**Title: Evaluation of Cost Reduction Potential for 1kW Class SOFC stack production:
Implications for SOFC Technology Scenario**

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Abstract

Recently, a commercial version of a residential solid oxide fuel cell (SOFC) system with a flat tubular cell has been developed. However, the system cost still remains very high, which is a barrier to its widespread use. In this study, the potential for cost reductions in SOFC stack production was investigated in order to contribute to the viability of the widespread use of such residential SOFC systems in future. A cost analysis of 700 W SOFC stack production based on a process integration modeling was conducted. The present bottom-up approach enabled us to perform a sensitivity analysis with a variety of parameters in terms of cell design, the production process and cell performance. This allowed us to investigate the effects of these factors on the production cost, thereby revealing the quantitative impact of each technological improvement on the cost reduction potential. The present analysis also revealed innovation pathways which could result in technology scenarios where residential SOFC systems could reach a break-even point in comparison with the baseload electricity cost. The analysis of the cost reduction potential presented here provides a useful viewpoint for developing a research strategy for state-of-the-art SOFC technology.

Keywords: solid oxide fuel cell; cost analysis; process integration modeling; cell design.

Main text

1. Introduction

Solid oxide fuel cells (SOFCs) are expected to be the key technology of decentralized power generation systems because of their high electrical energy conversion efficiencies and their ability to generate relatively high grade heat, which is then available for combined heat and power (CHP) systems. In fact, a recent 1 kW class SOFC system developed as a commercial product has achieved an electrical efficiency (LHV) of 45% [1]. A residential SOFC is generally used as a CHP system. Recently, in 2011, a 700 W residential SOFC system was released in Japan, and heralds the dawn of widespread use of SOFCs. Although the performance and reliability of SOFC operations have been improved steadily, further cost reduction is required to develop economically acceptable SOFC systems [2]. The current system cost of a 700 W residential SOFC, including stack, auxiliaries and hot water supply, is ca. 3,900,000 JPY/kW [3] (i.e., 39,000 US\$/kW: currency exchange rates is supposed that 1 US\$ = 100 JPY hereafter), which is still very high. To realize significant cost reductions, an evaluation leading to a new perspective on cost effective manufacturing of SOFC will be indispensable. In particular, the investigation of the production processes for a SOFC stack is a major challenge and its quantitative evaluation will help the commercial success of SOFC systems and improve the likelihood of their widespread use in future.

In this study, the production cost of a SOFC stack for residential use was investigated in detail. The cost prediction model is based on materials and process details, and can be expected to assist in the determination of the technology improvement pathways required to reach baseload electricity cost. In previous work [4-9], the cost and economic and environmental analyses, such as life cycle assessment and exergy analysis, have been performed in terms of the production of single cells and stack performance on stationary use. Even using these evaluation methods, the estimation and prediction of cost and economic

performance of SOFCs still have a problem of accuracy due to the relatively low resolution of the process integration. As for SOFC stack production itself, potential cost reductions based on technological developments has not been investigated. Taking up the challenge, we here have attempted to provide cost estimates based on process integration modeling, i.e., a bottom-up approach using detailed equipment. To our knowledge, such detailed process integration modeling for SOFC production has not been reported.

The framework of the method used here is shown in [Fig.1](#). The process integration modeling consists of two layers; the first layer utilizes basic knowledge of SOFC properties such as material properties, microstructure, cell design and power generation performance, and the second employs knowledge of SOFC stack production. This knowledge structure provides a flexible framework to evaluate the cost reduction potential for SOFC stack production with a variety of relevant parameters. Therefore, the advantages of the present method are not only the improved accuracy but also its ability to pinpoint the viability of the cost reduction potential in terms of technology improvements in SOFC performance and the production process. In that sense, a sensitivity analysis of the production cost was performed. Since the present cost prediction model is based on detailed equipment data, it can support variations of method and scale for manufacturers to estimate equipment-based capital investment. In addition, the sensitivity of power generation cost to SOFC performance requirements, such as power generation efficiency was also examined, which can expect to provide a useful perspective on the possibility of widespread use of residential SOFC systems in future, i.e., it provides a technology scenario for SOFC systems.

Thus, the specific aim of this work is the integration of manufacturing process capabilities and stack performance requirements into a cost prediction model in order to evaluate the cost viability of 700W residential SOFC stack and system. This paper consists of three parts; the first section is brief explanation of the process integration modeling, the

second section provides a sensitivity analysis for SOFC stack production, and final section will discuss innovation pathways to guide the widespread use of residential SOFC systems.

2. Evaluation method

2.1. Scope and procedure of the process integration modeling

Our process integration modeling evaluates SOFC stack production in terms of cost analysis. Through the analysis of the cost structure, this model provides pointers for large cost reduction potentials by technological improvements in SOFC stack production and their performance. This model is constructed in the following manner.

1. Defining the SOFC system selection and the production rate of SOFC stacks.
2. Quantifying raw materials requirement.
3. Setting up detailed SOFC production processes with the relevant capacities.
4. Estimating cost and weight of detailed production equipment.
5. Quantifying the requirements of utilities and labor.
6. Assessment of production cost.
7. Economic assessment with different options in terms of stack performance, cell dimension/design, material utilization and production technology.

2.2. Selection of cell types and boundary for SOFC stack production

This study focused on a flat tubular type SOFC as a standard case, as is used in a 700 W residential SOFC system released recently in Japan. In addition, a micro-tubular type SOFC was also evaluated as an advanced cell design [10-13]. The latter has the advantage in robustness in resisting thermal stress besides reducing the amount of material needed. The typical geometry and the component materials of a single cell of a flat tubular type are summarized in Table 1a. Additionally, the base properties, such as the operating conditions for

a flat tubular type cell are described in Table 1b. Schematic drawings of the single cells are also shown in Fig. 2. More detailed information of the cell and stack dimensions is found in our previous study [10]. The manufacturing process flow diagram of a flat tubular SOFC stack is shown in Fig. 3. The analysis covers the full range of processes involved in stack production, from granulation of the component powders to producing the casing, assuming sintering of the anode support and subsequent screen printing and sintering of electrode, electrolyte, interlayer and interconnect. The impact of the sintering pattern, such as individual sintering and co-firing of the components, on the production cost was also discussed in terms of improvements in the production technology.

2.3. Setting up detailed SOFC production processes

The individual manufacturing process steps for production of a SOFC stack are listed in Table 2. The processes were structured according to the previous studies [6-8]. They consist of three parts, i.e., granulation of the component powders, then fabrication of the layered structure of a single cell by screen printing and sintering, and, finally, the assembling of the stack.

To evaluate the production processes, the cost, weight and energy consumption of individual pieces of equipment i , i.e., $C_i(x_i)$, $W_i(x_i)$ and $E_i(x_i)$, were taken from an equipment cost database [14] and specifications in the catalogs of the equipment suppliers. Here, x_i is a specific index of a required capacity for an individual item of equipment i , such as rates of material feed, drying, sintering and other fabrication processes. The values of x_i were determined by the required production rate of SOFC stacks. To calculate the required number of a particular type of equipment i , X_i was defined as the total required capacity for the process performed by equipment i . Then, the numbers of pieces of that type of equipment was calculated using its maximum capacity, $x_{i,max}$. So, if $X_i > x_{i,max}$, the number of items of

equipment i , n_i , was calculated from $X_i = n_i x_i$. In addition, if $x_i < x_{i,\min}$, then, $C_i(x_i) = C_i(x_{i,\min})$, $W_i(x_i) = W_i(x_{i,\min})$ and $E_i(x_i) = E_i(x_{i,\min})$, where $x_{i,\min}$ is the minimum capacity for each type of equipment. Assuming that the energy consumption of a piece of equipment has a linear relation with the production scale, $E_i(x_i)$ consists of the standard energy consumption of equipment, $U(x_i)$ and a coefficient, m_i for the throughput capacity, i.e., $E_i(x_i) = m_i U(x_i)$. Total number of equipment items is ca. 670 in the standard case of flat tubular SOFC stack production (production rate: 1 M stack/y). For example, the costs of the major equipment items - furnace, extruder and screen printer - are summarized in [Table 3](#). The details of the cost structure in each process will be discussed later.

2.4. Technological improvements in SOFC production process and their effects on cost reduction

The impact of technological improvements on the cost reduction potential was investigated in terms of the manufacturing process, cell design and cell and material performance.

A. Technological improvement of SOFC stack production:

A.1. For the granulation process, two methods were examined: a dry process: solid state synthesis and a wet process: polymerized complex (PC) method (so-gel method). The PC method is chosen as the standard method in this study. Though the PC method needs additional raw materials and requires more processing steps, finer, more uniform particles can be obtained.

A.2. The effect of co-firing: several sintering patterns were also examined to conduct the sensitivity analysis for production cost: individual sintering (process No. P7, P8, P9, P10, P11, P12) and co-firings, pattern (a): P7-P10, P11, P12 (i.e., co-firing anode support (P7), anode (P8), electrolyte (P9) and interlayer (P10), and then firing cathode (P11) and interconnect

(P12) individually); pattern (b): P7-P12 (co-firing the whole processes). Considering a realistic process, the co-firing involved in pattern (b) is very difficult. However, we examined pattern (b) as an extreme case to investigate the impact of co-firing on cost reduction. For A.1 and A.2, 100% of material utilization is supposed as the ideal case.

A.3. A sensitivity analysis of material utilization was also conducted.

B. Cell design development:

B.1. The influence of reducing the thickness of a flat tubular type of cell on reducing the raw material cost was examined.

B.2. A design change from flat tubular to micro-tubular type was examined. Screen printing was employed for making the layers of a flat-tubular type, while dip coating was employed for the layers of a micro-tubular type.

C. Cell and stack performance improvements:

C.1. Power density is also influenced by a reduction in stack size. A sensitivity analysis of power density on cost reduction potential was investigated.

C.2. The impact of the insulator's property, i.e., thermal conductivity on the cost was also examined.

2.5. Other key assumptions

The basic assumptions used in the evaluations were the following.

A. The total cost of SOFC stack production integrated the raw materials cost, capital cost including equipment, off-site facilities and buildings, input energy for the production (i.e., utility cost) and labor. The details are shown in [Table 4](#). For assembling processes, industrial robots were employed for all the processes. Although the utilization of industrial robots for assembling processes such as cell-stacking is still under development, we supposed it for both of flat tubular and micro-tubular types in this study. Difference in production processes

between flat tubular type and micro-tubular type of cells was also taken into account (e.g., screen printing and dip coating), as already mentioned above.

B. The lifetime of an SOFC stack is assumed to be 10 or 15 years. According to the previous report [1], the degradation rate for energy conversion efficiency is estimated to be ca. 1%/year, and currently it will be improved further. Based on the data, we determined the value of life time assuming the limitation of 10% decrease of net energy conversion efficiency for the initial performance under the operating rate of 0.8.

C. The power generation cost, C_{power} (JPY/kWh), was estimated by the following formulation.

$$C_{\text{power}} = C_{\text{system}} + C_{\text{fuel}} \quad (1)$$

where C_{system} and C_{fuel} are the SOFC system cost and fuel cost, respectively. The SOFC system includes auxiliaries such as a heat exchanger, power converter, air blower, gas burner and hot water tank. Since the auxiliaries are relatively standard production items, a less detailed analysis was conducted for them. C_{system} is calculated as the SOFC system cost / total electricity generated. The function unit is 1 kWh of electricity generated by the SOFC system, but waste heat recovery was also considered in estimating power generation. Fuel cost is estimated in the following manner.

$$C_{\text{fuel}} = \frac{UC_{\text{LNG}}}{\frac{1}{100} \left(\eta_{\text{elec}} + \frac{1}{3} \eta_{\text{heat}} \right)} \quad (2)$$

where UC_{LNG} is the unit cost of liquid natural gas (LNG), $\eta_{\text{el,stack}}$ and η_{heat} are the power generation efficiency (net AC efficiency of the system) and waste heat recovery efficiency, respectively. Cell efficiency and power generation efficiency are expressed as follows.

Cell efficiency (DC):
$$\eta_{\text{cell}} = \frac{P_{\text{cell}}}{\Delta H_{\text{fuel}}} \quad (3)$$

Power generation efficiency:
$$\eta_{\text{elec,stack}} = \frac{P_{\text{stack}} - P_{\text{loss}}}{n \cdot \Delta H_{\text{fuel}}} \quad (4)$$

where ΔH_{fuel} is the enthalpy of combustion per unit time for the supplied fuel in a cell, n is the

number of cells per stack, P_{cell} (= cell current $\times$ cell voltage) is cell power, P_{stack} is stack power, and P_{loss} is the power loss due to dc-ac conversion and the operation of auxiliaries.

3. Results and discussion

3.1. Production cost of SOFC stack for a standard flat tubular type

The production cost of a flat tubular type SOFC stack was estimated for an annual production rate of 1 M stack/year as a standard case, as shown in Table 5. This is an ideal case since a material utilization of 100% is supposed. In this case, the production cost is ca. 37,000 JPY (370 US\$), i.e., 53 JPY/W (0.53 US\$/W). Considering the high value of present SOFC system cost (see the text in introduction), the obtained stack production cost suggests that a flat tubular type of cell has sufficient cost reduction potential. In the standard case, the raw material cost is a high proportion of the production cost. The details of raw materials weight and cost for the standard case are summarized in Table 6. The equipment cost structure in each process is also shown in Fig.4. In this study, the equipment items are categorized by storage/reaction, material transfer, heat control, separation, milling, extrusion, printing, drying/sintering, molding/cutting, assembling, transport and others (total number of the equipment items in Fig.4: 668). It is found that the contribution of furnaces to the cost is very high.

3.2. Sensitivity analysis of the cost structure for SOFC stack production

Production process improvement: Fig.5 shows the effect of scale on the cost structure for annual production rates (stack/y) of 0.1 M, 1 M, and also 10 M as an extreme case. At these supposed production scales, the raw material cost is dominant in the cost structures, suggesting that improvements related to the reduction in the cost of raw materials will be effective at overall cost reduction. In fact, the sensitivity analysis demonstrates that raw

material utilization has a large effect on the cost reduction (Fig. 6a). The influence of a cost reduction for the main raw materials such as ZrO_2 and Ni was investigated, and is shown in Fig. 6b. The impacts of a cost reduction ratio from 1 to 0.5 on SOFC stack production cost are around 6% for both of ZrO_2 and Ni. Figure 6c shows that the impact of a process change in granulation on SOFC stack production cost is 5%, and those of sintering pattern changes are 2% (pattern (a)) and 3% (pattern (b)), respectively for annual production rates of 1 M stack/y (Fig. 6d). Therefore, the impacts of process improvements involving granulation process (dry and wet syntheses) and co-firing on cost reduction are not so significant in the large production scale of 1 M stack/y.

Cell design evolution: As shown in Fig. 7, making the flat tubular type of cell thinner by reducing the anode support thickness from 2 mm to 1 mm as the minimum value, is effective in reducing the cost (53 JPY/W $\rightarrow$ 41 JPY/W, i.e., 0.53 US\$/W $\rightarrow$ 0.41 US\$/W). Moreover, a design change from a flat tubular type to micro-tubular type of cell produces a more effective cost reduction (53 JPY/W $\rightarrow$ 30 JPY/W, i.e., 0.53 US\$/W $\rightarrow$ 0.30 US\$/W) (Fig. 7). Here, it should be noted that the influence of the thickness reduction on pressure drop in gas flow channels is negligible, i.e., a rough estimation by the Hagen-Poiseuille equation suggests that the pressure drop, Δp , is very small for the present cell dimensions ($\Delta p < 0.2\%$). Therefore, under the supposed conditions, the reduction of support thickness may not be limited by pressure drop. The similar result was obtained for a micro-tubular type. Since the cell design change relates directly to reducing the amounts of raw materials, it can contribute effectively to the cost reduction. Cell design development thus provides a reliable pathway for innovation and has large cost reduction potential.

Cell and stack performance improvements: Table 1b has already revealed a standard value of 0.25 W/cm^2 was used for the current density. The influence of a current density change from 0.25 to 0.50 A/cm^2 at a constant cell voltage of 0.76 V to cost reduction of a 700 W stack, i.e.,

reducing the stack volume while fixing the power generation efficiency, is shown in [Fig. 8a](#). The values taken are based on our previous discussion of the effects of the anode, cathode and electrolyte properties on power density [\[10\]](#). We also assume that the material costs are the same as those of the standard materials to simplify the preconditions. The result suggests that the cost is potentially reduced by 23% with an increase in power density from 0.19 to 0.38 W/cm²: Even if the power density becomes double, the sizes of components such as insulator, stack case, manifold and single cell length etc., do not become half. Therefore, the cost reduction was limited such as the relatively small value of 23%. On the other hand, the influence of a cell voltage change from 0.76 to 0.88 V at a constant current density of 0.25 A/cm² on cost reduction of a 700 W stack, i.e., improving cell efficiency while fixing the current density, is shown in [Fig. 8b](#). The relationship between cell voltage and current density was obtained according to the *IV* curve calculated in our previous study [\[10\]](#). An increase in the cell voltage contributes to reduce the cost slightly, i.e., potentially by 6%, but it can affect the reduction of electricity cost directly, which will be discussed later. Though the effects of improving anode, cathode and electrolyte properties are potentially large, other problems such as durability and chemical stability need to be overcome [\[10\]](#).

In addition, the effect of a decrease in the insulator thickness, which is equivalent to a reduction of the thermal conductivity of the insulator, on the cost was examined. The value of 0.2 W/m K was employed as standard in this study. Considering the current state of insulator development, the value of the thermal conductivity was assumed to range between 0.2 and 0.04 W/m K. The present cost of a new insulator board of 0.04 W/m K (per unit weight) may be 3-4 times higher than that of the standard case, i.e., mullite, in [Table 6](#). Nevertheless, taking into account the future cost reduction, we supposed that the cost of the new insulator board was the same as that of the standard case in this study, because the material component is mostly the same as the standard case. By reducing of thermal conductivity by a factor of 1/5,

the cost is reduced by 24% (Fig. 9). Since the cost of an insulator is relatively high in a residential SOFC stack, the cost reduction achieved by reducing the insulator thickness is significant and is a promising approach.

Relationship of power generation efficiency improvement and electricity cost: To view the competitiveness of a residential SOFC CHP system, we examined the impact of power generation efficiency on electricity cost with changing SOFC system cost using Eqs. 1 and 2. The SOFC system cost includes stack, auxiliaries and a hot water tank. In Fig. 10, electricity cost vs. power generation efficiency, i.e., a Pareto-front like plot, is shown, supposing a typical LNG price for home use in Japan: 130 JPY/Nm³ (case A) and a lower price case: 100 JPY/Nm³ (case B). The results indicate that electricity cost can reach the break-even point of the baseload electricity cost, 23 JPY/kWh, for residential use. For example, in case A, if power generation efficiency > 50% and system cost < 500 JPY/W (i.e., 5 US\$/W), the electricity cost reaches the baseload cost. Alternatively, if a further cost reduction to < 400 JPY/W (i.e., 4 US\$/W) is achieved, a required improvement of power generation efficiency > 48% produces a baseload cost. In case B, the electricity cost fully reaches the break-even point if the power generation efficiency > 50% and the system cost < 700 JPY/W (i.e., 7 US\$/W). Considering the rate of advances in-SOFC technology, these requirements of cost and performance will almost certainly be fully achieved in future. Next, we will discuss an innovation pathway to achieve the required cost and performance.

3.3. Cost structure change based on an innovation pathway with an advanced technology concept

Finally, we discuss a technology scenario to reduce the cost for widespread use of a residential SOFC system in future. The innovations treated in the technology scenario also suggest research targets for SOFC development. According to the sensitivity analysis, several

key assumptions were selected, such as production scale, material utilization, cell design, power generation efficiency, and insulator-thickness reduction (thereby improving the thermal conductivity) to estimate possible cost structure changes for SOFC stack production (Table 7). Based on the key assumptions, a cost reduction impact for the innovation pathway is shown in Fig. 11. Considering other aspects of the current status of materials development, such as stability and durability, the analysis suggests that cell design development is an effective and reliable approach for the cost reduction.

Finally, power generation cost, i.e., the electricity cost was estimated for a 700W SOFC system. The cost of balance of system (BOS), i.e., the total cost of auxiliaries and hot water tank were determined according to the cost analysis reported by NEDO in Japan [15], i.e., BOS cost: 300,000 JPY (i.e., 3,000 US\$) in 2020 year and 200,000 JPY (i.e., 2,000 US\$) in 2030 year. More specially, the BOS cost was estimated from the material weight (MW), unit cost of raw material (UC) and factor (α) supposed by the relevant manufacturing process, i.e., $\text{cost} = \text{MW} \times \text{UC} \times \alpha$. The factors were determined according to reference data supplied by NEDO [15].

The cost change to a 700W SOFC system for this the innovation pathway is plotted in Fig. 12. By improving the power generation efficiency and reducing the SOFC system cost appropriately, the power generation cost can reach a break-even point in comparison with baseload electricity cost for home use, 23 JPY/kWh. The cell design change is very effective in reducing the production cost because of reductions in raw materials costs, and improving the power generation efficiency also contributes to a reduction in fuel cost. Achieving a power generation efficiency $> 50\%$ and reducing the system cost to < 500 JPY/W (i.e., 5 US\$/W) with a system lifetime > 10 year is necessary to reach the break-even point. Although developments in both system performance and cost reduction are indispensable to realize the widespread use of SOFC systems, the present analysis shows that such an approach is viable.

Conclusions

A cost analysis of SOFC stack production was conducted based on process integration modeling. The proposed method is very effective for evaluating the cost reduction potential of technology innovations on SOFC stack production. For the base case of 700 W SOFC stack production with a flat tubular cell, the production cost was obtained as 53 JPY/W (i.e., 0.53 US\$/W) for a production scale of 1M stack/year, suggesting that the current flat tubular type has sufficient cost reduction potential. The sensitivity analysis presented here showed the cost impact in terms of cell design, production process and cell performance. The results suggest that a cell design change is very effective in reducing the production cost: a micro-tubular cell can reduce raw materials cost significantly, resulting that a production cost was 30 JPY/W for a production scale of 1M stack/year. The present method can suggest an innovation pathway to reach a break-even point in comparison with baseload electricity cost. The present analysis revealed that achieving a power generation efficiency $> 55\%$ and reducing the system cost to < 500 JPY/W (i.e., 5 US\$/W) with a system lifetime > 10 year was necessary to reach the break-even point. This work thus provides a technological development framework based on market impact and can guide research targets for SOFC systems. We hope that this work may promote the widespread use of SOFCs in future.

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Figure captions

Fig. 1. Framework of process integration modeling for SOFC stack production.

Fig. 2. Schematic drawings of flat tubular type and micro-tubular type of cells.

Fig. 3. Manufacturing process flow diagram of a flat tubular type of SOFC stack. The boundary evaluated in this study is presented by a broken line.

Fig. 4. Equipment cost structure for SOFC stack production in the standard case (see Table 1) for an annual production rate of 1 M stack/y with supporting material utilization of 100% (ideal case).

Fig. 5. Dependence of production scale on the cost structure for annual production rates of 0.1 M, 1 M and 10 M stack/y with a flat tubular type of cell. Material utilization of 100% is supposed as an ideal case.

Fig. 6. Impacts of material utilization, raw material cost and process changes on SOFC stack production cost for annual production rates of 1 M stack/y. (a) material utilization; (b) main raw material costs: ZrO_2 and Ni; (c) granulation process change; (d) sintering process change (co-firing) (see text A.2 in chapter 2.4).

Fig. 7. Impacts of cell design change. Flat tubular A: 2 mm t thick anode support (standard case). Flat tubular B: 1 mm t thick anode support. Micro-tubular: tubular anode support of 2 mm ϕ diameter (advanced concept).

Fig. 8. Influence of cell performance on cost reduction for 700 W SOFC stack production. (a) Power density change from 0.19 to 0.38 W/cm² (i.e., current density change from 0.25 to 0.50 A/cm² at a constant cell voltage of 0.76 V.) (b) Cell voltage change from 0.76 to 0.88 V at a constant current density of 0.25 A/cm². Cell efficiency was calculated for a fuel utilization of 70% on a LHV base.

Fig. 9. Effect of improvements in thermal conductivity of an insulator on cost reduction for 700 W SOFC stack production. An insulator thickness of 8 cm is the standard case.

Fig. 10. Effect of power generation efficiency on electricity cost for various cost cases for a 700W residential SOFC CHP system. (a) LNG price: 130 JPY/Nm³ (case A); (b) 100 JPY/Nm³ (case B). Other key assumptions: operating rate of SOFC system: 0.8; lifetime: 10 years. Solid lines in the figure represent the value of electricity cost with changing SOFC system cost between 200 and 1,000 JPY/W. Broken line in the figure represents baseload electricity cost (23 JPY/kWh).

Fig. 11. Cost reduction potential for 700 W SOFC stack production according to the supposed innovation pathway in Table 6. 2020 A: thinner flat tubular type of cell 1; 2030 A': thinner flat tubular type of cell 2; 2030 B: advanced concept with micro-tubular type of cell.

Fig. 12. Electricity cost change according to the innovation pathway. 2013 (present): standard flat tubular cell; 2020 A: thinner flat tubular type of cell 1 (see Table 6); 2030 A': thinner flat tubular type of cell 2 (see Table 6); 2030 B: advanced concept with micro tubular type of cell. Broken line in the figure represents baseload electricity cost (23 JPY/kWh).

Table 1a. Typical single cell geometry and component materials of a flat tubular type of cell.

Anode thickness: support layer (mm)	2	Ni-YSZ
Anode thickness: active layer (μm)	30	Ni-YSZ
Electrolyte thickness (μm)	50	YSZ
Interlayer thickness (μm)	3	GDC
Cathode thickness (μm)	50	LSCF-GDC
Interconnector thickness (μm)	100	LCC
Current collector thickness (mm)	1	Steel (SUS430)
Current collector coat thickness (μm)	10	CMO
Material	Abbreviation	
(ZrO ₂) _{0.92} (Y ₂ O ₃) _{0.08}	YSZ	
Ce _{0.8} Gd _{0.2} O _{1.9}	GDC	
La _{0.6} Sr _{0.4} Co _{0.2} Fe _{0.8} O _{3-δ}	LSCF	
La _{0.8} Ca _{0.2} CrO _{3-δ}	LCC	
Co ₂ MnO ₄	CMO	

Table 1b. Base properties of a flat tubular SOFC stack module ^a.

Rated AC output power (W)	700
DC output power (W)	800
Average power density (W cm ⁻²)	0.19
Average current density (A cm ⁻²)	0.25
Average cell voltage (V)	0.76
Electrode area of a single cell (cm ²)	30
Number of single cells	140
Operating temperature (°C)	750
S/C ratio of fuel (humidified methane)	2.5

a. Ref.[10]

Table 1, J. Otomo et al.

Table 2. Manufacturing processes for the individual steps of SOFC stack production.

Process No.	Production step	Processes
P0	Common facilities	Feeding raw materials for granulation and paste ink
P1	YSZ powder synthesis	Granulation ^a ; drying; sintering; grinding
P2	GDC powder synthesis	Granulation ^a ; drying; sintering; grinding
P3	NiO powder synthesis	Granulation: precipitation method; centrifugation; drying; sintering; grinding
P4	LSCF powder synthesis	Granulation ^a ; drying; sintering; grinding.
P5	LCC powder synthesis	Granulation ^a ; drying; sintering; grinding
P6	CMO powder synthesis	Granulation ^a ; drying; sintering; grinding
P7	Anode support production	Slurry preparation; extrusion; drying; sintering; cutting.
P8	Anode layer making	Ink preparation; printing ^b ; drying; sintering ^c .
P9	Electrolyte layer making	Ink preparation; printing ^b ; drying; sintering ^c .
P10	Interlayer making	Ink preparation; printing ^b ; drying; sintering ^c .
P11	Cathode layer making	Ink preparation; printing ^b ; drying; sintering ^c .
P12	Interconnect layer making	Ink preparation; printing ^b ; drying; sintering ^c .
P13	Current collector coating	Molding steel band; ink preparation; dip coating; drying.
P14	Stack assembling	Assembling cells and manifold; sintering
P15	Casing	Molding steel sheet; cutting insulator board; assembling stack.

a. Granulation is conducted by polymerized complex (PC) method or solid state synthesis

b. Screen printing and dip coating were employed for making the layers of flat tubular and micro-tubular types of cell, respectively.

c. Several sintering patterns of individual sintering or co-firing of the components were examined to conduct the sensitivity analysis of production cost (see text: A.2 in chapter 2.4).

Table 3. Main equipment costs of flat tubular type cells for a variety of production scales.

Process No.	Equipment	Unit cost (MJPY)		
		0.1M stack/y	1M stack/y	10M stack/y
P1	Continuous furnace for drying and sintering	107	173	282
P7	Extruder	15	20	24
P8	Screen printer	14	24	29

Table 3, J. Otomo et al.

Table 4. Cost estimation procedure.

Production cost		Remark
Fixed cost		α = Annual expenditure rate (AER) = 0.2. ^a
Equipment	Equipment cost $\times \alpha$	
Off-site facility	Required utility $\times$ unit cost of off-site facility $\times \alpha$	
Installation	Equipment cost $\times$ IF $\times \alpha$ (for piping and power distribution)	Installation factor (IF): 0.5;
	Equipment weight $\times$ IC $\times \alpha$ (for equipment)	Installation cost (IC): 0.2 M JPY/t (inside); 0.15M JPY/t (outside)
Building	Area used for equipment $\times$ AF $\times$ UCC $\times \alpha$	Area factor (AF): 7 ^b Unit cost of construction (UCC): 0.16 M JPY/m ²
Variable cost		
Raw material	Input weight of raw material $\times$ UCM	Unit cost of material (UCM) ^c
Utility (electric power)	Required power $\times$ operation time $\times$ UCE	Operation rate: 0.8; unit cost of electricity (UCE): 12 JPY/kWh
Utility (others)	Required utility $\times$ UCM	Unit cost of utilities (UCM) ^c
Labor	Net number of operators $\times$ UCL	Unit cost of labor (UCL) 4 M JPY/person

a. AER was determined by interest rate, lifetime of equipment and maintenance.

b. AF was determined based on a factory design of 1M stacks/year, considering the configuration of equipment.

c. The unit costs are summarized in Table 6.

Table 4, J. Otomo et al.

Table 5. Summary: annual production 1M stack/y	
	Cost (JPY/stack)
Raw material	28,385
Running cost: Electricity	1,507
: Industrial water	26
: Steam (LNG)	92
Equipment : main process	2,443
: off-site facility	825
Building: plant & off-site	1,274
Employment cost	2,259
Total	36,810
	(53 JPY/W)

* process yield: 100% (ideal)

Table 6. Raw material weight and cost for stack production ^{a,b}

Raw material	Weight (kg)	Unit cost (JPY/kg)	Cost (JPY/stack)	Cost ratio (%)
ZrO ₂	1.90	3,000	5,703	20.09
Y ₂ O ₃	0.30	4,000	1,212	4.27
CeO ₂	0.05	3,000	151	0.53
Gd ₂ O ₃	0.01	3,000	40	0.14
Ni	3.03	1,700	5,143	18.12
La ₂ O ₃	0.18	1,000	177	0.62
SrCO ₃	0.01	70	1	0.00
Co	0.03	2,800	77	0.27
Fe ₂ O ₃	0.01	200	2	0.01
CaCO ₃	0.02	45	1	0.00
Cr ₂ O ₃	0.09	1,000	92	0.32
MnCO ₃	0.02	1,200	29	0.10
Steel	14.25	250	3,562	12.55
Stainless	4.03	250	1,008	3.55
SiO ₂ based glass	0.02	500	10	0.03
Mullite (Al ₂ O ₃ -SiO ₂)	8.41	1,000	8,411	29.63
HNO ₃ (neat)	11.69	50	585	2.06
H ₂ SO ₄ (neat)	0.06	45	3	0.01
Citric acid	4.21	250	1,053	3.71
Ethylene glycol	1.36	100	136	0.48
NaOH	4.12	22	91	0.32
Ethanol	1.94	130	252	0.89
Methyl cellulose	0.34	1,600	538	1.90
Dibutyl phthalate (DBP)	0.29	250	73	0.26
Polyoxyethylene alkyl ether phosphoric acid ester	0.02	1,000	19	0.07
Sorbitan sesquioleate	0.02	1,000	16	0.06
Summation	56.42		28,385	100.00

a. Exception of reformer and catalyst.

b. Process yield: 100% (ideal).

Table 7. Key assumptions in technology scenario for 700 W SOFC stack and CHP system.

	Present (2013)	2020	2030	2030
Cell type	Flat tubular (standard)	Flat tubular (thinner type1)	Flat tubular (thinner type2)	Micro-tubular (advanced concept)
Production scale (stack/year)	< 1000	100000	1000000	1000000
Material utilization (%)	-	70	80	80
Support thickness (or diameter)	2 mm t	1.5 mm t	1 mm t	2 mm ϕ
Reduction ratio of insulator thickness	1.0 (8 cm)	0.75 (6 cm)	0.5 (4 cm)	0.5 (4 cm)
Cell voltage ^a (V)	0.76	0.8	0.83	0.83
Fuel utilization (%)	70	73	77	77
Cell efficiency ^b (%)	51	56	62	62
Power loss ^c (W)	100	90	85	85
Power generation efficiency ^{b,c} (%)	45	50	55	55
Total efficiency (%)	75	80	85	85
Lifetime (year)	10	10	15	15
BOS cost ^d (JPY/system)	-	300,000	200,000	200,000
Stack cost (JPY/W)	-	81	37	24
System cost (JPY/W)	3860	510	322	310

a. Constant current density is assumed: 0.19 A/cm².

b. Efficiency was calculated on LHV base.

c. Power loss due to dc-ac power inverter and auxiliaries.

d. BOS (balance of system) cost includes auxiliaries and hot water tank.

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Fig. 2 J. Otomo et al.

Fig. 3 J. Otomo et al.

Fig. 4 J. Otomo et al.

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Fig. 11 J. Otomo et al.

Fig. 12 J. Otomo et al.