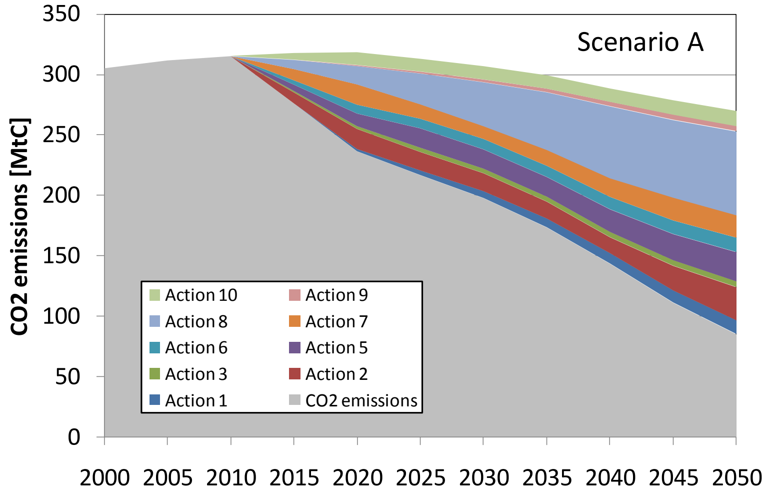
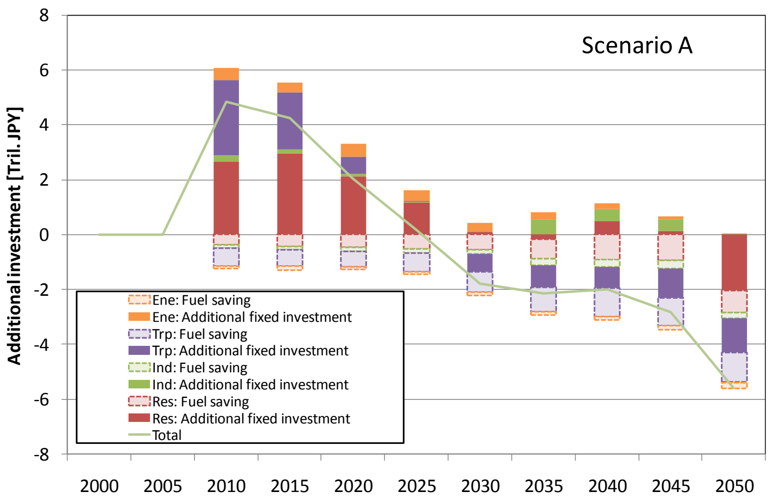
Global Environmental Research Fund (GERF)

Japan Roadmaps towards Low-Carbon Societies (LCSs)





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"2050 Japan Low-Carbon Society" Scenario Team

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Key conclusions

This study shows quantitative roadmaps for introducing countermeasures and policies for reducing CO_2 emission by 70% compared to the 1990 level by 2050 in Japan. This report is a series of Japan Low-Carbon Society scenario study, followed "Japan Scenarios and Actions towards Low-Carbon Societies (LCSs)".

<u>Assumptions</u>

- This study has analyzed roadmaps for reducing CO_2 emissions by 70% by 2050 minimizing the total cost from 2000 to 2050 while satisfying the future service demand assumed in Scenarios A and B shown in "Japan Scenarios and Actions towards Low-Carbon Societies (LCSs)".
- A list of 600 options (around 400 countermeasures and 220 policies) were prepared for each of which the necessary implementation period and cost were estimated based on literatures, expert judgments, and market survey.

<u>Overview of a methodology: Backcast model</u>

- The Backcast model used here has a linear optimization framework and can evaluate the possibilities of when and which options are invested so that service demand is satisfied under the minimization of total cost of options based on the actions suggested in "A Dozen Actions" and their relationships (see the Appendix for the detailed information of the model).
- The model includes performance improvements by future technical innovation and the 'learning-by-doing' of fixed costs as the cumulative amount of introduction increases.
- Outputs are: Pathways for reducing CO_2 which are in conformity with, the optimization standards, changes in the annual amount of investment, timings for implementing options, and development of Gantt chart for the time line.

<u>Major Findings</u>

- Taking early action could lead cost-minimizing way to achieve a low-carbon society by 2050.
- Early actions are advantageous mainly due to the following five reasons:

  Points revealed by the model analysis:

  1. Technologies have 'learning-by-doing' effects: An additional cost for reducing CO_2 emissions will be reduced as the technologies spread.
  2. If actions are delayed, 'learning-by-doing' effects may not work sufficiently, resulting in the increase the total investment required to achieve a low-carbon society.
  3. Infrastructure cannot be built immediately, making it difficult to switch suddenly to a low-carbon type just before 2050.
  4. The future technological development has several uncertainties. If the development of a dominant technology at this moment falls behind schedule, it will not be able to be spread as expected and CO_2 emission target will not be achieved. Early action creates for spreading alternative actions for the LCSs in case such a situation should come.

Another point to be investigated is:

5. Because the cumulative emissions affects global warming, reducing the CO2 emissions in only 2050 will not be able to stabilize the climate, which is the one of the important aim of a low-carbon society.

<u>Costs for early actions</u>

- A large investment is needed at the initial stage to achieve a low-carbon society in 2050 by taking early actions. Particularly, the residential and commercial sector needs an annual investment of 2.5 trillion JPY a year from 2010 to 2025, and the transportation sector needs 2.5 trillion from 2010 to 2015.
- Prompt investment will promote technology innovations as a result of increased domestic demand as well as will enhance international competitiveness of domestic industries since a low-carbon society is a global trend.
- If actions are delayed, other nations, not only developed countries but also developing countries like China and India, are likely to invest in low-carbon technologies, which will mature there. Low-carbon technologies introduced late in Japan leading up to 2050 will get developed in these nations and could adversely affect Japanese industries.

<u>Towards a low-carbon society in Japan</u>

- Strategies for achieving Japan low-carbon society require not only short-to-medium-term views but also approaches based on long-term and broad perspective backcasting view, which may involve thorough use of energy efficient and environmental-friendly technologies and structural changes such as switching to low-carbon infrastructure.
- Early actions are more likely to achieve a low-carbon society than delayed actions because of the learning-by-doing effects of spreading technologies, the necessary lead time for switching from the current infrastructure to low-carbon one, and uncertainties that may cause delays in technology R&D and the implementation of innovative technologies for reducing CO_2 emissions.
- The need for early actions is likely to be emphasized as cumulative CO_2 emissions by 2050 affect future temperature rises, but this is outside the scope of the present study.
- To achieve a low-carbon society with cost-minimization, investments should be focused first on those actions that have large rooms for future improvements in energy efficiency and costs reduction, such as energy efficient devices in homes and offices, well-insulated houses and next-generation automobiles in the transportation sector. The investments will expand the market, improve efficiency and reduce costs as well as will reduce CO_2 emissions.
- It is essential for achieving Japan low-carbon society in 2050 to draw up the target vision and take the first step in the correct direction by political leadership based on quantitative analyses and long-term broad-ranging scientific knowledge.

1. Introduction

In the Japan Low-Carbon Society Scenarios towards 2050 Project, which was sponsored by the Global Environment Research Fund (GERF) of the Ministry of the Environment, the backcasting approach was used to quantitatively investigate the pathways required to achieve a low-carbon society by 2050. Unlike forecasting, where a future image is drawn by gathering present measures, backcasting involves drawing up a target (or sometimes intolerable) image and investigating measures needed for achieving the target.

Earlier studies point out that, countermeasures for global warming and/or CO_2 reduction should be taken by waiting for more technology development in future. For the development of innovative technologies, various actions need to be taken in advance, including knowledge accumulation of technologies, changes of social/financial/market systems, and social infrastructure for accepting the new technologies. A backcast model has been used to investigate the timing of introducing each option considering these elements.

Prior to the analysis, two scenarios for achieving a low-carbon society in Japan by 2050 were developed and images of a society in 2050 in which CO_2 emissions are 70% lower than the 1990 level were quantitatively drawn up using various models. The images were then used as the target in the backcasting model. Combinations of options (countermeasures and policies) that are needed for achieving such a society were presented as "A Dozen Actions", which comprehensively describes various actions required to help achieve a low-carbon society and summarizes them based on their chronological inter-relationships. However, "A Dozen Actions" does not quantitatively investigate when and how strongly each option should be taken.

This study quantitatively assesses the procedures for implementing the actions using the backcasting model and summarizes the analysed results. An overview of the procedures of past studies and outcomes of this study has been elucidated below.

2. Procedure of developing low-carbon society scenarios towards 2050

As the first step of the Japan Low-Carbon Society Scenarios towards 2050 Study Project, requisites for achieving a low-carbon society by 2050 were defined. To stabilize the average global temperature to within 2°C higher than that prior to the Industrial Revolution, the study predicted future global emission paths of greenhouse gases and decided to set the carbon emission goal of Japan at 60 to 80% lower than the 1990 level.

In the second stage, the social and economic states of Japan in 2050 were predicted based on references and interviews with experts and depicted as two narrative scenarios shown in Table 1. Scenario A assumes a vivid and technology-driven society, and Scenario B is a slow and nature-oriented society. Using snap shot model, these two scenarios were confirmed to have combinations of measures that would reduce CO_2 emission by 70% in 2050 as shown in Figure 1.

Table 1 Two narrative scenarios for Japan low-carbon society at 2050

Scenario A	Scenario B
Vivid, Technology-driven	Slow, Natural-oriented
Urban/Personal	Decentralized/Community
Technology breakthrough Centralized production/recycling	Self-sufficient Produced locally, consumed locally
Comfortable and Convenient	Social and Cultural Values
2%/yr GDP per capita growth	1%/yr GDP per capita growth
Dependent on import products in agriculture sector	Revival of public interest in agriculture
Shifting production sites to overseas	High-mix low-volume production with local brand
Market deregulation	Adequate regulated rules apply in market

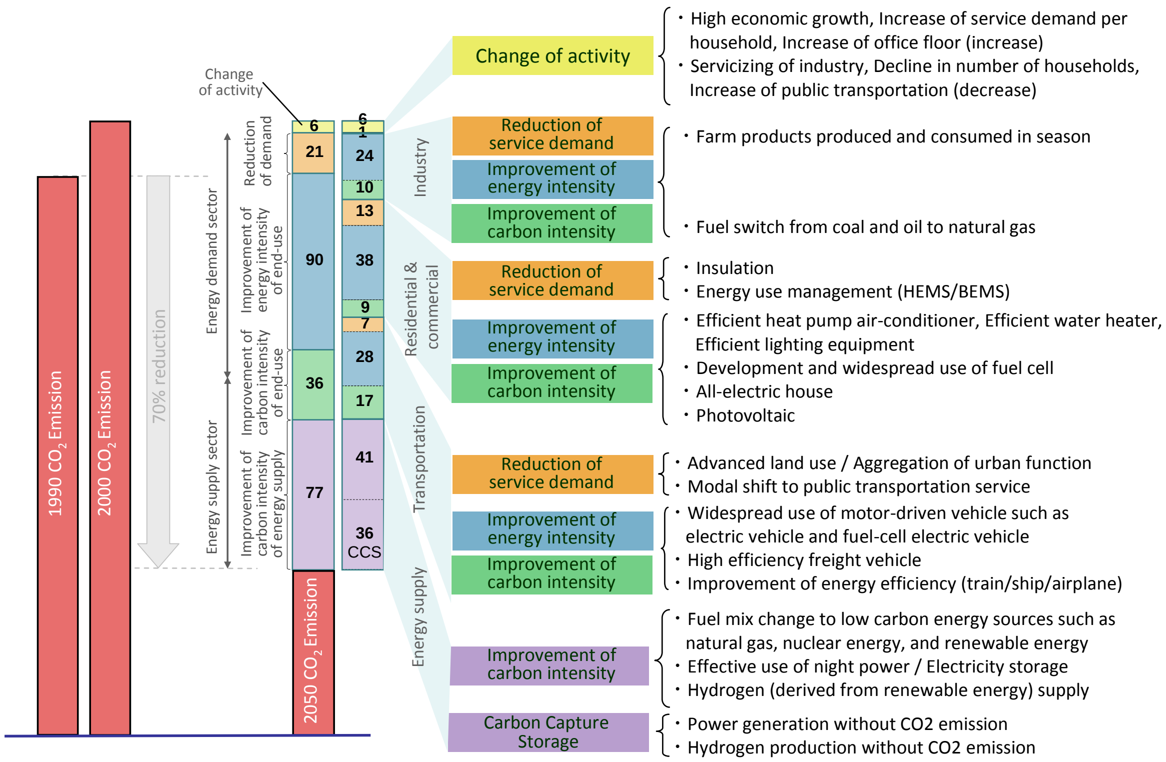


Figure 1 CO_2 emission in 2050 and options for achieving the reduction (Scenario A)

In Scenario A shown in Figure 1, CO_2 emissions will decline due to the following factors:

- The total service demand will be almost equal to the 2000 level, assuming that the annual growth rate per capita GDP will be 2%, the population will decrease by 20% from the 2000 level, and the industrial structure will be servisized like those in European and North American nations.
- In such a society, where people can live in pedestrian-friendly city, energy consumption will reduce, the energy service demand will decline, enabling a reduction of 40%. Additionally, the use of renewables, nuclear power, carbon capture and storage (CCS) and other low-carbon energy technologies will enable a further 30% reduction, making a total reduction of 70% from the 1990 level.
- Of the CO_2 emission reduction (about 40% lower than the 1990 level) by decrease in the end-use sector, 9% will be achieved by spread of energy efficient transportation machines, likeelectric vehicles etc., 7% by the introduction of energy-saving devices in industry, and 3% by the introduction of photovoltaic system, etc. into houses and offices. The remaining 21% will be achieved by the rational diffusion of about 400 elements of various technologies, including existing technologies and those which are expected to be commercialized by 2050.
- In the energy supply sector, widespread use of wind power and the safe use of nuclear power will be promoted, energy efficient natural gas will be used for thermal power generation instead of coal- and oil-fired power plants, and carbon capture and storage (CCS) facilities will be built adjacent to thermal power plants. This is estimated to achieve a 30% reduction out of the 70% reduction.

In the third stage, all possible options (countermeasures and policies) for reducing CO_2 emission by 70% compared to the 1990 level by 2050 were identified and compiled as “A Dozen Actions towards a Low-Carbon Society” as shown Figure 2 according to the relationships and compatibility among the options. There are several technical and social barriers to achieving the reduction, which must be overcome by taking action systematically and steadily. With such mutual relationships in mind, countermeasures and policies were combined, and those that are likely to be effective are called “Actions”. Each Action consists of a target future image, barriers to achievement, staged strategies, and qualitative progress schedule. The target future image is a narrative description of the social system to be constructed by 2050. As staged strategies, strategies for removing technical and/or social system barriers to achieving the future image are described. The progress schedule qualitatively shows the results of chronological combinations of measures and policies.

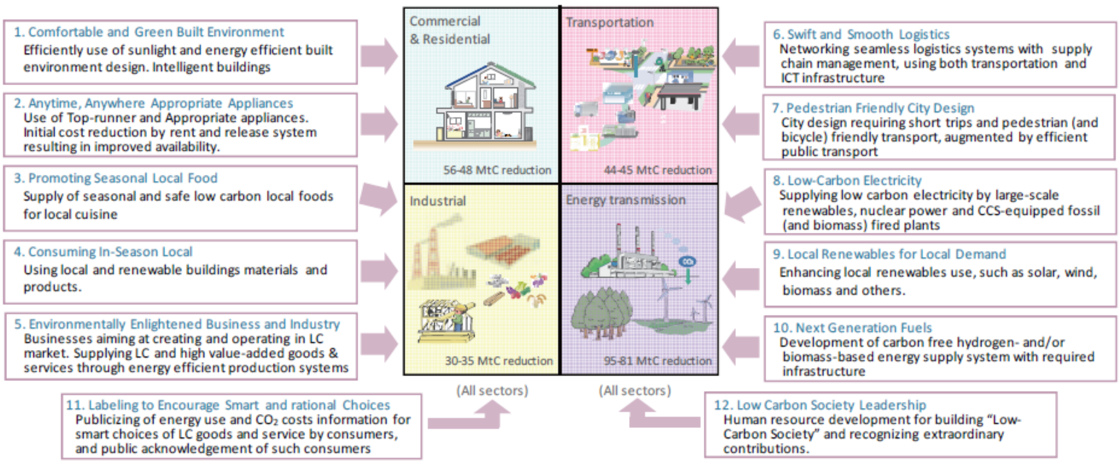


Figure 2 “A Dozen Actions” and its contribution to CO_2 reduction in 2050

The chronological images of the combinations of options (countermeasures and policies) shown in “A Dozen Actions” are qualitative, and need to be quantified to take actual actions. To do this, a backcast model was used. Identification of the pathways for introducing the options by conducting model analysis is the final stage of drawing up the Japan Low-Carbon Society Scenarios towards 2050, which quantitatively depict the pathways for introducing actions for achieving a low-carbon society in 2050 for Scenarios A and B separately. The backcast model was prepared by extending the linear optimization framework where investments are allocated to different time periods so that service demands are satisfied and the total cost of introducing the actions is minimized, thus enabling the actions investigated in “A Dozen Actions” and their relationships can be assessed. Using the model, the pathways for introducing the options were analyzed by setting the emission goal in 2050 as the limiting condition.

3. Pathways towards 70% reduction in 2050 using the backcast model

Pathways for achieving a 70% reduction of CO_2 emission compared to the 1990 level while satisfying service demands along Scenarios A and B were visualized as shown Figure 3by using the backcast model with the objective function as minimization of the total costs during the period (see the Appendix for the data of each option assumed and the details of the model structure). In cases where a CO_2 reduction goal was not established, the CO_2 emission was estimated to start decreasing after peaking around 2020 due to changes in the number of households and industrial structure, and the CO_2 emission in 2050 will be similar to the 1990 level, although the results slightly differ by scenario. As this result was far from the targeted 70% reduction, the CO_2 emission in 2050 was set as the limiting condition for the subsequent investigations.

In case where the CO_2 emission target in 2050 was set to be a 70% reduction compared to the 1990 level, the pathways to reach this in Scenarios A and B were quite similar, showing that the optimum course in terms of total cost is to start introducing measures as soon as in 2010, reducing emissions by 17% of 1990 level in 2020 and by 30% in 2030.

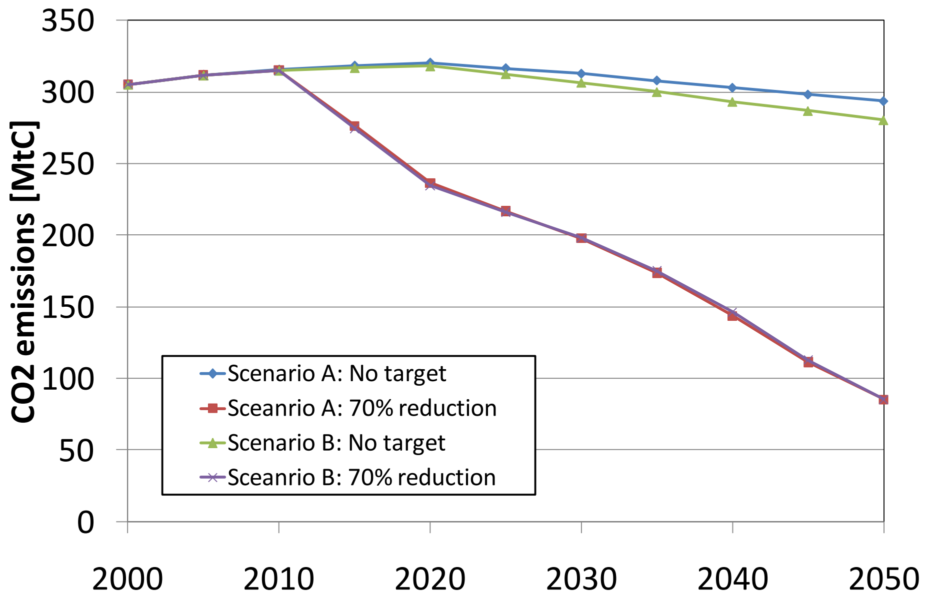
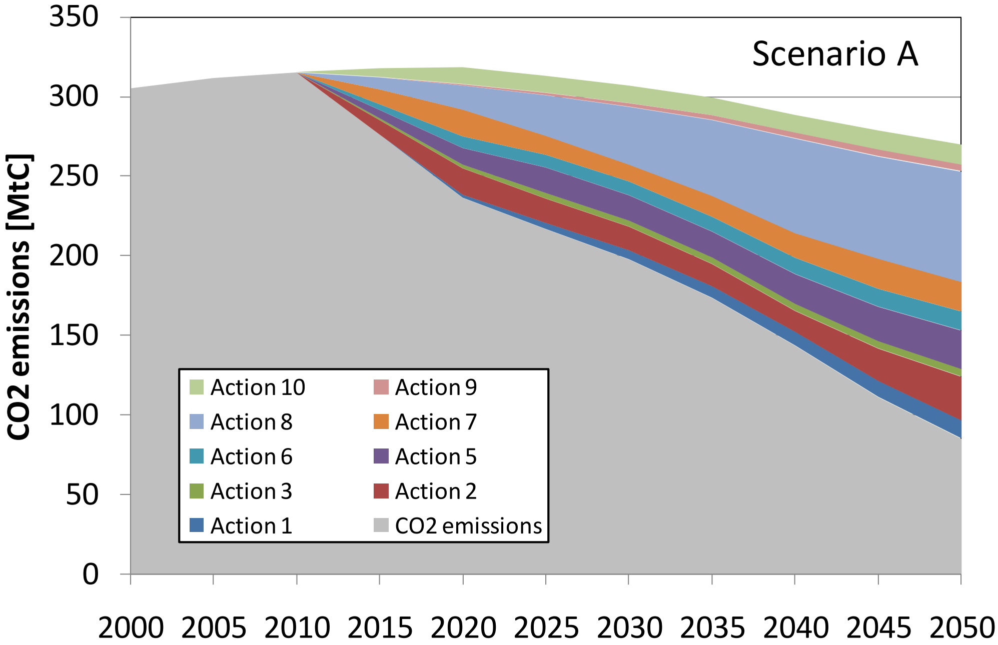


Figure 3 Pathways of CO_2 emissions toward 70% reduction in 2050

When the CO_2 emission was constrained, the reduction effects of the actions described in “A Dozen Actions” were analyzed as shown in Figure 4. Action 4 is included in Actions 1 and 2.The effects of Actions 11 and 12 are not explicitly shown because they are cross sectional. Introduction of all actions has been depicted to start at an early stage of the analyzed period.



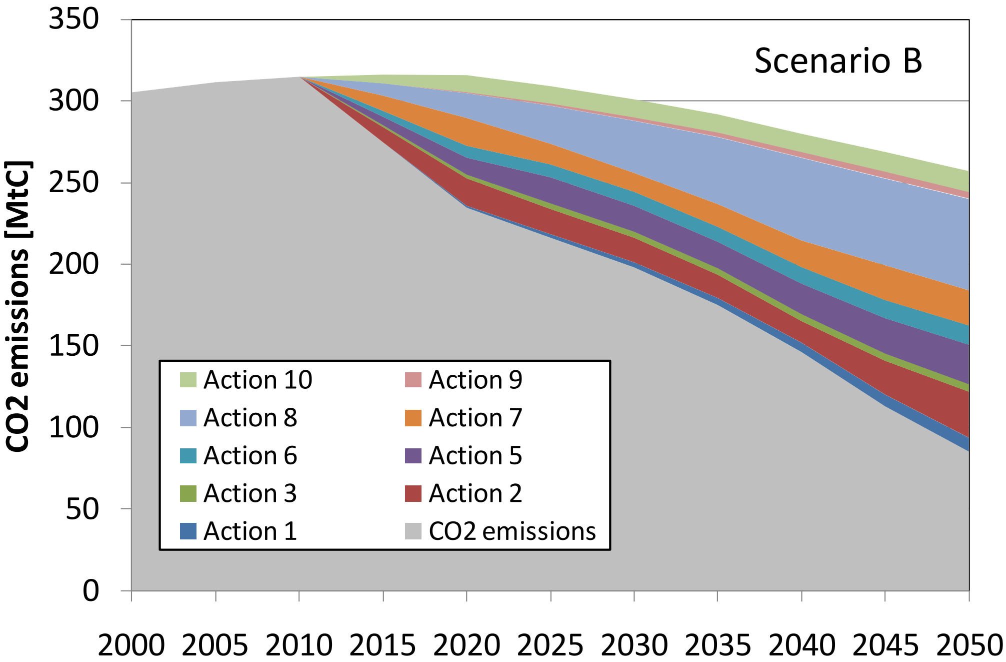
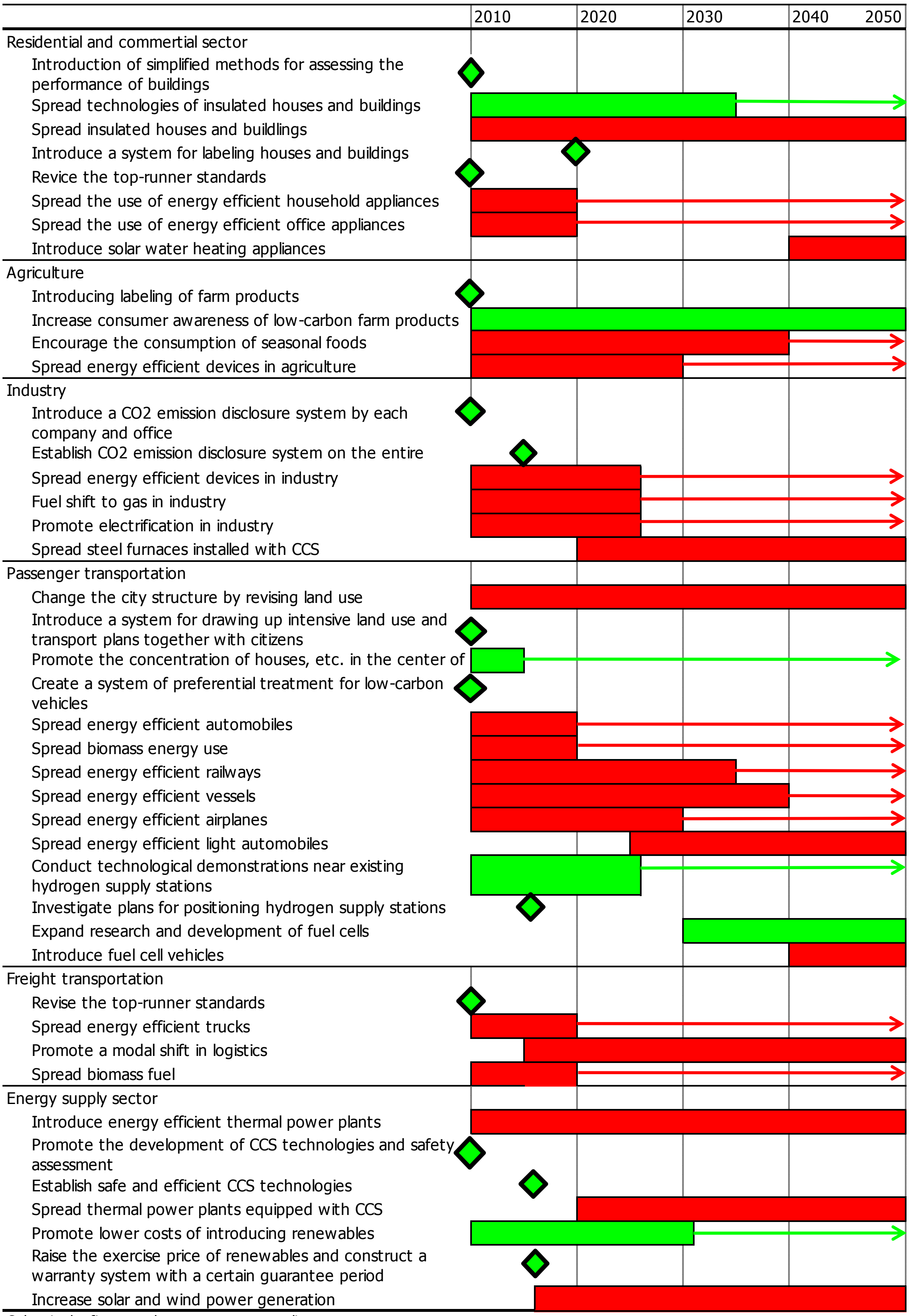


Figure 4 CO_2 reduction wedges by "A Dozen Actions" in Scenarios A and B

The timings of introducing the assumed options were organized in form of a Gantt chart (Figure 5). In the figure, countermeasures are shown in red and policies are shown in green. The periods shown with bars are those for actively spreading the measure or for spreading the policy nationwide. Arrows denote periods for maintaining the ratio of spread of the countermeasure or the period for continuing the policy. Diamonds are the timing for drawing up and enforcing the policy. The energy efficient household appliances in the figure were analyzed by preparing data for specific technologies separately, such as air conditioners and kerosene heaters, but the technologies are summarized in the figure as the analysis results were similar.



Colors in the figure: red: measure, green: policy

Width of the lines: Bars denote periods for actively spreading the measure or for spreading the policy nationwide. Arrows denote periods for maintaining the ratio of spread of the measure or the period for continuing the policy. Diamonds are the timing for drawing up and enforcing the policy.

Figure 5 Gantt chart of options towards 70% reduction of CO_2 emission by 2050

4. Viewpoints of future pathways: five reasons for taking early action

The investigation of the pathways until 2050 shows that options (measures and policies) towards a low-carbon society should be executed promptly to minimize the total cost needed to achieve the goal. As listed below, there are five main reasons for taking early actions. The investigation has also revealed a key issue in acting promptly i.e. to find necessary initial investment.

Key reasons for early action

1) Technologies have learning-by-doing effects, and the additional cost of low-carbon technologies will be reduced as the technologies spread.
2) If actions are delayed, learning-by-doing effects may not work sufficiently, thus increasing the total additional investment required to achieve a low-carbon society.
3) Infrastructure cannot be built immediately, making it difficult to replace suddenly to a low-carbon society before 2050.
4) The technological development in future has uncertainties. If the development of a dominant technology at this moment falls behind schedule, it will not be able to be spread as expected and CO_2 emission target will not be achieved. Early action creates for spreading alternative actions for the LCSs in case such a situation arises.
5) As the cumulative emissions affect global warming, reducing the CO_2 emissions in only 2050 will not be able to stabilize the climate, which is the one of the important aim of a low-carbon society.

Hereinafter, each of the reasons has been explained using investigated and quantitatively analyzed results. In this study the 'reason 5' has been mentioned but not analyzed in detail.

1) Learning-by-doing effects

Technologies have learning-by-doing effects in general. Costs are known to decrease as the introduction of technologies increases as shown in Figure 6. For example, the learning rate (the percentage cost reduction by doubling the cumulative amount) of photovoltaic (PV) system is estimated to be about 20% (Figure 7). According to a meta-study[1] on the learning-by-doing effects of various energy devices in end-use and energy supply sector, the learning effects vary depending on the technology and are not uniform. The learning-by-doing effects have been reported for various technologies besides PV system in the Table 2. In studying the pathways, the fixed costs of low-carbon technologies were assumed to decrease as the cumulative amount of introduction increases (as learning progresses).

[1] Alan McDonald, Leo Schrattenholzer (2001) "Learning rates for energy technologies" Energy Policy 29 (2001), PP 255-261

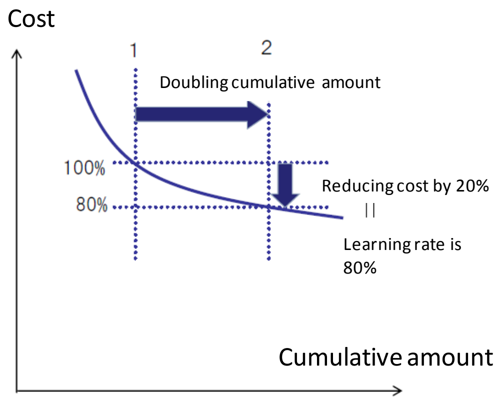


Figure 6 Schematics of learning-by-doing effects

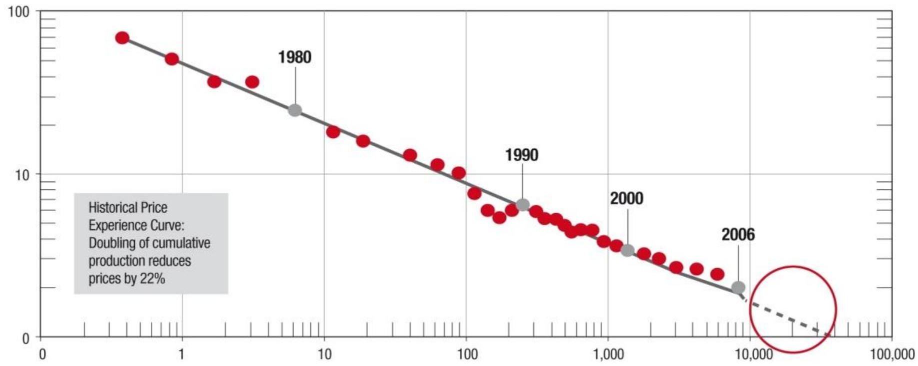


Figure 7 Historical learning curve of Photovoltaic system[2]

Table 2 Examples of learning-by-doing of energy technologies[3]

Technology	Regional scale	Period	Learning rate (%)	R^2
Gas turbine	World	1958-1980	13	0.94
Nuclear power plant	OECD	1975-1993	5.8	0.95
Hydro power plant	OECD	1975-1993	1.4	0.89
Coal-fired plant	OECD	1975-1993	7.6	0.90
Gus turbine combined cycle (GTCC)	OECD	1984-1994	34	0.78
Wind power	OECD	1981-1995	17	0.94
Photovoltaics	World	1968-1998	20	0.99
Ethanol production	Brazil	1979-1995	20	0.89
Bulb-shaped fluorescent lamp	U.S.	1992-1998	16	0.66
Air-conditioner	Japan	1972-1997	10	0.82

Whether to take learning-by-doing effects into account or not greatly affects the estimated cost and optimum timing of incorporating the options. Differences in the unit cost of introducing options for reducing CO_2 caused by learning-by-doing effects are shown in Figure 8 using water

[2] EPIA (2009) "Set for 2020 Solar Photovoltaic electricity: A mainstream power source in Europe by 2020"
[3] Alan McDonald, Leo Schrattenholzer (2001) "Learning rates for energy technologies" Energy Policy 29 (2001), PP 255-261

heaters in the residential sector as an example. When learning-by-doing effects are considered, the cost of introducing the appliances, which was assumed to start in 2010, were estimated to gradually decline after 2015.

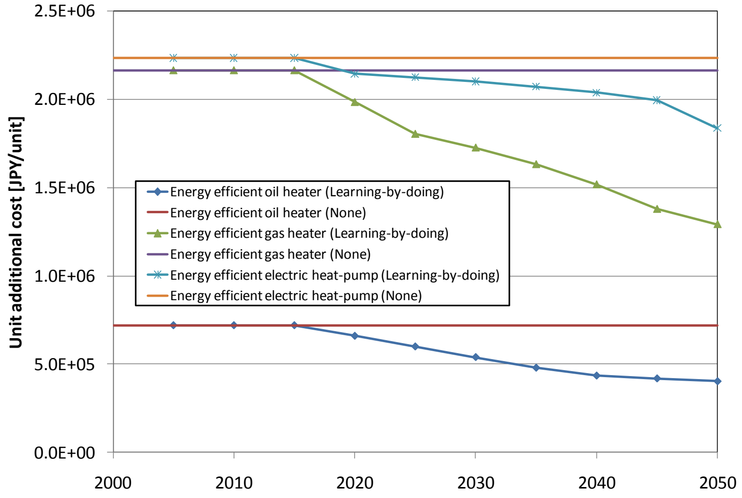


Figure 8 Differences in unit additional cost by learning-by-doing effects (water heater, Scenario A)

The differences in learning-by-doing effects also affect the optimum timing of introducing the options, and the pathway of CO_2 reduction will be delayed if there are no learning effects (Figure 9). Learning-by-doing effects also resulted in an almost three-fold difference in the estimated cumulative investment from 2000 to 2050 when reductions in fuel costs were also considered: 12 trillion JPY with learning effects and 34 trillion JPY without learning effects (assumed discount rate: 3%). This was also the similar in Scenario B.

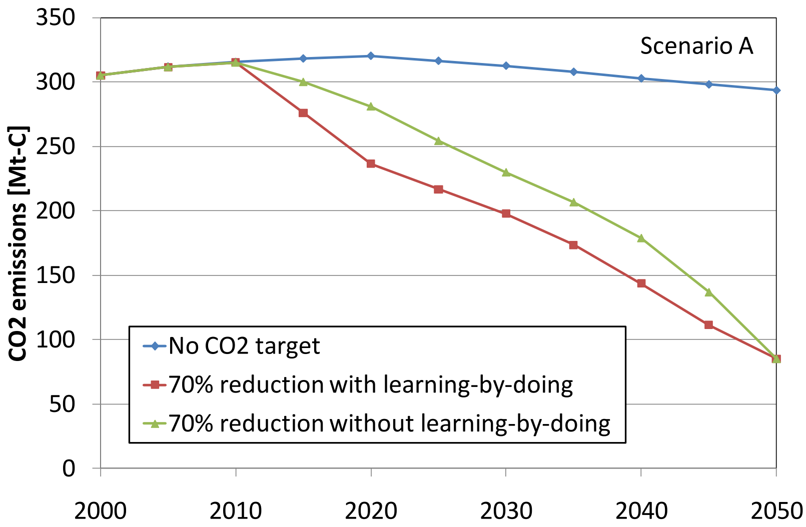


Figure 9 Comparison of CO_2 pathways with and without learning-by-doing effects

Introducing major CO_2 reduction options by quickly investing large sums will not only gradually reduce the cost by learning-by-doing effects but also reduce the total investment needed for achieving a low-carbon society. In this analysis, CO_2 reduction of only 70% by 2050 was investigated, but further reductions could be sought in future as international negotiations progress. Early investment and lower costs by learning effects will also help achieve such demands.

2）Delays in starting actions will result in higher costs

If initiation of actions is delayed, the total additional investment is likely to be higher as learning-by-doing effects will not be able to work effectively as shown Figure 10. In this analysis, fixed costs such as equipment costs and reduction of fuel costs by reduced energy consumption are considered and converted into present values at the discount rate of 3% to determine the total investment. Additional investment is the difference in fixed cost compared to that of conventional devices minus the reduction of fuel costs. As for the fuel costs in this study, we have usedthe future fuel prices based on assumptions of International Energy Agency and U.S. Department of Energy.

If actions are taken quickly (early action), the total additional fixed cost from 2010 to 2050 will be 80 trillion JPY in Scenario A and 62 trillion JPY in Scenario B, which are annual averages of 2 trillion JPY and 1.5 trillion JPY, respectively. The fuel cost reductions will be 68 trillion JPY and 69 trillion JPY, respectively. Thus, the resultant additional investment will be 12.7 trillion JPY in Scenario A and -7 trillion JPY in Scenario B. And if actions are delayed (started in 2020), the total additional fixed costs will increase as the learning-by-doing effects will not work to its potential and will be 93 trillion JPY in Scenario A and 91 trillion JPY in Scenario B. The reduction of fuel costs will be only 54 trillion JPY in both scenarios as the options will spread late. Thus, the resultant additional investment from 2010 to 2050 will be 39 trillion and 37 trillion JPY in Scenarios A and B, respectively.

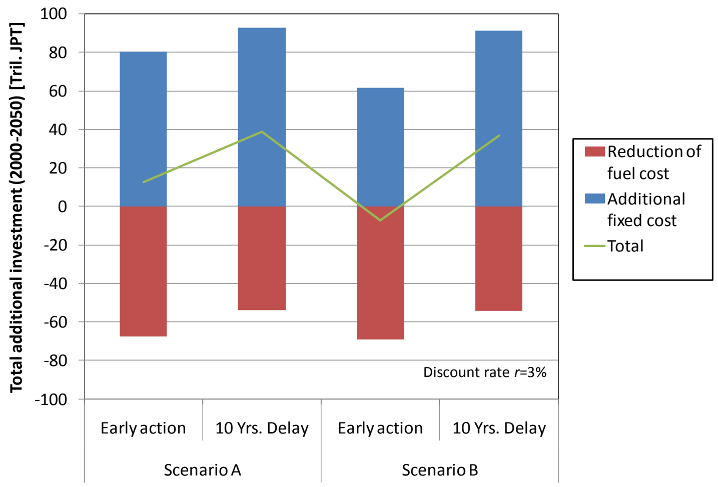


Figure 10 Comparison of total additional investment between early action and 10 Yrs delay

3）It takes time to construct infrastructure

Infrastructure (city infrastructure, transportation systems, energy infrastructure, buildings, etc.) generally has a long service life and cannot easily be modified once constructed. For example, according to “Social Capital of Japan” (Cabinet Office Director-General (2007)), the average service life[4] of roads and railways is 51 and 34 years, respectively, and almost all other infrastructure has life spans of 40 years or more[5] (Table 3). Thus, if the right timing for rebuilding infrastructure is missed, it will make it difficult to switch to a low-carbon infrastructure and to achieve the target CO_2 reduction (Table 4).

Table 3 Average service life of infrastructure in each sector

Sector/Assets	Average service life (Yr.)
Road	51
Harbor	49
Airport	16
Former Japan National Railways	22
Japan Railway Construction Public Corporation, etc.	26
Subways, etc.	34
Former Nippon Telegraph and Telephone Public Corporation	18
Sewerage	57
Waste disposal	40
Water works	39
City park	43
Education (Schools and academic facilities)	39
Education (social education, physical education and cultural facilities)	41
Flood control	85
Forestry conservation	50
Coastal protection	30
Agriculture	44
Forestry	49
Fishery	50
Postal service	18
National forest	47
Water works for industrial use	38

[4]Average service life of each sector: Because infrastructure is composed of a number of component assets that differ in service life, the mean service life is calculated by weighting and combining the service life of representative assets. There are various calculation methods, and all involve calculating not only the mean in a single year but also the means in two or more years and their simple average. Data shown was tentatively calculated by computing the mean service life of each sector based on the “Ministerial ordinance on the service life of depreciation assets (Ordinance No. 15 of the Ministry of Finance on March 31, 1965)”, collecting more data, and revising the life spans.

[5] The average service lives of these sectors are cited from the reference and are for information only. These values were not assumed as prerequisites in the model analysis.

Table 4 Delays in infrastructure shift to low-carbon and possibility of CO2 reduction in 2050 [MtC]

	Delays in infrastructure				
	Early action	Start in 2020	Start in 2030	Start in 2040	Start in 2050
Scenario A (Compared to the 1990 level)	85.2 (-70%)	86.7 (-69.5%)	109.5 (-61.4%)	134.6 (-52.6%)	161.3 (-43.2%)
Scenario B (Compared to the 1990 level)	85.2 (-70%)	85.2 (-70%)	106.2 (-62.6%)	131.7 (-53.6%)	158.3 (-44.3%)

Furthermore, the best possible low-carbon designs need to be incorporated into newly constructed or rebuilt infrastructure to minimize the investment and achieve a low-carbon society because huge and continuous investments are required to build infrastructure.

The infrastructure that is built today is likely to be in use in 2050. Thus, building of the framework of a low-carbon society has already started.

4）Uncertainties exist in the technological research, development and deployment

The development and spread of technology involves four stages: development, demonstration, deployment and diffusion. Japan has carried out development projects for various technologies, such as hydrogen fuel, fuel cells, and the nuclear fuel cycle, which are in their final stage of spreading. Some of them have diffused as planned, but others are lagging and have not yet been introduced in the market.

If we consider the fuel cell technologies, which are recently attracting attention world over, are not particularly new: Its development was started by the National Aeronautics and Space Administration (NASA) in 1961. In Japan, the Moonlight Project to develop phosphoric acid fuel cells (PAFC) was carried out from 1981 to 1986. Later in 1990s, the basic technologies were demonstrated and subsequent projects including the New Sunshine Project and the Fixed-type PAFC Millennium Project of the Japan Gas Association (2000 to 2004) highlighted its potentials. However, so far, fuel cells have only been introduced on a trial basis or for demonstration purpose by electric and gas supply companies and have not yet established a solid position in the market. The status of the nuclear fuel cycle and nuclear power technologies are similar.

The conclusions described in Section 3 are the results of an analysis is based on assumption that all technological developments and diffusion processes progress as scheduled. If this process falls 10 years behind schedule, the estimated CO_2 emission in 2050 will vary depending on whether early actions are taken or not: it will be 97.7 Mt-C (-65.6% compared to the 1990 level) with early actions at a maximum but 107.0 Mt-C (-62.3% compared to the 1990 level) if actions are taken only after 2020 (Figure 11). If development is delayed by 30 years, the CO_2 emission will be reduced to 116.6 Mt-C (-59.0% compared to the 1990 level) with prompt actions at a maximum but will be 125.9 Mt-C (-55.7% compared to the 1990 level) if actions start in 2020, a difference of almost 5% compared to the 1990 level. This is because acting early will provide opportunities to switch to another technology if a scheduled low-carbon technology does not progress as anticipated. Taking action now to achieve a low-carbon society will encourage active technology development, improve efficiency, reduce costs by learning-by-doing effects, spread the portfolio of alternative actions, prepare for future uncertainties, and thus raise the possibility of achieving a cost-efficient low-carbon society.

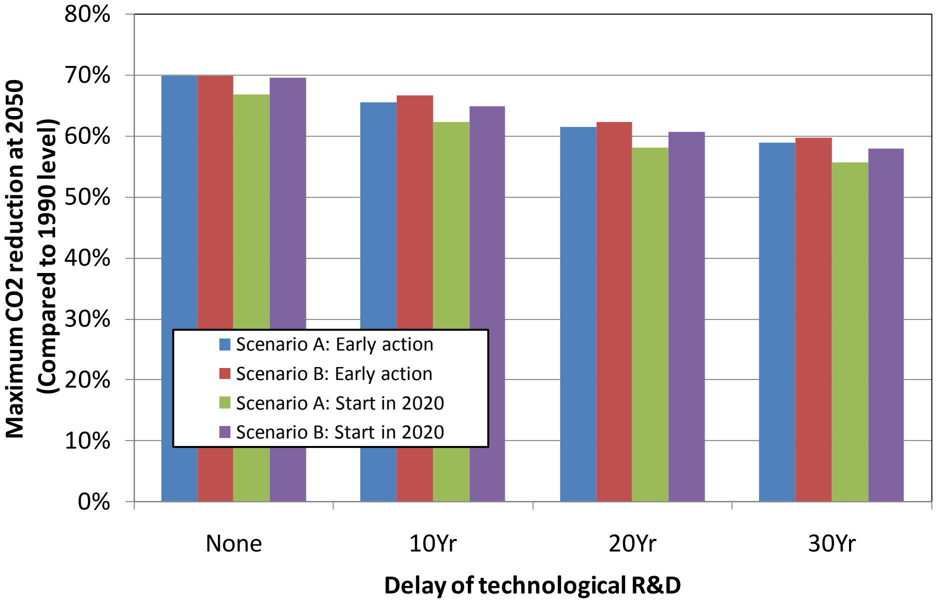


Figure 11 Delay of technology development and possible CO_2 reduction in 2050

Early action was shown to be necessary for achieving a low-carbon society, but this requires additional investment at the initial stage of the roadmap.

A large-scale additional investment is needed at the initial stage.

Changes in the annual additional investment were investigated for the pathways that will incur the lowest total costs. In both Scenarios A and B, additional investment of about 5 trillion JPY annually will be needed at the initial stage even when fuel cost reductions are considered (Figure 12). In both scenarios, the necessary additional fixed costs in 2010 will be 2.5 trillion JPY in the residential and commercial sector and 2.5 trillion JPY in the transportation sector. The additional fixed costs in the transportation sector will be sharply reduced thereafter due to learning-by-doing effects and reduced demand for transportation services by changes in the structure of cities and will be almost zero in 2020. However, the additional fixed costs in the residential and commercial sector will continue to be around 2 trillion JPY a year until 2030. These investments are for options that can largely improve efficiency and reduce costs, such as next-generation vehicles in the transportation sector and energy efficiency appliances and highly insulated houses in the residential and commercial sector.

The total additional investment in the entire period from 2010 to 2050 will be 12.7 trillion JPY in Scenario A and -7 trillion JPY in Scenario B as the additional fixed costs will be reduced by learning-by-doing effects. Particularly in Scenario B, the sum may be less than the investment in conventional types of systems. Without introducing expensive low-carbon technologies by investing large sums at the initial stage, no progress will be made.

Considering that the global trend is moving toward achieving a low-carbon society, Japanese industries may lose their international competitiveness if Japan does not invest in low-carbon technologies in early because other nations will invest in such technologies and learning-by-doing advances.

For establishing new industries, continuous investment and research and development of low-carbon technologies are important. For example, Photovoltaic systems (PV) have recently become a new industry in Japan, Germany and the US because R&D on PV has been conducted for a long time and industrial infrastructure has been built. On the other hand, nations that have recently started to actively introduce PV as a matter of policy are depending on imports for the majority of systems. In Spain, PV usage was only 22 MW in total until 2004 but grown to 3,166 MW in 2008, a 100-fold increase in 4 years and surpassing the generation in Japan[6]. However, in 2008, PV produced in Spain did not account for even 10% of those introduced because domestic production could not keep pace with the demand. The Spanish government is encouraging people to introduce PV by setting the purchase price of PV high, which is resulting in large social costs being spent on introducing large quantities of imported products.

The sudden introduction of low-carbon policies just before 2050 will merely result in

[6] IEA PVPS (2008) "Trends in photovoltaic applications - Survey report of selected IEA countries between 1922-2007" and EPIA (2009) "Global Market Outlook for Photovoltaic until 2013"

funds flowing to foreign firms unless continuous efforts have been made to spread technologies and to build the production infrastructure for better diffusion of technologies and become internationally competitive. Delaying action increases the possibility of other nations investing earlier and learning-by-doing low-carbon technologies, which may adversly affect the Japanese industry. Investing in low-carbon technologies earlier and/or imposing stricter environmental restrictions than other nations to foster technology learning will enhance the international competitiveness of Japanese industry.

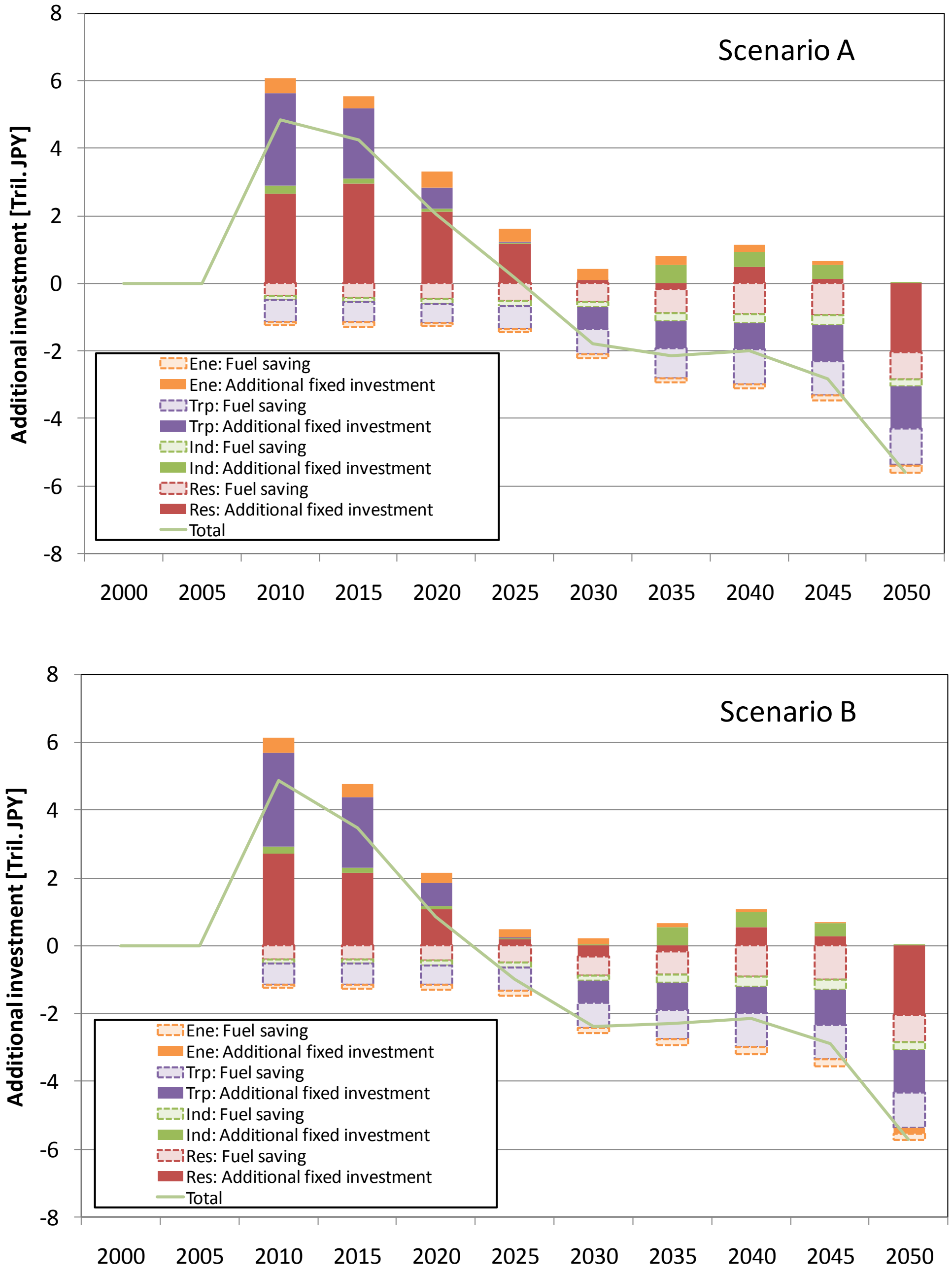


Figure 12 Changes in additional investment for achieving a low-carbon society

5. Summary

The challenges towards a low-carbon society include not only short-to-medium-term viewpoints, like the Kyoto Protocol and the mid-term targets of CO_2 emissions, but also long-term and broad-ranging actions for achieving a 70% reduction of CO_2 emission compared to the 1990 level by 2050 through the diffusion of energy efficient and environmental-friendly technologies, shifting to low-carbon cities and other infrastructure, construction of low-carbon socioeconomic structures by servisizing and partly returning to agriculture, forestry and fishery.

This study quantitatively analyzed when, how and at what intensities the "A Dozen Actions" proposed in the May 2008 report should be carried out in order to achieve the 70% reduction by 2050, which was judged to be technically feasible as described in the February 2007 report, based on technical feasibility and economy.

Some analyses conducted using energy-based models have recommended that actions will start after (low-carbon) technologies get developed and inevitably will become cheaper. However, taking actions quickly increases the possibility of preventing global warming in view of the learning-by-doing effects by technology diffusion, such as those shown in today's market for Photovoltaic, the necessary lead time for converting energy infrastructure such as power plants, power cables and gas pipelines, into low-carbon systems, and uncertainties regarding future technological development, such as delays in deployment of fuel cell vehicles. The effects of cumulative CO_2 emissions on future temperature rises are also a strong reason for acting now, but are not analyzed and assessed in this study.

The results show that it is worth seriously investing now in actions to improve energy efficiency and reduce costs, such as developing and introducing energy efficient devices in homes and offices, building highly insulated houses and developing and diffusing next-generation automobiles in the transportation sector, to expand the market, improve efficiency and reduce costs. The government should take the initiative by setting a target vision based on long-term perspectives and scientific knowledge and take the first steps in the correct direction.

Appendix: Quantitative assessment using a backcast model

1. Overview of a backcast model

A backcast model was used to investigate what options (countermeasures and policies) should be introduced when and at what intensity in order to achieve the future social and economic activities portrayed in the scenarios while also satisfying the service demand today and throughout the period until the target year based on certain criteria, and to present a Gantt chart that also includes pathways of CO_2 emission and investment and quantitative data. The activities of the sectors were determined based on the scenarios and changes in social structure and population composition and were taken as exogenous variables in the model. The energy consumption, industrial structure, and CO_2 emission composition in the standard and target years were analyzed using the Energy Snapshot Tool (ESS) and the CGE-type model, and the values for the other years (intermediate years) were estimated endogenously by the model. Mixed integer programming was used for formulation and the Cplex solver with General Algebraic Modeling System (GAMS) was used to derive the optimum solution.

In this study, the base and target years were set to be 2000 and 2050, respectively. Pathways for achieving the target society (Scenarios A and B) of 70% CO_2 emission reduction compared to the 1990 level were investigated by estimating the investment in CO_2 reduction options and energy balance every 5 years so as to minimize the total cost during the entire analysis period, which is calculated in present value, while maintaining the activities of the scenarios under the CO_2 emission restrictions in 2050.

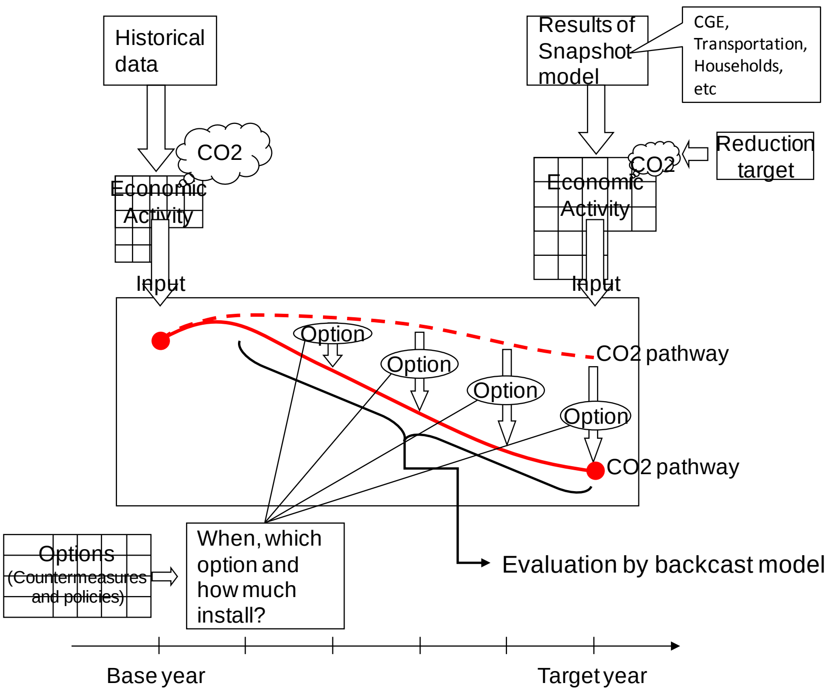


Figure A.1. Outline of the flow of estimation using a backcast model

2. Overview of assessment using the backcast model

The pathways toward the 70% reduction of CO_2 emission by 2050 were investigated by the following five steps. Hereinafter, endogenous variables are expressed in uppercase, and indices and exogenous variables are expressed in lower case.

1) Predicting future service demands
2) Listing possible options (countermeasures and policies) for achieving future scenarios
3) Quantifying options
4) Adding relationships among options
5) Quantitative investigation using the backcast model

2.1. Predicting future service demands

The future service demand by service *j* in sector *i* was put as an exogenous variable depending on the social conditions assumed in Scenarios A and B. For example, the demands were calculated from the future production of steel in the steel sector and from the number of households and the activity per household for the residential sector.

2.2. Listing possible options for achieving future scenarios

As options (countermeasures and policies) toward a low-carbon society in 2050, the main countermeasures listed in the "Japan Scenarios and Actions towards a Low-Carbon Society" and main policies listed in "A Dozen Actions" were investigated. For example, actions in the residential sector included countermeasures such as "insulated houses" and "energy efficient air conditioners" mentioned in the former, and policies such "introducing a system for labeling environmental performance buildings" and "revising top-runner standards" mentioned in the latter. The numbers of measures and policies investigated in this analysis are summarized in Table A.1 for each action.

Table A.1. Numbers of measures and policies (Each is counted only once for the principal action.)

Action	Policy	Countermeasure
1. Comfortable and green environment	19	5
2. Anytime, anywhere appropriate appliances	45	48
3. Promoting seasonal local foods	15	8
4. Sustainable building materials	13	-
5. Environmentally enlightened business and industry	9	112
6. Swift and smooth logistics	11	16
7. Pedestrian friendly city design	11	26
8. Low-carbon electricity	28	14
9. Locally renewable resources for local demand	14	6
10. Next-generation fuels	32	32
11. Labeling to encourage smart and rational choices	10	-
12. Leadership for a low-carbon society	12	-
Total	219	267*

*: About 400 when a countermeasure is counted separately for multiple actions.

2.3. Quantifying options

For each countermeasure and policy, (1) the necessary period for introduction (the least number of years needed for introduction) and (2) the costs for introduction were calculated.

(1) Necessary period for introduction

There are options that can be completed immediately such as establishing institutional systems and those that may take several decades such as building insulated houses. For each option, the least number of years necessary for accomplishing the options was estimated by studying references and interviewing of experts. In principle, the period was the service life for countermeasures and was the mean number of years from the start of discussion until enactment for policies. In the pathway analysis, the period was used as a limiting condition, assuming that options cannot be introduced faster than the periods thus estimated (Figure A.2).

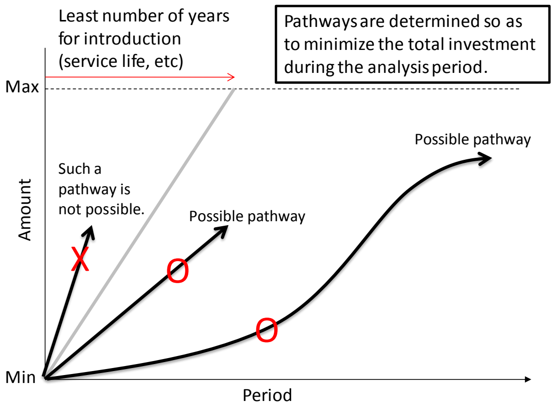


Figure A.2. Relationship between the periods needed for implementing an option and assessment of the pathways for introducing the option

(2) Costs for introduction

Fixed costs and fuel costs were considered as the costs required for introducing the options, and the differences from the conventional type were used as standards for assessing the timing for introducing the options. Fuel costs were not considered for policies, and costs that are known to be needed for investigating and formulating the policy were included as fixed costs.

The fixed costs for each year are endogenously determined by the model that takes learning-by-doing effects into account. The initial value $c_{f,\mathrm{init}}$ [JPY/unit] is exogenously set as the difference between the initial fixed cost $f_{lcs,\mathrm{init}}$ [JPY/unit] of the measure and f_{conv} of the conventional alternative:

$$c_{f,\mathrm{init}} = f_{lcs,\mathrm{init}} - f_{conv} \qquad \text{(A.1)}$$

The fixed costs of conventional alternatives were assumed differently depending on the kind of countermeasure or policy. The average stock costs of conventional devices were put as the conventional fixed costs for countermeasures that aim to improve efficiency. The costs of the devices before fuel conversion were used as measures for fuel shifts, and the costs of thermal power plants that are not equipped with CCS (carbon capture and storage) were used for CCS. For policies, the costs of conventional policies were assumed to be zero. The initial fixed cost of a options and the fixed cost of its conventional alternative were determined based on the "Energy Conservation Catalog" (in Japanese) (2000, 2005 and 2008) of the Energy Conservation Center, "Energy Technology Perspective (2008)" of the IEA, "Assessment and investigation of technologies for preventing global warming (in Japanese)" of the Ministry of the Environment, references of the Central Environment Council, "Japanese Motor Vehicles Guidebook (2007-2008)" of Japan Automobile Manufacturers Association, Inc., and the results of market research by ourselves.

2.4. Adding relationships among options

Many options require preliminary options to have been introduced in advance. Such preliminary options are called prerequisite options. For example, electric power supply stations must have been established before electric vehicles can proliferate. In order to spread insulated houses that match the local climate and consume the minimum energy, the present insulation standards need to be revised to classify regions precisely to enable adjustment to the actual climatic conditions, and a third-party system for assessing the insulation performance of houses should be constructed. In this analysis, the relationships between the measures and policies for the "A Dozen Actions" and their prerequisite options were investigated by classifying the relationships into "absolute connection" and "partial restriction."

Absolute connection is a relationship in which a certain option cannot be started without the full introduction of its prerequisite option. This relationship is widely seen between options and its prerequisite policies (Fig. A.3).

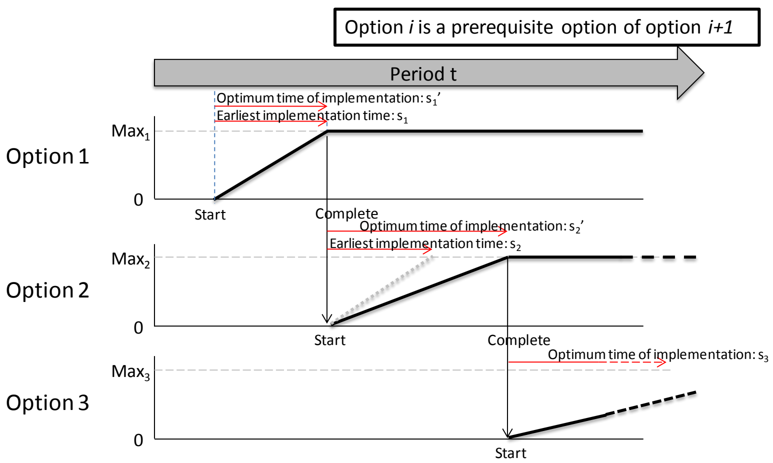


Figure A.3. Overview of absolute connection

A partial restriction is a relationship in which the amount of introduction of a prerequisite option at time *t* limits the amount of introduction of the target option at time *t+1* (Figure A.4). For example, if power supply stations have been established in 10% of the area by time *t*, electric vehicles will be able to be spread in the 10% area at time *t+1*.

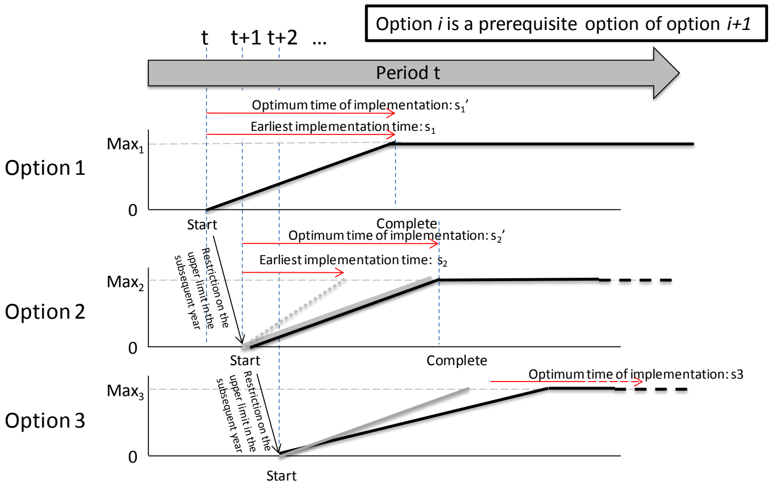


Figure A.4. Evaluation of the amount of introduction of measures with partial restriction

2.5. Quantitative investigation using the backcast model

(a) Preliminary conditions of the model

In this investigation of pathways, the base year t_0 and the target year were set as 2000 and 2050, respectively. To eliminate the end effects of the simulation, the final year t_L in the calculations was set as 2070. The service demands in and after 2050 were determined by extrapolating the trends up to 2050 and assuming the same CO_2 emission limit as for 2050.

(b) Objective functions in optimization

The flow quantity $Q_{f,m}(t)$ of a option *m* in each time period is in principle determined by minimizing the costs during the analysis period. In this model, the flow quantity of an option is the increment in the number of a low-carbon system introduced or in the percentage of diffusion, and the flow quantity of a policy is the progress of investigations on policies related to a low-carbon society.

Costs assessed were fixed costs and fuel costs, which were converted to present values at a discount ratio of *r* = 3%:

$$\min T_C = \sum_{\tau=t_0}^{t_L} \left\{ \frac{1}{(1+r)^{\tau-t_0}} \times \sum_m \left(F_m(\tau) - V_m(\tau) \right) \right\} \qquad \text{(A.2)}$$

T_C: Total costs during analysis period [JPY]

$F_m(t)$:	Total additional fixed costs for option m during period t [JPY]

$V_m(t)$:	Reduction in the total fuel costs during period t by option m (reductions are expressed as positive values) [JPY]

The total additional fixed cost $F_m(t)$ of each year was calculated from the flow quantity of the option during period t and the fixed cost $C_m(t)$ [JPY/unit] by considering the learning-by-doing effects during period t (Equation A.3). Learning-by-doing effects were not considered for calculating the fixed costs of policies.

$$F_m(t) = \left(C_m(t) - f_{conv}\right) \times Q_{f,m}(t) \quad \text{(A.3)}$$

Changes in fuel costs were calculated by multiplying the stocks $Q_m(h)$ [unit] of options that belong to cohort h operating at time t and the reduction in energy $e_{red,m}(h,i,j,k)$ consumed by service j of sector i per unit quantity of introduction in each cohort and adding the price $p_k(t)$ of the fuel k at time t. The stocks of measures are the total number of units introduced or the total percentage of diffusion at time t, and the stocks of policies are the actual investigation states of the policies at time t, where, H_t is the group of cohorts that are operating at time t:

$$V_m(t) = \sum_k \left\{ p_k(t) \times \sum_{i,j} \left(\sum_{h \in H_t} e_{red,m}(h,i,j,k) \times Q_m(h) \right) \right\} \quad \text{(A.4)}$$

(c) Evaluation of learning-by-doing effects

The cost $c(t)$ at time t is generally expressed as:

$$c(t) = c_0 \times QCUM(t)^{\frac{\log p}{\log 2}} \quad \text{(A.5)}$$

where, c_0 is the initial cost, $QCUM(t)$ is the cumulative amount of introduction, and p is the learning rate.

This is a non-linear relation. In this study, learning curves were used after linearization because the backcast model constructed based on linear optimization framework. A learning curve was divided into two or more lines, and their sum was used to express the reductions in costs by learning. Learning effects were assumed only for countermeasures, and policies were assumed to have no learning effects and require constant fixed costs. For example, in Figure A.5, the learning curve was divided into six lines. This method calculates costs higher than the theoretical values for cumulative amounts smaller than 1. To avoid this and adjust the values also for small cumulative amounts to the theoretical values, a line was added to the region of cumulative amounts smaller than 1.

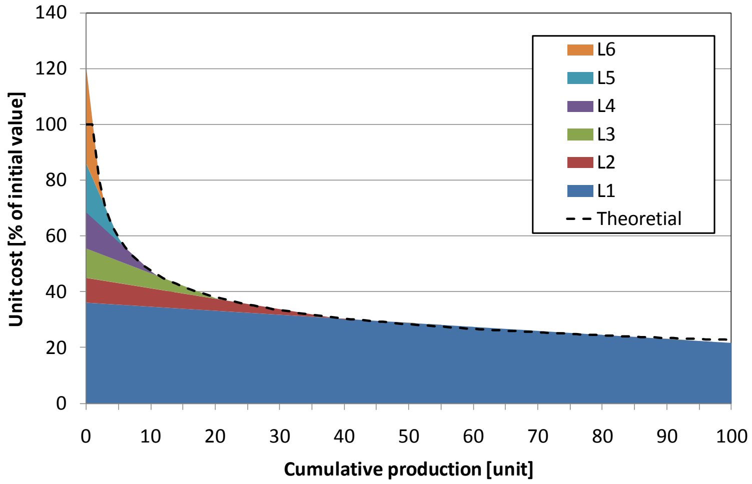


Figure A.5. Linearization of a learning curve

Specifically, the fixed cost $C_m(t)$ [JPY/unit] of option m at time t was calculated by multiplying the initial value $f_{lcs,\text{init}}$ [JPY/unit] and the sum of l number of lines $L_l(t)$ that linearize the learning curve and the line $L_c(t)$ that has an inclination of g_c and section of n_c for correcting the values for cumulative amounts smaller than 1. Each of the lines $L_l(t)$ was calculated from the cumulative introduction $QCUM_m(t)$ [unit] and the inclination g_l and intercept n_l determined by the linearization of the learning curve. $L_l(t)$ was assumed to be not smaller than zero.

$$C_m(t) = f_{lcs,\text{init}} \times \left(\sum_l L_l(t) + L_c(t) \right) \quad \text{(A.6)}$$

$$L_l(t) = g_l \times QCUM_m(t) + n_l \quad (\text{if} > 0), 0 \, (\text{otherwise}) \quad \text{(A.7)}$$

$$L_c(t) = g_c \times QCUM_m(t) + n_c \quad (\text{if} < 0), 0 \, (\text{otherwise}) \quad \text{(A.8)}$$

(d) Energy supply and CO_2 emission

In the investigation of pathways, all exogenously given service demands had to be satisfied regardless of implementation of options. In this model, service demands were not directly handled but were first converted into energy consumptions and then formulated.

Changes in CO_2 emission were estimated by 1) calculating the energy demand at Business as usual (BAU) $d_{BAU}(t,i,j)$ [Mtoe] in service j of sector i at time t and the energy consumption (BAU)

$e_{BAU}(t,i,j,k)$ [Mtoe] for each kind of fuel by assuming that all energy was supplied by conventional methods, 2) determining the amount of the measure to be introduced so that the total of the conventional-type energy consumption $E_{conv}(t,i,j,k)$ [Mtoe], the energy $E_{lcs}(t,i,j,k)$ [Mtoe] consumed for introducing the measure, and the reduction $E_{red}(t,i,j,k)$ [Mtoe] in energy consumption by the introduction was equal to the energy consumption $e_{BAU}(t,i,j,k)$ [Mtoe], and 3) calculating the CO_2 emission $CO2(t)$ [t-CO_2] after introduction of the measure.

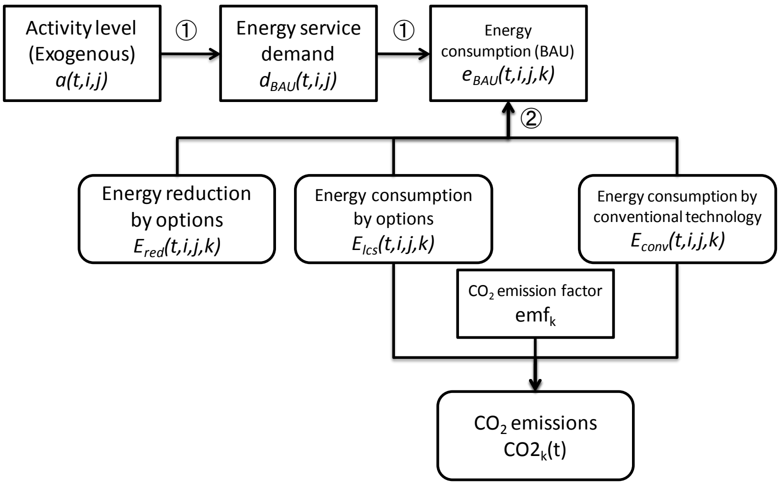


Figure A.6. Calculation flow of CO_2 emission

(1) Calculating the demands for energy supply and energy consumption (BAU)

Energy service demand (BAU) $d_{BAU}(t,i,j)$ [Mtoe] was calculated by multiplying the service demand (activity level) $a(t,i,j)$ [unit] of service type j of sector i and the energy service demand $u(t,i,j)$ [Mtoe/unit] per unit service demand:

$$d_{BAU}(t,i,j) = a(t,i,j) \times u(t,i,j) \tag{A.9}$$

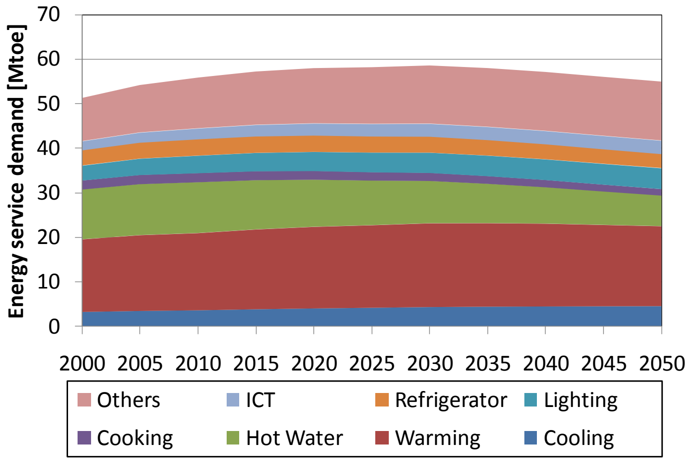


Figure A.7. Examples of energy service demand in BAU (Residential sector, Scenario A)

As an example, the energy service demand (BAU) in the residential sector in Scenario A is shown in Figure A.7. There are options that cause direct changes in energy service demand, but their effects were also converted into changes in energy consumption in this study.

The energy consumption $e_{BAU}(t,i,j,k)$ [Mtoe] was calculated by assuming that all the demanded energy was supplied by conventional methods. The calculation involved multiplying the energy service demand $d_{BAU}(t,i,j)$ [Mtoe], the average efficiency of conventional appliances $\eta_{conv}(t,i,j,k)$ [-] and the share of the fuel $s_{conv}(t,i,j,k)$ [-]:

$$e_{\mathrm{BAU}}(t,i,j,k) = d_{\mathrm{BAU}}(t,i,j) \times \eta_{\mathrm{conv}}(t) \times s_{conv}(t,i,j,k) \qquad \text{(A.10)}$$

(2) Balance of energy consumption

The energy consumption $e_{BAU}(t,i,j,k)$ [Mtoe] was assumed to be equal to the sum of conventional-type energy consumption $E_{conv}(t,i,j,k)$ [Mtoe], the energy $E_{lcs,m}(t,i,j,k)$ [Mtoe] consumed for introducing option m, and the reduction $E_{red,m}(t,i,j,k)$ [Mtoe] in energy consumption by introducing the option:

$$E_{conv}(t,i,j,k) + \sum_{m} \left(E_{lcs,m}(t,i,j,k) + E_{red,m}(t,i,j,k) \right) = e_{BAU}(t,i,j,k) \qquad \text{(A.11)}$$

Here, the reduction $E_{red,m}(t,i,j,k)$ [Mtoe] in energy consumption by introducing the options was determined by multiplying the stock of option $Q_m(h)$ [unit] of cohort h operating at time t and the reduction $e_{red,m}(h,i,j,k)$ [Mtoe/unit] in energy consumption per unit introduction of the cohort:

$$E_{red,m}(t,i,j,k) = \sum_{h \in H_t} e_{red,m}(h,i,j,k) \times Q_m(h) \qquad \text{(A.12)}$$

For options that cause changes in the power consumption in the residential, commercial and industrial sector, the energy balance and changes in CO_2 emission were calculated by converting the energy consumption into the rate of change in electricity consumption caused by implementing the options in the entire power supply demand using the following equations and assuming that the changes were changes in energy consumption in the electricity sector:

$$E_{red,m}(t,Ele,j,k) = eBAU(t,Ele,j,k) \times \left(1 + S_{red}(t,Ele)\right) \qquad \text{(A.13)}$$

$$S_{red}(t,Ele) = \sum_{i,j} \left\{ \frac{\sum_m \left(\sum_{h \in H_t} e_{red,m}(h,i,j,Ele) \times Q_m(h) \right) - e_{BAU}(t,i,j,Ele)}{eBAU(t,i,j,Ele)} \right\} \quad \text{(A.14)}$$

(3) CO_2 emission

The CO_2 emission *CO2(t)* [t-CO_2] at time *t* was determined by multiplying the conventional-type energy consumption $E_{conv}(t,i,j,k)$ [Mtoe], the energy $E_{lcs,m}$ (t,i,j,k) [Mtoe] consumed for introducing option *m*, and the coefficient of CO_2 emission emf_k [t-CO_2/Mtoe]:

$$\sum_k \left\{ emf_k \times \sum_{i,j} \left(E_{conv}(t,i,j,k) + \sum_m E_{lcs,m}(t,i,j,k) \right) \right\} = CO2(t) \quad \text{(A.15)}$$

The coefficient of CO_2 emission of each fuel was assumed to be constant throughout the analysis period.

In the investigation of pathways, the CO_2 emission in and after 2050 was constrained to be 30% of the 1990 level or less:

$$CO2(t)_{|t \geq 2050} \leq (1-0.7) \times CO2_{1990} \quad \text{(A.16)}$$

(e) Constraint on the amount of introduction

The stock $Q_m(t)$ [unit] of option *m* at time *t* is expressed as the sum total of the stocks in cohort *h* operating at the time when there are no additional constraints:

$$Q_m(t) = \sum_{h \in H_t} Q_m(h) \quad \text{(A.17)}$$

The stock $Q_m(t)$ [unit] of option *m* was constrained to not exceed the maximum introduction amount $q_{max,m}$ [unit] adopted for investigating the 70% reduction scenarios:

$$Q_m(t) \leq q_{\max,m} \quad \text{(A.18)}$$

When there is a prerequisite option m_p, a constraint was imposed on the stock based on the relationship.

For prerequisite options of absolute connection, flag $P_{mp}(t)$ [-] was established for showing whether the prerequisite option is completed by time t or not. When the flag is 1 (the prerequisite option is completed), the option at time $t+1$ was assumed to be able to be introduced up to the maximum stock value $q_{max,m}$. When the flag is 0 (the prerequisite option is not completed), the stock at time $t+1$ was constrained to be zero. Assuming that an option may be in absolute connection with two or more prerequisite measures, the flag of the smallest value was used as the constraint among those of all prerequisite options in absolute connection:

$$Q_m(t+1) \le q_{\max,m} \times \left(\min_{m' \in m_p} P_{m'}(t) \right) \tag{A.19}$$

$$P_m(t) = 1 \,(\text{if } Q_m(t) = q_{\max,m}), \quad 0\,(\text{otherwise}) \tag{A.20}$$

A partial restriction is a relation by which the amount of stock of a prerequisite option at time t serves as the upper limit of the stock of the upper level option at time $t+1$. Here, the stock was normalized at the maximum amount of introduction and was used as the constraint. As in absolution connection, an option was assumed to be possibly in a partially restrictive relation with two or more prerequisite options. The stock of the smallest value among all prerequisite options in partial restriction was used as the constraint.

$$Q_m(t+1) \le q_{\max,m} \times \left(\min_{m' \in m_p} \frac{Q_{m'}(t)}{q_{\max,m'}} \right) \tag{A.21}$$

For the introduction (flow) of a option at time t, a constraint was imposed on the implementation period s_m [year] of the measure. The maximum introduction $q_{max,m}$ [unit] was divided by the implementation period s_m [year] to determine the largest possible amount of introduction (flow), and the introduction of the option (flow) was constrained to be smaller than the value.

$$Q_{f,m}(t) \le \frac{q_{\max,m}}{s_m} \tag{A.22}$$

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