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Narrative scenario development based on cross-impact analysis for the evaluation of global-warming mitigation options

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Abstract

Social, technological, economic and environmental issues should be considered comprehensively for the evaluation of global-warming mitigation options. Existing integrated assessment models include assessment of quantitative factors; however, these models do not explicitly consider interactions among qualitative factors in the background – for example, introductions of nuclear power stations interact with social acceptability. In this paper, we applied a technological forecasting method – the cross-impact method – which explicitly deals with the relationships among relevant factors, and we then developed narrative scenarios having consistency with qualitative social contexts. An example of developed scenarios in 2050, assuming the global population and the gross domestic product are the same as those of the A1 scenario of the IPCC Special Report on Emissions Scenarios, tells us that: (1) the Internet will be extensively used in all regions; (2) the global unified market will appear; (3) regional cultures will tend to converge; (4) long-term investments (of more than 30 years) will become difficult and therefore nuclear-power stations will not increase so remarkably; (5) the self-sufficient supply and diversification of primary energy sources will not progress so rapidly;

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and (6) due to the widespread use of the Internet, people will be more educated in global environmental issues and environmental costs will be more socially acceptable.

Keywords: Global-warming mitigation; Social context; Narrative scenario; Cross-impact method; Step-by-step analysis

1. Introduction

Global-warming mitigation options should be evaluated taking into account future social, economic and environmental changes, which may be caused by interactions among various factors. Existing integrated assessment models for evaluating the global-warming mitigation options – for example, Asian Pacific Integrated Model (AIM) [1] and Model for Evaluating Regional and Global Effects of GHG reductions (MERGE) [2] – have included the assessment of future quantitative factors, such as population, economic growth, technology developments, energy and resources, and global-warming impacts. However, the quantitative factors are also influenced by qualitative background social contexts – for example, energy-technology developments will interact with not only economic growth but also the cost acceptance of renewable energy sources and material recycling. Therefore, global-warming mitigation options should be evaluated in such a way that combines quantitative model analyses and qualitative scenarios regarding social contexts.

The importance of considering social contexts has already been pointed out in the Special Report on Emission Scenarios (SRES) [3], which was proposed by the Intergovernmental Panel on Climate Change (IPCC). In SRES, qualitative scenarios called 'storylines' were firstly constructed as possible alternative futures, and then emission scenarios of greenhouse-gases were quantified using a number of models for each storyline. However, the relationships among qualitative factors, which might be employed to generate the storylines, have not yet been shown.

It would be very useful if the relationships among qualitative factors could be explicitly shown. For instance, regarding the introduction of nuclear-power generations and renewable energy sources that will be strongly affected by the social contexts, the relationships must be instructive to interpret numerical values in quantitative model analyses. The intention of this study is to develop narrative scenarios having the consistency with social contexts by clearing the relationships among qualitative factors. For the sake of scenario development, we used a theoretical method – a cross-impact (X-I) method – which has been developed for the technological forecasting.

2. Technological forecasting and cross-impact method

Technological forecasting has similar characteristics to the evaluation of global-warming mitigation-options in that policy-makers and managers have to make decisions based on the complicated inter-relationships among social, economic and environmental factors. In the second half of the twentieth century, due to the rapid development of new technologies in many fields including energy, transportation, information and communications, decision-makers faced difficulties to evaluate and establish the technology strategies. For instance, they had to decide when, and to what extent, such new technologies should be implemented replacing the conventional ones. To help with their decision-making, a number of technological forecasting methods based on experts' judgments were eagerly developed in 1960s and 1970s.

The X-I method used in this study is one of the technological forecasting methods. This is a technique to construct consistent future scenarios, taking into account the causality among relevant events, based on experts' judgments. When the n events are noticed, experts are required to estimate the probabilities of occurrence of the events and the impact probabilities for all combinations of any two events (two-dimensional probabilities). The estimated probabilities are mathematically rationalized to consist of n-dimensional probabilities. Applying the consistent probabilities to a mathematical model, scenario probabilities for n-dimensional states are stochastically calculated. A state is explained by a set specifying occurrences or incurrences – 1 or 0 – for each of the n events, and is called a 'scenario'. The scenario that has the highest probability is selected to be the most likely scenario. (The outline of the X-I method is presented in the Appendix. Details of the method are described by Kaya et al. [4] and Mori et al. [5].)

There are some studies in the energy field that have applied the X-I method as follows: a scenario development regarding nuclear-power generation [5] and a simulation analysis of oil price by a hybrid model associated with the X-I method and an econometric model [6]. In this study, we applied the X-I method to qualitative social and economic events, to take into account the causality among the events, and we then constructed narrative scenarios of the world in 2050 having consistency with the social contexts.

3. Cases and events to be considered for scenario development

SRES has four alternative storylines, which are entitled A1, A2, B1 and B2. They have been described as branches of a two-dimensional tree. The two-dimensions indicate the global-regional and the development-environmental orientation, respectively. The main characteristics of the storylines are briefly described below.

The A1 storyline: It is a world of very rapid economic growth and low population growth. Globalization is progressing due to strong commitment to market-based solutions. The regional average incomes per capita converge.

The A2 storyline: It is a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Market-based solutions are not highly valued. The population growth is the highest of all the four storylines.

The B1 storyline: It is a convergent world, with the same low population growth as the A1 storyline, but with heightened environmental consciousness.

The B2 storyline: It is a world in which emphasis is on local solutions to economic, social and environmental sustainability. The population growth is moderate based on the United Nations median projection.

In this study, we set up four cases in which the global populations and gross domestic products (GDPs) per capita were the same as those of the A1, A2, B1 and B2 storylines in SRES, respectively, as shown in Table 1. Other characteristics were alike but not necessarily the same as those of the storylines in SRES. We selected eight events, which were thought to play important roles in generating the social contexts, taking relevant topics in SRES into account. Contents and keywords of the eight events are listed in Table 2. Interactions among the different regions are also important. Therefore, we defined four regions in the world: the OECD (countries belonging to the Organization for Economic

Table 1
Assumed population and GDP per capita for four cases in this study

Case	Global population in 2100 (millions)	GDP per capita in 2100 (US$)
A1	7100	75,000
A2	15,100	16,000
B1	7100	47,000
B2	10,400	23,000

Table 2
Events to be considered as social and economic changes by 2050

Event number	Contents of event	Keywords	Regions
1	World economy is covered by a unified large market	Unification of markets	WORLD
2	For the sake of ris'k-hedging of primary energy supply, self-sufficient and diversified energy sources rapidly progress	Self-sufficient supply and diversification of primary energy sources	OECD, REF, ASIA and ALM
3	Constructions of new nuclear-power stations become remarkable	Constructions of new nuclear-power stations	OECD, REF, ASIA and ALM
4	Ideas of making payments of environmental additional costs (e.g., relatively expensive costs of renewable energy sources and material recycling) penetrate people	Social acceptance of environmental costs	OECD, REF, ASIA and ALM
5	Long-term investments by a government or companies for more than 30 years become difficult	Difficulty in long-term investments	OECD, REF, ASIA and ALM
6	Internet becomes familiar and most people use it	Penetration of Internet	OECD, REF, ASIA and ALM
7	Education of global environmental issues is widespread	Penetration of education of global environmental issues	OECD, REF, ASIA and ALM
8	People value traditional cultures and customs of their region rather than accept foreign ones	Valuing traditions	OECD, REF, ASIA and ALM

Cooperation and Development, as of 1990); REF (the East European countries, the Middle East countries and the Newly Independent States of the former Soviet Union); ASIA (all developing countries in Asia); and ALM (all developing countries in Africa and Latin

America). Events 2–8 were defined in each region, although event 1 was common in the world (WORLD) only. Consequently, we set 29 events (1 event * 1 region + 7 events * 4 regions) for each case. For simplicity, WORLD, OECD, REF, ASIA and ALM are represented by W, O, R, A and L, respectively, and each event is described by a combination of the region and the event number (e.g., A3 for event 3 in ASIA).

4. Questionnaire about occurrence probabilities of events and impacts

For the X-I analysis, the following were assessed via questionnaires that were given to Japanese experts in February and March 2004: (1) the probability of occurrence of event i by 2050,[1] and (2) the impact of event j on event i by 2050 under the assumption that event j will occur around 2010.[2] The experts were in the field of global-warming, and their affiliations were universities and research institutions. To reduce the workload of the experts, we required experts to provide answers for one of the four cases. In the impact assessment, we required them to provide answers concentrated on pairs of events that were thought to have important interactions. The answers were collected from 3, 5, 3 and 5 experts for cases A1, A2, B1 and B2, respectively. We presumed that the experts could maintain consistency for all cases as they had discussed global-warming issues and the object of this study to a sufficient degree before the questionnaires were issued, and it seemed that they had common views on the relationships among the events and the backgrounds.

Table 3 shows the estimated occurrence probability of event i (P_i) and an impact matrix, which are arranged by the estimated impact of event j on event i ($\alpha_{j\rightarrow i}$) for case B2. The values shown in the table are mean values across experts. Estimated vales for other cases are provided in Ref. [7]. The major features of the estimated occurrence probabilities are briefly described below:

The estimated occurrence probabilities of event W1 are 0.80, 0.52, 0.67 and 0.43 for cases A1, A2, B1 and B2, respectively. The probabilities are relatively high in cases A1 and B1, in which high GDPs per capita were assumed.

In all the cases, the occurrence probabilities of events 3 were estimated to be highest in ASIA.

In all the cases, the occurrence probabilities of events 4, 6 and 7 were estimated to be highest in OECD.

The occurrence probabilities of events 8 in REF, ASIA and ALM were estimated to be highest in case A2 and lowest in case A1, respectively.

The estimated impacts are described in the following section.

[1] The experts were required to provide numerical values of the occurrence probabilities. The following relationship between the numerical values and the statements expressing the likelihood of occurrence were presented to the experts: ‘1’, ‘0.9’, ‘0.8’, ‘0.7’, ‘0.6’, ‘0.5’, ‘0.4’, ‘0.3’, ‘0.2’, ‘0.1’ and ‘0’, meaning ‘occur’, ‘almost certain to occur’, ‘probable’, ‘likely’, ‘more likely than not’, ‘50–50 chance of occurrence’, ‘more unlikely than not’, ‘unlikely’, ‘improbable’, ‘almost certain not to occur’ and ‘not occur’, respectively.

[2] In the impact assessment, the experts were required to answer by selecting one of the following nine ranks, ‘+0.4’, ‘+0.3’, ‘+0.2’, ‘+0.1’, ‘0’, ‘−0.1’, ‘−0.2’, ‘−0.3’ and ‘−0.4’, which mean ‘promote very strongly’, ‘promote strongly’, ‘promote moderately’, ‘promote slightly’, ‘of no influence’, ‘demote slightly’, ‘demote moderately’, ‘demote strongly’ and ‘demote very strongly’, respectively.

Table 3

Occurrence probability of event i and an impact matrix among events estimated by experts for case B2

B2	Event i																												
Event j assumed to occur around 2010	O8	R8	A8	L8	O6	R6	A6	L6	W1	A7	L7	O7	R7	O4	R4	A4	L4	O5	R5	A5	L5	O2	R2	A2	L2	O3	R3	A3	L3
O8	*0.28*	0.07	0.07	0.07					−0.17	0.00	0.00	−0.07	0.00									−0.07	0.00	0.00	0.00				
R8	0.03	*0.40*	0.03	0.03					−0.20	0.00	0.00	0.00	−0.07									0.07	−0.07	0.07	0.07				
A8	0.03	0.03	*0.35*	0.03					−0.23	−0.07	0.00	0.00	0.00									0.00	0.00	−0.03	0.00				
L8	0.03	0.03	0.03	*0.40*					−0.20	0.00	−0.07	0.00	0.00									0.00	0.00	0.00	−0.07				
O6	G1 (O8,R8,A8,L8)				*0.95*	0.03	0.03	0.03	0.07			0.10		0.03	0.00	0.00	0.00												
R6					0.03	*0.75*	0.10	0.07	0.17				0.20	0.00	0.07	0.00	0.00												
A6					0.03	0.07	*0.65*	0.07	0.13	0.20				0.00	0.00	0.07	0.00												
L6					0.03	0.07	0.03	*0.62*	0.20		0.23			0.00	0.00	0.00	0.10												
W1	0.00	0.00	0.00	0.00	−0.03	0.10	0.10	0.10	*0.43*									0.00	0.07	0.03	0.03	0.00	0.07	0.10	0.03				
A7	0.00	0.00	0.07	0.00	G2 (O6,R6,A6,L6,W1)					*0.70*	0.03	0.03	0.03	0.07	0.07	0.23	0.07												
L7	0.00	0.00	0.00	0.07						0.03	*0.60*	0.03	0.03	0.07	0.07	0.07	0.20												
O7	0.00	0.00	0.00	0.00						0.07	0.03	*0.87*	0.07	17	0.10	0.10	0.07												
R7	0.00	0.03	0.00	0.00						0.07	0.10	0.07	*0.75*	10	0.27	0.13	0.13												
O4												0.00		*0.85*	0.10	0.13	0.10									−0.30	−0.10	−0.13	−0.10
R4													0.00	0.07	*0.57*	0.03	0.03									0.00	−0.25	0.00	0.00
A4										0.03				10	0.07	*0.65*	0.07									−0.07	−0.03	−0.30	−0.03
L4											0.03			0.03	0.03	0.07	*0.60*	G4 (O5,R5,A5,L5)								0.00	0.00	0.00	−0.20
O5					−0.07					G3 (A7,L7,O7,R7,O4,R4,A4,L4)								*0.20*	−0.03	0.00	−0.03	−0.13				−0.33	−0.20	−0.20	−0.20
R5						−0.03												0.03	*0.38*	0.03	0.03	0.20	−0.10	0.25	0.15	−0.03	−0.30	−0.03	−0.03
A5							−0.03											0.00	0.03	*0.32*	0.03			−0.13		−0.10	−0.15	−0.33	−0.10
L5								−0.03										0.03	0.03	0.03	*0.28*				−0.13	−0.10	−0.10	−0.10	−0.27
O2												0.00										*0.63*	0.07	0.10	0.07	0.07	0.03	0.07	0.07
R2													0.00									0.13	*0.33*	0.10	0.10	0.10	0.07	0.17	0.13
A2										0.00												0.03	0.03	*0.43*	0.03	0.07	0.07	0.03	0.10
L2											0.03											0.03	0.03	0.03	*0.33*	0.07	0.07	0.10	0.03
O3												0.07		0.07	0.00	0.00	0.00	0.00				0.10	0.10	0.10	0.10	*0.53*	0.10	0.10	0.13
R3													0.07	0.00	0.07	0.00	0.00		0.00			0.07	0.10	0.07	0.07	0.07	*0.68*	0.07	0.17
A3										0.07				0.00	0.00	0.03	0.00			0.10		0.07	0.07	0.03	0.07	0.03	0.03	*0.78*	0.03
L3											0.07			0.00	0.00	0.00	0.03				0.07	0.07	0.07	0.07	0.00	0.03	0.07	0.03	*0.58*

G5 (O2,R2,A2,L2,O3,R3,A3,L3)

Diagonal cells show estimated occurrence probabilities of event i by 2050 (P_i) and non-diagonal cells show the estimated impacts of event j on event i by 2050 ($\alpha_{j \to i}$) under the assumption that event j will occur around 2010. Non-diagonal cells construct an impact matrix.

Empty cells show that we could not collect answers from more than half of the experts. Regarding the empty cells, we used zero values in the X-I analyses.

Shadowed cells show that the absolute values of estimated impacts are greater than 0.1.

Broad rectangles show event groups and G1,G2,...,G5 are groups' numbers (see text in Section 5).

5. Hierarchical structure based on estimated impacts among events

It is not advisable to calculate scenario probabilities in X-I analyses for more than approximately eight events as the number of scenarios increases by nth power of 2 (where n is the number of events) and the scenario probabilities become very small. Therefore, we classified the 29 events for each case into hierarchical groups based on the estimated impacts, and applied the X-I method to each of the groups step-by-step. Grouping was performed by a method similar to that described in Ref. [8], so that events having relatively strong interactions with each other were included in a group.[3] Groups were hierarchically ordered from a group, which had large impacts on other groups and small impacts from other groups (that is called low-layer groups in this study), to a group, which had small impacts on other groups and large impacts from other groups.[4]

Table 3 shows an impact matrix that was rearranged based on a hierarchical structure of groups in case B2. Henceforth, G1, G2, ..., G5 are group numbers that are numbered from the lowest-layer group, and letters in brackets for the group number are events in the group. From this matrix, we can read the following impact structure in case B2:

G1(O8,R8,A8,L8) have negative impacts on G2(W1).

G2(O6,R6,A6,L6) have positive impacts on G3(A7,L7,O7,R7). They also affect the progress of G3(O4,R4,A4,L4) through positive impacts of G3(A7,L7,O7,R7) on G3(O4,R4,A4,L4).

G4(O5,R5,A5,L5) have negative impacts on G5(O2,R2,A2,L2,O3,R3,A3,L3). G5(O3,R3,A3,L3) are also affected by G3(O4,R4,A4,L4).

In cases A1 and B1, although impact matrixes of the cases are not shown in this paper, there is a structure that (O6,R6,A6,L6) interacts with (O8,R8,A8,L8) through W1, which belongs to both groups [7].

6. Cross-impact analyses

6.1. Data and analysis methodology

The X-I method was applied to each of the groups step-by-step. Data relating to the occurrence probability ($P(i)$) and the impact probability ($P(j \rightarrow i)$)[5] for X-I analyses were calculated for each group based on the following equations:

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[3] In the study of Ref. [8], the grouping was performed by computer calculation, and events to be included in a group were sought under the condition that the sum of absolute values of impacts among the events was over a threshold level. In this study, we used the following simpler method. Firstly, we assessed cells of an impact matrix, the absolute values of which were larger than 0.1. Secondly, five groups were conducted by rearranging columns and rows of the impact matrix so that more cells having absolute values larger than 0.1 located inside five rectangles along a diagonal line of the impact matrix (see Table 3). An event could belong to two groups, taking the contents of the events into account.

[4] The groups were rearranged so that more cells having absolute values larger than 0.1 located on an upper side from a diagonal line of the impact matrix than on a lower side.

[5] According to the X-I method described in Refs. [4,5], the impact of event j on event i is presented not by a conditional probability $P(i|j)$ but by an impact probability $P(j \rightarrow i)$. The reason for this is that a conditional probability cannot explain a situation in which there is an impact of event j on event i only and in which there is no impact of event i on event j, because$P(i|j) > P(i) \leftrightarrow P(j|i) > P(j)$ is always induced from $P(i|j)P(j) = P(j|i)P(i)$. The impact probability $P(j \rightarrow i)$ is converted to the two-dimensional probability $P(i,j)$ using a Markovian model [4].

$$P(i) = P_i \times \prod_m (1 + \alpha_{m \to i}) \quad (0.1 \leqslant |\alpha_{m \to i}|), \tag{1}$$

$$P(j \to i) = P(i) + \alpha_{j \to i} \quad (0 \leqslant P(j \to i) \leqslant 1), \tag{2}$$

where P_i and $\alpha_{j \to i}$ are the occurrence probability of event i by 2050 and the impact of event j on event i by 2050, respectively, as estimated by the experts. m is an event forecasted by the X-I analyses for lower-layer groups that will occur or an event assumed to be in the same group that will occur.[6] The term $\prod_m (1 + \alpha_{m \to i})$ in Eq. (1) is a coefficient that was used to guess the occurrence probability of event i, as estimated by the experts under the assumption that event m would occur around 2010. The coefficient was used as a technique for managing the workload of the experts so that they did not necessarily have to answer the questionnaire step-by-step. It is necessary to develop other techniques and to compare the techniques with the above-mentioned technique. However, the X-I method uses a process in which $P(i)$ and $P(j \to i)$ are rationalized to be mathematically consistent with high-dimensional probabilities. Therefore, we presumed that there was no significant problem in the data calculated based on Eq. (1).

For a group that has common events with lower-layer groups, the likely scenario was selected from scenarios in which the results of the common events (that is, occurrence or incurrence) were the same as for those of the lower-layer groups.

6.2. Results

The results of the step-by-step X-I analyses are summarized in Table 4. In the table, likely scenarios for each group are presented together with the scenario probability. For instance, in case A1, the table tells us that the G1(O6,A6,R6,L6,W1) were assumed to occur because the occurrence probabilities were larger than 0.9, and then they were excluded from the objects of the X-I analysis. The most likely scenario for G2(W1,O8,A8,R8,L8) indicates that only event W1 will occur; this is consistent with the assumption in group G1. Regarding G3(O5,R5,A5,L5,O3,R3,A3,L3), the most likely scenario indicates that event R5 will occur and event O5 will not occur, whereas in the second most likely scenario the results for the two events are opposite. Scenarios for G4 and G5 were analyzed for each of the most likely and second most-likely scenarios of G3, and the results show that the most-likely scenarios for G4 and G5 groups do not depend on whether events O5 and R5 in Group G3 will occur or not.

7. Narrative scenarios in 2050

7.1. Narrative scenarios based on the results of cross-impact analyses

Taking the impact structure mentioned in Section 5 into account, the results of the X-I analyses are interpreted to yield the following narrative scenarios in 2050. Outlines of the scenarios for cases A1 and B2 are shown in Fig. 1.

[6] Events, the occurrence probabilities of which were more than 0.9, were assumed to occur, and were excluded from the objects of X-I analyses.

Table 4
Scenarios in 2050 as outputs of the step-by-step X-I analyses

Case	Scenario	G1					G2					G2 prob.	G3								G3 prob.	G4								G4 prob.	G5								G5 prob.
		O6	A6	R6	L6	W1	W1	O8	A8	R8	L8		O5	R5	A5	L5	O3	R3	A3	L3		O3	R3	A3	L3	O2	R2	A2	L2		O4	O7	R4	R7	A4	A7	L4	L7	
A1	A1−1	1_p	1_p	1_p	1_p	1_p							0	1	1	1	0	0	0	0	(0.16)	0	0	0	0	0	0	0	0	(0.23)	1	1	1	1	1	1	1	1	(0.33)
A1	A1−2						1	0	0	0	0	(0.25)	1	0	1	1	0	0	0	0	(0.14)	0	0	0	0	0	0	0	0	(0.23)	1	1	1	1	1	1	1	1	(0.33)

Case	Scenario	G1				G1 prob.	G2					G2 prob.	G3								G3 prob.	G4								G4 prob.	G5				G5 prob.
		O8	R8	A8	L8		O6	R6	A6	L6	W1		O4	O7	R4	R7	A4	A7	L4	L7		O5	R5	A5	L5	O3	R3	A3	L3		O2	R2	A2	L2	
A2	A2−1																					0	0	0	0	0	1	1	1	(0.16)	0	1	0	0	(0.31)
A2	A2−2	1	1	1	1	(0.27)	1_p	1_p	1_p	1	0	(0.41)	1_p	1_p	1	1	1	1	1	1	(0.40)	1	1	1	1	0	0	0	0	(0.15)	0	0	0	0	(0.37)
A2	A2−3																					0	0	0	0	1	1	1	1	(0.14)	0	1	0	0	(0.31)
A2	A2−4																					0	0	0	0	0	1	1	1	(0.17)	0	1	0	0	(0.32)
A2	A2−5	0	0	0	0	(0.20)	1_p	1_p	1_p	1_p	1_p		1_p	1_p	1	1	1	1	1	1	(0.49)	0	0	0	0	1	1	1	1	(0.16)	0	1	0	0	(0.28)
A2	A2−6																					0	0	0	0	0	0	1	0	(0.14)	0	0	0	0	(0.31)

Case	Scenario	G1					G1 prob.	G3					G3 prob.	G2								G2 prob.	G4				G4 prob.	G5								G5 prob.
		O6	A6	R6	L6	W1		W1	O8	R8	A8	L8		O7	O4	R7	R4	A7	A4	L7	L4		L5	A5	R5	O5		O2	O3	R2	R3	A2	A3	L2	L3	
B1	B1−1	1	1	1	1	1	(0.36)							1_p	1_p	1_p	1_p	1_p	1_p	1	1	(0.59)	1	0	0	0	(0.27)	0	0	1	1	0	0	0	0	(0.17)
B1	B1−2							1	1	1	1	1	(0.29)															0	0	1	1	1	1	0	0	(0.15)

Case	Scenario	G1				G1 prob.	G2					G2 prob.	G3								G3 prob.	G4				G4 prob.	G5								G5 prob.
		O8	R8	A8	L8		O6	R6	A6	L6	W1		A7	L7	O7	R7	O4	R4	A4	L4		O5	R5	A5	L5		O2	R2	A2	L2	O3	R3	A3	L3	
B2	B2−1						1_p	1	1	1	1	(0.33)	1	1	1	1	1	1	1	1	(0.36)	0	0	0	0	(0.37)	0	0	0	0	0	0	0	0	(0.20)
B2	B2−2	0	0	0	0	(0.33)																					1	0	0	0	0	0	0	0	(0.17)
B2	B2−3						1_p	1	1	0	0	(0.20)	1	1	1	1	1	1	1	1	(0.32)	0	0	0	0	(0.37)	0	0	0	0	0	0	0	0	(0.21)
B2	B2−4																										1	0	0	0	0	0	0	0	(0.18)

1 (0) for an event means that the event will occur (will not occur) for a scenario. 1_p means that the event was assumed to occur and was excluded from the objects of the X-I analyses.
Values in round brackets show the scenario probabilities of the X-I analyses.

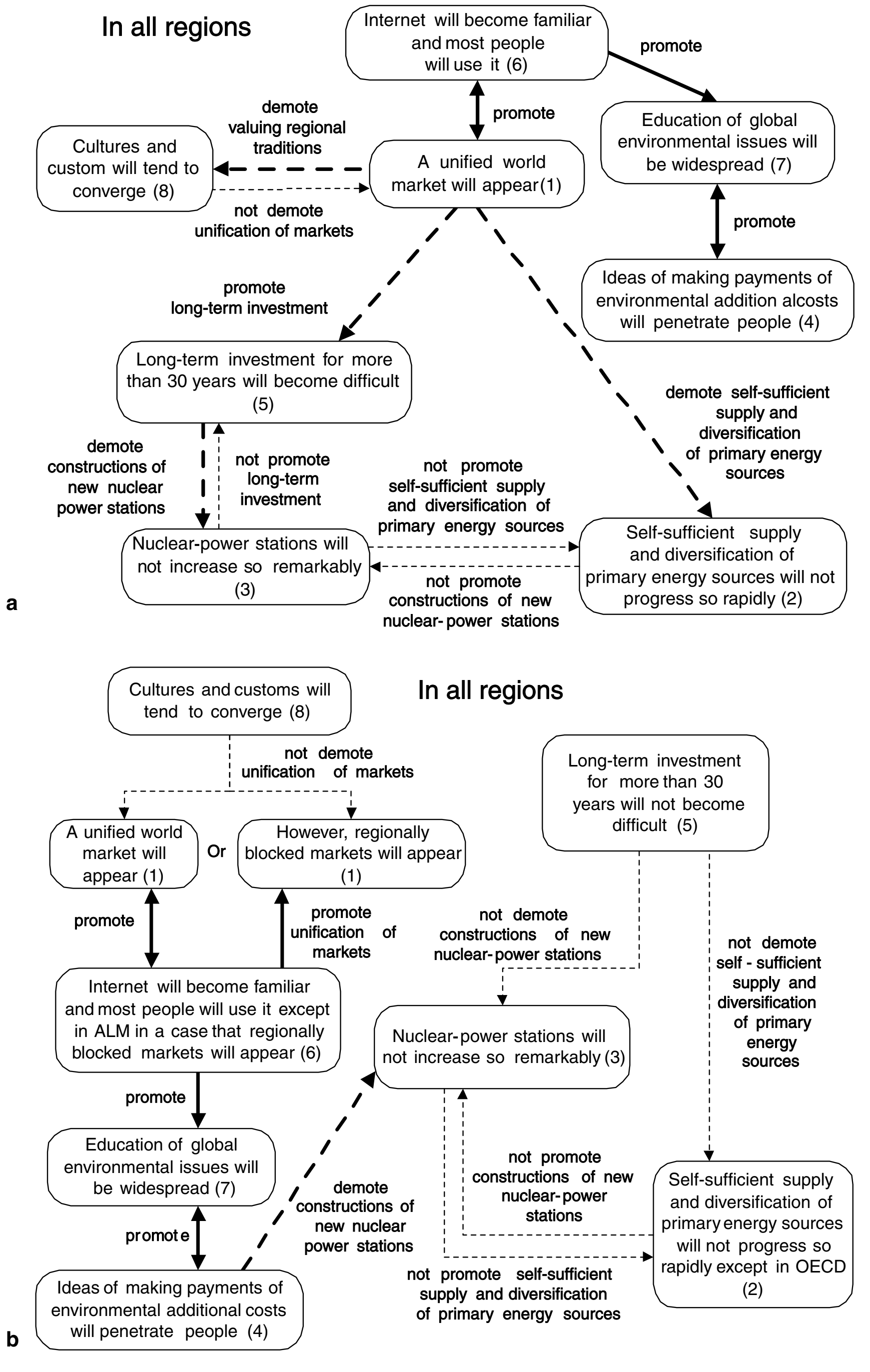

Fig. 1. Outlines of developed narrative scenarios of the world in 2050: (a) Case A1, (b) Case B2. Estimated results are shown in rectangles with round corners. Numbers in round brackets, (1),(2),…,(8), correspond to event numbers shown in Table 2. A broad solid-arrow and a broad dashed-arrow show promoting and demoting impacts among events, respectively. A thin dashed-arrow denotes that a promoting or demoting impact will not function because an event causing the impact will not occur.

In case A1, which has high per-capita income and low population growth, the Internet will be extensively used in all regions and a global unified market will appear; the regional cultures will tend to converge; long-term investments (of more than 30 years) will become difficult and therefore nuclear-power stations will not increase so remarkably; the self-sufficient supply and the diversification of primary-energy sources will not progress so rapidly; and due to the widespread use of the Internet, knowledge of global environment issues will become familiar and environmental costs will be more socially accepted.

Case A2, which has high population growth and lower income, suggests that there are two possibilities regarding traditional values: one in which the traditional cultures and customs will dominate the society; and another in which traditional values will not play main roles. In the former case, the regionally blocked market will tend to appear, and the long-term investments will either become difficult or not. In the latter case, the global unified market will appear, and the long-term investments will not become difficult. If long-term investments are not difficult to procure, constructions of new nuclear-power stations will be remarkable in ASIA and also in other regions. The self-sufficient supply and the diversification of primary-energy sources will not progress so rapidly in all regions except for REF. The Internet will be extensively used in all regions, and the penetration of global environmental education and the acceptance of environmental costs will be promoted.

In case B1, which has low population growth and medium per-capita income, the Internet will be extensively used in all regions and the global unified market will appear as in case A1; also, education of global environmental issues will be widespread, and acceptance of environmental costs will be well recognized. The difference from case A1 is that the globalization of the economy and the penetration of global environmental education will promote traditional values being accepted and therefore the regional cultures and custom will be recognized more compared with case A1, leading to simultaneous appearance of globalization of the economy and localization of cultures. The localization of cultures will promote the self–sufficient supply and the diversification of primary-energy sources and therefore constructions of new nuclear-power stations will become remarkable in REF and also ASIA. Long-term investments will have few difficulties in being procured in the OECD, REF and ASIA.

In case B2, which has medium population growth and low-medium per-capita income, regional cultures will tend to converge as in case A1. Regarding the economy, there are two possibilities: either it will be globally unified as in case A1; or it will be blocked by regions such as in A2. The Internet will be extensively used and will advance education levels of global environmental issues and the social acceptance of environmental costs. Due to the recognition of environmental costs, constructions of new nuclear-power stations will not be promoted, although the long-term investment will not become difficult. There is a probability that in OECD countries a self-sufficient supply and diversification of primary energy sources will rapidly progress.

As mentioned above, in all cases, the Internet will become extensively used, there will be an increase in global environment education, and environmental costs will be more accepted. The market will be globally unified in cases A1 and B1; on the other hand, in cases A2 and B2 the global unified market will either appear or not appear. There is a probability that constructions of new nuclear-power stations will become remarkable mainly in ASIA and REF in cases A2 and B1.

7.2. Considerations

Background theories, which might be employed to induce the above narrative scenarios, are considered as follows:

- The scenarios show that a global unified market will appear in cases A1 and B1, which have relatively high per-capita incomes, but will not necessarily do so in cases A2 and B2, which have relatively low per-capita incomes. It seems that the experts had the common sense that high per-capita income would be achieved by globalization of the economy.
- According to the scenarios for cases A1 and B1, cultures and customs will tend to converge in case A1, but will be blocked by region in case B1, although a global unified market will appear in both cases. It seems the experts recognized for case B1 that valuing regional traditions would be promoted due to heightened environmental consciousness.
- The probabilities of long-term investments becoming difficult are forecasted to be higher in case A1 than in cases A2, B1 and B2. It seems that the experts recognized following situations: people would prefer investments that would be able to be withdrawn in the short-term to those that would be long-term in case A1, which has rapid economic growth; in case A2, in which there is little value on market-based solutions, a situation that would be opposite to that in case A1; and long-term investments would be accepted due to heightened environmental consciousness in cases B1 and B2.
- Remarkable constructions of new nuclear-power stations are forecasted in some scenarios for cases A2 and B1 in which the long-term investments will be accepted in almost all regions and in which self-sufficient supply and the diversification of primary-energy sources will progress in REF. It seems that the experts recognized that the above two events were conditions imposed on the construction of new nuclear-power stations.
- The Internet is forecasted to be used in almost all regions in all cases. It seems that the experts believed that the Internet would extensively penetrate more people than anticipated by the current trend.

It should be noted that the narrative scenarios constructed in this study do not strictly correspond to the storylines of SRES: for instance, in case A2, two types of scenarios are constructed, one in which self-reliance and preservation of local identities will underlie cultures and economy, and another in which globalization of cultures and economy will be progressed. It is interpreted that experts recognized two types of possible future: one in which conservatism would become strong, similar to that seen in the A2 storyline of SRES, and another in which switching the orientation would be needed to support the large population.

8. Concluding remarks

We developed narrative scenarios of the world in 2050 for the evaluation of global-warming mitigation options. To construct scenarios having the consistency with qualitative social contexts, we applied the X-I method, which explicitly deals with the relationships among the relevant social and economic events. For X-I analyses, the occurrence probabilities of the events and the impacts among the events were estimated by Japanese experts.

The number of events to be dealt with were large; therefore, the events were classified into hierarchical groups, based on the impacts estimated by the experts, and then the X-I method was applied to each of the groups step-by-step.

Needless to say, it is advisable that the scenarios are backed up by the experts in order to discuss the results and the interpretations, and the occurrence probabilities of the events and impacts among the events should be estimated again as the need arises. However, this study shows a procedure for constructing consistent scenarios for worldwide issues such as global-warming. In addition, it shows that background theories, which might be employed to induce the scenarios, can be presented simultaneously. We believe that the narrative scenarios are helpful for the evaluation of global-warming mitigation options. For instance, regarding the introduction of nuclear-power generations and renewable energy sources that will be strongly affected by the social contexts, the scenarios must be instructive to interpret numerical values in quantitative model analyses.

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Appendix. Outline of cross-impact method

The cross-impact method is a technique for constructing consistent scenarios at a future time point, taking into account the impact of relevant events based on experts' judgments. In this method, experts estimate the following occurrence probabilities ($P(i)$) and impact probabilities ($P(j \to i)$):

$P(i)$: the probability of occurrence of event i during a period concerned.

$P(j \to i)$: the probability of occurrence of event i during a period concerned, given event j occurring at the very beginning of the period.

The impact probability is converted to the two-dimensional probability $P(i,j)$ by a Markovian model [4].

A scenario is defined as a state that specifies the occurrence of n events as follows:

$$S_k = (\theta_k^1, \theta_k^2, \cdots, \theta_k^i, \cdots, \theta_k^n), \tag{A.1}$$

where $i = 1,2,\ldots,n$, $k = 1,2,\ldots,N(=2^n)$ and

$$\theta_k^i = \begin{cases} 1 : \text{if event } i \text{ occurs,} \\ 0 : \text{otherwise.} \end{cases}$$

If the occurrence and two-dimensional probabilities are mathematically consistent, they satisfy Eqs. (A.2) and (A.3). Henceforth, $P^*(i)$ and $P^*(i,j)$ show consistent probabilities.

$$\sum_{k=1}^{N} \theta_k^i \pi_k = P^*(i), \tag{A.2}$$

$$\sum_{k=1}^{N} \theta_k^i \theta_k^j \pi_k = P^*(i,j), \tag{A.3}$$

where π_k is an n-dimensional probability (or, for simplicity, a scenario probability) for S_k, and

$$\sum_{k=1}^{N} \pi_k = 1, \tag{A.4}$$

$$\pi_k \geqslant 0. \tag{A.5}$$

Generally, probabilities in human judgment contain inconsistencies. Consistent probabilities can be obtained by quadratic programming:

$$\sum_{i} \{P^*(i) - P(i)\}^2 + \sum_{i<j} \{P^*(i,j) - P(i,j)\}^2 \rightarrow \min, \tag{A.6}$$

which is subject to (A.2), (A.3), (A.4), and (A.5).

By applying linear programming of conditions in (A.2), (A.3), (A.4) and (A.5), the upper and lower bounds of each scenario probability can be determined. A scenario can be selected, for which the maximum probability of occurrence of which is highest amongst all the scenarios. This is considered to be the most likely scenario [4,5].

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