ELSEVIER

Journal of Power Sources 101 (2001) 10–26

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

The environmental impact of manufacturing planar and tubular solid oxide fuel cells

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Received 22 July 2000; received in revised form 22 November 2000; accepted 30 December 2000

Abstract

This paper examines the environmental impact of manufacturing two types of solid oxide fuel cell (SOFC) system. The tubular SOFC (based on a 100 kW Siemens–Westinghouse design), and the planar SOFC (based on a 1 kW Sulzer design). Using different levels of detail, the environmental impact of the manufacture of the PEN and interconnect, the balance of plant and the production of precursor materials has been assessed for both systems. The results demonstrate that the production and supply of materials for the manufacture of both the balance of plant and the fuel cell are responsible for a significant share of the overall environmental burden associated with each of the fuel cell systems studied. Nonetheless, the total emissions associated with the manufacturing stage still only contribute an additional 1% to lifetime CO_2 emissions for both fuel cell types. The relative contribution arising from the manufacturing phase to several other regulated pollutants is high, but this reflects the low levels associated with the SOFC in use phase, rather than indicating a significant burden arising from manufacture. It is proposed that end-of-life reuse or recycling could play a key role in further reducing environmental burdens.

Keywords: Solid oxide fuel cell; Life cycle analysis; Manufacturing; Environmental impact; Energy assessment; Recycling

1. Introduction

Solid oxide fuel cells (SOFCs) are an emerging technology which offer many advantages over conventional methods of power generation, including higher efficiencies and reduced emissions. Research efforts in this area are presently focused on issues such as SOFC stack performance, durability and cost. Information on the present status of SOFC development can be found in [1–4].

The increasing emphasis on fuel cells as a candidate power generation system of the future [5,6] means that there is a growing need to look at the environmental impact of the whole life cycle of the system. This includes the manufacturing, in-use, and end-of-life stages. While the potential environmental impacts of SOFC in-use are well documented [7–9] there is a great deal of uncertainty concerning the environmental impact of the manufacturing and end-of-life stages. A first step towards exploring the potential environmental impacts of the manufacturing stage has been reported by Hart et al. [10,11] who compared energy related emissions from six different methods for the fabrication of the thick film components (PEN) for an SOFC system using a life cycle analysis approach.

This paper is based on a study carried out by the authors for the UK Department of Trade and Industry (DTI) advanced fuel cells programme [12]. The aim of the study was to build an understanding of the wastes and emissions to the environment generated by the manufacturing of two fuel cell systems; the SOFC and the solid polymer fuel cell (SPFC). This paper presents the main results related to the manufacturing of the SOFC system, together with a discussion of their implications on commercial development.

2. Methodology

2.1. Scope of the analysis

The study uses a life cycle assessment (LCA) cradle-to-grave assessment approach. LCA is an analytical environmental management tool (see for example [13]) used to inform decision making within environmental product,

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PII: S0378-7753(01)00482-7

process and systems design, as well as a recommended step in the implementation of environmental management systems [14]. It is used to assess the environmental burden of a product, process or activity over its entire life cycle starting with raw materials extraction and ending with the final waste disposal. The four steps of an LCA are:

1. *Goal definition and scoping*: Defines the purpose of the study, i.e. comparative assessment and its scope, i.e. system boundaries, functional unit.
2. *Inventory analysis*: Quantifies the energy and raw material requirements, air emissions, waterborne effluents, solid waste and other environmental releases of each stage of the life cycle of the product, process or activity. The inputs and outputs may thus be aggregated over the total life cycle.
3. *Impact assessment*: Data resulting from the inventory are translated into their corresponding environmental impacts for various impact categories.
4. *Improvement assessment*: Aims to identify and evaluate different options to reducing the environmental impact of the system under study.

In this study only the first two steps of the LCA have been carried out for the fuel cells systems, followed by a discussion on likely environmental burdens based on inventory data. The stages of the life cycle of a fuel cell system are presented in Fig. 1. The complete life cycle involves raw materials extraction, manufacture and assembly of the stack and balance of plant (BoP), their installation, operation and eventual decommissioning.

The focus of this study is on stage 3, for which a life cycle inventory has been produced. Much of the primary data on material and energy inputs includes limited information on the emissions associated with resource extraction, and so stages 1 and 2 are also largely included. Stage 7 is considered qualitatively in the discussion on the basis of assumptions made for possible end-of-life options. The environmental characteristics of stages 5 and 6 (fuel cells in-use and the full fuel cycle) have been examined in previous studies [7,8].

The study involved identifying the key manufacturing stages of the fuel cell system, and thus the flow of materials, energy, intermediate products and finished "goods" (i.e. the fuel cell stack and BoP). This process description formed the framework for the collation of the inventory data on material and energy inputs and outputs, and its subsequent analysis.

Data for the inventory was gathered from a variety of sources. LCA data banks [15,16] were consulted for data regarding the environmental burden of key materials, information from manufacturers and potential recyclers was used to determine process characteristics and associated

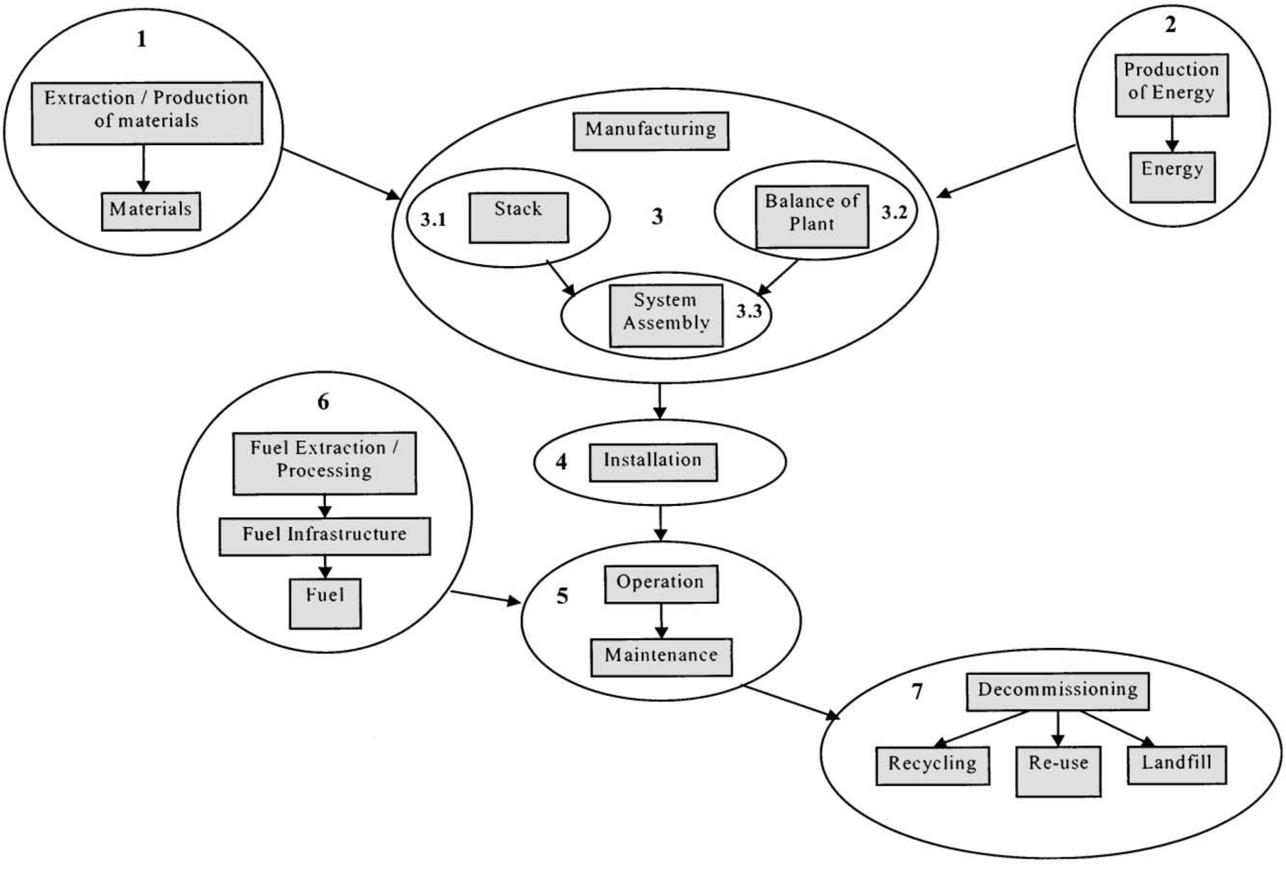

Fig. 1. Concept diagram of a fuel cell system's life cycle in seven stages.

environmental burdens. Where data was unavailable, assumptions were made and are detailed in the text.

2.2. Boundaries of the study

The main aim of the study was to explore the interaction between the manufacturing stage of the life cycle (stage 3, as shown Fig. 1) and the environment. While keeping the main focus on the manufacturing process of the fuel cell system, a relative comparison of the environmental impacts of the manufacturing process itself with the impact to the environment from the production of the main materials used was also explored. Such a comparison was intended to identify areas of concern and possible improvements outside the manufacturing plant, for example related to the selection of materials used. Three levels of detail were used in the analysis of the different stages of the manufacturing of the fuel cell system and are presented below.

2.2.1. Unit cell manufacture

Includes the manufacture of the positive–electrolyte–negative (PEN) plus the interconnect. For this stage, detailed data collection took place describing the inputs and outputs of every processing step. These components represent the heart of the fuel cell system, and the highest level of detail was therefore used for this analysis. The resultant inventory enabled a comparison of the environmental burden associated with different production stages, e.g. anode production compared with cathode production. It also allowed a comparison of different steps within a specific manufacturing process, e.g. mixing compared with drying in the manufacture of an electrode.

2.2.2. Balance of plant manufacture

For the purpose of this paper, BoP includes all the components present in the SOFC system other than the unit cell, (see Table 1). Many of these components, such as heat exchangers and power converters, are relatively standard. A less detailed analysis was therefore carried out, aimed at providing average figures for materials and energy requirements to enable comparison with other stages of the fuel cell life cycle.

2.2.3. Precursor materials

Aggregated data on the environmental impact of the production of the precursor materials (e.g. organics) used in the production of the SOFC system were collected, up to the gate of the fuel cell manufacturing plant. This allowed a general comparison to be made between the environmental burdens of the main manufacturing process, and the production of the materials used.

2.3. SOFC system selection

This study focused on two SOFC variants, the tubular SOFC, and the planar SOFC. To enable a full analysis to be carried out it was necessary to select a specific stack design representing both of these variants. The study therefore focused on the Siemens–Westinghouse tubular SOFC, and the Sulzer HEXIS planar SOFC.

2.3.1. Siemens–Westinghouse tubular SOFC

The Siemens–Westinghouse tubular SOFC concept is aimed at medium scale stationary power generation in the 100 kW to 10 MW range with an operating temperature of about 950°C. Its tubular design simplifies some of the sealing problems associated with planar high temperature SOFCs [17,18]. At present several tubular SOFC stacks of 100 kW size have been built and tested [19–21]. The status of the Siemens–Westinghouse tubular SOFC has recently been reviewed [22,23]. Our study examines the 100 kW Westinghouse SOFC System as tested by Osaka Gas/Tokyo

Table 1
Main components of the balance of plant for the planar and tubular SOFC system

Component	Planar system	Tubular system	Description
Casing	✓		A two-layer steel vessel casing for the whole system. Thermal insulation is provided by a vacuum between the two layers of the casing
Pressure vessel		✓	Steel vessel containing the system
Pressure vessel insulation		✓	Microporous alumina–silica material used for thermal insulation
Air plenum assemblies		✓	Components made of alumina provide air to the SOFC tubes
Air and fuel supply systems	✓	✓	This includes all pipe-work, valves, blowers, compressors, etc. for providing continuous supplies of the fuel gas and air to the SOFC stack
Desulphurizer	✓	✓	In this component potentially deleterious sulphur compounds are removed from the hydrocarbon fuel
Pre-reformer/gas burner	✓		Fuel is pre-reformed with the use of catalyst. The gas burner is used to provide the necessary heat for start up
Stack reformer boards		✓	Internal reforming of the fuel takes place on nickel boards
Air pre-heater		✓	This component is used to provide heat for start up
Heat exchangers	✓	✓	Heat generated during operation is utilised by the heat management system composed of a number of heat exchangers
Power conditioning system	✓	✓	The ac current produced by the fuel cell system is converted to dc
Conventional gas heating unit	✓	✓	Increases overall system efficiency by burning unused fuel

Gas (1995–1997). At the heart of the system are the ceramic tubular cells of 150 cm active length, 834 cm^2 active area, operating at maximum power density of 0.25 W cm^{-2}. The basic cell design consists of closed-end ceramic tubes bundled together to form modules. The stack contains reformer boards to enable indirect internal reforming. A detailed description of the Siemens–Westinghouse stack can be found in [24].

2.3.2. *Sulzer HEXIS planar SOFC*

The Sulzer HEXIS planar SOFC concept is aimed at an entirely different market, small scale power units in the 1–10 kW range with an operating temperature of about 900°C. The power density of the flat-plate SOFC design is in principle greater than that of a tubular unit and so more compact systems are possible, suitable for home or small business applications [25]. One of the main advantages of the planar configuration is that fabrication of the flat-plate components can be accomplished using well-known ceramic mass production techniques that should be less costly and time consuming than those used to manufacture the tubular fuel cell. This study examined the small scale (1 kW) Sulzer HEXIS system, a description of which can be found in [26]. A power density of 0.2 W cm^{-2} was assumed, such that the stack contained 50 circular PENs connected in series (each of 120 mm diameter, active area 100 cm^2, [27]). A power density of 0.5 W cm^{-2} was taken as a future performance target (see Section 4.1).

2.4. *Key assumptions*

The basic (starting) assumptions used in the formulation of the analysis were the following:

- The functional unit for the study is 1 kW of electricity generated by the SOFC system.
- The study does not consider the energy and the materials input required for manufacturing the equipment used in the production of the fuel cell system, nor the impact of land use associated with the manufacturing plant. Neither does it include the energy required for air-conditioning or ventilation within the manufacturing plant.
- The BoP analysis is based on those materials that make up at least 95% of the mass of the component analysed. Secondary materials are aggregated into ‘‘other materials’’.
- The environmental impact associated with the transport of materials to the fuel cell manufacturing plant are not considered. The aggregated data for precursor materials production in many cases includes emissions related to transport. However, it has not always been possible to identify which sets of data do, and which do not, include transport.
- The study assumes that emissions associated with transport within the fuel cell manufacturing plant will be insignificant.
- The rate of fuel cells production for both systems is based on published forecasts [7,8].
- When calculating energy related emissions, that energy is taken to be 100% electricity.
- Two sets of emission factors are used to calculate energy related emissions, relating to electricity production using either combined cycle gas turbines or the UK average fuel mix. The same emission factors were used in previous studies [7,8], enabling a comparison to be made.

2.5. *Manufacturing flowsheets*

Analysis of the manufacture of both SOFC systems was divided into the following two sections:

1. *PEN and interconnect manufacture:* Includes the manufacturing of electrodes (anode and cathode), electrolyte, and interconnect, for both tubular and planar designs.
2. *Balance of plant manufacture:* Includes the manufacture of all other components comprising the SOFC system.

2.5.1. *PEN and interconnect manufacture*

The manufacture of planar SOFCs is characterised by wet chemical processing of ceramic oxide powders for electrolyte, cathode and anode. For the planar design two options were considered. Fig. 2 illustrates the manufacturing flowsheet assuming separate sintering stages for all components. Fig. 3 presents an alternative flowsheet, in which the anode and the cathode are co-sintered [28,29].

As already indicated, manufacture of the Siemens–Westinghouse SOFC concept is a far more complex process than that of the planar design, being based on the use of electrochemical vapour deposition (EVD) for deposition of the electrolyte, and plasma spraying for the interconnect. Further details can be found in [18]. The process for manufacturing a single tubular cell is illustrated in Fig. 4.

2.5.2. *Balance of plant manufacture*

Table 1 describes the main components of the BoP for the planar and the tubular SOFC systems considered in this study.

The study assumes that the main processes used for manufacturing these components are: metal forming, welding, catalyst preparation and general assembly of pre-manufactured components (e.g. power converter assembly). Most of the components comprising the SOFC balance of plant are based on established technology. In fact, this is necessary since an SOFC that relied on many specialist components would be uneconomic. The components associated with the supply of gases are well known in many industries. Only those components that are in contact with high temperature fuel and air streams are constructed from less conventional materials.

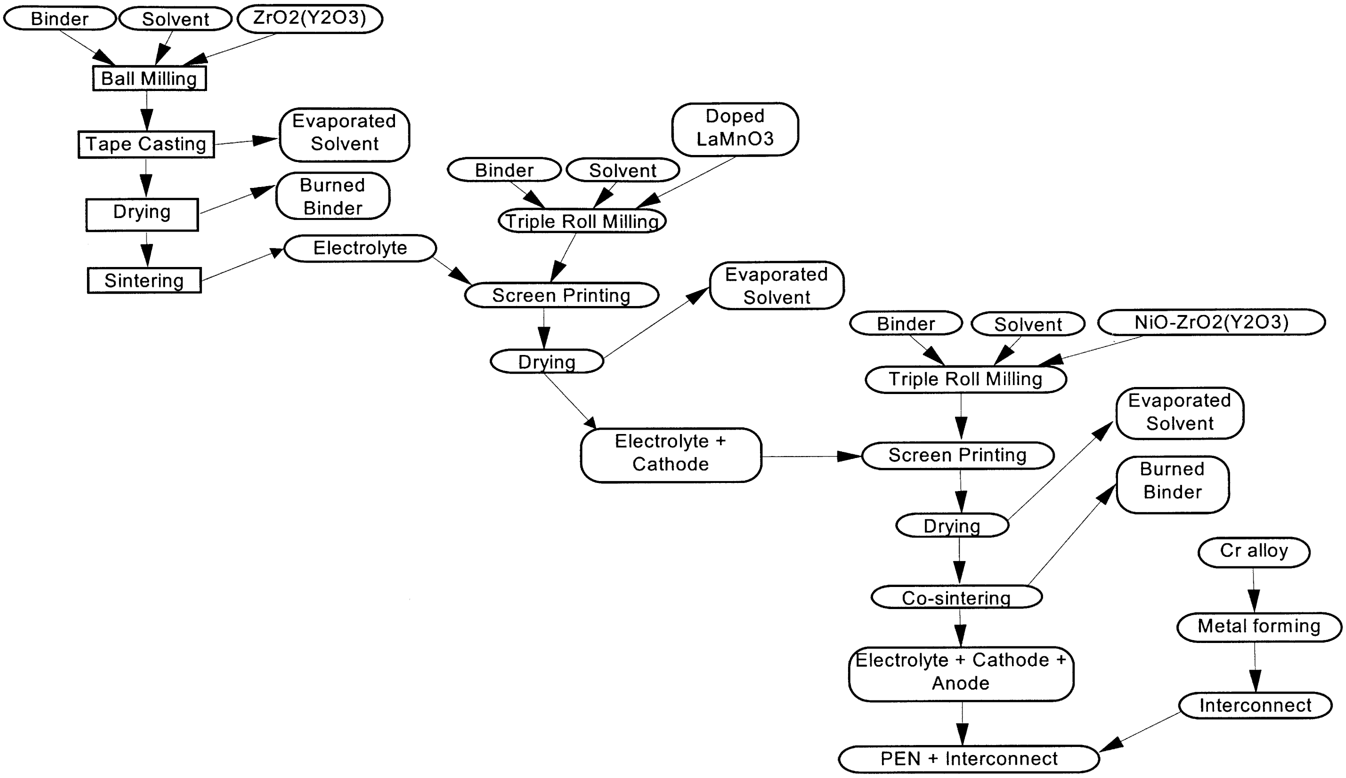

Fig. 2. Manufacturing of the PEN and interconnect for the planar SOFC.

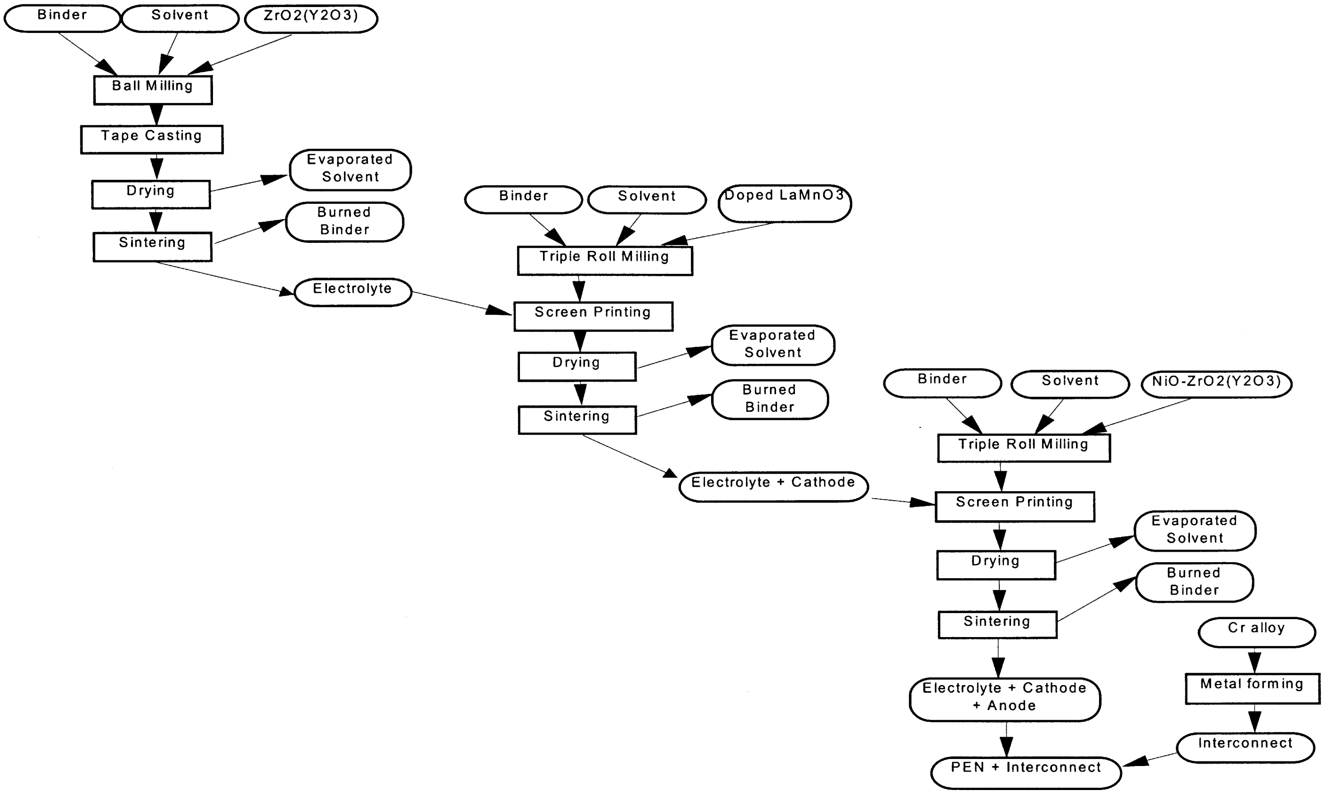

Fig. 3. Manufacturing of the PEN and interconnect for the planar SOFC (co-sintering option).

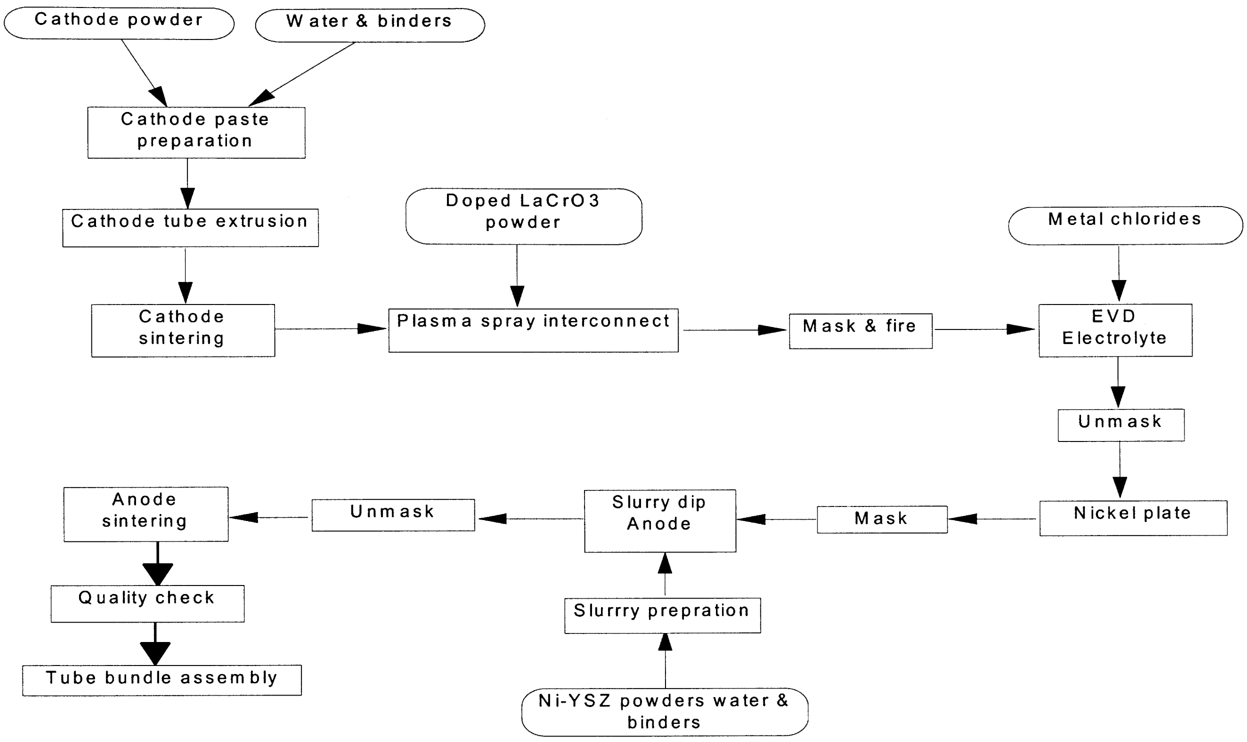

Fig. 4. Manufacturing of PEN and interconnect for the tubular SOFC system.

3. Results

3.1. Materials and energy inputs

The data for manufacturing the two SOFC systems (planar and tubular) are presented in two sections; material/energy inputs for the manufacturing of the PEN and interconnect, and material/energy inputs for the manufacturing of the BoP. The energy inputs are further divided into energy used for the production of materials, and energy used during the manufacturing process. It should be noted that all the material and energy input data presented in Tables 2–12, and Figs. 5–8, are based on a quantitative analysis of primary data obtained from a wide variety of sources.

3.1.1. Materials and energy inputs to PEN and interconnect manufacture

Tables 2 and 3 present the material and energy inputs for the manufacturing of PEN and interconnect for the planar and tubular SOFC, respectively. The materials input allows

Table 2
Energy and material inputs for manufacturing the PEN and interconnect of the planar SOFC

Material	Materials input (kg kW^{-1})	Energy inputs for materials production (MJ kW^{-1})	Process	Energy inputs for manufacturing processes (MJ kW^{-1})
$ZrO_2(Y_2O_3)$	4.03	55.97	Ball milling	0.95
Polyvinyl butyral	0.21	10.55	Tape casting	0.07
Ethanol	0.75	38.37	Drying	1.71
Trichloroethylene	1.57	71.09	Sintering	10.53
Polyethylene glycol 200	0.19	11.63	Preparation of cathode ink	0.14
Dibutyl phthalate	0.17	21.85	Screen printing	0.13
Ni–$ZrO_2(Y_2O_3)$	0.13	1.77	Drying	1.71
Doped $LaMnO_3$	0.12	2.45	Sintering	8.60
Cr alloy	13.41	3543.24	Preparation of anode ink	0.15
			Screen printing	0.13
			Drying	1.71
			Sintering	8.60
			Metal forming interconnect	0.43
Total		3756.91		34.84

Table 3
Energy and material inputs for manufacturing the PEN and interconnect of the tubular SOFC

Material	Materials input (kg kW^{-1})	Energy inputs for materials production (MJ kW^{-1})	Process	Energy inputs for manufacturing processes (MJ kW^{-1})
Doped $LaMnO_3$	4.26	221.73	Cathode paste preparation	0.36
Water	0.98	0.02	Cathode extrusion	0.82
Doped $LaCrO_3$	0.06	3.21	Cathode sintering	8.15
$ZrCl_4$	0.83	28.76	Deposit interconnect (atmospheric plasma spray)	207.36
YCl_3	0.12	4.23	Mask	0.60
Ni	0.00[a]	0.02	Fire in continuous furnace	0.61
Ni oxide	0.08	0.50	Deposit electrolyte (EVD)	46.29
$ZrO_2(Y_2O_3)$	0.08	2.70	Demasking	1.83
Polyvinyl butyral	0.03	1.57	Remasking for anode	0.06
Ethanol	0.19	9.62	Nickel plating	0.12
Polyethylene glycol 200	0.01	0.71	Anode slurry preparation	0.24
Dibutyl phthalate	0.01	1.55	Anode slurry dipping	0.12
			Anode sintering	8.15
Total		274.63		274.70

[a] The value for Ni is 0.0001 kg kW^{-1}.

for estimated process losses. The losses are due to material utilisation effects, and rejection of faulty products at the end of each process. For the following calculations neither recycling nor reuse have been taken into consideration. Recycling or reuse of components and materials could significantly decrease the material requirements of the manufacturing process.

Table 2 shows that the material input for $ZrO_2(Y_2O_3)$ during the manufacturing process is high. This is due to the comparatively low yield (~80%) of the first sintering stage. During this stage a number of plates crack or bend and have to be rejected. The high figures for inputs of $ZrCl_4$ and YCl_3 (see Table 3) arise from the low materials utilisation of the EVD process (~20%) [30]. As also shown in Table 2, the energy requirement of the manufacturing stage is dominated by thermal processes such as sintering and drying. Energy inputs for materials production are almost 100 times bigger than the energy used during the manufacturing stage, (see Section 4 for a detailed discussion of these figures). Co-sintering the anode and cathode can lead to significant energy reductions, as sintering is the most energy intensive stage of the manufacturing process. However, when calculating the overall emissions from the manufacturing of the planar SOFC, separate sintering of the anode and cathode has been assumed.

As shown in Table 3, the energy inputs for the materials production stage and the manufacturing step are almost the same in the case of the tubular SOFC system. This is due to the high energy consumption of the plasma spray and EVD processes [30]. Plasma spraying and EVD are responsible for almost 90% of the total energy requirement.

3.1.2. Materials and energy Inputs to the balance of plant manufacture

Table 4 presents the material and energy inputs for manufacturing the BoP for both planar and tubular designs. The study assumed process energy inputs to be 5% of the energy required for materials production. The energy requirement for the production of "other" materials was determined to be 10% of the total.

3.2. Emissions

As shown in Fig. 5, in terms of some key emissions to air, BoP related emissions are higher than those for manufacture of the PEN and interconnect. This reflects the greater mass materials used for the BoP, with an increase in the associated energy requirement.

The planar fuel cell is associated with higher emissions to air of CFC/HCFCs, VOCs and metals, reflecting the greater range of materials used in the system. The emission of metals, for example, is due predominantly to the production of the chromium-yttrium alloy, with VOCs generated equally from production of chromium-yttrium and trichloroethylene. The emissions of regulated pollutants arise mostly from trichloroethylene production, with just 0.2 g kW^{-1} from the production of dibutyl phthalate. The stack is also responsible for many of the emissions to water, again reflecting a diverse range of materials production processes, the details of which are outside the scope of this study.

Fig. 6 illustrates the source of emissions for the tubular system. The distribution is different, with the unit cell manufacture responsible for significant shares of CO_2, NO_x and hydrocarbons, but little of the other emissions (the share of organics to water and to land are significant, but at a low level). This pattern has two main causes: firstly, the process energy in manufacture of the tubular stack is significant, giving rise to emissions at the power station. With the assumption here that CCGT is the electricity source, CO_2, NO_x and hydrocarbons are the main emissions, with low levels of particulates or SO_x. Secondly, the data on

Table 4
Material and energy inputs for manufacturing the balance of plant for both planar and tubular SOFCs

Component	Materials	Planar			Tubular		
		Material input (kg kW^{-1})	Energy inputs for materials production (MJ kW^{-1})	Energy inputs for manufacturing process (MJ kW^{-1})	Material input (kg kW^{-1})	Energy inputs for materials production (MJ kW^{-1})	Energy inputs for manufacturing process (MJ kW^{-1})
Casing	Steel	10	224	11.2	NA	NA	NA
Pressure vessel	Steel	NA	NA	NA	50	1120	56
Pressure vessel insulation	Microporous alumina–silica	NA	NA	NA	0.5	10	0.5
Air and fuel supply system	Steel	20	448	22.4	5	112	5.6
Air plenum assemblies	Alumina	NA	NA	NA	4.2	72.9	3.64
Stack reformer boards	Ni	NA	NA	NA	0.2	58.3	2.91
Desulphuriser	Steel	0.5	16.2	0.8	0.005	1.6	0.08
	Zn	0.1			0.01		
Air pre-heater	Steel	NA	NA	NA	2	44.8	2.24
Pre-reformer/gas burner	Steel	5	257.7	12.9	NA	NA	NA
	Catalyst (Ni)	0.5			NA		
Heat exchangers	Incaloy	2	94.1	4.7	2	94.1	4.70
	Steel	2			2		
Power conditioning system	Aluminium	0.3	86.6	4.3	0.3	86.7	4.33
	Purified silica	0.004			0.004		
	Plastics	0.020			0.020		
	Cu	0.006			0.006		
Conventional gas heating unit	Steel	50	1120	56	NA		
Other			224.7			160	
Total			2471.3	112.3		1760.4	80

Table 5
Annual production of cells for the planar SOFC

Power density (W cm^{-2})	Cells per kW	Cells per year
0.5	20	2000000
0.2	50	5000000

Table 7
Energy inputs for manufacturing the PEN and interconnect of the tubular SOFC

Process	Contribution to energy inputs (%)
Cathode paste preparation	0.13
Cathode extrusion	0.30
Cathode sintering	2.97
Deposit interconnect (atmospheric plasma spray)	75.49
Mask	0.22
Fire in continuous furnace	0.22
Deposit electrolyte (EVD)	16.85
Demasking	0.67
Remasking for anode	0.02
Nickel plating	0.04
Anode slurry preparation	0.09
Anode slurry dipping	0.04
Anode sintering	2.97

emissions for production of some of the ceramics used in the tubular cell are incomplete, leading to an underestimation the fuel cell's share of emissions.

3.3. Comparison of emissions related to process energy use with emissions from materials production

As shown in Fig. 7, all key air emissions are much higher from activities relating to material production than from the processes involved in fuel cell and BoP manufacture.

The share of some process energy related emissions are more significant for the tubular type, reflecting primarily the much higher process energy requirements for manufacture of the tubular fuel cell, notably CO_2, NO_x and hydrocarbons, which are the most significant emissions from CCGT electricity generation.

4. Discussion of the inventory results

The following examines the sensitivity of results referring to the manufacturing of PEN and interconnect for both planar and tubular SOFCs to a number of factors.

4.1. Influence of power density on energy and materials input (planar SOFC)

When calculating the energy and material inputs during the manufacturing of the PEN and interconnect of the planar SOFC system, the study assumed a cell production rate sufficient to manufacture 100 MW of fuel cell system per annum. Table 5 presents the number of cells to be manufactured per year for two power density assumptions.

Table 6 presents the influence of a change in power density of the cell from 0.2 to 0.5 W cm^{-2} to the energy requirements of the manufacturing process. Based on the selected equipment capacity, the change from 2 to 5 million cells per year only makes a small change in the energy input per cell. As shown in Table 6, it only affects screen printing. A significant influence however, would be anticipated in the capital cost per kW produced. In contrast with the small influence on the energy inputs per unit cell, the energy inputs for manufacturing 1 kW of fuel cell system is heavily influenced. A shift from 0.2 to 0.5 W cm^{-2} gives a 40% decrease of energy inputs for the same unit of output, i.e. a linear relationship exists between the two over this power

Table 6
Energy inputs for manufacturing the PEN and interconnect of the planar SOFC at two differing cell power densities

Processing step	0.2 W cm^{-2}		0.5 W cm^{-2}		Potential energy saving per kW produced (%)
	Energy input per cell (kWh)	Energy input per kW of fuel cell system (MJ kW^{-1})	Energy input per cell (kWh)	Energy input per kW of fuel cell system (MJ kW^{-1})	
Ball milling	0.0053	0.9530	0.0053	0.3812	40.00
Tape casting	0.0004	0.0669	0.0004	0.0267	40.00
Drying	0.0095	1.7057	0.0095	0.6823	40.00
Sintering	0.0585	10.5337	0.0585	4.2135	40.00
Preparation of cathode ink	0.0008	0.1403	0.0008	0.0561	40.00
Screen printing	0.0007	0.1254	0.0003	0.0251	20.00
Drying	0.0095	1.7057	0.0095	0.6823	40.00
Sintering	0.0478	8.5989	0.0478	3.4396	40.00
Preparation of anode ink	0.0008	0.1481	0.0008	0.0593	40.00
Screen printing	0.0007	0.1254	0.0003	0.0251	20.00
Drying	0.0095	1.7057	0.0095	0.6823	40.00
Sintering	0.0478	8.5989	0.0478	3.4396	40.00
Metal forming interconnect	0.0024	0.4320	0.0024	0.1728	40.00
Total	0.1936	34.8396	0.1929	13.8857	39.86

Table 8
Sensitivity analysis on the energy needed for the production of some key materials used in the manufacture of the PEN and interconnect of the planar SOFC

Material	% of total material weight	Energy inputs for materials production (MJ kW^{-1})	% of total energy inputs for material production	Energy inputs for materials production (MJ kW^{-1})[a]	% of total energy inputs for material production[a]
$ZrO_2(Y_2O_3)$	19.52	55.97	1.49	111.94[a]	2.93
Polyvinyl butyral	1.02	10.55	0.28	10.55	0.28
Ethanol	3.62	38.37	1.02	38.37	1.01
Trichloroethylene	7.58	71.09	1.89	71.09	1.86
Polyethylene glycol 200	0.94	11.63	0.31	11.63	0.30
Dibutyl phthalate	0.81	21.85	0.58	21.85	0.57
Norwegian fish oil	0.39	0.00	0.00	0.00	0.00
Ni–$ZrO_2(Y_2O_3)$	0.62	1.77	0.05	3.54[a]	0.09
Doped $LaMnO_3$	0.56	2.45	0.07	4.90[a]	0.13
Cr alloy	64.94	3543.24	94.31	3543.24	92.83
Total		3756.91		3817.10	

[a] Double energy requirement to manufacture this material.

Table 9
Sensitivity analysis on the energy needed for the production of some key materials used in the manufacture of the PEN and interconnect of the tubular SOFC

Material	% of total material weight	Energy inputs for materials production (MJ kW^{-1})	% of total energy inputs for material production	Energy inputs for materials production (MJ kW^{-1})[a]	% of total energy inputs for material production[a]
Doped $LaMnO_3$	63.44	221.73	80.74	443.46[a]	82.84
Water	14.65	0.02	0.01	0.02	0.00
Fish oil	0.89	0.00	0.00	0.00	0.00
Doped $LaCrO_3$	0.92	3.21	1.17	6.42[a]	1.20
$ZrCl_4$	12.34	28.76	10.47	57.52[a]	10.74
Ycl_3	1.82	4.23	1.54	8.47[a]	1.58
Ni	0.00	0.02	0.01	0.02	0.00
Ni oxide	1.16	0.50	0.18	0.50	0.09
$ZrO_2(Y_2O_3)$	1.16	2.70	0.98	5.41[a]	1.01
Polyvinyl butyral	0.47	1.57	0.57	1.57	0.29
Ethanol	2.79	9.62	3.50	9.62	1.79
Polyethylene glycol 200	0.18	0.71	0.26	0.71	0.13
Dibutyl phthalate	0.18	1.55	0.56	1.55	0.29
Total		274.63		535.27	

[a] Double energy requirement to manufacture this material.

Table 10
Material inputs for manufacturing the balance of plant for both the planar and tubular SOFC

Material	Planar (%)	Tubular (%)
Steel	98.97	92.10
Zn	0.11	0.02
Ni	0.55	0.30
Aluminium	0.33	0.45
Purified silica	0.00	0.01
Plastics	0.02	0.03
Cu	0.01	0.01
Microporous alumina–silica	–	0.75
Alumina	–	6.34
Total	100	100

density range. The same finding applies also to material inputs for the manufacturing of PEN and interconnect. Again a shift in the power density of the cell from 0.2 to 0.5 W cm^{-2} results in a 40% decrease in the material input needed to manufacture 1 kW of fuel cell system capacity.

4.2. *Sensitivity of process energy calculations for the manufacturing of PEN and interconnect for the tubular SOFC*

The relative contribution made by differing manufacturing processes to the overall energy consumption when manufacturing the PEN and interconnect of a tubular SOFC cell is shown in Table 7. This shows that the energy input is

Table 11
Comparison of the emissions associated with the use phase of a 100 kW SOFC with the total emissions associated with manufacturing the fuel cell system

	In-use (100 kW) (g kWh^{-1})	In-use lifetime (g kW^{-1})	Manufacture (planar) (g kW^{-1})	Manufacture (tubular) (g kW^{-1})	Ratio of manufacture to in-use emissions (planar)	Ratio of manufacture to in-use emissions (tubular)
Particulates	0.000	0	650	242	–	–
CO	0.001	40	2112	1438	52.8	36.0
CO_2	218.540	8741600	382997	199028	0.04	0.02
SO_x	0.005	200	2975	1026	14.9	5.1
NO_x	0.021	840	746	377	0.9	0.45
Hydrocarbons	0.202	8080	810	214	1.0	0.03

Table 12
Comparison of the emissions associated with the use phase of a 100 kW SOFC with the process energy emissions associated with manufacturing the fuel cell system

	In-use (100 kW) g kWh^{-1}	In-use lifetime (g kW^{-1})	Manufacture (planar) (g kW^{-1})	Manufacture (tubular) (g kW^{-1})	Ratio of manufacture to in-use emissions (planar)	Ratio of manufacture to in-use emissions (tubular)
Particulates	0.000	0	0.01	0.08	–	–
CO	0.001	40	3.9	30.6	0.097	0.765
CO_2	218.540	8741600	4020	31811	0.0	0.004
SO_x	0.005	200	0.11	0.84	0.001	0.004
NO_x	0.021	840	7.0	55.7	0.008	0.066
Hydrocarbons	0.202	8080	4.0	31.5	0.0	0.004

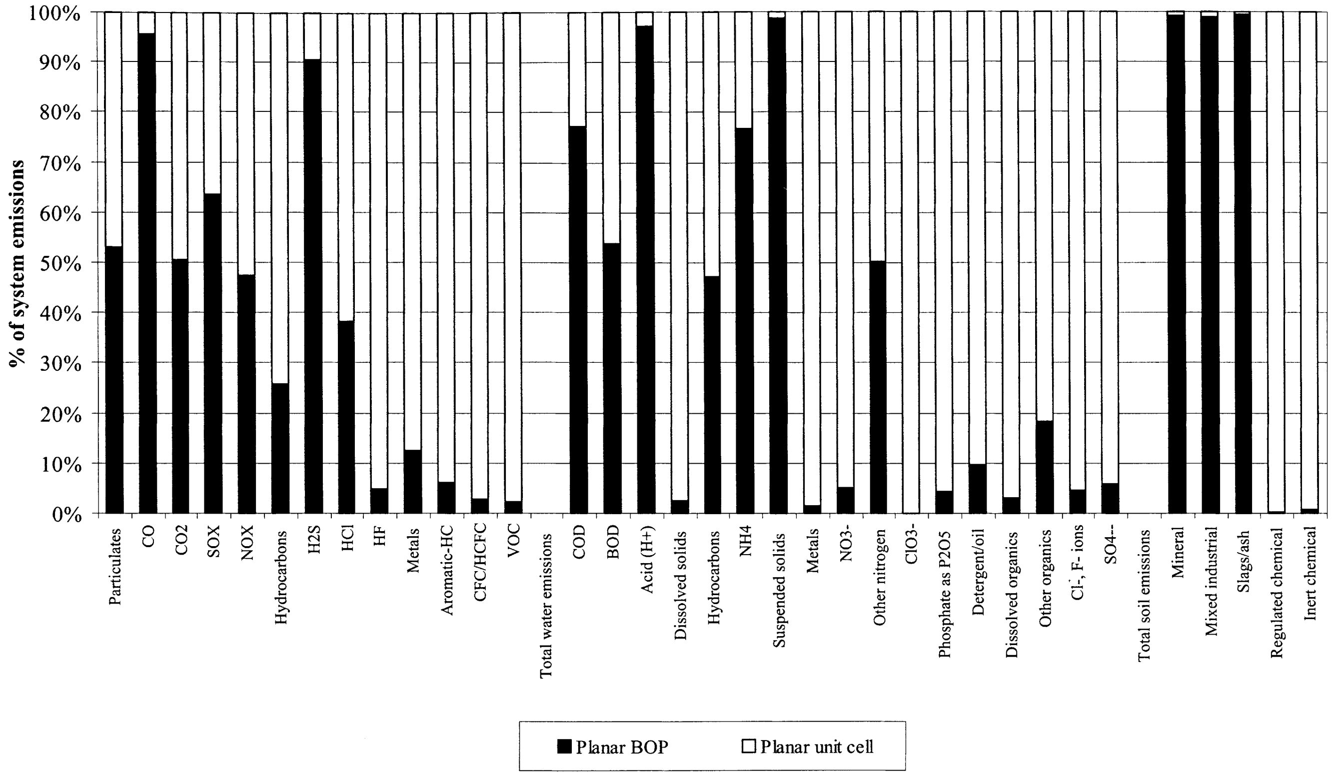

Fig. 5. Share of emissions between BoP and unit cell, planar SOFC.

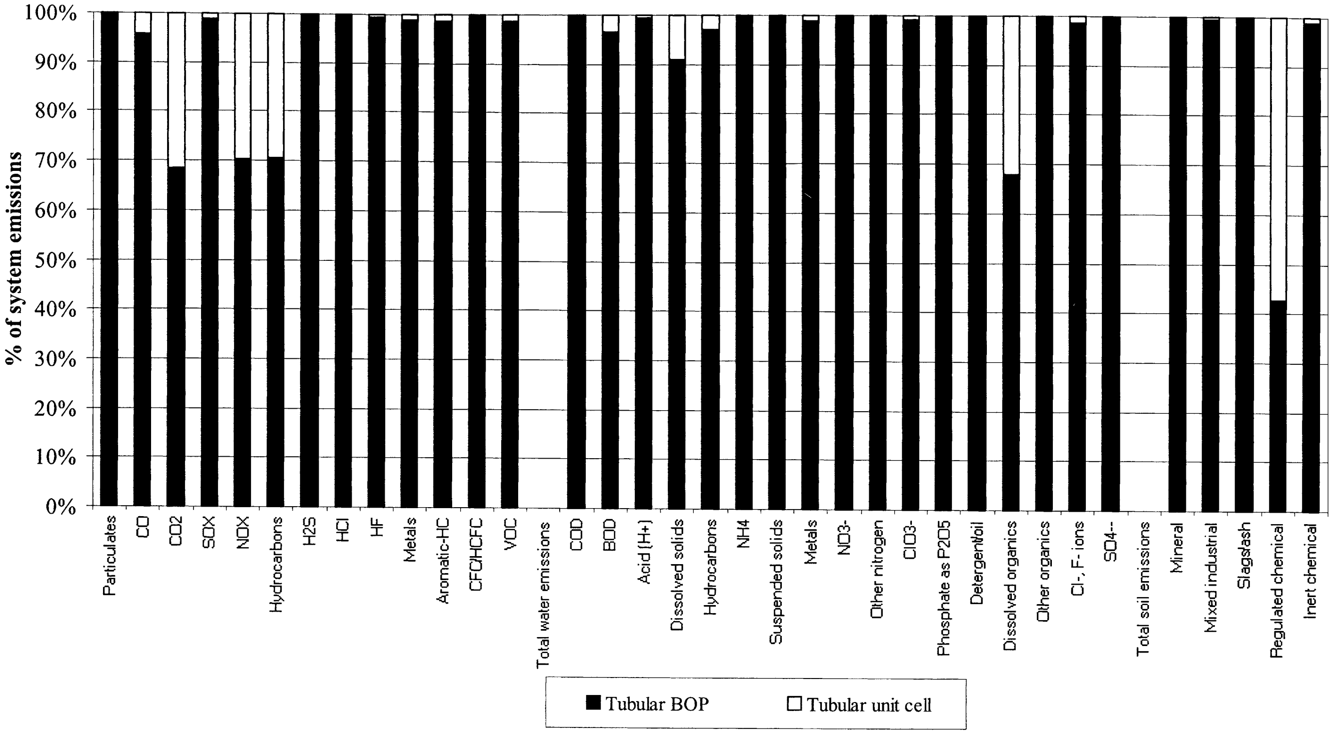

Fig. 6. Share of emissions between BoP and unit cell, tubular SOFC.

dominated by two processes; atmospheric plasma spraying and EVD. The rest of the processes make up only 7.7% of the total energy input. Evidently energy consumption calculated for the manufacturing of the PEN and interconnect is highly sensitive to these two processes. The data for atmospheric plasma spray and EVD used in this study are from [30]. These data represent relatively high estimations, the values are expected to decrease for mass production. However, these two processes are expected to continue to be the main contributors to total energy consumption during the manufacturing of the PEN and interconnect of the tubular SOFC.

4.3. Uncertainties in materials production and inputs for PEN and interconnect

Due to commercial confidentiality it was not possible to obtain detailed data for the production of some key

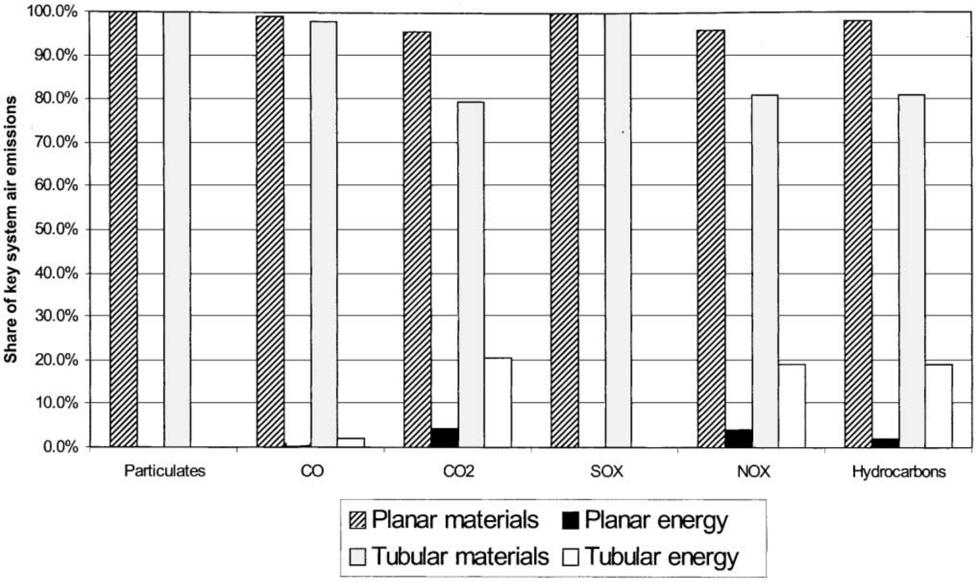

Fig. 7. Share of key air emissions from material production and process energy.

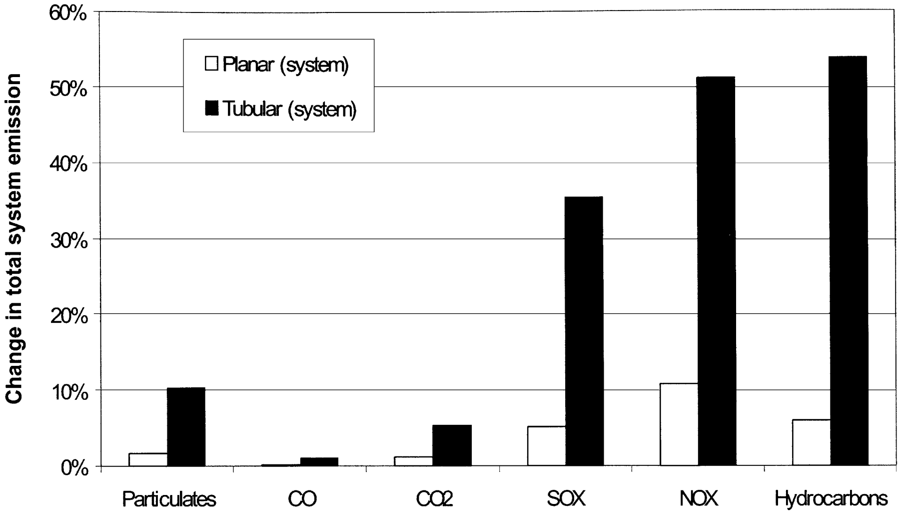

Fig. 8. Effects from changing from CCGT to UK average mix on the emissions associated with manufacturing both planar and tubular SOFC.

materials. To compensate for the missing data, assumptions were made based on the production of alumina. The materials affected by these assumptions are, doped $LaMnO_3$, doped $LaCrO_3$, $ZrCl_4$, YCl_3 $ZrO_2(Y_2O_3)$, and $NiO–ZrO_2(Y_2O_3)$. The assumptions cover only the energy inputs for materials production and do not include process emissions.

Tables 8 and 9 examine the sensitivity of the calculated energy inputs for the production of materials to the assumptions made. The tables present the figures calculated for the energy inputs for materials production which were used in the study, together with the same analysis in which the energy required to manufacture some key materials was taken to be doubled.

As shown in Table 8, energy inputs for the production of material for the manufacturing of PEN and interconnect for the planar SOFC are dominated by the Cr alloy material used in the interconnect. The figure expressing the total energy requirements is not very sensitive to the energy used to produce the key materials. Doubling the figures only resulted in a 1.6% increase in the total energy requirement.

Exactly the opposite trend is seen in the data referring to the tubular SOFC. In this case the dominant material is doped $LaMnO_3$, which is present in a significant quantity in this cathode supported design. Doubling the energy requirements to produce this material caused an increase to the total figure of about 96%.

4.4. Uncertainty in the material inputs for manufacturing the balance of plant for the SOFC systems

Table 10 shows a breakdown of the materials assumed to be required to manufacture the BoP for the planar and tubular SOFC system.

The figures concerning the emissions from materials production for the manufacturing of the BoP are mainly derived from the production of steel. For the tubular system, inputs from Al_2O_3 production also make a small contribution. Emissions from material production for manufacturing the BoP are particularly sensitive to changes in these figures. In contrast, an increase or decrease of any other material, even by 50%, does not cause any significant change in the overall emissions.

There is uncertainty related with the figures covering the production of steel and alumina from ore in the ground. As long as the main contribution to the overall emissions for the manufacturing of the BoP comes from these materials, the factors of uncertainty related with these emission figures can be summarised by the following:

- mining location;
- mining process;
- refining and production of the material;
- final refining to meet the requirements of the fuel cell manufacturer;
- transport within the ore processing operation, and transport to the manufacturing plant.

These uncertainties can only be addressed when a specific manufacturing process and the equivalent supply route for materials have been established.

Data used in this study is derived from LCA software databases [15,16], based on average figures concerning the manufacturing process. As such they cannot assess local variations. The degree of uncertainty increases when transport needs have to be assessed. General LCA data, such as those used in this study, include in many cases average transport requirements. These figures may be used as a guide, but more detailed assessment has to take place including information on the location of manufacturing plant and raw material providers.

It is evident that reuse and recycling of materials/components (in-house and post-consumer) will further decrease the material requirements, with an equivalent impact on emissions related to the production of these materials.

4.5. Sensitivity to electricity generation source

Fig. 8 illustrates the effect on total system air emissions of changing from CCGT to the UK average mix as the energy source for the manufacturing process, for both the planar and tubular SOFC types. For both fuel cell designs, the choice of generation type has a significant effect on energy-related emissions, since all emission factors are significantly higher for the UK average mix.

However, for the planar system, energy-related emissions make up less than 5% of the total when using CCGT emission factors, as shown in Fig. 7, and thus total emissions are affected by less than 10% from the switch to UK average mix. However, as discussed earlier, data for actual process energy use (and related emissions) for BoP manufacture are not available, and emissions were therefore assumed to be 1% of the BoP material emissions. For the planar design, the BoP process energy emissions account for some 76% of total energy-related emissions, and thus uncertainty in the BoP process energy figures have a strong effect on overall planar process energy figures. Hence the precise figures illustrated in Fig. 8 should be treated with some caution.

For the tubular SOFC, the results shown in Fig. 8 are more certain, as BoP process energy accounts for only some 23% of total energy use. The figure shows strong sensitivity to the electricity source assumption, reflecting the greater share of total system air emissions attributable to process energy for the tubular type.

5. Comparison of the manufacturing phase with the use phase

Table 11 compares key air emissions arising from the use phase of a stationary SOFC power plant with those associated with its manufacture. The in-use emission factors per kWh have been taken from [7] for a 100 kW SOFC. These have been converted into lifetime emissions in grams per kW of output, assuming 40,000 h operation at full load. Comparison is normalised on a per kW basis, to allow some comparison of the relative performance of both the small scale (1 kW) planar system and the larger (100 kW) tubular system. However, comparisons with the small planar system must be regarded with greater uncertainty.

SO_x, CO and particulate emissions in-use are inherently low, and thus these emissions are dwarfed by the corresponding figures from manufacture. NO_x emissions are comparable from both stages of the lifecycle. Lifetime CO_2 and hydrocarbon emissions are far higher from the in-use stage, reflecting the assumption of fossil-based fuel for the fuel cell. It is important to note that these comparisons all reflect the assumption that manufacturing energy is sourced from CCGT or some average fuel mix, whose emissions are generally higher in-use than for the fuel cell. Clearly the relative weight of the manufacturing emissions would change if the electricity source was itself fuel cell based. The emissions from each life cycle stage have not been compared on an equal basis, but that reflects the reality of the early stages in fuel cell penetration.

Table 12 compares the same in-use emissions with emissions arising from the process energy used in manufacture of the stack alone. Only carbon monoxide emissions from stack manufacture appear significant compared to those generated in-use. The dominance of in-use emissions arise because the energy inputs to manufacture are relatively low; approximately 10 and 76 kWh for planar and tubular types, respectively, representing just 0.02 and 0.2%, respectively, of lifetime energy production by the fuel cell.

The comparisons within Table 12 reflect more closely the current concerns of potential fuel cell producers, as energy or emissions ‘embedded’ within material inputs to manufacture are at present rarely considered. However, there is growing interest amongst policy-makers and environmental regulators in widening the traditional remit to include these issues, through application of life cycle or whole-life evaluation.

6. Conclusions

The LCA tool — as introduced in Section 2 — identifies and indeed assesses in its four steps the environmental burdens of a product, process or activity over its entire life cycle. In this study, only the first two steps of the LCA have been carried out for the fuel cell systems, i.e. the goal definition and scoping, and the inventory analysis. Based solely on the inventory, no assessment of environmental burden can be made. Also, based on the inventory, no assessment can be made of whether a particular emission in a certain quantity is more or less environmentally benign than any other substance in a certain quantity. Impact categories would need to be established and substances allocated to the relevant categories. This will need to be the subject of a future study. The inventory also does not provide information about the location of any specific emission. Environmental impacts, however are strongly related to the concentration of a particular pollutant and/or emission. Thus, more specific information on where materials are being processed, and in what quantity, are needed to allow a full environmental assessment.

However, an examination of the inventory data can be used to identify the following environmental pressure points:

- The process used to manufacture the fuel cell system uses solvents. While they might not be deemed to be toxic they might be involved in the creation of photochemical ozone and thus contribute to ill-health effects. To examine this point detailed data on the management of solvents are needed.
- Other materials appearing in the inventory tables have a potential impact on human health, (e.g. particulates, NO_x,

H_2S, Pt, Cr, di-butyl phthalate (an endocrine disruptor), Cl^- and F^- ions), on biota (e.g. COD, BOD, P_2O_5), on water (e.g. metals, phosphate, SO_x, $SO_4{}^{2-}$), or on ozone generation or depletion (e.g. CO, CO_2, hydrocarbons).

Further work will need to be carried out to expand on the above observations. This will need to include more information on material selection, production process, origin, etc. as well as the availability of alternatives, and an awareness of technical and economic considerations.

The study did not look at the sourcing of materials in detail. However, as both the bulk chemical and specialist materials industries are international in character, it can be concluded that in general the emissions associated with materials supply will be widely dispersed geographically. In comparison with an industry sourcing locally or with a higher share of manufacturing emissions, this will reduce problems for the final manufacturing plant in compliance with local emissions regulations and reduces exposure to local environmental taxation. However, there is a growing emphasis by regulators and policy-makers on life-cycle evaluation, and there is a growing trend towards internalisation of environmental costs in many other countries (for example through carbon taxes), including those of potential material suppliers, which would act to drive up material costs. Thus, emissions related to the material production should be considered seriously.

There are significant material inefficiencies during some manufacturing stages for the process flows analysed, in terms of both product rejects and process scrap. Material inefficiency is of great importance since material inputs were shown to account for a large share of the environmental burdens associated with production of the overall system. Fortunately, financial considerations will also guide the manufacturer to improve material efficiency.

This study assumed that there is no recycling of process waste. Thus, a worst case scenario has been produced. End-of-life material recovery and reuse or recycling will be important in reducing the burdens associated with material supply. However, the current state of development of the industry means that end-of life options have so far been given little consideration, and little data is available. It was therefore inappropriate to define explicit recycling scenarios for this study, and further examination of the opportunities are warranted.

It is clear, however, that recycling of key materials can be expected to significantly reduce the environmental burden associated with materials supply. The range of options for end-of-life material recovery is large, ranging from melting the entire fuel cell in a blast furnace to complete disassembly for component reuse. The final solution will lie somewhere between these extremes, with ‘design for disassembly’ facilitating recovery of the more resilient and valuable components, coupled with recovery of materials from other parts through chemical leaching or pyrometallurgical techniques.

In some specific cases, material recovery already seems highly attractive for industry. However, growing pressures to recycle, including directives within the EU producer responsibility programme, are likely to require manufacturers to take-back their products at the end-of-life.

Within the manufacturing stage, energy requirements are dominated by relatively few thermal processes, for example, sintering or plasma spray deposition. The analysis can help pinpoint parts of the process which will benefit most from careful design and optimisation, for example the possibility to co-sinter the SOFC anode and cathode, with net energy savings. However, the overall manufacturing energy consumption is relatively small, and thus improvement opportunities may be marginal.

For the SOFC, the BoP manufacture makes the major contribution to most emissions, reflecting, for example, assumptions about the relatively large mass of steel for the system casing. Clearly it will be important for final mass-production to minimise the material requirements for BoP wherever possible.

The tubular SOFC exhibits higher manufacturing energy inputs for the stack, but lower emissions related to material supply. Optimisation of the manufacturing process is already a high priority due to its present complexity and related cost, but the energy efficiency of the overall process should receive explicit consideration.

The power density of the cell has significant impact on overall environmental burdens, since higher densities reduce requirements for some of the key materials and associated processing. Developers are pursuing higher densities for a variety of reasons, including cost, and these wider life-cycle benefits should add to the incentives.

The overall emissions results were shown to be sensitive to the choice of CCGT or an average UK mix for electricity generation especially in the case of tubular SOFC. This highlights a need for manufacturers to consider environmentally efficient energy provision for their plants. For example, energy analyses can inform about the most efficient systems [14]. The sensitivity to the electricity source assumption also highlights the importance of considering the assumptions made when comparing studies.

As shown in the initial comparison of the manufacturing emissions with fuel cells in-use, when both material production and process emissions are included, the manufacturing stage contributes only an additional 1% to lifetime CO_2 emissions for both SOFC systems. However, emissions of several regulated pollutants from a fuel cell in use are so low, that the manufacturing emissions by comparison are very large. Until detailed comparisons are made with the manufacture of other power systems, it is not possible to fully evaluate this finding. However, the findings suggest that such further analysis is warranted.

7. Recommendations for future work

This study focused on the processes involved in the manufacturing of fuel cell systems. It is clear that there are major environmental burdens associated with the production and supply of material inputs to manufacturing, and whilst this study has been able to highlight the likely scale of the burdens and identify key areas of concern, significant uncertainties remain in the data. Further investigation of the material supply chain is a high priority.

The possible location of emissions has emerged from the present study as an important factor, given the likelihood of a diverse set of material suppliers. To develop a more clear picture of the material supply routes, further analysis should be undertaken of the likely location and geographic concentration of emissions which will improve understanding of both environmental impacts and exposure to regulatory or fiscal measures.

Life cycle inventory data for production of some of the key materials is particularly uncertain at present. An important task, either independently or as part of a wider investigation of materials, is to develop better primary data on the production and supply of a range of key materials, and associated environmental burdens.

The comparison of manufacturing emissions with emissions in-use have shown a significant contribution for some pollutants arising from the manufacturing stage. It would be of great interest to make detailed comparisons of the life-cycle emissions of a fuel cell system with those of other stationary or mobile power sources. Further research into the relative burdens associated with the life cycles of a wider range of technologies expands into a much larger undertaking, as primary data collection and analysis is required. This is a high priority for the longer term.

End-of-life material recovery and reuse or recycling could play a key role in reducing some environmental burdens. Further examination of the opportunities are warranted, as little previous research has been undertaken in this area. In a further step the technical and economic feasibility of the recycling scenarios might be investigated and their environmental efficiency assessed.

Fuel cell manufacturing is still in its infancy and thus the environmental effects of a future mass production system can currently only be assessed on the basis of pilot plant data and assumptions. Competitors for future markets use different production and indeed material selection scenarios for their fuel cells. The results presented in this paper thus provide only the first estimate of the likely environmental burden associated with the manufacturing of SOFCs. The study clearly showed that the production and supply of materials for the manufacture of both BoP and the fuel cell are responsible for a large share of the overall environmental burden associated with each of the fuel cell systems studied.

Overall, in many cases the incentives for process and material optimisation on environmental grounds run in the same direction as other commercial pressures to reduce costs. However, there are potentially serious commercial concerns associated with the environmental burden of SOFC manufacturing, and great emphasis needs to be given to investigating and addressing these issues explicitly.

Acknowledgements

The authors would like to thank the DTI Advanced Fuel Cell Programme for the funding which supported this research, and AEA Technology for their programme management.

References

[1] N.Q. Minh, T. Takahashi, Science and Technology of Ceramic Fuel Cells, Elsevier, Amsterdam, 1995.

[2] S.C. Singhal, M. Dokiya (Eds.), in: Proceedings of the 6th International Symposium on SOFCs, Honolulu, Hawaii, Electrochem. Proc. 99-19 (1999).

[3] D.G. Lovering (Ed.), in: Proceedings of the 6th Grove Fuel Cell Symposium, J. Power Sources 86 (1/2) (2000).

[4] Proceedings of the 4th European SOFC Forum, Lucerne, Switzerland, 10–14 July 2000.

[5] K. Joon, J. Power Sources 71 (1998) 12–18.

[6] G. Edge, Markets wake up to fuel cell revolution, FT Energy Econ. 220 (2000) 15–16.

[7] D. Hart, A. Bauen, Further assessment of the environmental characteristics of fuel cells and competing technologies, ETSU Report F/02/00153/REP/1, 1998.

[8] D. Hart, G. Hörmandinger, Initial assessment of the environmental characteristics of fuel cells and competing technologies, Vol. 1, ETSU Report F/02/00111/REP/1, 1997.

[9] D. Hart, G. Hörmandinger, J. Power Sources 71 (1998) 348–353.

[10] N. Hart, N.P. Brandon, J. Shemilt, Mater. Manufac. Processes 15 (2000) 47–64.

[11] N. Hart, N.P. Brandon, M.J. Day, J.E. Shemilt, Proceedings Fuel Cell 2000, Lucern, 2000, pp. 389–397.

[12] V. Karakoussis, M. Leach, R. van der Vorst, D. Hart, J. Lane, P. Pearson, J. Kilner, Environmental emissions of SOFC and SPFC system manufacturing and disposal ETSU report F/01/00164/REP, 2000.

[13] SETAC, 1993 and 1997.

[14] R. van der Vorst, A. Grafe-Buckens, W. Sheate, JEAPM 1 (1999) 1–26.

[15] Boustead Model 4, Boustead Consulting Ltd., 1999.

[16] Boustead Model 4.1, Boustead Consulting Ltd., 1999.

[17] S.C. Singhal, in: F. Gross, P. Zegers, S.C. Singhal, O. Yamamoto (Eds.), Proceedings of the 2nd International Symposium on SOFC, Athens, 2–5 July, Commission, European Communities Report EUR 13546 EN, 1991, pp. 25–33.

[18] W.J. Dollard, J. Power Sources 37 (1992) 133–139.

[19] S. Takeuchi, A. Kusunoki, H. Matsubara, Y. Kikuoka, J. Ohtsuki, T. Satomi, K. Shinozaki, in: S.C. Singhal, H. Iwahara (Eds.), Proceedings of the 3rd International Symposium on SOFC, Honolulu, 16–21 May, The Electrochem. Soc., 1993, pp. 678–683.

[20] K. Shinozaki, S. Washio, T. Satomi, S. Koike, in: S.C. Singhal, H. Iwahara (Eds.), Proceedings of the 3rd International Symposium on SOFC, Honolulu, 16–21 May, The Electrochem. Soc., 1993, pp. 684–689.

[21] H. Hashimoto, in: Proceedings of the 3rd Grove Fuel Cell Symposium, Imperial College, London, 28 September to 1 October 1993.

[22] R. George, J. Power Sources 86 (1/2) (2000) 134–139.

[23] N.F. Bessette, J.F. Pierre, in: Proceedings of the Fuel Cells Seminar, Portland, OR, USA, 30 October to 2 November 2000, pp. 519–521.

[24] R. George, N.F. Bessette, J. Power Sources 71 (1998) 131–137.

[25] M. Schmidt, in: Proceedings of the Fuel Cell Technology for Stationary Power Generation Conference, Hamburg, Germany, 9–10 November 1999.

[26] R. Diethelm, M. Schmidt, B. Doggwiler, M. Keller, in: Proceedings of the 3rd European SOFC Forum, Nantes, 1998, pp. 87–93.

[27] R. Diethelm, E. Battawi, K. Honnegar, in: Proceedings Fuel Cell 2000, Lucern, 2000, pp. 203–211.

[28] H. Takagi, H. Taira, A. Shiratori, S. Kobayashi, Y. Sugimoto, S. Sakamoto, K. Tomono, in: S.C. Singhal, H. Iwahara (Eds.), Proceedings of the 3rd International Symposium on SOFC, Honolulu, 16–21 May, The Electrochem. Soc., 1993, pp. 738–743.

[29] M. Shimotsu, M. Izumi, K. Murata, in: S.C. Singhal, H. Iwahara (Eds.), Proceedings of the 3rd International Symposium on SOFC, Honolulu, 16–21 May, The Electrochem. Soc., 1993, pp. 732–737.

[30] M. Ippommatsu, H. Sasaki, S. Otoshi, Int. J. Hydrogen Energy 21 (2) (1996) 129–135.