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Conceptual study of a 250 kW planar SOFC system for CHP application

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Abstract

In August 2002, Wärtsilä Corporation and Haldor Topsøe A/S entered into a co-operation agreement to start joint development program within the planar SOFC technology. The development program aims to bring to the market highly efficient, clean and cost competitive fuel cell systems with power outputs above 200 kW for distributed power generation with CHP and for marine applications.

In this study, the product concept for a 250 kW natural gas-fuelled atmospheric SOFC plant has been studied. The process has been calculated and optimised for high electrical efficiency. In the calculations, system efficiencies more than 55–85% (electrical co-generation) have been reached. The necessary balance of plant (BoP) components have been identified and the concept for grid connection has been defined. The BoP includes fuel and air supply, anode re-circulation, start-up steam, purge gas, exhaust gas heat recovery, back-up power, power electronics and control system.

Based on the analysed system and component information, a conceptual design and cost break down structure for the product have been made. The cost breakdown shows that the stack, system control and power electronics are the major cost factors, while the remaining BoP equipment stands for a minor share of the manufacturing cost. Finally, the feasibility of the SOFC plants has been compared to gas engines.

Keywords: SOFC; SOFC system; Conceptual study; SOFC system development

1. Introduction

This conceptual study of a 250 kW planar SOFC power unit has been carried out jointly by Wärtsilä Corporation (Wärtsilä) and Haldor Topsøe A/S (HTAS). In several studies made by both of the companies, planar SOFC technology has been identified as one of the most promising technologies for future power generation in commercial and industrial CHP applications in a power range of 0.2–5 MW.

Among one of the first co-operation areas, Wärtsilä and HTAS started to analyse structural, operational and economical aspects of the targeted product. In the study, different areas of a SOFC system have been identified and analysed down to component level where a realistic cost structure, preliminary design and operational logic can be analysed. The areas where further technological and economical development is necessary have been identified in order to start development activities prior to product commercialisation. Product targets that were set prior to the study are presented in Table 1.

2. System overview

The analysed 250 kW SOFC system is considered to be a natural gas (NG)-fuelled power unit which can operate either in grid-parallel or grid-independently. However, it should be noted that electricity from grid is needed during the start-up phase for electrical heaters and blowers. The pressurised natural gas is supplied to sulphur removal unit where sulphur is removed in a ZnO bed. The sulphur-free natural gas is partially reformed by an adiabatic pre-reformer prior to entering into the stack. The reformer is a fixed-bed reactor where all higher hydrocarbons are converted with steam in to methane, hydrogen and carbon oxides. In order to improve the system efficiency and to supply steam and carbon dioxide for the pre-reformer a part of the anode exhaust gases is circulated back to the reformer inlet. The rest of the anode off gases are sent to a catalytic after-burner where the residual fuel is burned.

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Table 1
Performance target for the conceptual study [1]

Parameter	Value/quality
Nominal electrical power output	250 kW
Electric (LHV) efficiency	47%
Total efficiency	80–85%
Electrical connection	Grid-independent, grid-parallel
ac voltage	420 V_{ac}, 50 Hz
Fuel alternatives	Natural gas
Emissions	
CO_2/CO	420 kg/MWh/negligible
NO_x/So_x	0.2 ppm/negligible
Stack lifetime	40,000 h
System lifetime	20 years
Maintenance Interval	7,000 h
Target system weight	15–20 kg/kW
Target system cost by 2010	US$ 500/kW

The cathode air is supplied by a blower and pre-heated in a heat exchanger prior to entering the stack. Most of the heat exchanged cathode off gas is passed to the heat recovery system, but a small fraction of it is used in the catalytic burner.

In addition to the air and fuel management systems, start-up steam, purge gas, exhaust heat recovery, back-up power, power conversion and control systems are included in the study. The basic system flow-sheet is shown in Fig. 1 [1,8].

2.1. Nominal heat balance

The SOFC system was modelled by HTAS with a general heat and mass balance program, GHEMB, which is an in-house proprietary code used by HTAS. The code uses a stack model originally developed at Risø National Laboratory [2]. The system studies were also made by Wärtsilä by using Aspen Plus™ software.

The flow configuration used in the study was a parallel feed pattern. Both anode and cathode side are fed in parallel, i.e. each cell receive same flow and composition of reactants. Adiabatic performance of the system was analysed at beginning of life (BoL) and at end of life (EoL) conditions.

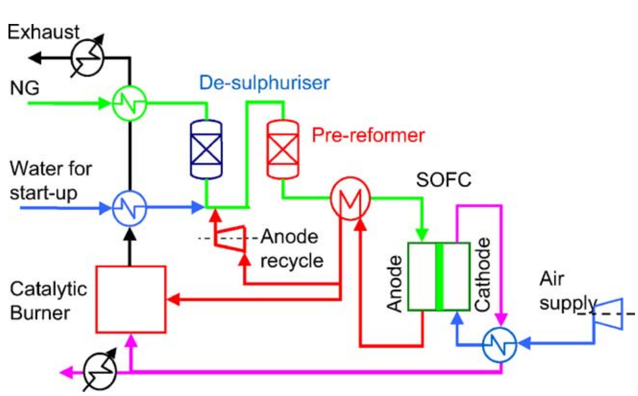

Fig. 1. Basic flow-sheet for the SOFC system [1,8].

Table 2
Nominal heat balance for the 250 kW SOFC system [1]

	Energy input	Energy output
Fuel (LHV) (kW)	447.2	
Air blower (kW)	28.1	
Recycle blower (kW)	2.6	
SOFC, dc (kW)		295.4
SOFC, ac (kW)		280.7
Net power output (kW)		250.0
Heat recovery (90 °C) (kW)		125.8
Net electric efficiency (%)		55.9
Total efficiency (%)		84.7

The system performance will decrease during it's lifetime due to cell degradation. The degradation rate is usually defined as percentage decline of the cell voltage per 1000 h. A 0.25%/1000 h degradation rate is used in this study. There are several ways to counteract degradation. They are discussed separately in [3]. In this study, the operating temperature of the stack has been increased over the stack lifetime to lower the area specific resistance of the stacks. By counteracting the degradation the electrical efficiency for the system has kept almost constant during the stack lifetime. Nominal heat balance for a 250 kW SOFC unit is shown in Table 2.

The achieved, net electrical efficiency of 55.9% is clearly higher than the set target efficiency of 47%. This result underlines the potential of the SOFC technology and shows that the target efficiency is clearly achievable. It should, however, be noted that heat losses have been ignored in this study.

3. System packing

In the study a preliminary packaging of the system was made. Dimensioning of the reactor volumes for pre-reformer and de-sulphuriser, the units have been assumed to operate 7000 h/a, with 2 years service interval for catalyst. The system has been packaged into a standard ISO container with dimensions of 5.8 m × 2.3 m × 2.3 m (length × width × height) [4]. This would allow the system to be easily transported. A three-dimensional model of the packing is presented in the Fig. 2.

The following components are presented in Fig. 2:

1. Fuel cell stacks
2. Fuel pre-reformer
3. Process gas heater
4. Fuel de-sulphuriser
5. Air pre-heater
6. Post-combustion
7. Heat recovery
8. Fuel management
9. Air blower
10. Control unit
11. Power conversion unit
12. Back-up power unit

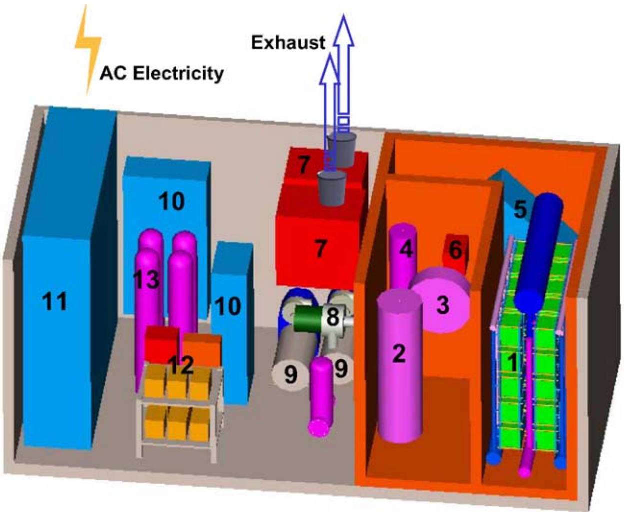

Fig. 2. Preliminary packaging of a 250 kW CHP unit [1].

13. Purge gas
14. Water purification for start-up steam

The packing is divided into three temperature regimes. A hot regime (750–850 °C) where stack and air recuperator are located. Sulphur removal and fuel reforming with heat exchangers are located in the intermediate regime (450–550 °C). The control systems and power electronics together with other BoP components are located in the cold environment.

The system weight was calculated as 12 350 kg giving a specific weight of 49 kg/kW. When comparing the size and specific weight with competing technologies, it can be clearly noted that in the future development program both the system size and weight needs to be further optimised and significantly decreased.

4. System properties

4.1. Cell and stack

The analysis is based on an anode supported SOFC manufactured and developed by a consortium between HTAS and Risø National Laboratory. The cell consists of ceramic materials where the active cell components are encased by metallic interconnects and end plates. Cell properties and performance are described in [5]. The cell layers and used materials are presented in Fig. 4.

In the stack assembly, each anode-supported cell (Fig. 3) with the dimensions 12 cm × 12 cm is positioned together with seals and metallic interconnect plates. In the study, a 2.2 kW stack with internal manifolding and counter flow arrangement was calculated. In order to decrease the number of stacks needed in a 250 kW system, a larger cell size will be developed. According to current experience, cells with an active area of 400 cm^2 can be manufactured [1]. The larger cell size is used in the packaging study described above.

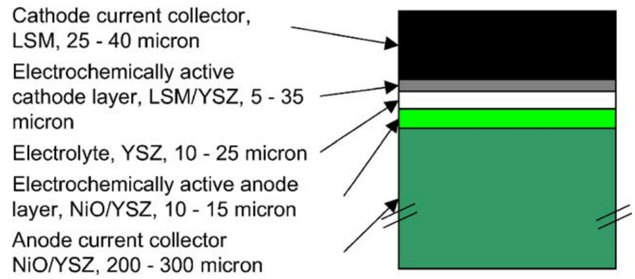

Fig. 3. Anode-supported cell [5].

The internal manifolding ensures design simplicity and optional characteristics of fuel and air flow geometry (cross-flow, counter-flow or co-flow). Furthermore, stack-modularity is an obvious possibility. Cells and interconnects with minimal thickness are used to provide high power density, low weight and low cost of the stack. The inter-connected plates providing internal gas distribution channels in-between the cells are made of ferittic stainless steel. The metallic plates are pre-coated to protect the material against hot corrosion and to ensure optimal electrical contact at the interfaces. Simplicity in stack manufacturing is obtained based on the thin-multilayer design and rapid manufacturing methods.

Critical issues of stacking such as

- Seal reliability
- Durability of electrical contacts between stack components
- Stability of metallic interconnect
- Electrolyte gas-tightness robustness
- Thermal cycle stability

have been identified based on test with short stacks in hydrogen as well as in methane. Durability tests have been carried out for more than 2000 h.

4.2. Sulphur removal

The gas quality used in the study is natural gas from North-Sea region with composition shown in Table 3.

Table 3
Composition of fuel used in the study [6]

Component	vol.%
CH_4	88.1
C_2H_6	6.4
C_3H_8	2.8
C_5H_{12}	1.0
C_6H_{14}	0.18
N_2	0.06
NH_2	0.3
CO_2	1.3
H_2S (ppm)	10

The sulphur is removed by passing the pre-heated natural gas through activated, high surface zinc oxide (HTZ-5).The reaction [7] occurring in the reactor is

$$ZnO + H_2S \leftrightarrow ZnS + H_2O \quad (1)$$

The operating temperature of the reactor is 400–450 °C. Hydrogen sulphide could also be absorbed at lower temperature but the sulphur capture efficiency increases and comes more complete at higher temperatures.

4.3. Fuel pre-reformer

The pre-reformer is an adiabatic, fixed-bed steam reformer in which higher hydrocarbons are completely converted into hydrogen and carbon oxides. Steam reforming reactions of methane are strongly endothermic. Whereas, the shift reaction (4) is slightly exothermic. The conversion of natural gas is carried out at 500–450 °C according to reactions presented in Table 4.

Reaction (2) is the endothermic steam reforming of higher hydrocarbons. Reaction (3) is steam reforming of methane. This reaction is reversible, which explains why there is actually a net production of methane over the pre-reformer with the natural gas used. Some of the CO produced from the higher hydrocarbons is methanated with hydrogen to form methane. The shift reaction (4) is usually in equilibrium in the presence of a steam reforming catalysts. The catalyst used in the study is AR-301, a nickel catalyst on a support, which makes it resistant toward carbon formation from higher hydrocarbons at low steam-to-carbon ratio. The critical ratio of steam to higher hydrocarbons to avoid carbon formation is calculated to be 6.20.

The steam needed in the fuel reformer is supplied by anode re-circulated flow. Anode exhaust gas contains also carbon dioxide, which may substitute part of needed steam for hydrogen production according to the reaction (5).

After leaving the pre-reformer, the gas temperature has dropped by about 55 °C and it needs to be heated to the stack inlet temperature of around 650 °C. This is accomplished by the anode inlet heat exchanger using the anode exhaust off gas as a heating medium.

Table 4
Steam reforming reactions [7]

								ΔH_{298} (kJ/mol)	
C_nH_m	+	nH_2O	$\leftrightarrow$	nCO	+	$(n + m/2)\ H_2$		−1175[a]	(2)
CH_4	+	H_2O	$\leftrightarrow$	CO	+	$3H_2$		−206	(3)
CO	+	H_2O	$\leftrightarrow$	CO_2	+	H_2		41	(4)
CH_4	+	CO_2	$\leftrightarrow$	$2CO$	+	$2H_2$		−247	(5)
CH_4			$\leftrightarrow$	C	+	$2H_2$		−75	(6)
$2CO$			$\leftrightarrow$	C	+	CO_2		172	(7)
CO	+	H_2	$\leftrightarrow$	C	+	H_2O		131	(8)

[a] For *n*-heptane.

4.4. Anode re-circulation

Part of the anode off gas is re-circulated back to the reformer inlet by a blower operating at high temperature. The blower is a vane-type compressor driven by an electrical motor, the speed of which is controlled by a frequency converter. The anode recycle serves three different purposes

1. It provides steam and carbon dioxide for the pre-reforming step.
2. It increases the overall fuel utilisation by recycling un-used hydrogen and carbon monoxide from the stack.
3. It pre-heats the combined flow of natural gas and anode recycle to the optimum pre-reformer inlet temperature of around 500 °C.

For the anode re-circulation blower a 56% overall efficiency has been assumed which would allow the use of commercial components from automotive turbochargers.

4.5. Heat exchangers

The air and gas heaters in the study are made out of high temperature steel alloy. For an optimal heat transfer and compact design, plate-type heat exchangers have been selected. The cathode air heater is the most critical heat exchanger due to it's large capacity. In the study, the transferred heat duty of the cathode air pre-heater is 528 kW [1,8]. Due to the high operating temperature and the risk for poisoning cathode due to Cr-evaporation, the material should be carefully selected.

Both fuel pre-heaters, the one before de-sulphuriser and the one after pre-reformer are also plate heat exchangers with heat duties of 10 and 20 kW, respectively. During the development project prototypes of the heat exchangers have been manufactured and these will be tested for performance and durability.

4.6. Air supply

The system use two different blowers, one for air supply and the other one for anode re-circulation discussed above. Also, the cathode air supply blower is a vane-type compressors driven by an electrical motor, the rotational speed of which is controlled by a frequency converter. In the study, one redundant air blowers have been used to increase the system reliability. The blower efficiency is an important factor for the overall system efficiency. For the air supply an overall efficiency of 72% is used.

A suitable air blower with high efficiency and an anode circulation blower operating at high temperature are components that have to be further developed in order to meet the operational and economical targets for the SOFC system.

4.7. Catalytic after-burner

In the study, the after-burner is considered to be of the catalytic combustion type, which will be able to handle the very lean and varying feed gases without harmful emissions. Part of the anode exhaust gas, which contains high amounts of carbon dioxide and water, is recycled back to the pre-reformer inlet. Most of the residual anode off gas, which contains also hydrogen (8.2%) and carbon monoxide (2.7%) is burned catalytically together with part of the off gas from the cathode. The sensible heat in this flue gas stream serves to generate steam for the pre-reformer during start-up and pre-heat of the natural gas before the de-sulphurisation.

In the preliminary test of the after-burner full conversion of hydrogen (H_2) and carbon monoxide (CO) was reached already at 400 °C. Methane was fully converted at the operating temperature of 700 °C. No NO_x emissions were detected with measuring accuracy of ±1 ppm. These results give a good confidence that SOFC plants can reach extremely low emission levels.

4.8. Power electronics

Since the stack dc voltage is in the range of 70–95 V_{dc}, several stacks have to be connected into series before transformation to suitable ac current. With a 400 V_{ac} output, the dc input voltage for an inverter has to be in the range of 410–1000 V_{dc}. There are at least three alternatives to convert low stack voltage to sufficient ac voltage

1. Low stack voltage is connected to switch-mode dc–dc converter followed by dc–ac inverter.
2. Stack voltage is connected to a dc stabiliser followed by a dc–ac inverter.
3. High enough stack voltage is directly connected to a dc–ac inverter.

The large number of stacks used in the study makes it possible to achieve a high enough dc voltage with good reliability to be directly connected to the dc–ac inverter. Also, higher conversion efficiency can be achieved with this method.

4.9. Control and automation

The system control is divided into three main areas: master control; power control and back-up control. Programmable logic control (PLC) equipment functions as a master control unit, which controls the overall system. In order to control the operation of the system and keep the system within its operational window, five basic parameters need to be adjusted.

1. Fuel flow control valve, which will determine the fuel flow to the stacks.
2. Speed of the air blower, which will control the amount of air fed to the system, thus controlling stack temperature.
3. Speed of the anode recycle blower, which will control the amount of anode off gas that is recycled.
4. A valve controlling the air flow to catalytic after-burner, thus controlling the outlet temperature of the burner.
5. Power control for steering the stack voltage.

Table 5
Cost structure of a 250 kW SOFC system [1]

Stack	31%
Fuel system	8%
Air system	6%
Exhaust system	2%
Start-up system	2%
Purge gas system	0%
System control	17%
Power electronics	15%
Insulation	3%
Structure	2%
Labour and overheads	15%

In addition to the above described BoP components, the following sub-systems are needed during various operational phases of the power unit:

- Start-up heaters are electrical heaters for heating up the cathode air flow. Both the sulphur removal unit and the fuel reformer are equipped with heating element both for warming-up and temperature control purposes.
- Purge gas is needed during heating-up and cooling down phases in order to protect both fuel reformer and anode from possible oxidation.
- Start-up steam is supplied to the fuel reformer before stack is loaded and anode re-circulation is started.
- Battery back-up is needed for air circulation during cooling down phase in case the grid is not available.

5. Cost structure

The production costs of the system have been analysed for a 250 kW SOFC power unit with an annual production volume of 100 U (25 MW). Major cost items are stacks (31%), power electronics (15%), control system (17%), and labour and overheads (15%). The cost estimation is based on given offers or estimated cost for the identified components. In the study, the system control is slightly over dimensioned which would give saving potential for commercial products. On the other hand, the air system including cathode air recuperator might be under estimated due to the limited amount of experience over the durability of the components. The cost structure for the 250 kW SOFC system is presented in Table 5.

6. Competitiveness of SOFC power plants

In the study, the competitiveness of a SOFC power plant in a commercial CHP application was compared with gas engines. The economic parameters used for the calculations are 25 years utilisation time and 7% real discount rate. Gas price of 17 €/MWh is used in the analysis. This corresponds to an average gas price in the cities of Helsinki, London, Rome, Boston and Los Angeles. Profitability of a SOFC application

Table 6
Economic and technological characteristics used in the competitiveness calculations [1]

	2010	2015	2020
Total net investment			
SOFC unit (optimistic) (€/kW)	1589	980	676
SOFC unit (pessimistic) (€/kW)	2603	1589	1082
Gas engine plant (300 kW) (€/kW)	863	759	656
Total non-capital cost			
SOFC unit (optimistic) (€/MWh)	37.3	31.8	29.7
SOFC unit (pessimistic) (€/MWh)	53.2	43.3	38.1
Gas engine plant (300 kW) (€/MWh)	37.9	36.1	34.6
Efficiency			
SOFC electric (%)	48	52	55
SOFC co-generation (%)	85	88	90
Gas engine electric (%)	35	36	37
Gas engine co-generation (%)	77	79	81

is highly dependent both on the utilisation of the thermal energy and the ratio between gas and electricity prices. Both of these factors vary between the cities mentioned above. Thus, the analysis shows only the average costs of power plants in typical European and American locations.

6.1. Commercial CHP plants

The electricity generation costs of a SOFC power plant and a gas engine in commercial applications in the years 2010, 2015 and 2020 have been estimated. The comparison was made with optimistic and pessimistic investment cost assumption for the SOFC power plant for each year. Investment cost estimates for the turnkey plant and technological parameters used in the calculations are given in Table 6.

Table 7
Generation cost of electricity [1]

	2010	2015	2020
SOFC 250 kW unit (optimistic) (€/MWh)	54.4.	42.3	36.9
SOFC 250 kW unit (pessimistic) (€/MWh)	81.1	60.4	49.7
Gas engine 300 kW plant (€/MWh)	47.1	44.3	41.6

The analysis shows that in the optimistic price scenario, the SOFC plants are able to compete with gas engines already by 2010. In the pessimistic price development, the gas engines produce electricity at a lower cost until 2020. For commercial markets the investment cost of an industrial SOFC power unit should be below 1500 €/kW. Analysis is done without possible incentives that could improve the competitiveness of fuel cell applications. Comparison of electricity production costs is presented in Fig. 4. The non-capital costs include system operation costs such as fuel and maintenance cost as well as fixed operational costs. Table 7 summarises the values in detail.

7. Technical development of the SOFC system

Development phases of different fuel cell technologies were analysed in the study. It was concluded that the SOFC units are 5–10 years behind the PAFC and MCFC development. Out of the alternative SOFC technologies, tubular units may enter the commercial market for industrial applications several years earlier than planar SOFC. However, SOFC technology, especially planar, has a significantly better development potential than the other mentioned technologies [1]. An estimate over the future technological development of the planar SOFC technology is presented in Table 8.

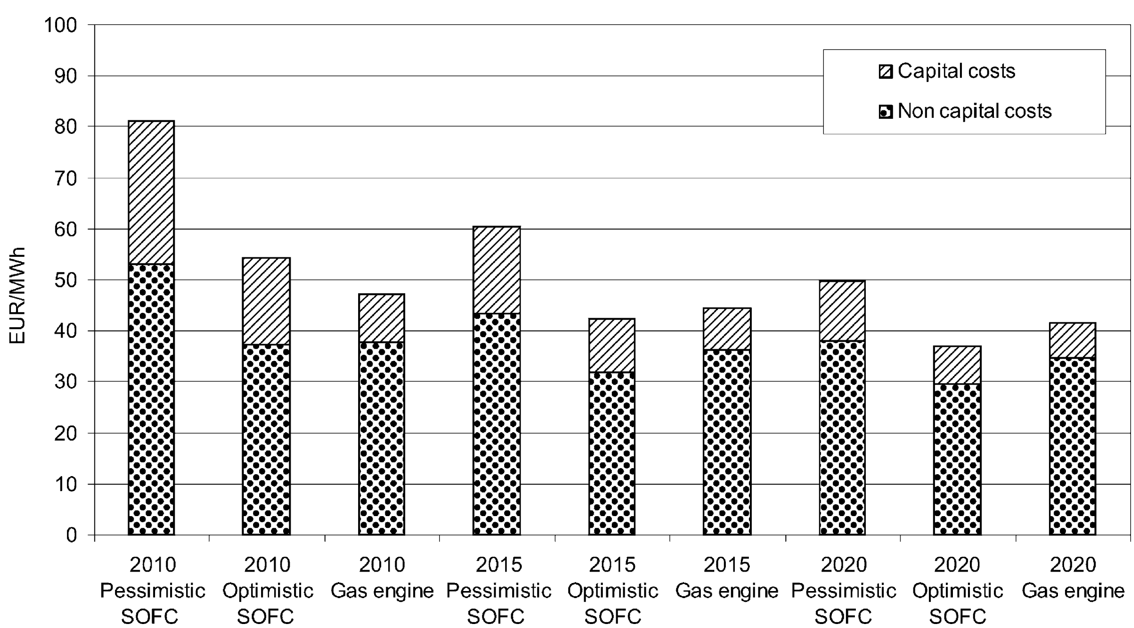

Fig. 4. Generation cost of electricity in natural gas-fuelled SOFC and gas engine CHP plants at 2010–2020 [1].

Table 8
Estimated development schedules of SOFC planar technology in demonstration or pre-commercial units [1]

	2000–2005	2005–2010	2010–2015	2015–2020
Stack unit size (kWe)	1–5	5–25	25–50	50–100
Max. unit size	5–20 kWe	50–250 kWe	0.25–1 MWe	2–5 MWe
Stack lifetime (h)	2000	16,000	40,000	50,000
Stack degradation (%/1000 h)	2	0.5–1	0.2–0.5	0.1
Electrical efficiency (%)	43	48	52	55
Co-generation efficiency (%)	80	85	88	90

7.1. Cost-saving potential

The current cost level of the SOFC technology is too high to become commercially competitive with the existing commercial technologies. Based on this study and the several discussions with different technology developers the manufacturing cost of the system can be decreased to an attractive level in the future.

Fuel cell stacks are the major cost item in the system. The current stack cost estimate is based on the manufacturing volume of 25 MW/a, which already requires an automated manufacturing process. The cost should decrease with increased production volumes and competition. Also, development of several new stack technologies may have a significant influence on the future stack cost.

Since the system control is the second largest cost item, it should have considerable cost saving potential. In serial production, the system control equipment will be based on integrated PC cards in-stead of the currently used PLC equipment. The cost development is also supported strongly by the general development of automation and control technologies. The cost of system control can also be decreased by simplifying the control logic and by reducing the number of components.

Equipment for power electronics is based on the currently used standard products and the future saving potential is highly dependent on the general cost development within the technology.

The fuel cleaning and reforming technologies are under development. It is estimated that in the future sulphur tolerance of the stack will increase together with oxidation tolerance. In addition, alternative fuel reforming technologies, which are simpler and more sulphur tolerant than the adiabatic steam reforming, are developed. The oxidant resistant technology would decrease the system cost if purge gas and back-up power systems could be avoided. The de-sulphuriser can be avoided when a more sulphur tolerant anode together with alternative fuel reforming technologies have been developed.

The other trend in the fuel reforming is the increased share of the internal fuel reforming which occurs in the stack. Internal reforming reduces the stack temperature and decreases the need of cooling air, which on the other hand will reduce the size of the recuperators and manifolds. In general, the thermal management of the system can be further optimised.

With these currently foreseeable cost saving potential a investment cost level of 1500 €/kW should be achievable.

8. Conclusions

Based on this conceptual study, the planar SOFC technology shows outstanding properties, such as high efficiency and low emissions, for stationary CHP applications. In mass manufacturing the technology has also potential to become cost competitive in several commercial and industrial applications. It is estimated that demonstration and pre-commercial markets for commercial and industrial applications are established during the time frame of years 2005–2015. During these development phases public support and incentives are needed for the commercialisation of the technology.

Both SOFC-related and more conventional technology within BoP have to be further developed and optimised. In addition to the critical development items in cells and in stack, the importance of the BoP components should not be underestimated. From cost and system efficiency point of view the air blower, cathode heat exchanger and power electronics as well as control system equipment are critical areas.

The expected high reliability and durability of SOFC products will be demonstrated on the up-coming demonstration and pre-commercial markets. Not only technical and commercial barriers have an influence on the market development of SOFC products. Some of the other areas that will have an influence on the future SOFC markets are development of clean fuels, future emission legislation and taxation as well as development of de-centralised energy markets.

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