with mid- and long-term changes, which present a variety of uncertainties at multiple levels (Swart et al. 2004). Although forecasting techniques using mathematical models such as extrapolating historical data into the future are often used to address future problems, their reliability diminishes as uncertainty rises (Huss 1988).

Scenarios will play an important role as sustainability science addresses this challenge by envisioning alternative futures in creative, rigorous, and policy-relevant ways that reflect the normative nature of sustainability (Swart et al.

Handled by Yuya Kajikawa, Tokyo Institute of Technology, Japan.

✉ Yusuke Kishita
kishita@ceids.osaka-u.ac.jp

[1] Center for Environmental Innovation Design for Sustainability (CEIDS), Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

[2] Department of Precision Engineering, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

2004). There are many definitions of the term scenario, one of which describes scenarios as stories that connect narrative descriptions of futures with the present in a series of causal relationships (Glenn and the Futures Group International 2003). Another definition refers to consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for actions (van Notten 2005). Either way, emphasis is placed on the idea that a scenario is not a prediction; rather it is an imaginative explication of possible future images that might unfold (Brewer 2007; Schwartz 1991; van der Heijden 1996). Many research organizations have already developed a wide variety of scenarios as an approach to solving various types of environmental and sustainability problems. For convenience, this paper calls such scenarios sustainability scenarios. A sustainability scenario here refers to a scenario that looks at any kind of sustainability aspect on any regional scale. Examples of sustainability scenarios include greenhouse gas emissions scenarios (IPCC 2007) and global energy demand and supply scenarios (IEA 2009). Along with the development of sustainability scenarios, a number of methods and tools have been developed for building them. For example, scenario planning is a prevalent way of thinking for strategic decision-making in the business world (Schwartz 1991; Wack 1985a).

As many researchers have already pointed out, designing scenarios is a powerful approach to articulating possible future images and pathways for a sustainable future through discussions among stakeholders (Swart et al. 2004; van Leeuwen et al. 2013). In attempting to encourage designing sustainability scenarios toward delineating a holistic view of sustainable futures, one core research question is how we should support scenario design in the context of sustainability science. In this paper, we differentiate scenario design from merely writing scenarios. Rather, to deepen an understanding of and share diversified views on the future, we define scenario design as a sequence of activities required to build scenarios by involving various stakeholders, through which the scenario is detailed in a stepwise manner to its completion. Scenario design activities should include not only writing scenarios but also idea generation, data gathering, simulations, and appraisal (more details about scenario design are elaborated in “Basic concept of scenario design cycles”. To the best of our knowledge, however, few papers have discussed challenges being faced by or research agendas for the support of scenario design. Historically, there have been few research efforts to develop common frames or theories for scenario design, partly because scenario experts usually work as consultants in the business sector (Kirsch 2004; Martelli 2001).

This paper aims to clarify requisites and challenges to be overcome in supporting scenario design, particularly in the domain of sustainability science. To this end, we attempt to understand the roles and potential of scenario design by reviewing a number of studies relevant to existing sustainability scenarios and scenario design methodologies.

The rest of this paper is organized as follows. The next section gives a brief history of scenario studies and presents a list of existing sustainability scenarios. This is followed by a presentation of the concept of scenario design and requisites for supporting it in sustainability science. The third section reviews existing scenario methods and tools, and classifies them based on the scenario design concept. Based on the literature review, the fourth section discusses research needs and challenges faced in supporting scenario design within sustainability science. The final section concludes the paper.

Scenario design for sustainability science

Historical evolution of scenario studies

The history of scenario studies can roughly be divided into three phases. First, scenario-based analysis originally emerged from World War II in military strategic planning in the United States, where it was applied to war gaming and military exercises (DeWeerd 1967; Kahn and Wiener 1967). Second, in the late 1960s and early 1970s, Royal Dutch Shell adopted a scenario technique, now known as scenario planning, in its corporate planning (Wack 1985a, b). Royal Dutch Shell successfully managed to come through the oil crisis in 1973 by assuming the rise and subsequent fall of oil prices in advance. After that, scenario planning became highly popular in both public and private sectors for facilitating strategic planning processes (Glenn and the Futures Group International 2003; Schwartz 1991; Shell International 2008; van der Heijden 1996). Third, since the Brundtland Report was released in 1987 (WCED 1987), scenarios have been applied in coping with environmental and sustainability problems. Famous examples of sustainability scenarios include the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC) (2007), the scenarios of biodiversity loss on human well-being by Raskin et al. (2005), and the Energy Technology Perspectives (ETP) by the International Energy Agency (IEA) (2010) (see Table 1 for more examples). It should be noted that, prior to the beginning of scenario studies in the context of environmental problems and sustainability, a number of mathematical simulation models have been studied since the 1970s in the course of policy exercises on environmental issues relating to, for example, environmental pollution,

Table 1 Examples of sustainability scenarios by theme

No	Scenario title	Theme	Type of scenario			Number of sub-scenarios[a]	References
			Qualitative/ quantitative	Forecasting/ backcasting	Expert analysis/ stakeholder participation		
1. Climate change and energy problems							
1.1	Special report on emissions scenarios (SRES)	Climate change	Combined	Forecasting	Expert analysis	4 scenario families	IPCC (2007)
1.2	World energy outlook (WEO)	Future energy supply and demand	Combined	Forecasting	Expert analysis	2 scenarios	IEA (2009)
1.3	Energy technology perspectives (ETP)	Energy strategies toward a low-carbon society	Combined	Forecasting and backcasting	Expert analysis	2 scenarios	IEA (2010)
1.4	Low-carbon Japanese lifestyle in 2050	Changing lifestyles by introducing information communication technology (ICT)	Qualitative	Backcasting	Expert analysis	4 scenarios	Fujimoto (2007)
1.5	2050 Japan low-carbon society scenario	Japan's greenhouse gas emissions	Combined	Backcasting	Expert analysis	2 scenarios	Nishioka (2008)
1.6	Tyndall decarbonisation scenarios	Energy mix for a decarbonized society in the UK	Combined	Backcasting	Stakeholder participation	5 scenarios	Mander et al. (2008); Anderson et al. (2008)
2. Water, food, and land use							
2.1	World water vision	Freshwater crisis	Combined	Forecasting and backcasting	Stakeholder participation	2 scenarios	Cosgrove and Rijsberman (2000)
2.2	Conventional and sustainable world scenarios in water	World water withdrawals and water stress	Combined	Forecasting and backcasting	Expert analysis	2 scenarios	UNEP (2012)
2.3	Water for food, water for life	Water use and agriculture	Combined	Forecasting	Expert analysis	5 scenarios	CA (2007)
2.4	World agriculture: Towards 2030/2050	Food and agriculture	Combined	Forecasting	Expert analysis	1 scenario	FAO (2006)
2.5	Future rural landscapes in Denmark	Landscape planning	Qualitative	Forecasting	Stakeholder participation	4 scenarios	Tress and Tress (2003)
3. Biodiversity							
3.1	Millennium assessment (MA) report	Ecosystem services and human well-being	Combined	Forecasting	Stakeholder participation	4 scenarios	Carpenter et al. (2005)
3.2	Global biodiversity strategies	Global biodiversity loss up to 2050	Combined	Forecasting	Expert analysis	2 scenarios	Ten Brink et al. (2010)
4. Waste and minerals resources							
4.1	Vision 2040: Innovation in mining and minerals	Visions for Australia's mining industry future	Qualitative	Backcasting	Stakeholder participation	3 scenarios	Lederwasch et al. (2011)
4.2	Resource/waste management system scenario	Resource & waste management	Qualitative	Forecasting	Expert analysis	4 scenarios	Hashimoto et al. (2009)
5. Sustainability and businesses/manufacturing industries							
5.1	WBCSD global scenarios	Business and sustainability	Combined	Forecasting	Expert analysis	3 scenarios	WBCSD (1997)
5.2	FutMan scenario	Future of manufacturing in Europe	Qualitative	Forecasting	Expert analysis	4 scenarios	Geyer et al. (2003)
5.3	The future of manufacturing	Future of UK manufacturing	Combined	Forecasting	Expert analysis	3 scenarios in 2035	Foresight (2013)

Table 1 continued

No	Scenario title	Theme	Type of scenario			Number of sub-scenarios[a]	References
			Qualitative/ quantitative	Forecasting/ backcasting	Expert analysis/ stakeholder participation		
5.4	Sustainable manufacturing scenario	Japan's sustainable manufacturing industry in 2050	Combined	Backcasting	Expert analysis	5 scenarios	Mizuno et al. (2014)
6. Transportation							
6.1	Sustainable freight transport systems for Europe	Low-carbon freight transport systems in Europe in 2050	Quantitative	Forecasting and backcasting	Stakeholder participation	4 scenarios	Mattila and Antikainen (2011)
6.2	Visions for transport climate policy	Transportation and CO_2 emissions in Finland to the year 2050	Combined	Backcasting	Stakeholder participation	5 scenarios	Tuominen et al. (2014)
7. General global/regional environmental problems (including climate change, biodiversity, land, water, and environmental pollution)							
7.1	IMAGE scenarios	Global environmental change	Quantitative	Forecasting	Expert analysis	3 baseline scenarios	Alcamo et al. (1996)
7.2	International Institute for Applied Systems Analysis (IIASA) scenarios	Future environments in Europe	Combined	Forecasting	Expert analysis	Approx. 4 scenarios	Stigliani et al. (1989)
7.3	Global environment outlook	Global environment	Combined	Forecasting	Stakeholder participation	4 scenarios	UNEP (2002)
7.4	Global scenarios	Sustainability of the global system	Combined	Forecasting	Expert analysis	6 scenarios	Gallopin et al. (1997); Raskin et al. (2002)
7.5	OECD environmental outlook to 2050	Global environmental problems	Combined	Forecasting and backcasting	Stakeholder participation	2 scenarios	OECD (2008)

Updated and arranged by the authors after Alcamo (2001), UNEP (2012), and van Vuuren et al. (2012)

[a] The number here counts sub-scenarios in the final version of each scenario. In general, the number of sub-scenarios is subject to change during the scenario design process

deterioration of ecosystem services, and climate change (Clark and Munn 1986; Meadows et al. 1972; Parson and Fisher-Vanden 1995).

Characteristics of existing sustainability scenarios

As depicted in Table 1, existing sustainability scenarios cover a wide variety of themes and aspects of sustainability, including climate change, energy, water, food, land use, biodiversity, wastes and minerals resources, transportation, and sustainability and business. Regardless of the theme, each sustainability scenario is composed of several sub-scenarios exploring a range of possible futures.

Sustainability scenarios have three characteristics in common. First, they often combine qualitative descriptions and quantitative simulations (Alcamo 2001; Alcamo et al. 2006). Qualitative descriptions explain future situations, such as global economy trends and people's lifestyles, while quantitative simulations provide scientific underpinnings for the scenarios by dealing with complex physical and social phenomena (Alcamo 2001). One of the biggest differences between scenarios and simulations is how they are presented. Scenarios are represented as narrative stories, whereas simulations deal with quantitative matters. For example, the climate model used for developing the IPCC's scenarios (IPCC 2007) played a central role in giving scientific rigor to the scenarios based on a great deal of data and calculations using massive computational resources. Qualitative descriptions and simulations complement each other in designing scenarios. Qualitative descriptions are essential in explicitly stating the assumptions and rationales upon which quantitative simulations are run.

Second, as illustrated in Fig. 1, sustainability scenarios can typically be categorized into two types—forecasting scenarios and backcasting scenarios (Alcamo 2001; van

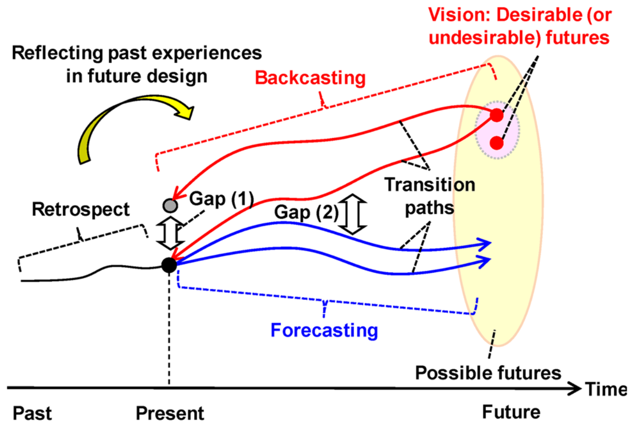

Fig. 1 Sustainability scenario conceptualization. Forecasting and backcasting scenarios differ in terms of their starting points (i.e., the present or a vision). Note that there are two types of gaps—gap (*1*) depicts a range of destinations reachable from the vision (desirable or undesirable future) by backcasting, and gap (*2*) depicts the differences between the transition paths drawn by forecasting and those by backcasting

Notten et al. 2003). Forecasting scenarios define the present as the starting point for drawing futures, while backcasting scenarios explore paths backward from predetermined future visions to the present to discuss what is necessary to arrive at the envisioned future (Robinson 1990). A vision refers to a desirable or undesirable state in the future (Quist 2007; Wiek and Iwaniec 2014). Backcasting scenarios allow for identifying technology and policy needs if a desirable future is to be sought. If an undesirable future is assumed as a vision, backcasting scenarios can be used to analyze how undesirable changes can be avoided or responded to (Robinson 1990). It should be noted that, however, backcasting does not necessarily reach the present status from the vision. Therefore, as depicted with gap (1) in Fig. 1, there would be multiple destinations that are reachable from the vision by backcasting. Forecasting scenarios, on the other hand, are useful for drawing multiple transition paths that may occur, but do not guarantee the connection between the present status and a vision (desirable or undesirable future). Mainly caused by the different starting points in forecasting and backcasting scenarios (i.e., the present or the vision), there would be another type of gap [gap (2) in Fig. 1] between the transition paths drawn by forecasting and backcasting. For example, the IPCC's Emissions Scenarios, which are forecasting scenarios, describe several storylines to analyze the impact of greenhouse gas emissions on global warming (IPCC 2007). Temperature projections differ in specific scenarios depending on population growth, GDP growth, energy use, etc. The 2050 Japan Low-Carbon Society scenario (Nishioka 2008), on the other hand, is a backcasting scenario. It first sets a desirable future in which CO_2 emissions in 2050 are 70 % lower than the 1990 level, then draws paths between the present and the future. Backcasting is considered suitable for addressing long-term problems that require drastic changes, such as establishing a sustainable society from our present one (Dreborg 1996).

Third, sustainability scenarios are often developed with stakeholder participation to accommodate their diversity of knowledge, expertise, and disciplines (Glenn and the Futures Group International 2003; Rotmans et al. 2000). Workshops, questionnaires, and interviews are often used to generate and share various stakeholders' ideas regarding the futures (Glenn 2003). Since sustainable future visions are inherently normative and stakeholders have different sets of values and mental frameworks, many researchers have already applied a participatory approach in developing backcasting scenarios for sustainable societies (Carlsson-Kanyama et al. 2008; Quist and Vergragt 2006). For example, the Tyndall Decarbonisation Scenarios (Mander et al. 2008; Anderson et al. 2008), which describe the UK's decarbonized societies achieving a 60 % reduction in CO_2 emissions from 1990, were developed through workshops involving stakeholders and academics. In contrast, the Special Report on Emissions Scenarios (IPCC 2007) was developed based on expert analysis by involving a large group of experts, where lay stakeholders were not explicitly involved in the scenario development process (Alcamo 2001).

Basic concept of scenario design cycles

Scenarios have been widely used in various fields, such as scientific research, public policy, and business, as a means of understanding future uncertainties and gaining deeper insight into multiple possible futures (Bradfield et al. 2005). Designing scenarios produces benefits by promoting shared understanding among stakeholders and helping to explicate tacit ideas about the future (Berkhout et al. 2002). Additionally, as Berkhout et al. (2002) described scenarios as "learning machines", one of the most important roles of designing scenarios is providing stakeholders with a mutual learning process or a communicative function (van der Heijden 1996). Scenarios allow for more intuitive imagination and understanding because of their narrative or story-telling nature than do complex simulation models (Berkhout et al. 2002; Swart et al. 2004).

To maximize scenarios' potential value, the process of designing them should contain iterative cycles of divergence and convergence of a variety of ideas using a participatory approach (Börjeson et al. 2006). The aim of such iterative processes is to gradually articulate new insights regarding the futures through questions raised by various participating stakeholders (van der Heijden 1996). Based on ideas presented by previous work (Bishop et al. 2007;

Kishita et al. 2011; Mizuno et al. 2013), we propose the conceptual diagram of scenario design cycle illustrated in Fig. 2. We see scenario design processes as, while beginning with problem definition and ending with scenario documentation, encompassing an iterative cycle of three steps: (a) idea generation, (b) idea integration and scenario description, and (c) scenario evaluation. Accordingly, we propose executing a small (unit) loop consisting of steps (a) through (c) followed recursively that can incrementally detail scenario descriptions until the scenario is completely designed. At the beginning of the processes (i.e., in the process of problem definition), it is important that the scenario designers have a clear view of the scenario design and share it with other participants involved, as noted in Jäger et al. (2007). More concretely, the scenario designers should clarify at least the objective of the scenario design, the spatial and temporal boundary of concern, and who should be involved in the scenario design processes. Clarifying problem definition is a prerequisite for a constructive dialog among participants in the scenario design processes.

Each of steps (a)–(c) in Fig. 2 encompasses the following tasks:

(a) *Idea generation* A wide variety of ideas is generated through brainstorming and discussions among the participants. Interviews with experts, questionnaires, surveys of statistical data, and literature reviews are often conducted in this step.

(b) *Idea integration and scenario descriptions* Pieces of the stories of the scenario are written by integrating ideas generated in step (a). Scenario descriptions are thus added in an incremental manner. To gradually embody the scenario, this step may include describing the causal relationships between its constituent elements and quantifying the scenario with mathematical models.

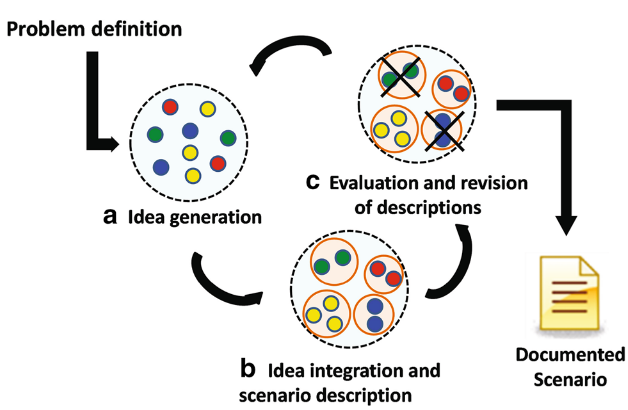

Fig. 2 Conceptual scenario design cycles

(c) *Evaluation and revision of descriptions* The contents of the scenario described in step (b) are evaluated by the participants, after which the scenario is revised based on that evaluation. Examples of evaluation criteria include internal consistency, creativity, and comprehensiveness (Alcamo et al. 2006; Glenn and the Futures Group International 2003).

The final output of the scenario design cycles is a scenario document, normally represented in text format, including graphs and tables where necessary.

Requisites for supporting scenario design in sustainability science

In the context of sustainability science, the goal of designing sustainability scenarios is to deepen an understanding of sustainable futures, provide holistic views of those futures, and clarify necessary actions to be taken (Komiyama and Takeuchi 2006). Given the characteristics of sustainability scenarios (see "Characteristics of existing sustainability scenarios") and the scenario design concept (see "Basic concept of scenario design cycles"), we summarize requisites that should be taken into account to support scenario design into the following three points.

First, although a large number of scenarios focusing on specific aspects of sustainability have been developed (see Table 1), more sustainability scenarios on various themes should be designed and related to each other to elucidate a holistic view of sustainability. Since sustainability problems intrinsically span various domains and fields, synthesis and structuring of knowledge are key in overcoming contradictions that may arise when looking into specific issues and domains individually (Jerneck et al. 2011; Yoshikawa 2008). For example, if the diffusion of large amounts of low-carbon energy technologies (e.g., wind power generators and electric vehicles) is promoted to mitigate climate change problems, other sustainability issues, such as the depletion of mineral resources, might be induced since such low-carbon technologies often use critical metals, including rare earth metals. However, in current scenario research, less effort has been made in clarifying the interrelationships among various sustainability scenarios. This is partly because each of such scenarios tends to focus on a specific domain of sustainability for enabling detailed analysis with a rich amount of relevant data.

Second, the participants involved in the scenario design process should be helped to more easily generate diversified ideas and organize them to delineate a variety of possible futures that may occur, as well as to craft shared visions of sustainable societies. Toward this end, sufficient methods and tools to support the execution of scenario design cycles, as illustrated in Fig. 2, should be available. These methods and tools should cover the design of sustainability scenarios in a way that allows the combination of narrative stories with quantitative simulations, as mentioned in "Characteristics of existing sustainability scenarios". Although many different methods and tools have been used to build sustainability scenarios in Table 1, research efforts have to be made to integrate the concept of scenario design cycles into designing forecasting and backcasting scenarios. Examples of such methods and tools are explained in "Scenario design tools" and "Scenario design procedures".

Third, to find a solution-oriented approach (Komiyama and Takeuchi 2006), there must be collaboration between real-world stakeholders and researchers/scientists from diverse disciplines with a wide variety of knowledge. Together they can derive meaningful solutions by designing scenarios that address problems that actually exist in our society (Schneider and Rist 2014). Such collaboration enables us to contextualize the normative concept of sustainability to match the problem being tackled in the scenario design (Miller et al. 2014; Wiek et al. 2011). Stakeholder participation is important in legitimizing the effort so that agendas proposing action and follow-up based on the scenarios can be endorsed and then realized (Quist and Vergragt 2006). Here, to create new knowledge and values, it is important that stakeholders are explicitly involved in the scenario design cycles shown in Fig. 2. Looking at existing sustainability scenarios, however, more than half of the scenarios in Table 1 (specifically, 17 out of 26 scenarios) were developed by expert analysis, not involving stakeholders.

Studies related to scenario design methodologies

Overview

We carried out an extensive literature review on scenario design, aiming to clarify research challenges in the light of the requisites noted above. The sources included several journals (e.g., *Sustainability Science*, *Futures*, *Technological Forecasting & Social Change*, *European Journal of Operational Research*, *Foresight*, *Energy Policy*, and *Journal of Cleaner Production*), books, reports, conference proceedings, and websites.

In what follows, we consider two aspects of scenario design, scenario design tools and scenario design procedures. Scenario design tools refer to tools available to execute parts of the scenario design cycles presented in Fig. 2. Scenario design procedures, on the other hand, define a sequence of stages of the development of scenarios in a recursive unit loop [comprising steps (a)–(c) in Fig. 2]. In many cases, the use of scenario design tools is embedded within the scenario design procedures (see "Scenario design procedures" for examples).

Scenario design tools

Table 2 shows a list of tools available to help scenario designers drive scenario design cycles (see Fig. 2), where a tick (✔) indicates steps that each tool can support. Note that the list is not exhaustive.

Tools for step (a) help participants generate a variety of ideas that can potentially be used for building scenarios. The Delphi method is used for choosing events that are likely to emerge in the future, where the decision is basically based on experts' judgment. Political, economic, social, and technological (PEST) analysis encourages participants to come up with a variety of elements associated with a given theme (e.g., energy issue). The KJ method and other similar methods are utilized in brainstorming with multiple people in workshops, often using pens, paper, and sticky notes. Future maps, morphological analysis, and causal layered analysis support step (a) but are also useful for (b) because they help construct narrative stories for sub-scenarios based on ideas generated by participants. In particular, future maps help to organize participants' collective ideas, which are finally compiled in shared visions. This tool may be useful in designing backcasting scenarios.

For step (b), morphological analysis is used to generate the kernels of scenarios as combinations of uncertainties (Coyle 2003), while system dynamics is used to visualize cause–effect chains connecting the elements of a system and to build mathematical models to quantitatively analyze the system (Ward and Schriefer 2003). The Shell/GBN matrix, a kind of morphological analysis, is one of the most famous tools (Wack 1985a). The Shell/GBN matrix contains two dimensions of uncertainty, where each of the four quadrants in the matrix expresses the kernel of a possible future. The IPCC's scenarios were created using this matrix based on the two dimensions of strong economic values versus strong environmental values and globalization versus regionalization (IPCC 2007).

Tools for step (c) are relevant to appraising and improving scenarios in the scenario design process. Multi-criteria assessment and system dynamics serve to assess designed scenarios from various angles, e.g., economic and environmental aspects. In particular, system dynamics is applicable to both qualitative and quantitative analyses. It is used to delineate stories of scenarios in a series of causal relationships while checking internal consistencies between their constituent elements. Both trend impact analysis and cross-impact analysis are used to evaluate how probable designed scenarios are.

Table 2 Categorization of scenario design tools

No	Tool	Description	Steps that the tool supports			References
			(a) Idea generation	(b) Description	(c) Evaluation	
1	Delphi method	A tool to forecast an event of interest based on opinions of a group of experts through a series of intensive questionnaires to obtain the most reliable consensus	✔			Dalkey and Helmer (1963); Landeta (2006)
2	PEST analysis	A tool to list external factors that would affect business activities of enterprises, classified into political, economic, social, and technological aspects	✔			Healey (1994)
3	Q-methodology	A tool to analyze people's subjectivity in decision-making processes, helping to examine differences and similarities in subjectivities of a group of people	✔			Browne et al. (2007)
4	KJ method	A tool to generate ideas by organizing qualitative data, where each piece of data is described on a card and several cards are grouped based on the data's similarity.	✔			Kawakita (1974)
5	Future map	A tool to generate a sequence of events that leads to each end-state, where the end-states are pre-defined	✔	✔		Mason (2003)
6	Morphological analysis (Shell/GBN matrix)	A tool to create alternative futures based on different states of uncertainties. This tool is called the Shell/GBN matrix if two dimensions of uncertainty are considered, in which four combinations of the poles of two uncertainties are generated	✔	✔		Coyle (2003); Schwartz (1991)
7	Causal layered analysis	A tool used in workshops to analyze different approaches to solving a problem among participants by layering the participants' values and thoughts at multiple levels	✔	✔		Inayatullah (1998)
8	System dynamics	A tool to describe causal relationships among the elements of a system to quantitatively analyze behaviors of the system. It also helps to check internal system causality consistencies		✔	✔	Hjorth and Bagheri (2006); Sterman (2000); Ward and Schriefer (2003)
9	Fuzzy cognitive maps	A tool to represent mental models suggested by multiple participants in a workshop as causal relationships, with each causal link being weighted within a range of -1 to 1 depending on the strength of causality		✔	✔	Jetter and Schweinfort (2011)
10	Multi-criteria assessment	A tool to assess impacts and consequences of futures described in scenarios based on multiple criteria (e.g., economic performance and environmental impact)			✔	Mander et al. (2008)
11	Trend impact analysis	A tool to estimate probabilities of occurrence and impacts of future events based on experts' judgment. The extrapolation of historical data is used to assume unprecedented future events			✔	Gordon (2003a)
12	Cross-impact analysis	A tool to calculate relative probabilities of occurrence of scenarios based on the conditional probabilities of an event given the occurrence of any other event			✔	Gordon (2003b)

Updated and arranged by the authors after Börjeson et al. (2006) and Bishop et al. (2007)

Table 3 mentions another list of scenario design tools, where a tick (✔) indicates that each tool is applicable according to the characteristics of sustainability scenarios. The twelve tools listed in Table 3 are widely available across most types of sustainability scenarios. The Delphi method, PEST analysis, Q-methodology, and the KJ method are applicable to any type of sustainability scenarios as they can support idea generation generally. Some tools have limitations in their applicability. For example, morphological analysis (Shell/GBN matrix) helps create storylines of forecasting scenarios since it draws multiple futures based on uncertainties by assuming that the present status is a starting point.

Scenario design procedures

Many researchers have proposed procedures for designing scenarios (e.g., Alcamo 2001; Leney et al. 2004; O'Brien 2004; Robinson 1990). As mentioned in "Characteristics of existing sustainability scenarios", there are two approaches to designing scenarios—forecasting and backcasting. Some methods related to each approach are shown below.

Procedures for designing forecasting scenarios

There are a number of studies that have demonstrated a sequence of stages for building forecasting scenarios. In the field of scenario planning, many relevant methods are available for decision-making support in corporate strategic planning. Examples include methods by O'Brien (2004), Schwartz (1991), Shell International (2008), Wright et al. (2009), Wilkinson (1995), and van der Heijden (1996). Commonly, these methods involve moving through stages to describe multiple business environments by changing the status of exogenous variables surrounding the business (e.g., global economic situations and national policies) to analyze various influences of future uncertainties from the present.

In recent studies, many scholars have proposed procedures for describing forecasting scenarios in the context of sustainability. For example, Jäger et al. (2007) proposed a 4-stage procedure based on the story-and-simulation approach, which integrates narrative stories and quantitative analysis (Alcamo 2001). The stages are as follows: (1) clarifying the purpose of scenario building, (2) laying foundations for the scenarios (e.g., how many sub-scenarios are to be developed?), (3) developing scenarios and undertaking quantitative analysis, and (4) communication and outreach. In stage (2), the Shell/GBN matrix approach is used to determine the axes for delineating sub-scenarios. This method postulates the combination of narrative descriptions and quantitative analysis, which is consistent with one of the characteristics of sustainability scenarios (see "Characteristics of existing sustainability scenarios"). Likewise, Wada et al. (2011) proposed a method for designing forecasting scenarios in 4 stages: (1) problem settings, (2) constructing causal networks to represent the targeted system, (3) describing storylines of scenarios, and (4) describing details, including parameterization and quantification, of each sub-scenario. Stage (2) is similar to using system dynamics in terms of clarifying underlying cause–effect chains.

Procedures for designing backcasting scenarios

Research on procedures for designing backcasting scenarios has been advancing since Prof. Robinson at University of British Columbia coined the term "backcasting" (Robinson 1982). Existing methods regarding backcasting scenarios have been, in most cases, applied to sustainability problems (e.g., Carlsson-Kanyama et al. 2008; Giurco et al. 2011; Höjer and Mattsson 2000; Holmberg and Robèrt 2000; Mander et al. 2008; Mizuno et al. 2012; Robinson et al. 2012; Svenfelt et al. 2011). The history of existing backcasting methods can be divided into two generations. First-generation studies are intended mainly for desk research involving experts, researchers, or scientists, whereas second-generation studies attempt to embark on stakeholder participation to create shared visions of sustainable futures via the process of designing backcasting scenarios.

Regarding first-generation methods, Robinson (1990) presented a generic procedure for describing backcasting scenarios in 6 stages. These were (1) determining the purpose of scenario building, (2) specifying goals, constraints, and targets, (3) describing the present system, (4) specifying exogenous variables of the backcasting, (5) undertaking scenario analysis (including developing scenarios), and (6) undertaking impact analysis (including comparison of scenario results with predetermined goals). As with methods for forecasting scenarios, some researchers integrated scenario design tools into procedures for describing backcasting scenarios. For example, Mizuno et al. (2012) proposed a procedure for developing backcasting scenarios in which one feature of the method was to employ logic trees to support backward thinking from a desired vision to the present.

Second-generation studies are often called participatory backcasting (Quist and Vergragt 2006), which involves, with stakeholder participation, the process of developing a single or multiple visions and pathways to reach those visions. Mander et al. (2008) proposed a procedure for building backcasting scenarios with multi-criteria assessment. As already explained in "Characteristics of existing sustainability scenarios", their procedure includes convening participatory workshops with both academics and

Table 3 Applicability of scenario design tools according to sustainability scenarios' characteristics

No	Tool	(I) Qualitative/quantitative/combined			(II) Forecasting/ backcasting		(III) Expert analysis/ stakeholder participation		Remarks
		Qualitative	Quantitative	Combined	Forecasting	Backcasting	Expert analysis	Stakeholder participation	
1	Delphi method	✔	✔	✔	✔	✔	✔	✔	Originally, this tool was intended for experts, but it is also available under the condition of public involvement (Liimatainen et al. 2014; Nowack et al. 2011; Tuominen et al. 2014)
2	PEST analysis	✔	✔	✔	✔	✔	✔	✔	This tool is generally available for brainstorming in a workshop
3	Q-methodology	✔	✔	✔	✔	✔	✔	✔	Ibid
4	KJ method	✔	✔	✔	✔	✔	✔	✔	Ibid
5	Future map	✔		✔		✔	✔	✔	This tool is intended for backcasting scenarios as it helps describe events to reach end-points (Mason 2003)
6	Morphological analysis (Shell/GBN matrix)	✔		✔	✔		✔	✔	This tool helps create forecasting scenarios as it draws multiple futures based on uncertainties, by assuming the present status as a starting point (Coyle 2003; Schwartz 1991)
7	Causal layered analysis	✔		✔	✔	✔	✔	✔	This tool helps create scenario narratives based on different views of participants in a workshop (Lederwasch et al. 2011)
8	System dynamics	✔	✔	✔	✔	✔	✔	✔	This tool helps scenario development with quantitative analysis based on causal relationships (Hjorth and Bagheri 2006; Ward and Schriefer 2003)
9	Fuzzy cognitive maps	✔	✔	✔	✔	✔	✔	✔	This tool is available for a systematic understanding of worldviews of participants in a workshop (Jetter and Schweinfort 2011)

Table 3 continued

No	Tool	(I) Qualitative/quantitative/combined			(II) Forecasting/backcasting		(III) Expert analysis/stakeholder participation		Remarks
		Qualitative	Quantitative	Combined	Forecasting	Backcasting	Expert analysis	Stakeholder participation	
10	Multi-criteria assessment	✔	✔	✔	✔	✔	✔	✔	This tool is used for undertaking comparative analysis of scenarios (Mander et al. 2008)
11	Trend impact analysis	✔	✔	✔	✔		✔	✔	This tool is used for estimating the probability of forecasting scenarios based on future events that may happen (Gordon 2003a)
12	Cross-impact analysis	✔	✔	✔	✔		✔	✔	This tool analyzes the relationships between a set of future events, helping determine which scenarios are more likely to occur (Banuls and Turoff 2011)

stakeholders. By extending Robinson's method (Robinson 1990), Tuominen et al. (2014) proposed a procedure for developing multiple desirable visions using the Delphi method, then applied it to Finland's sustainable transport systems in 2050. Other methods include the one by Giurco et al. (2011), which seems to be a relatively researcher-led procedure but in which experts and government stakeholders were invited for data gathering and review of described scenarios.

As described above, existing methods for participatory backcasting differ in the way different types of participants (e.g., researchers/scientists, policy makers, NGO/NPO representatives, business professionals, and citizens) work in the scenario design process. Although the role played by each type of participants varies on a case-by-case basis, it is common that the potential value of participant involvement lies in not only making use of a wide range of expertise, country/regional knowledge, and thematic knowledge (Foresight Horizon Scanning Centre 2009; Patel et al. 2007), but also gaining an in-depth understanding of the lay public's perspectives (Rauschmayer and Wittmer 2006). It is worth noting that, in any case, researchers should maintain an open and balanced dialog to gain an in-depth understanding and to increase interactions with participants. This is partly because, if researchers focus solely on expressing their knowledge, other non-academic participants tend to be passive receivers of information, thereby resulting in one-way communication (McKee et al. 2015). This may lead to undermining the potential power of knowledge production based on the interaction among participants. Researchers would rather play a central role in designing the scenario design process, recruiting the participants, organizing the workshops, undertaking the analysis, and writing up the project outputs (Eames and Egmose 2011).

Research challenges for supporting scenario design in sustainability science

The results of our literature review in the previous sections showed that many sustainability scenarios and scenario design methods have already been developed. However, existing studies do not fulfill all the three requisites mentioned in "Requisites for supporting scenario design in sustainability science". By comparing those requisites and our review results, we extracted several research challenges yet to be addressed for supporting scenario design in sustainability science. Below are potential research challenges associated with each of the three requisites.

Research challenges for understanding a comprehensive view of sustainability

To achieve a comprehensive view of sustainability, the design of sustainability scenarios on a broad spectrum of themes should be more encouraged beyond those listed in

Table 1. Existing scenarios, models, and databases could be useful sources of information when designing new sustainability scenarios (Swart et al. 2004). Hence, one research challenge for supporting the design of new scenarios is to accumulate existing scenarios and associated simulation models in such a way that allows other scenario designers to access them.

Another research challenge is to clarify the multi-faceted structure of sustainability by elucidating the complex interactions between individual sustainability scenarios. As mentioned in "Requisites for supporting scenario design in sustainability science", each individual sustainability scenario, partly listed in Table 1, focuses on a specific aspect of sustainability (e.g., biodiversity, energy, and transportation) to undertake detailed analysis on that topic. The question is how sustainability scenarios should be designed so as to allow synthesis of individual scenarios to compromise and balance different aspects of sustainability. This is because whenever scenario designers attempt to come up with a scenario in a specific problem setting (i.e., theme, time horizon, and regional scale), they encounter incompatibilities between various aspects of sustainability. The scenario designers should take into account the potential influence of various external situations that always exist outside the spatial and temporal boundary being considered. For example, when scenario designers focus on Japan's sustainable energy supply systems to 2050, they should also look at energy demand worldwide as the energy market is highly globalized. It is also important to look into not only interactions and discrepancies between different sustainability aspects, but also the influences of different regional scales. For example, national policies, such as nuclear power policies, will affect lower scales (downward deployment), and conversely, grass-root activities on a municipal scale might bring about a change on a national scale (upward deployment). Interaction between different regional scales may serve as a key driver as well as a barrier toward sustainability transitions.

Addressing the above challenges can indeed lead to a promising approach to structuring knowledge in sustainability science.

Research challenges for developing scenario design procedures and tools

Although there are a number of existing scenario design procedures and tools, one critical problem in current scenario studies is how to systematize them to facilitate scenario design in a holistic manner. Two research questions, described below, emerge in consideration of this problem.

Integrating the concept of scenario design cycles into scenario design procedures

The essence of scenario design is iterative cycles involving brainstorming, review, reflection, and revision to co-produce new knowledge, findings, and insights through participatory discussions (Vergragt and Quist 2011; Wiek and Iwaniec 2014). The first question is how the concept of scenario design cycles can be reflected in an entire scenario design procedure. One potential answer is to mobilize a variety of scenario design tools available since, as indicated in Table 2, each individual tool is helpful in parts of the scenario design cycles shown in Fig. 2. The above question can be broken down into the following sub-questions:

- How should appropriate scenario design tools be chosen to conduct an entire scenario design procedure? For example, morphological analysis is appropriate for describing forecasting scenarios rather than backcasting scenarios because it focuses on changes of uncertainty from the present.
- How should internal consistencies within the scenario be ensured so that the details of the scenario, determined by repeating scenario design cycles, remain rational? Difficulties here include the fact that scenario contents usually evolve as various information is integrated from different sources including texts, scenario design tools (e.g., morphological analysis and system dynamics), and complex mathematical models.

Related to the first sub-question, developing catalogs and guidelines for using scenario design tools is useful. Bishop et al. (2007) is an enlightening reference. Furthermore, more scenario design tools need to be developed to comprehensively support the design of sustainability scenarios. For example, there are few tools to objectively assess the effectiveness of sustainability scenarios, where metrics may include internal consistencies, creativity, and legitimacy (Alcamo et al. 2006; Glenn and the Futures Group International 2003).

Looking at the second sub-question, more efforts should be made to enable scenario designers to understand the whole structure of the scenario. One research task here is to develop a method for representing sustainability scenarios in a systematic way. As a relevant study, Mizuno et al. (2012) proposed a computer-aided method for representing the entire contents of scenarios using graph theory.

Further development of scenario design procedures for sustainability scenarios

The second question is about what procedures should be further developed for designing sustainability scenarios. To achieve a sustainable future, we must first define sustainability, which entails the concept of backcasting (Dreborg 1996; Höjer and Mattsson 2000; Robèrt et al. 2002). At the same time, as sustainability science aims to be solution-oriented, designed scenarios should not be just science fiction, but effective enough to offer profound implications based on scientific analysis. In other words, the feasibility of predetermined visions derived from a backcasting approach should be ensured, despite various future uncertainties that might happen between now and the future end point. This is why incorporating a backcasting approach to visioning sustainable futures and a forecasting approach to analyzing initial conditions and drivers of change is appropriate (Swart et al. 2004). The forecasting approach helps to identify the bandwidth of initial trajectories and available measures and actions that make it possible to proceed toward defined visions (Quist and Vergragt 2006; Swart et al. 2004).

The integration of forecasting and backcasting approaches is both an old and new research issue (Banister et al. 2000; Carlsson-Kanyama et al. 2008; Dortmans 2005; Gaziulusoy et al. 2013; Kok et al. 2011; Milestad et al. 2014; Robinson et al. 2012; van Vliet and Kok 2015). Quist and Vergragt (2006) presented a sequence of stages that integrate participatory backcasting and forecasting approaches. Kok et al. (2011) applied a similar method to water scenarios in Europe, where they took a participatory backcasting approach in which obstacles and opportunities to achieve desirable visions were analyzed by developing forecasting scenarios. Schneider and Rist (2014) carried out a backcasting scenario exercise on water use and governance, in which forecasting scenarios were described to simulate future water demand.

Still, most existing studies are rather case centric and not well generalized as to how to integrate forecasting and backcasting approaches. New methods that incorporate procedures and tools should be developed to support the design of sustainability scenarios. For example, Dortmans (2005) suggested using a tool called field anomaly relaxation (FAR) to analyze the discrepancy between desirable and possible futures.

Research challenges for making scenario design more solution oriented

Collaboration between researchers/scientists and stakeholders aims at mutual learning and co-production of knowledge (Robinson 2003; Schneider and Rist 2014; Swart et al. 2004). Higher order mutual learning leads to changes in mindsets or mental models, thereby broadening the space for actions and behavioral changes (Quist and Vergragt 2006; Robinson 2003). Researchers/Scientists bring knowledge of relevant processes, while stakeholders enrich scenario contents by adding human perspectives (Swart et al. 2004).

According to the actual cases in Table 1, a participatory approach is commonly taken to designing sustainability scenarios, where the scenario design process may include organization of workshops and consultation with experts to review draft scenarios. However, stakeholder participation is less frequently used when compared with expert analysis (see Table 1). For example, The Future of Manufacturing (Foresight 2013) was developed using a participatory approach, but being categorized in expert analysis since the participants involved were industry and academic experts only. Therefore, research on executing scenario design under collaboration between researchers/scientists and stakeholders should be further progressed. There are at least two challenges as described below.

Operationalizing participatory scenario design

One challenge is to operationalize the collaboration between researchers/scientists and stakeholders. This is divided into the following two research questions.

1. How can a common understanding between researchers/scientists and real-world stakeholders be facilitated?
2. How can researchers/scientists and stakeholders be engaged in the scenario design procedure to encourage scenario design?

As for the first question, the narrative nature of sustainability scenarios plays an important role in visualizing assumptions about future situations and worldviews of scenario designers. However, as scenarios are generally written in text format, their underlying logic is not necessarily transparent to readers. This is a dilemma in which although richer scenario contents will bring greater insights and impressions, they may hinder functional clarity and simplicity, making it difficult to provide a basis for strategies and decisions (Berkhout et al. 2002). These impede a common understanding of scenarios, preventing constructive dialog among the participants. Given stakeholder participation, scenarios should be described in a way that enables the participants to rationally understand their contents. One promising solution is to take a computer-aided approach to designing scenarios. Examples include Arizona State University's Decision Theater (Miller et al. 2014), which helps in visualizing participants' opinions and differences, and the Sustainable Society Scenario (3S) Simulator (Umeda et al. 2009, 2011), which provides an integrated platform to explicitly visualize the logical structure of scenarios so that participants can share a common understanding. More effort still needs to be made in the field of computer-aided scenario design.

Concerning the second question, which stakeholders should be engaged in which part of the design procedure is a case-by-case choice. General recommendations for potential research topics in organizing a scenario design team include the following:

- Mechanisms that enable cooperation among the participants are needed to realize multi-actor governance (Shiroyama et al. 2012).
- More expertise from communication studies in such fields as interactive communication, knowledge integration, and facilitation tools should be brought to bear. This will facilitate and strengthen interdisciplinary collaboration between stakeholders and researchers/scientists in different fields.

Making scenario design ready to implement in the real world

The other challenge is how to make scenario design ready to implement in the real world. For example, what is needed to make scenario design more effective in supporting actual policy-making? Many relevant studies have been conducted in the business world (e.g., Chermack 2011; van der Heijden 1996). For example, designed scenarios should be kept under review in preparation for new factors coming into play (Chermack 2011; Leney et al. 2004; Millett 1988). As yet, however, there are not enough case studies to analyze what is needed in scenario design for effective scenario deployment. Profound knowledge is yet to be established about what should be done to help real-world decision makers utilize the outcome of scenario design.

Conclusion and future directions

In this paper, we demonstrated a comprehensive literature review to present requisites and challenges for supporting scenario design. The contributions of the paper facilitate scenario design research in sustainability science through the following three points.

First, the roles and potential of scenario design were identified. The community of sustainability science recognizes that scenario design is a powerful approach to delineating visions of a sustainable society and finding pathways to reach the visions, with the scenario design process being seen as a learning process among researchers/scientists and lay stakeholders (e.g., Berkhout et al. 2002; Schneider and Rist 2014; Swart et al. 2004; Wiek and Iwaniec 2014). Participatory and reflexive processes of scenario design are helpful to accommodate a variety of expertise and knowledge and accelerate a mutual understanding of sustainable futures, to clarify holistic views of sustainable futures and actions that should be taken (Foresight Horizon Scanning Centre 2009; Komiyama and Takeuchi 2006).

Second, by surveying a number of existing sustainability scenarios (see Table 1), we extracted the three requisites to support scenario design; that is, the integration of scenarios involving various themes for a holistic view, the generation and conversion of diverse ideas and the creation of shared visions, and collaboration between researchers/scientists and stakeholders in society.

Third, the review results revealed that many methods and tools for scenario design are already available. Many researchers have proposed scenario design procedures for forecasting and backcasting scenarios and, moreover, there are a variety of scenario design tools (e.g., PEST analysis and multi-criteria assessment) to assist the execution of scenario design cycles in Fig. 2.

However, current scenario studies still lack support for designing sustainability scenarios in several points. We found several research challenges that must be met to systematize scenario design research in pursuit of knowledge structuring and effective collaboration between stakeholders and researchers. More concretely, these include (1) accumulating existing scenarios and simulation models as an approach to knowledge structuring, (2) ensuring the transparency of the underlying logic of scenarios to facilitate communication between the participants involved, and (3) developing scenario design methods by incorporating forecasting and backcasting approaches while mobilizing appropriate scenario design tools. Through addressing these challenges, the community of sustainability science needs to enhance collaboration by researchers from diverse disciplines and real-world stakeholders, aiming to co-produce new ideas, knowledge, and values for sustainability.

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