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Scenarios of solid oxide fuel cell introduction into Japanese society

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Abstract

In this paper, strategies to successfully introduce solid oxide fuel cells (SOFCs) into industry and society are discussed using a scenario approach. Scenarios for Japanese energy systems are developed to portray the situation up to the year 2050, in order to consider the potential interrelation of SOFCs with other power generation technologies, and to direct further investigation and stimulate discussion among researchers and stakeholders. Scenarios are constructed by combining a number of scenario options, such as technical, social, political and economic aspects. Specific attention is focused on the lifecycle of SOFCs. A power generation planning model developed in a previous study was extended to model decision-making for power generation capacity planning based on cost minimization, subject to other constraints and requirements over the focal time period of 2001–2050. In this way, it is possible to assess for each scenario not only the feasible introduction rate of SOFCs, but also the CO_2 emissions, cost, and energy security requirements for the entire energy system, including both distributed and centralized power systems. The results of the analyses elucidate the effectiveness of different technical and political alternatives, such as technological breakthrough, recycling, security of materials and production facilities, on the successful introduction of SOFCs in Japanese power systems.

Keywords: SOFC; Resource management; Lanthanum intensity; Recycling; Scenario development; Technology assessment

1. Introduction

The solid oxide fuel cell (SOFC) is envisioned as an efficient and useful power generation device that could contribute to global sustainability through increased efficiency and flexibility in the use of energy and resources. Different forms of SOFC implementations are predicted to be widely available for use in society in the near future. In order to develop strategies that successfully introduce a new device such as the SOFC into industry and society under the concept of sustainability, the contributions of that device should be measured from social, economic and ecological viewpoints. However, the number of options for the introduction of SOFCs, such as manufacturing and recycling processes, cell types, target sites and future energy policies, have increased greatly. Simultaneously the number of stakeholders directly affected by the introduction of SOFCs is growing. The sustainability concept also requires us to consider the temporal axis. Middle to long-term strategies must be developed for the viewpoints described above. Ideally, analyses of the various alternatives should give results that are optimal not for just a single generation, but for future generations as well.

To tackle such a broad and complex problem, scenarios that are developed using integrated models to portray possible futures under different conditions could be effective for directing further investigation and stimulating discussions among stakeholders. While this kind of scenario development cannot avoid uncertainties that may undermine the validity of the results, a scenario approach is still useful for understanding the mechanisms by which the parameters and assumptions affect each other as well as the overall SOFC introduction scenario from multiple sustainability issues and stakeholder viewpoints.

In this study, we developed SOFC introduction scenarios to analyze the effects of both planned strategies and unforeseeable events on the potential for successful introduction of SOFCs into Japanese society and industry.

2. Development of scenarios

In this chapter, we present the structure of our scenario development approach and the reference scenario. The scenarios that we develop will be used to discuss the choices and possible consequences of SOFC technology introduction into Japanese society within the time frame of 2001–2050.

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SOFC technologies are predicted to be used both in distributed and centralized power generation. In our scenarios here, we have assumed that for centralized power generation systems SOFC modules are combined with gas turbines to produce only electric power, while the same SOFC modules are used without gas turbines in decentralized cogeneration systems to supply both heat and power.

In order to develop introduction scenarios of SOFC, interactions with other power generation technologies, both competitive and synergistic, should be taken into account. In this study, we consider both a hybrid systems of the SOFC and gas turbine (SOFC/GT) fuelled by LNG and a NaS battery load balancing system as new centralized power systems, and we introduce SOFC cogeneration and photovoltaic systems as new decentralized applications, because those technologies are most likely to be available in Japan within the focal period. The existing power generation options included in our analysis are nuclear, oil-fired, LNG-fired, gas combined cycle (GCC), hydropower and hydro pump power systems. Oil-fuelled SOFC, integrated coal gasification fuel cell combined cycle (IGFC), integrated gasification gas combined cycle (IGCC), biogas-fuelled SOFC, ceramic turbine and wind power generation technology can also be considered potential future power generation options within the focal period. We intend to investigate the introduction potential of some of these technologies in future work.

Major causal relationships that affect the introduction of SOFCs, including competitive and synergistic interactions at different stages of the SOFC lifecycle are described in Fig. 1. Boxes show the different causes that drive the state of the situation. Arrows show positive (solid line) and negative (dotted line) effects from the source to the destination.

The decisions to both install and operate a power system such as the SOFC/GT system (S1) and the NaS battery system (N1) in the centralized power system for the studied region are made from a cost minimization perspective under the constraints of several power planning conditions and policy requirements together with the consideration of the technical characteristics of the power generation systems. In this study, we use the power generation mix model (PGMM) developed in previous work [1] to approximate the actual decision-making process. We extended the model in order to support dynamic economic optimization over a 50 year period with 10 year intervals, and we added to the model all of the technologies, strategies and events that we included in our scenarios. The extension includes integration of dynamic life cycle model of SOFC/GT, which enables the consideration of the different lifetime of modules in the system [2]. Installation of distributed power sources in the scenarios,

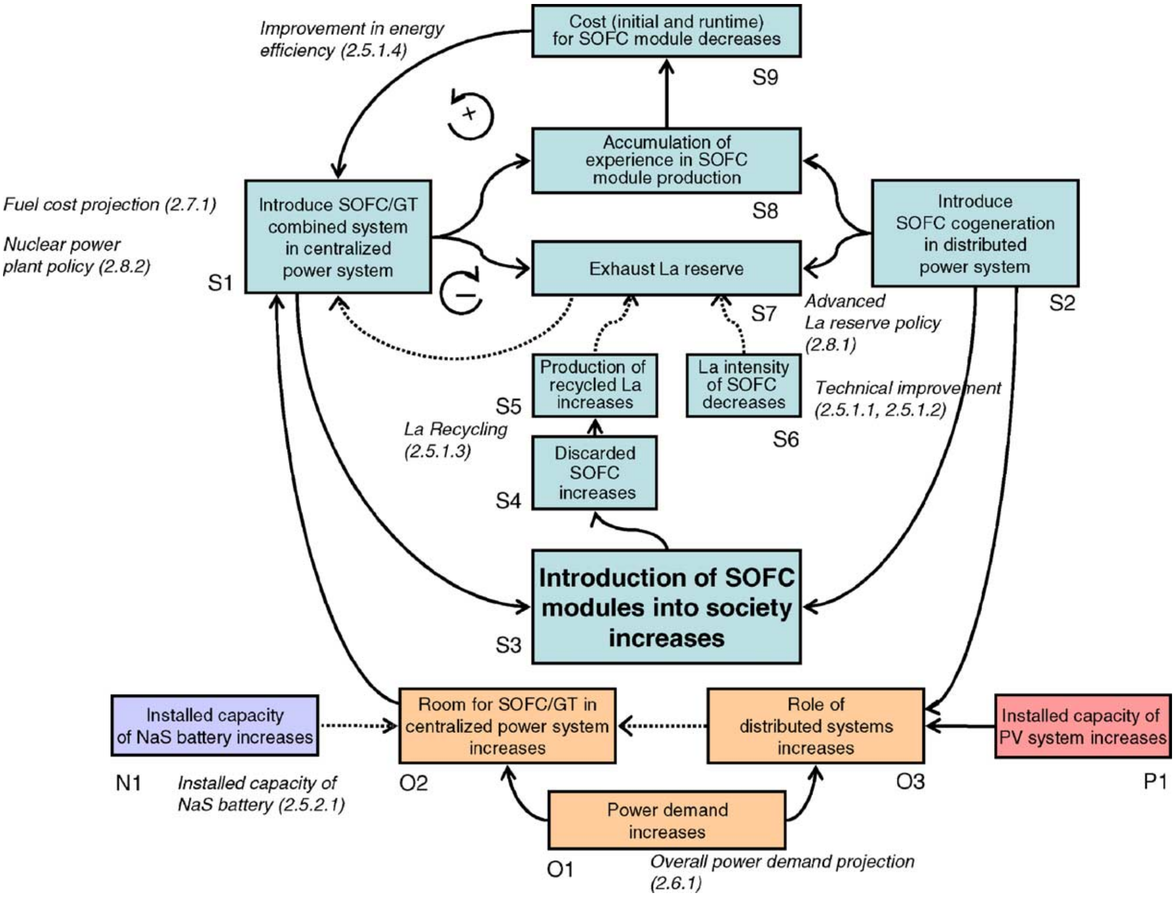

Fig. 1. Major causal relationship behind the introduction of SOFC into the society.

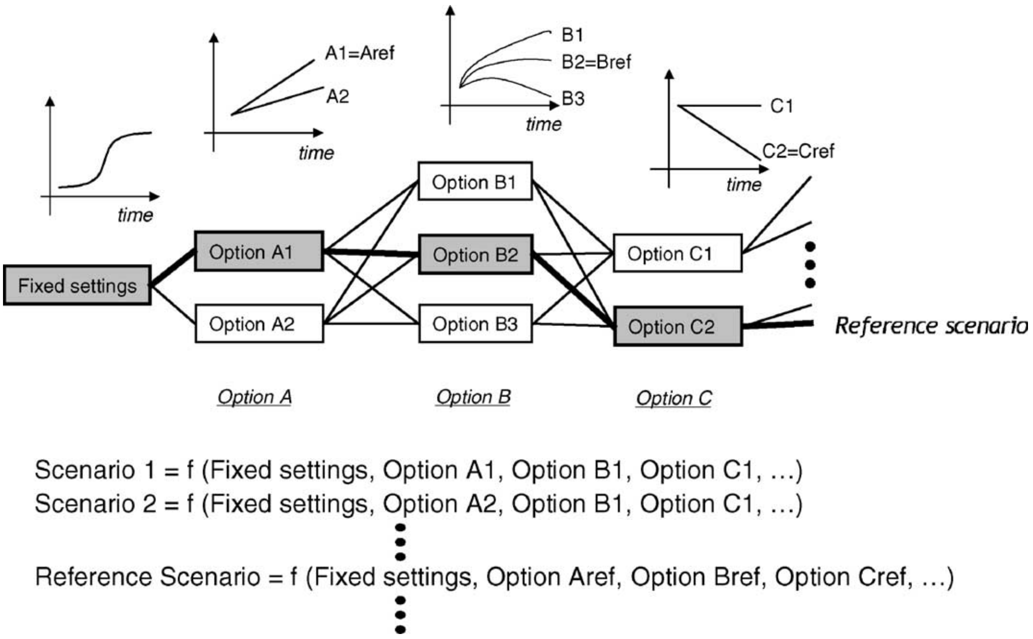

Fig. 2. Structure of scenario development in this study.

i.e. PV (P1) and SOFC cogeneration (S2), are given exogenously based on consideration of press releases from organizations such as New Energy and Industrial Technology Development Organization (NEDO) of Japan and past trends.

As shown in Fig. 1, the introduction of SOFC/GT (S1) increases experience in the manufacture of SOFC modules (S8), decreasing both the manufacturing costs and the running costs as greater manufacturing experience leads to increases in the efficiency of the manufactured device (S9). Initial introduction of SOFC/GT therefore generates a positive feedback loop that increases the potential for larger-scale introduction in the centralized system. This positive feedback loop can be accelerated by introducing the SOFC cogeneration system (S2) because that system uses the same SOFC modules as the SOFC/GT. On the other hand, large-scale acceleration of S1 and S2 might result in depletion of natural resources for the various rare elements that are included in the component materials used in SOFC modules. In this study, we focused on lanthanum (La) as such a ‘bottleneck’ element. S1 and S2 both accelerate the depletion of La reserves (S7). Declined availability of La results in a negative feedback loop on S1, and thereby possibly limiting the successful introduction of SOFCs. Both technical improvements to decrease the La intensity in SOFCs (S6) and development of recycling systems (S5) could help to relax this constraint. Political actions such as enhancement of the annual availability of La, or introduction of a more efficient La reserve could also contribute to overcoming the La constraint.

Growth of the overall power demand in the region (O1) has a positive effect on SOFC introduction (S1) by providing increased demand for power generation capacity that could be occupied by the SOFC/GT in the centralized power system (O2). Introduction of other centralized power system technologies such as the NaS battery (N1) for load balancing in this study will show the counter-effect as a negative growth of the overall power demand. However, it must be noted that the characteristics of each technology, such as load following ratios, are also important. Consequently, N1 might not have a negative effect on S1 in some situations. As the fraction of the overall power demand supplied by distributed power sources increases (O3), the requirement for generation capacity of the overall centralized power system will decrease, which negatively affects O2.

We have built into our model the causal relationships presented above that describe all of the mechanisms that we consider within the scope of our study. Therefore different scenarios can now be expressed simply as sets of different parameter values in our models. In order to analyze different scenarios in a systematic way, we introduced the scenario development structure that is described in Fig. 2. Each scenario is constructed by combining the common fixed settings with different scenario options. A reference scenario is constructed from the combination of reference scenario options. Cornerstone scenarios are particular scenarios that serve as the ‘cornerstones’, by describing the extreme sets of options, thereby helping us to assess the possible range of future projections (Fig. 3).

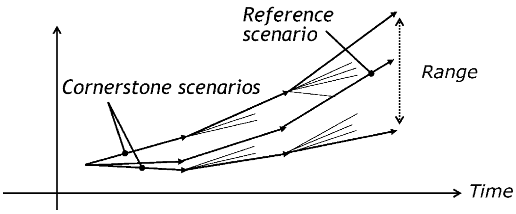

Fig. 3. Schematic images of reference and cornerstone scenarios.

Table 1
Energy conversion efficiencies of other power generation technologies over the focal period (2001–2050)

	2001	2010	2020	2030	2040	2050	Notes
Oil-fired	0.38	0.38	0.38	0.38	0.38	0.38	Current Japanese policy prohibits installation of new oil-fired power plants
Coal	0.36	0.38	0.40	0.42	0.44	0.46	Japanese policy promotes technical Innovation of coal in order to increase energy security
LNG-fired	0.39	0.39	0.39	0.39	0.39	0.39	No plans for future construction of simple LNG-fired power plants because of transition to GCC or SOFC/GT for LNG-fueled facilities
GCC	0.44	0.46	0.48	0.50	0.52	0.54	+2% per decade
Hydro	–	–	–	–	–	–	No change, construction of new dams in Japan is difficult
NaS battery	0.9	0.9	0.9	0.9	0.9	0.9	No change, efficiency is already high
Pump	0.65	0.66	0.67	0.68	0.69	0.70	+1% per decade

2.1. Fixed technical settings

Although our primary goal is to investigate the potential for SOFC installation and to analyze the effectiveness of strategies to introduce SOFCs into the society, we also need to study the other power generation technologies described in the previous section with sufficient detail. For the energy conversion efficiency, we used the future projections as shown in Table 1, that we determined by the considering a number of various political and technical conditions (see ‘notes’ in Table 1). The initial values, i.e. efficiencies in 2001, are assumed to be the same with those in the literature [3]. We assumed that the energy conversion efficiencies of each of the power generation technologies are constant regardless of how the technologies are operated in a day, meaning that we do not consider the effects of partial loads on efficiencies, which is the same assumption that is used in the literature [3]. We justify this assumption by considering that the installations of each power generation device will be scaled such that they can be operated at the optimal partial load.

As described in the previous section, we set future introduction rates of distributed power sources exogenously. These rates are shown in Table 2. Installation of photovoltaics (PVs) is projected to increase with 5% annually. We predicted the introduction rate of SOFC cogeneration systems based on the promotion plans published by NEDO of Japan.

We estimated the daily power generation profiles for SOFC cogeneration [4] and PV for 7 representative days (average weekday and weekend in summer, spring/fall and winter, and the annual peak load day). We then subtracted the distributed power system generation profiles from the overall power demand profiles (discussed in Section 2.6.1) to produce seven demand profiles for the centralized power system. We use those profiles as input data to the power generation mix model.

Table 2
Installed capacities (in GW) of distributed power sources over the focal period (2001–2050)

	Year					
	2001	2010	2020	2030	2040	2050
Photovoltaics	0.2	0.33	0.53	0.86	1.41	2.29
SOFC cogeneration	0	0.002	1	1.5	2	2

2.2. Fixed political settings

Currently, Japan does not trade electric power with other countries mainly due to the geographical separation. We assume that this situation will remain unchanged over the focal period.

2.2.1. Lanthanum availability

Lanthanum (La) is one of the important rare earth metals used in the manufacture of semiconductor devices and high temperature ceramics. For this reason, the Japanese government maintains a strategic stockpile of La. Natural resources of rare earth metals are unevenly distributed around the world—China has 57.2% of world reserves and around 80% of world production of rare earth metals in 2001 [5]. Presently, Japan is the largest importer of rare earth metals from China. In 2001, Japan imported around 85.6% of the country’s overall La demand, or 1498t-La oxide [6]. Therefore, even if the Clark number of La is not particularly low (0.0018 wt.%, 35th of all the elements), its use should be considered carefully from the viewpoint of resource security. The SOFC configuration that we have assumed in this study contains La as a main component in the cathode, in the form of $La(Sr)MnO_3$. Because the SOFC is a power generation technology, large scale introduction of SOFCs should be considered to be an energy security issue. In this study, we set the availability of pure La for use specifically in SOFCs as shown in Fig. 4.

2.2.2. Plant dismantling

A certain amount of redundancy in power generation capacity and the fuel mix are important from the perspective of energy security. Therefore, some of the power plants that would be dismantled from a purely economic viewpoint are not always dismantled in our scenarios.

For LNG-fired power plants, we assumed that 20% of the total capacity in 2001 is dismantled every decade.

The Petroleum Association of Japan states that Japan will need to continue to use at least as much oil as is currently

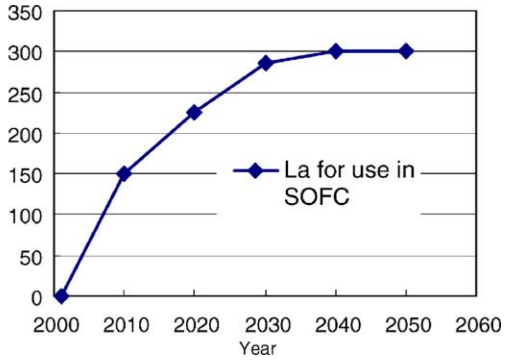

Fig. 4. Assumptions on La availability for SOFC industry in Japan (2001–2050).

being consumed to maintain energy security by assuring diversity in the fuels for power sources [7]. On the other hand, Japanese national policy aims to reduce dependency on oil as a fuel also from the energy security perspective. In this study, we set the amount of oil use to be at least 1.5×10^8 l, which is the present level of use in Japan. The total capacity of oil-fired power plants is determined according to this condition and the efficiency of the oil-fired power plant technology (Table 1).

We did not consider the capacity decrease for any of the other power technologies, except for nuclear in one of the scenario options.

2.2.3. CO_2 emission mitigation policy

Japan has ratified the Kyoto protocol, and consequently Japan will have to continue to decrease carbon intensity of electricity generation (tons CO_2 per GWh). Therefore, we assumed that the mix of technologies for the central power system will be determined so as not to increase the carbon intensity throughout the focal period.

2.3. Fixed economic settings

In this study, we exogenously set the cost at each time period for the SOFC module, the gas turbine in the SOFT/GT system, and the other expenses as shown in Table 3. In particular, we have assumed that these costs are independent of the cumulative units of production. SOFC module cost decreases about 20% per decade. Because gas turbine technology is considered to be mature, we assumed the cost of gas turbines to be constant. The other expenses to install SOFC/GT system, which includes BOP and assembling cost, are assumed to be 50% of the SOFC module cost. We assumed that as the efficiency of gas turbines improves (see Table 1) due to the system size increase, the fraction of electric power generated by gas turbines will increase in the SOFC/GT system. SOFC/GT system cost is calculated as the sum of the SOFC module cost, the other expenses, and the cost of the gas turbine. We do not consider import or export of SOFCs to and from Japan, although it is likely that SOFC will be an important international trade commodity.

Table 3
Settings in SOFC/GT system cost[a]

	2010	2020	2030	2040	2050
SOFC module	400,000	320,000	256,000	204,800	163,840
Gas turbine	150,000	150,000	150,000	150,000	150,000
Other expenses	200,000	160,000	128,000	102,400	81,920
GT ratio (%)	20.0	22.5	25.0	27.5	30.0

[a] JPY per kW.

2.4. Fixed social settings

Peak loads in Japan occur in the afternoon on hot summer days, due to the large cooling load. We assume that the climatic conditions in Japan will not change over the investigated period.

2.5. Technology scenario options

We investigated technology scenario options related both to SOFCs and to the other power systems included in this study. Both of these types of technical options play important roles in determining the possible ranges for SOFC introduction as described in Fig. 1.

2.5.1. SOFC technology related scenario options

We consider two kinds of technology scenario options related to SOFCs that accelerate the positive feedback loop, and decelerate the negative feedback loops on SOFC introduction that were described in Fig. 1, respectively.

2.5.1.1. Lifetime of SOFC module and gas turbine. The lifetime of the SOFC module affects the production capacity and also the material requirements, particularly of La, for manufacturing the cells. Based on the fact that the Siemens-Westinghouse Power Corporation (SWPC) configuration has been successfully operated for 10 years, we set three scenario options, i.e. 10 (reference), 20 and 40 years. These scenario options help us to see how the lifetime of the SOFC module affects the overall potential for introduction of SOFC related systems into society and industry. The costs for SOFC module production are assumed to be the same irrespective of the assumed lifetime in this study. The lifetime of the gas turbines used in SOFC/GT system is assumed to be 40 years for all calculations in this study.

2.5.1.2. Reduction in La intensity. We have set the reference SOFC technology to be the tubular type cell configuration developed by SWPC. However, in the future, if the existing problems in microtubular cell and planar cell designs are solved, it may be possible to decrease the La intensity of cells by a factor of 10 [8]. In this study, we set two scenario options in order to take into account this possibility for cell configuration improvement, as shown in Table 4. Under the ‘moderate’ option, which is the reference

Table 4
Settings in La intensity (in kg La per kW) for moderate and breakthrough scenario options

	2001	2010	2020	2030	2040	2050
Moderate	1.5	1.5	1.4	1.3	1.2	1.1
Breakthrough	1.5	1.5	0.15	0.15	0.15	0.15

scenario option, we assume that the SWPC configuration is used until 2050 with only a gradual reduction in La use. The 'breakthrough' option has a drastic change of La intensity in 2020 that corresponds to a breakthrough in microtubular or planar cell design.

2.5.1.3. Lanthanum recycling. Recycling of cell components is a potentially effective option to mitigate the resource limitation. We set two scenario options here. The reference scenario option does not include any recycling. The recycling scenario option assumes that 100% of the used cells are recycled. In this study, we did not include the additional costs that would result from the introduction of the recycling system. We also assumed that the SOFCs fabricated from recycled La are sold with the same price and have the same performance as the cells fabricated using La from ore.

2.5.1.4. Energy conversion efficiency of SOFC/GT. In this study, we assumed that the average energy efficiency of SOFC/GT installed as a centralized power system increases throughout the focal period as shown in Table 5. We assumed that SOFCs could achieve an energy conversion efficiency of 50% at the year of 2010 based on the consideration that SWPC's first generation hybrid system had achieved 53% (220 kW, LHV) [9]. For the SOFCs manufactured in 2050, we took the highest reported value of 70% [10]. However, in our actual analysis, we have used slightly lower values even with the high efficiency scenario, because the efficiency that we use here is the average of all of the SOFC systems that are installed at each time period. The intermediate option was used as the reference scenario option.

2.5.2. Technology scenario options related to other power systems

Other technologies that can affect the installation of SOFCs both positively and negatively should be taken into account.

2.5.2.1. Installed capacity of NaS battery. We have included a NaS battery system as a potential component of the centralized power grid system in this study. Although the NaS batteries will normally be installed at the distributed sites, we have assumed that they will be managed by the power company, based on consideration of demand loads both at the distributed site and for the whole region.

Table 5
Energy conversion efficiency improvement scenario options (in %)

	2010	2020	2030	2040	2050
Low	51	52	53	54	55
Intermediate	52	54	56	58	60
High	53	56	59	62	65

Table 6
Scenario options for NaS battery installed capacity (in GW)

	2001	2010	2020	2030	2040	2050
Low	0	0.5	2	5	5	5
Intermediate	0	0.5	3	10	10	10
High	0	0.5	3	10	15	20

We have developed three scenario options as shown in Table 6. The intermediate option was used as the reference scenario option.

2.6. Social scenario options

Because we are investigating the introduction of an emerging technology into society, variations in social situations of the region where the technology is to be implemented can affect the successfulness of SOFC introduction in each of the scenarios. In this study, overall power demand is considered as a representative social scenario option.

2.6.1. Overall power demand

The population and economic situation of a region are strongly interrelated with the use of energy. Taking into account the unique conditions of Japan, such as the recent economic stagnation, the composition of population and changes in lifestyle, a number of different future trends in power demand can be estimated.

In this study, we have estimated the growth of annual power demand over the focal period from the predicted future demographic trends [11] shown in Fig. 5 together with the low, intermediate and high level growth per capita assumptions i.e. 0, 0.7 and 1.4% annual growth per capita, respectively.

For each 10 year interval within the focal period, we developed power demand patterns for 7 representative days as described earlier (average weekday and weekend for summer, spring/fall and winter, and the day having maximum power demand in the year) based on simple extrapolation of measured data from the previous work [1].

2.7. Economic scenario options

Because we have assumed that power planning will be done primarily on an economic basis, economic scenario options could affect the results significantly. Although the fixed costs are assessed in the form of the initial investment and maintenance costs, estimated running costs will be affected by fuel cost projections.

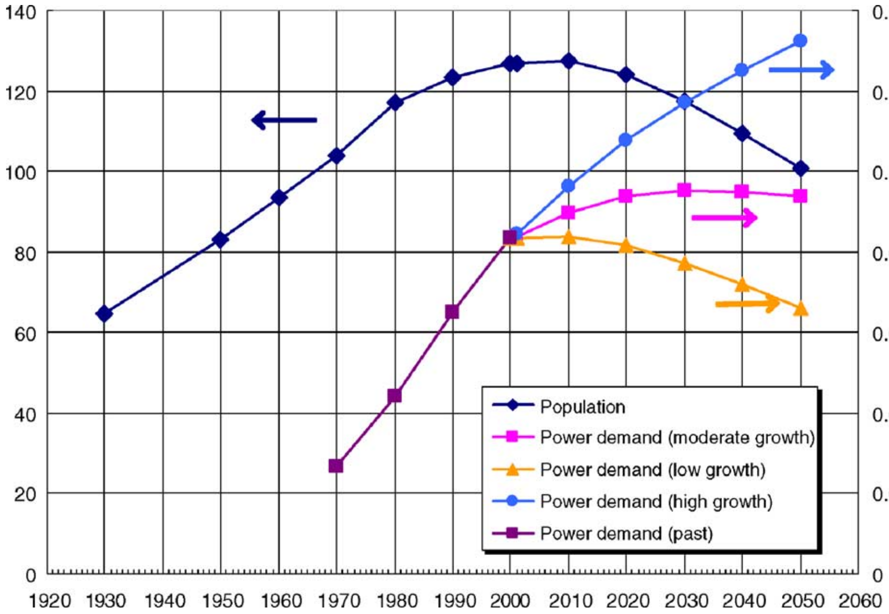

Fig. 5. Past and future trends of population and power demand in Japan (1920–2050) [11,12].

2.7.1. *Fuel cost projections*

The literature gives several different projections for fuel costs. We used the projection by Nagata et al. [3] shown in Fig. 6a as the reference, and we added the EU projection [13] shown in Fig. 6b as an alternative scenario option.

2.8. *Political scenario options*

One of the major objectives in this study is to elucidate the effectiveness of political options for accelerating the introduction of SOFCs. In this study, we focused on the La reserve policy and nuclear power policy.

2.9. *Advanced La reserve policy*

Currently, Japan maintains a strategic stockpile of La at the national level. In this study, we set the upper limits in La use for SOFC manufacture as described earlier. As a policy option, we assume that a national reserve of La specifically for SOFCs will be introduced, and furthermore that the La not consumed for SOFC manufacture in a given year will be stored for use in future years.

2.9.1. *Nuclear power policy*

According to Japanese ministry of economy, trade and industry (METI) plan, there will be 60 GW of nuclear power generation capacity (about 15 GW are under construction) in the year 2010. We used this plan as a basis for developing the scenarios that are shown in Table 7.

2.10. *Reference scenario*

In this section, we discuss the reference scenario as a basis for further scenario analyses. Fig. 7 and Table 8 show the

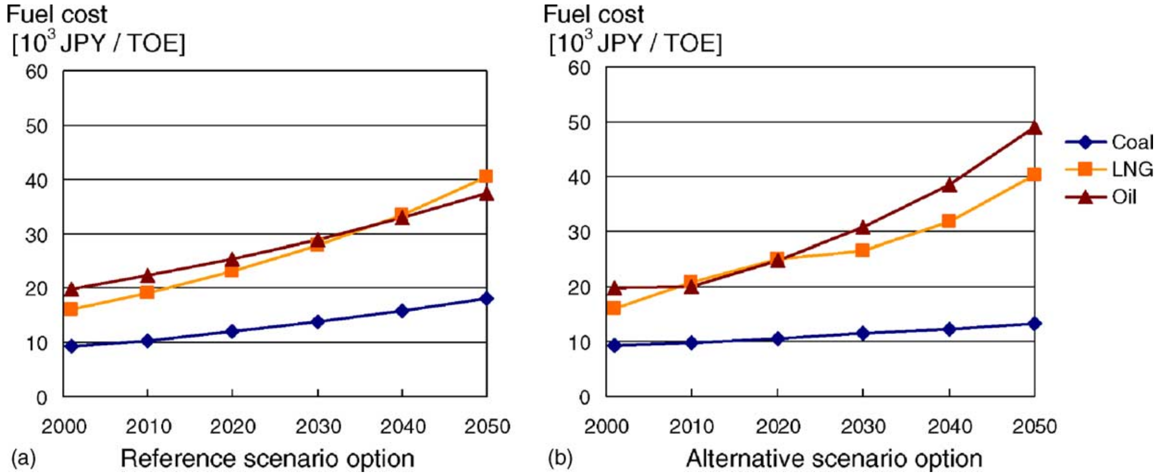

Fig. 6. Fuel cost projections (2001–2050) for Japanese society: (a) reference scenario option; (b) alternative scenario option.

Table 7
Scenario options for the nuclear power policy in Japan

	2001	2010	2020	2030	2040	2050	Notes
Low	45	60	70	70	60	50	Stop planning new power plants + close old power plants
Reference	45	60	70	70	70	70	Stop planning new power plants + maintain or renovate old power plants
High	45	60	70	80	80	80	Plan more new plants

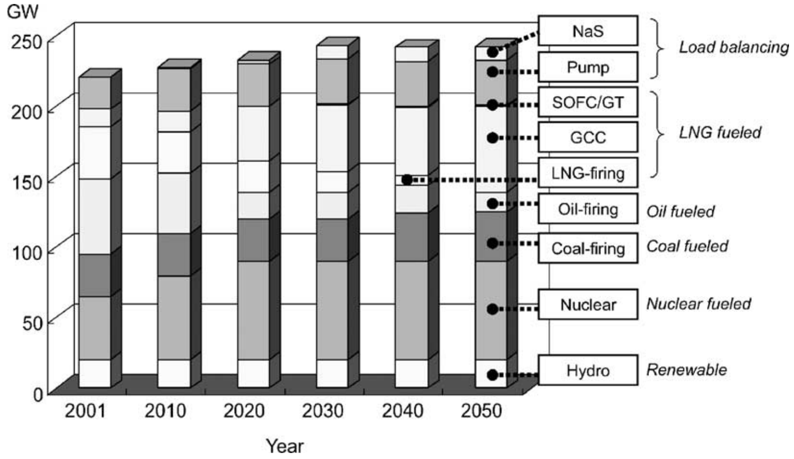

Fig. 7. Installed capacities of centralized power sources (reference scenario).

installed capacities of the SOFC/GT systems into Japanese centralized power system at each time period in the reference scenario. SOFC/GT systems do not appear in the centralized power system until 2030, and the total installed capacity only reaches around 1 GW by the year 2050. The scenario conditions regarding the dismantling of LNG-fired power plants result in the reduction of power generation capacity by 36.7 GW in 50 years. Furthermore, there is an overcapacity of oil-fired power plants in 2001; the installed capacity of oil-fired power plants is substantially reduced from 54 GW down to 14 GW in 2050. Consequently, other power sources must fill the demand. The role of peak load supply initially played by LNG is filled by coal-fired and GCC systems in the reference scenario. Because of the lower installation cost, coal-fired power plants are introduced preferentially to others, as long as the CO_2 emission constraints can be met. The remaining power supply requirement for peak load is filled by the less CO_2-intensive GCC systems.

From 2030, SOFC/GT begins to take a small role in the centralized power system to meet the base load. Although the substantial load following capacity of the SOFC/GT makes it ideal for meeting peak loads, the SOFC/GT appears as a base load power system because the investment cost is relatively high and therefore a higher capacity usage ratio is most favourable for this device. After 2040, SOFC/GT systems are produced and installed at the maximum rate that can be supported by the La usage limits. If the La limits are removed, SOFC/GT capacity could reach 51.6 GW. Manufacture of this capacity of SOFC/GT would require 14.4 times as much La as the scenario limit in 2050 for the same scenario conditions (i.e. no recycling, no breakthrough technology and no advanced La reserve policy).

Table 8
Installed capacity (in GW) of SOFC/GT (reference scenario)

2001	2010	2020	2030	2040	2050
0	0	0	0.67	0.67	0.99

From these analyses, we can confirm that La availability could be the bottleneck factor in the introduction of SOFCs.

Fig. 8 shows the breakdown of the fuel types that are consumed in the reference scenario. Even with the increase in capacity of GCCs, LNG consumption decreases because the GCCs are primarily used for peak loading and therefore the actual capacity usage ratio is low (12.8%).

Both total carbon emissions and the carbon intensity of power generation decrease over the 50 year focal period (Fig. 9). The results show that the carbon intensity constraint

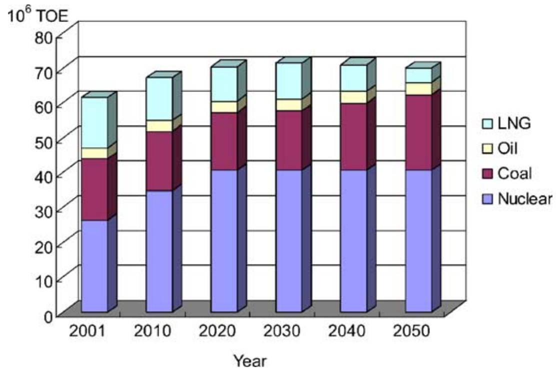

Fig. 8. Fuels consumed in centralized power sources (reference scenario).

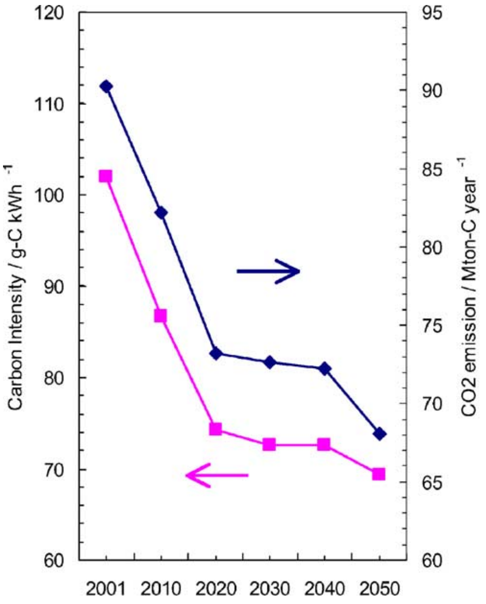

Fig. 9. Carbon intensity and CO_2 emission (reference scenario).

described in Section 2.2.3 did actually change the power mix. When the carbon intensity constraint is removed, the results showed increases in both carbon emissions and the carbon intensity in 2040, because the pump power is operated more for load balancing, allowing more coals and less GCC to be used. However, this change did not affect the introduction of SOFC/GT.

3. Results from scenario analysis

We have analyzed scenarios not only by focusing on the quantitative results or by establishing which single scenario is the most probable or optimal forecast, but also by studying how the different scenario options affect the overall system that is modeled in our study. Even though some of the uncertainties are high, we have been able to obtain useful information on how the aspects of the Japanese energy market system affect the introduction of new energy technologies such as SOFCs from the scenarios we have developed.

3.1. Analysis on SOFC relevant options

By examining the scenarios that have different SOFC relevant options, we have derived several suggestions for which directions of SOFC-related research and development could be most effective.

3.1.1. Significance of energy conversion efficiency of SOFCs in the introduction scenario

Improvement of energy conversion efficiency will reduce fuel use. On the one hand, fuel is relatively cheap compared with investment and thereby does not affect installed capacity in many cases. If not installed in a large scale, the efficiency improvement only affects the capacity of GCCs and coal-fired power plants in a very small scale (if any), because the differences of power generation is so small that it could be cancelled by decreasing the capacity usage ratio of coal-fired systems and GCCs.

However, on the other hand, fuel use is important from environmental perspectives such as CO_2 emissions. The scenarios showed that the efficiency of SOFC affects the CO_2 emission significantly when it is installed in a large scale.

3.1.2. Lifetime of SOFC module

The lifetime of SOFC module affects the introduction of SOFC in two ways; cost and frequency of module replacement. Extension of module lifetime reduces the total cost of providing the SOFC power generation capacity that is needed over the focal period. Reduction of cost directly increases the amount of SOFCs that will be installed, as shown in Table 9. The costs shown in Table 9 include tax, interest and depreciation. In the 40 year lifetime scenario, SOFC/GT is introduced earlier than in the other scenarios, due to the lower investment cost, which is at the level of 2040–2050 in 10 year lifetime (reference) scenario.

3.1.3. Difference in La intensity

Towards the end of the focal period, SOFC/GT becomes more economical than GCCs as LNG-fuelled devices. Therefore, if the La constraint is relaxed, a long-term strategy would aim for a larger SOFC/GT capacity in the later years of the focal period. We can see this behaviour in the

Table 9
SOFC/GT installation under the different cell lifetime scenario options (other options are reference settings)

			2010	2020	2030	2040	2050
10 years	Installed capacity	GW	0	0	0.67	0.67	0.99
	SOFC module cost (new)	JPY/10 years	575,677	460,542	368,433	294,747	235,797
	SOFC module cost (average)	JPY/10 years	–	–	368,433	294,747	235,797
20 years	Installed capacity	GW	0	0	2.25	3.64	4.40
	SOFC module cost (new)	JPY/10 years	395,050	316,040	252,832	202,266	161,813
	SOFC module cost (average)	JPY/10 years	–	–	252,832	234,013	174,372
40 years	Installed capacity	GW	0	0.79	3.04	5.80	9.69
	SOFC module cost (new)	JPY/10 years	308,920	247,136	197,709	158,167	126,534
	SOFC module cost (average)	JPY/10 years	–	247,136	210,791	186,323	163,134

Table 10
Oil, GCC and SOFC/GT installation (in GW) under the breakthrough and moderate improvement scenario options in La intensity (other options are reference settings)

		2001	2010	2020	2030	2040	2050
Oil	Breakthrough	53.97	43.00	25.09	21.78	15.57	15.57
	Moderate	53.97	43.00	19.41	19.41	19.41	13.94
GCC	Breakthrough	12.51	14.88	32.97	32.97	32.97	40.57
	Moderate	12.51	14.88	38.66	46.98	48.23	60.94
SOFC/GT	Breakthrough	0	0	0	12.30	24.40	24.40
	Moderate	0	0	0	0.67	0.67	0.99

comparison of installed capacities of GCCs and oil-fired power plants from 2010 to 2020 in Table 10. With the SOFC technology breakthrough, the GCC capacity does not increase much after 2010. Instead, more of the oil-fired power plant capacity is kept on line in order to meet the power supply requirements until the SOFC/GT systems become available. These results indicate that if the breakthrough could be foreseen, the long-term cost could be reduced by avoiding construction of GCC facilities, which would otherwise result in a future excess of power generation capacity and thereby increase costs in the long term.

The La limit constrains the introduction rate of SOFC/GT after 2040, even with the breakthrough scenario option.

3.1.4. Comparison and synergy of recycling and advanced La reserve policy

Both SOFC recycling and an advanced La reserve policy could alleviate La supply limitations. However, if applied independently, these two scenario options affect the strategies for introduction of SOFC/GT differently. Recycling makes it possible to use La again in the next generation of SOFC modules. Therefore, SOFC should be introduced in the centralized power system early and continually remanufactured as the La becomes available through recycling. On the other hand, an advanced La reserve policy makes it possible to store La until SOFC becomes cheaper to introduce. The strategy then would be to save La until the cost for SOFC manufacture is sufficiently low, and then to use the La with higher intensity to produce a large quantity of SOFCs at once.

The different strategies described above are reflected in the results shown in Table 11. In the reference scenario, SOFC/GT is introduced at a small scale in 2030. Under the advanced La reserve policy, SOFC/GT is not introduced until 2050. With the implementation of a recycling system, the strategy is to secure as much La as possible in 2050; therefore, SOFC/GT is introduced as early as 2020, even if the average efficiency of the GT is lower than it would be in 2050, which means more SOFC modules are needed for a same capacity of SOFC/GT. Although the overall amount of secured La is greater with the advanced La reserve policy than with the recycling system by definition, the installed capacity in 2050 is greater with the recycling system. The reason for this is that because the installation of SOFC/GT is postponed under the advanced La reserve policy, the capacity of other power sources are increased to fill the power generation capacity gap opened by the phasing out of LNG-fired power plants in 2010–2040. Consequently, the demand for SOFC/GT power generation capacity in 2050 is smaller.

Table 11
SOFC/GT installation (in GW) in reference, advanced La reserve policy, recycling and combined scenario options (other options are reference settings)

	2001	2010	2020	2030	2040	2050
Reference	0	0	0	0.67	0.67	0.99
Advanced La reserve policy	0	0	0	0	0	6.04
Recycling	0	0	0.79	3.21	6.42	11.20
Both	0	0	0	4.77	8.11	13.05

As seen in Table 11, the combination of both policies results in a synergistic effect on the introduction of SOFC/GT. The advanced La reserve policy causes introduction of SOFC/GT to be postponed until 2030, when La can be used more efficiently (decreased kg of La per kW capacity). The recycling system encourages an earlier introduction of SOFC/GT than the advanced La reserve policy alone, so that the total installed capacity in 2050 is increased. Under this scenario, after 2030, the entire La reserve is used for SOFC/GT manufacture.

3.2. Analysis of overall energy systems

By looking at different scenarios that have varying options for the overall energy systems, SOFC researchers and developers can obtain how important knowledge on how surrounding situations can affect the potential of their technologies.

3.2.1. Nuclear power policy

SOFC/GT introduction rates in low, reference and high nuclear power introduction scenarios are shown in Table 12. Higher introduction of nuclear power plants will tend to reduce the overall power generation cost, due to the lower fuel costs of nuclear power.

In the reference scenario, SOFC/GT is introduced from 2030, while in both the high and low nuclear power introduction scenarios SOFC/GT is not introduced until 2040. The delay in SOFC/GT introduction is the cause for the

Table 12
SOFC/GT installation (in GW) in low, intermediate and high nuclear power policy options (other options are reference settings)

	2001	2010	2020	2030	2040	2050	Cost (10^{14} JPY per 50 years)
Low nuclear	0	0	0	0	0.69	1.01	4.88
Reference	0	0	0	0.67	0.67	0.99	4.80
High nuclear	0	0	0	0	0.69	1.01	4.77

difference in the installed capacity at 2050. Because the lifetime of the SOFC module is 10 years in the reference scenario, in every scenario all of the SOFC modules are replaced in 2050. However, the overall energy conversion efficiency of SOFC/GT in 2050 differs due to the difference in the average efficiency of the gas turbines whose lifetime is 40 years. Even though the amount of La used in SOFC/GT systems is the same in all scenarios in 2040 and 2050, in the reference scenario gas turbines with lower energy conversion efficiencies that were installed in 2030 will still be used in 2050.

In the low nuclear power introduction scenario, other power sources need to fill an additional 20 GW of power generation capacity in 2050 (see Table 7). Because nuclear power is used to supply the base load, coal and oil-fired plants are best suited to fill the capacity gap. For that reason, the steep increase of GCC capacity installation that occurred in the reference scenario from 2000 to 2010 is no longer required because the excess capacity in the future is no longer needed.

On the contrary, in the high nuclear introduction scenarios, 10 GW of the GCC and coal capacity forecasted in the reference scenario after 2030 is met by nuclear, so the capacity of GCC and coal decreases after 2030.

3.2.2. Variations in overall energy demand

For the high demand scenarios, SOFC/GT and GCC systems are used to fulfil the power demand. SOFC/GT is installed up to the La limits, and the rest of the capacity is filled with GCCs and coal-fired power plants. Oil-fired power plants are used at the minimum level throughout the focal period, even in the high demand scenario.

On the contrary, in the low power demand scenarios, construction of new facilities tends to be avoided. Oil-fired power plants are used more extensively in such scenarios than in the reference scenario, because they are a flexible power source that can be used both for base and peak loads.

3.2.3. Variation due to the different fuel cost projections

According to the projection by the EU commission, LNG is predicted to be relatively higher priced than other fuels compared to the reference projection. However, the two different projections did not make any difference in the installed capacity of SOFC/GT. The differences in fuel prices only affected the distribution of capacity installation between oil- and coal-fired power plants and GCCs. When the EU commission projection was used in the reference scenario, coal was substituted for GCC from 2020 to 2040, and coal and oil together were substituted for GCC in 2050.

3.2.4. Variation due to different forecasts for installation of NaS battery

Changing the capacity of the NaS battery system affects the shape of the demand profile for other power sources in the centralized power system. The reference, high, and low NaS battery introduction scenarios showed that variations in the installed capacity of NaS battery affect the installed capacities of GCC, oil-fired and coal-fired power plants; however, they do not affect SOFC/GT (Table 13). La availability remains the main limiting factor on the introduction of SOFC/GT in all three scenarios.

NaS battery is operated at the maximum level in all three scenarios when installed, due to its high efficiency and high investment cost. However, changes in the load balancing capability as a whole system is reduced, because a decrease in pump power cancels the load balancing effect of the NaS battery system, as seen in Table 14. When more (or less) NaS is introduced and thereby used, less (or more) pump being used.

3.3. Cornerstone scenarios

In many of the low overall power demand scenarios, SOFC/GT did not penetrate into the centralized power

Table 13
Differences in installed capacities (in GW) with reference scenario caused by changing installed capacity of NaS battery

NaS introduction		2001	2010	2020	2030	2040	2050
High	GCC	0	0	0	0	−0.22	0.95
	Oil	0	0	0	0	0	−0.89
	Coal	0	0	0	0	0.22	−0.09
	NaS	0	0	0	0	5	10
Low	GCC	0	0	−0.09	−0.09	−0.39	−1.52
	Oil	0	0	0.09	0.09	0.09	1.12
	Coal	0	0	0	0	0.31	0.47
	NaS	0	0	−1	−5	−5	−5

Table 14
Differences in power generation (in GWh per year) with reference scenario caused by changing installed capacity of NaS battery

NaS introduction		2001	2010	2020	2030	2040	2050
High	Pump	0	0	0	0	−4632.8	−8976.0
	GCC	0	0	0	0	−2946.1	−1245.1
	Oil	0	0	0	0	0	0
	Coal	0	0	0	0	1590.4	−1407.3
	NaS	0	0	0	0	6532.0	10749.8
Low	Pump	0	0	632.8	6126.3	6192.1	6469.4
	GCC	0	0	1906.9	1865.0	1391.3	672.1
	Oil	0	0	0	0	0	0
	Coal	0	0	−1831.6	−34.7	295.6	1040.7
	NaS	0	0	−2127.8	−8081.2	−8895.2	−9538.2

Table 15
Installed capacities (in GW) of SOFC/GT systems in highest cornerstone scenarios

Lifetime of SOFC module	Advanced La reserve policy	2001	2010	2020	2030	2040	2050
10 years	Introduced	0	0	0	41.8	78.4	111.3
	Not introduced	0	0	1.3	26.0	52.9	81.4
20 years	Introduced	0	0	0	56.7	83.4	112.1
	Not introduced	0	1.2	16.6	53.2	80.1	108.9
40 years	Introduced	0	0	0	56.6	83.5	112.1
	Not introduced	0	1.2	19.3	44.0	70.9	112.5

generation system at all. The reference scenario is among the lowest cornerstone scenarios, with only 1 GW of SOFC/GT introduction in 2050.

The highest cornerstone scenarios for 10, 20 and 40 year SOFC module lifetime scenario options are presented in Table 15. The effects of the advanced La reserve policy can be seen here again; the ability to stockpile La leads to the strategy of installing more SOFCs in later years when the investment cost is lower and the energy conversion and La use efficiency is higher. For any of the lifetime scenario options for SOFC modules, implementation of the advanced La reserve policy brings the installed capacity in 2050 to over 110 GW. For the 10 and 20 year lifetime scenario options, the advanced La reserve policy does result in an increase in the installed capacity in 2050 through synergies with recycling and technology breakthrough in La use, as described in Section 3.1.4. However, with the 40 year lifetime scenario option, the policy is less effective. This is because as the lifetime gets longer, the annualized investment cost is lower, and therefore the SOFC/GT can be introduced earlier. When the SOFC/GT is introduced earlier, recycling has a similar effect as a reserve policy.

4. Conclusions

We have developed scenarios of SOFC introduction into Japanese society. Our ‘reference’ scenario does not represent a single forecast of SOFC introduction; rather it is used as a baseline to measure the effectiveness of all of the other scenarios. The scenarios show that the limitations in La supply could be a possible bottleneck for successful introduction of SOFCs in most of the cases. Our analysis of the scenarios also shows the synergistic and competitive interrelations between the different scenario options. The scenario that includes a technology breakthrough in La intensity, La recycling, became the upper cornerstone scenario with a total SOFC/GT capacity introduction of 112 GW in 2050. In the scenarios with 10 and 20 year module lifetimes, implementation of the advanced La reserve policy increased the installation capacity of SOFC/GT by 30 and 3 GW, respectively. Differences in fuel cost projections, efficiencies of SOFCs, and installed capacities of NaS battery did not have significant effects on the introduction of SOFCs into society.

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