ELFORSK

SOFC pilot system

Prestudy

Elforsk rapport 05:07

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Förord

Denna rapport är framtagen inom Elforsks program för Stationära bränsleceller av ABB AB, Corporate Research och Institutionen för Värme- och Kraftteknik, Lunds Tekniska Högskola. Syftet är att beskriva förutsättningarna för att utveckla och demonstrera en SOFC-bränslecell genom ett nordiskt samarbete.

Projektet har följts av styrelsen för programmet Stationära bränsleceller; Britt Marie Bertilsson, MISTRA, Per Carlson, Göteborg Energi, Eva Fontes, Catella Generics, Bernt Gustafsson, Energimyndigheten, Per Holmberg, Vattenfall Utveckling, Göran Lindbergh, KTH, Peter Lund, Helsingfors Tekniska Högskola, Bertil Nygren, ABB Group Services Center Corporate Research, Claes-Göran Olsson, FMV, Bengt Ridell, Carl Bro Energikonsult, Lars Sjunnesson, Sydkraft, Per Sjöbom, Fortum T&M och Tord Torisson, LTH.

Stockholm februari 2005

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Programområde El- och värmeproduktion

Summary

The intention of this pre-study was to investigate the conditions of projecting, organizing, financing, constructing and finally evaluation of a small (5 kW) SOFC demonstration plant. It should be situated on Swedish soil and running on natural gas.

Discussions between Haldor Topsoe, Wärtsilä and ABB have open the possibilities to create a "Nordic SOFC-project" with the final goal to build a field demo of 50kW and connect it to the Swedish natural gas grid. The total cost for such a plant, including four consecutive project phases, is estimated to approximately 30 MSEK and would take 4-5 years.

During the first phase, 12 months, a detailed engineering study of a 5 kW pilot plant is suggested. An industrial consortia agreement including project finance of the whole project will be finalized. Binding quotations from subcontractors, preferentially Nordic industry will be negotiated. Estimated cost 1 MSEK, financed by Elforsk. Topsoe and Wärtsilä will at own costs give in-put to this phase based on the experiences from ongoing project at Espoo.

If a positive result is got from phase one the pilot plant will be built and placed in the Department of Heat and Power Engineering at LTH. Including evaluation this phase will take 18 months and will cost approximately 10 MSEK. Finance by Nordic Energy Funds is suggested.

In phase three critical components for a 50 kW demo plant will be developed. The finance and ownership of the demo plant will be finally settled. The cost of this 12 months phase is estimated to be 5 MSEK. Finance by Nordic Energy Funds is suggested.

In phase four the 50 kW demo plant will be built and evaluated in 18 months to a cost of approximately 15 MSEK. Finance by Nordic Energy Funds is suggested.

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1 Background

Fuel cells can in a global perspective significantly increase its share in electricity generation. Major arguments in favor of the fuel cell technology are the potentially high efficiency and environmental advantages. This is valid for large as well as small-scale systems (< 1MW).

The importance/place of the fuel cell technology in the Swedish stationary energy system is unclear today. The "Life Cycle Cost" will be the determining factor. Polymer fuel cells, PEMFC, show a potential of low investment costs if the technique gets a break through in the transport sector. Solid oxide fuel cells, SOFC, have due to its high efficiency the possibility to result in low operation costs. High efficiencies can especially be achieved in combined systems with both fuel cells and heat engines.

Fuel cells have in different rounds and by initiative of ELFORSK been tested in Sweden. Phosphoric acid fuel cells, PAFC, were evaluated the last time at the end of 1990's. The system worked technically satisfying; however the costs were estimated to be too high also in the future. PEMFC are currently being tested by ELFORSK in a research plant at KTH.

ABB and Fortum are performing tests on a PEMFC demonstration plant in Hammarby Sjöstad. The City of Stockholm, office of LIP, will evaluate SOFC in some small-scale plants also in Hammarby Sjöstad. However no installation of those SOFC-stacks has been made yet due to delayed delivery.

As seen from international activities, the research resources are shifted towards PEMFC and SOFC. One way for Sweden to take part in this development is to actively participate in studies of pilot/demonstartion plants. No large-scale effort exists today within Sweden to develop SOFC-stacks. Swedish initiatives are mainly found within universities for example in performing modeling studies. The main interest of the technology comes from potential end users and system integrators.

A potential manufacturer of SOFC-stacks can be found in Denmark at Haldor Topsoe. According to experiences from the PEMFC plant at KTH, it is utterly important for the building of a pilot plant to have intimate cooperation between the fuel cell supplier and the other component manufacturers. The intention of this prestudy was to investigate the conditions of projecting, organizing, financing, constructing and finally evaluation of a small (5 kW) SOFC demonstration plant. It should be situated on Swedish soil and running on natural gas. Thanks to the good relations already established between Haldor Topsoe and the Department of Heat and Power Engineering at LTH, it has been logical to try to formulate a broad project with development from the Nordic countries. The results of those efforts are given below.

2 Vision, goal and activities

The vision is that Sweden in the future will generate an important part of the electricity and heat in SOFC-hybrid plants.

The purpose of the prestudy is to engage Swedish and Nordic industry and Swedish universities in a joint-project with applied SOFC development activities in order to even further put Sweden on the "SOFC-map". The activities are intended mainly to be financed by Nordic governmental research funds.

The project goal of the prestudy is to define and specify a test system of an atmospheric stand-alone SOFC plant and/or, depending on the results generating during the project, a SOFC- hybrid plant. The defining and specifying will be done in natural development steps from pre-engineering to a final test system. The test system shall as far as possible be manufactured with components from Nordic industry.

Defined part project goals are:
- to present a detailed formulation of the whole project with a time schedule and a resource plan
- to find a suitable project organization including industry and university
- to suggest and establish the financing of the project

The most important activities within the prestudy are:

1. to achieve a detailed project description for the realization of an atmospheric SOFC demonstration plant on Swedish soil, being the development step 1 of the pilot plant

2. to achieve a detailed test program for the development step 1

3. to achieve a detailed plan for a simulation work for the integration of SOFC with a heat engine (gas engine or gas turbine, development step 2)

4. to summarize the involved parties' (main project) expectations of the demonstration project

5. to achieve an established finance and time plan for both development steps

6. to achieve a state-of-the art description of the SOFC technology and a draft description of a future SOFC-hybrid plant for demonstration purpose (provided that the atmospheric demonstration plant shows positive results).

3 Results

The results from the prestudy are presented as different activities, acitivity 1-6 below.

3.1 The atmospheric SOFC (activity 1)

The idea is to in a first step build a SOFC pilot plant of about 5 kW electrical output and to have it ready by 2005. Such an atmospheric system has been investigated.

The following items have been studied:
Detailed system description of an atmospheric SOFC pilot plant, process layout, components etc.
Specifications on the components from different manufacturers
Discussions around quotes, collection of and list the preliminary quotes.

3.1.1 System description - atmospheric SOFC

An atmospheric SOFC system is considered with net power output of 5 kW. The system configured is designed for simplicity and having minimal moving parts (due to high temperatures in the system). These are critical for maintenance and longevity for the power plant. A simplified process flow diagram of the system with state points is shown in Figure 1 and the values for each point are given in Table 1. In the table the values in the brackets are given for an alternative 2 kW system.

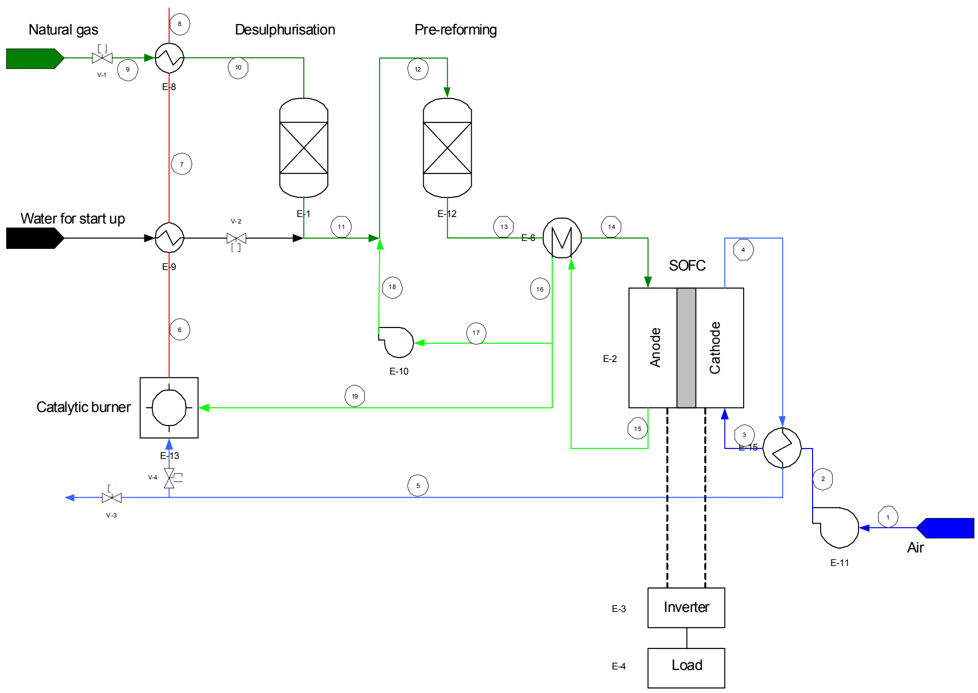

Figure 1: SOFC system with anode gas recycle blower. Reference[1]

In the system natural gas is preheated and desulphurised. During normal operation the fuel feed is after desulphurization mixed with anode effluent which is partially recycled in order to provide steam and heat for external reforming of the fuel; the remains is burned in a catalytic combustor together with the cathode off-gas. In the pre-reformer all heavy hydrocarbons are steam reformed to form a mixture of methane, hydrogen, carbon monoxide and carbon dioxide[1]. After pre-reforming, the fuel stream is heated in an anode recycle heat exchanger in order to increase the inlet fuel temperature to the required level. An additional electric heater (not shown in the figure) needs to be available in the system after the heat exchanger, in case the anode exhaust temperature is not high enough to bring the anode inlet temperature to the operating level.

On the cathodic side air is first compressed in a blower and preheated in a heat exchanger before it enters the fuel cell [1]. The cathode off-gas, which consists of depleted air, is sent partly to a catalytic burner together with the anode effluent [1]. The amount of the cathode off-gas sent to the burner is regulated by a control valve and it depends on the burners' outlet temperature which is fixed in the system. The feedback ratio of the recirculation loop is controlled by variation of rotational speed of the recycle fan. An exhaust gas heater boiler (not shown in the figure) is supplied to provide a source of steam for plant start up.

Table 1: State point estimates for a 5kW system with anode gas recycle blower (2 kW within brackets). The data is a combination of information taken from [1] and the calculations by the authors.

Stream	Mass flow (kg/s)	Pressure (Pa)	Temperature (°C)
1	0.02 (0.005)	101325	25
2	0.02 (0.005)	109699	67
3	0.02 (0.005)	108613	650
4	0.02 (0.005)	106483	750
5	0.02 (0.005)	105429	167
6	0.02022 (0.005)	103362	700
7	0.02022 (0.005)	102338	600
8	0.02022 (0.005)	101325	242
9	2.2e-4 (4.4e-6)	101325	25
10	2.2e-4 (4.4e-6)	100312	400
11	2.2e-4 (4.4e-6)	100312	400
12	4.4e-4 (8.8 e-6)	110796	600
13	4.4e-4 (8.8 e-6)	109699	500
14	4.4e-4 (8.8 e-6)	108613	650
15	4.4e-4 (8.8 e-6)	106482	750
16	4.4e-4 (8.8 e-6)	105417	600
17	2.2e-4 (4.4e-6)	105417	600
18	2.2e-4 (4.4e-6)	110796	600
19	2.2e-4 (4.4e-6)	105417	600

A critical component in this configuration is the blower for the anode gas recirculation. Since the first estimates of the temperature of this blower is pretty high (600°C) either a new design of the blower needs to be developed operating at such high temperature or an air cooler needs to be introduced in the system to protect the anode recirculation blower from excessive temperatures.

Alternatively, the anode recycle blower in the system could be replaced by an ejector, which can handle high temperatures. In order to achieve necessary driving pressure for the ejectors' motive flow, a fuel gas blower can be introduced upstream the desulphuriser. This concept is represented in Figure 2 and state point data given in Table 2. A possible problem with this system is that the ejector needs to be designed for operation at various flows ranges corresponding to the part load operation of the system. Further, a couple of high temperature valves are placed into a hot exhaust stream and a proper design of those is also required.

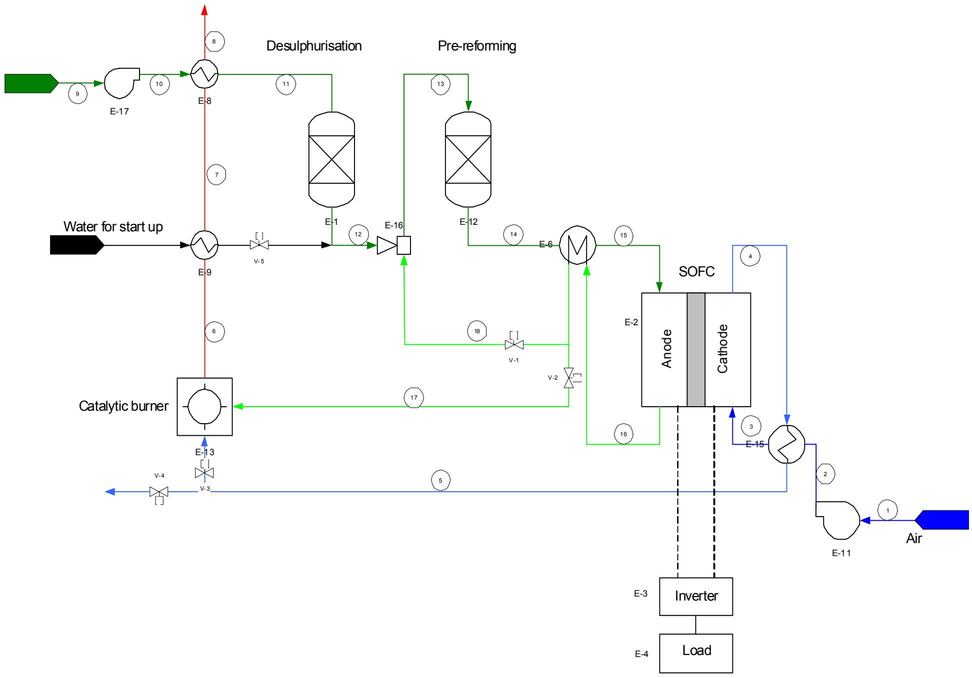

Figure 2: SOFC system with anode gas recycle ejector

3.1.2 Component specifications

The fuel cell stack

The fuel cell stack features the planar SOFCs with state-of-the art materials (based on earlier work together with Haldor Topsoe). The stack is designed to deliver 5 kW_e with capability of internal reforming of methane. It is based on anode supported technology with metallic interconnector. To construct an electric SOFC generator, individual cells are connected in series. A cell in such stack operates at 0.75 V, 85% fuel utilization and has an active area of 12x12 cm^2 [1]. The proposed fuel cell stack consists of about 200 such cells. Operational temperature of the stack is 750°C [1].

Table 2: State point estimates for 5 kW system with anode gas recycle ejector (2 kW within brackets)

Stream	Mass flow (kg/s)	Pressure (Pa)	Temperature (°C)
1	0.02 (0.005)	101325	25
2	0.02 (0.005)	116520	67
3	0.02 (0.005)	114500	650
4	0.02 (0.005)	112470	750
5	0.02 (0.005)	110440	167
6	0.02022 (0.005)	105378	700
7	0.02022 (0.005)	103350	600
8	0.02022 (0.005)	101325	242
9	2.2e-4 (4.4e-6)	101325	25
10	2.2e-4 (4.4e-6)	122606	42
11	2.2e-4 (4.4e-6)	120580	400
12	4.4e-4 (8.8 e-6)	110570	400
13	4.4e-4 (8.8 e-6)	118550	600
14	4.4e-4 (8.8 e-6)	116530	500
15	4.4e-4 (8.8 e-6)	114500	650
16	4.4e-4 (8.8 e-6)	112470	750
17	2.2e-4 (4.4e-6)	110440	600
18	2.2e-4 (4.4e-6)	110440	600

Pre-reformer

The pre-reformer is introduced in the plant to completely remove all higher hydrocarbons from the natural gas feed to avoid possibility of higher hydrocarbons decomposing and causing carbon deposition in the high temperature sections of the anode side of the plant. The pre-reformer is required typically to convert 30% of the natural gas supplied to hydrogen. The remaining methane is converted directly in the fuel cell.

To eliminate the need of an external steam supply, during normal operation, the pre-reformer is positioned in the anode recycle loop to utilize the steam in the recycle. The pre-reformer needs to be designed to operate at very low pressure drop (about 2 %) to enable recirculation fan to achieve the flow rates required, and to operate adiabatically with a reforming (outlet) temperature of 500°C [1].

Desulphuriser

Natural gas contains sulphur compounds which could poison both the reformer catalyst and the nickel anode of the fuel cell installed in the plant. To achieve optimum activity the desulphurization vessel should be designed to operate at the temperature of 400°C [1].

Catalytic burner
The main design criterion for the combustor is that, ideally, it should burn anode gas composition corresponding to the full range of operating conditions of the SOFC. The properties of the anode and cathode exhaust gases depend on many factors, including the mode of operation of the fuel cell. The operation with the anode recycle corresponds to the gas composition having very lean flammable gas. Therefore the option of catalytic combustion has been proposed. The combustor should be designed for the exhaust gas temperature of 700°C [1].

Heat exchangers
In the systems there are several heat exchangers which are required to operate at high temperatures. (Anode gas pre-heating, cathode gas pre-heating, water vapor for start up and inlet fuel pre-heating). Both compact heat exchangers and shell and tube heat exchangers can be considered for the test rig.

Anode gas recirculation blower
Design operation of the system assumes recirculation of 50 % of the anode exhaust mass flow. The design temperature for the recirculation blower is about 600°C. It is required to overcome lower pressure drops with relatively small process gas flow rates. Further it is required that the blower is protected of leaking the combustible gases into the surroundings, which implies design of a special seal.

Boost ejector
As mentioned, given the operating temperature a boost ejector is required instead of the blower for anode gases recycle. The boost ejector is a custom made item. Detail design followed by testing and tuning would be required.

Air blower
The design of the blower requires overcoming lower pressure drops with relatively small flow rates.

Valves
In the system with anode gas recycle ejector there are two valves (V1, V2), which are exposed to higher gas temperature (600°C). All valves (in both systems) are of control type except for the valve, which controls the water supply for pre-reforming. This is a simple on/off valve, which is closed during normal operation when water for the pre-reforming is provided by anode gas recirculation.

Startup Boiler
An exhaust gas driven boiler is supplied to provide a source of steam for plant start up. The steam outlet is piped to the mixer valve where the steam is mixed with desulphurized fuel gas prior it enters the pre-reformer. Boiler operation is manually controlled for the short time that it is needed. The boiler is used only for plant startup and is drained and laid up dry for a prolonged period of inactivity during normal plant operation.

3.1.3 Potential suppliers

In table 3 and 4 potential suppliers have been summarized for the two different system designs. Labels given in column called "Tag" can be found in figures 1 and 2 respectively.

Table 3: Hardware suppliers for system with anode recycle blower

Equipment List		
Tag	**Description**	**Manufacturer**
E-1	Desulphuriser	Haldor Topsoe (DK)
E-12	Steam reformer	Haldor Topsoe (DK)
E-6	High temperture HEX	Laminova (S)
E-3	Solid Oxide Fuel Cell	Haldor Topsoe (DK)
E-15	High temperture HEX	Laminova (S)
E-11	Air blower	Autorotor (S)
E-3	DC/AC inverter	ABB (S)
E-10	Gas blower	Autorotor (S)
E-4	Load bank	ABB (S)
E-9	High temperture HEX	Laminova (S)
V-3-4	High temperture valves	YPAB AB (S)
E-13	Catalytic burner	Haldor Topsoe
E-8	High temperture HEX	Laminova (S)

Table 4: Hardware suppliers for system with anode recycle ejector

Equipment List		
Tag	**Description**	**Manufacturer**
E-17	Natural gas blower	Autorotor (S)
E-1	Desulphuriser	Haldor Topsoe (DK)
E-16	Ejector	Körting (G)
E-12	Steam reformer	Haldor Topsoe (DK)
E-6	High temperture HEX	Laminova (S)
E-3	Solid Oxide Fuel Cell	Haldor Topsoe (DK)
E-15	High temperture HEX	Laminova (S)
E-11	Air blower	Autorotor (S)
E-3	DC/AC inverter	ABB (S)
E-4	Load bank	ABB (S)
E-9	High temperture HEX	Laminova (S)
V-1-4	High temperture valves	YPAB AB (S)
E-13	Catalytic burner	Haldor Topsoe
E-8	High temperture HEX	Laminova (S)

The most critical component is the SOFC-stack itself. There are some potential suppliers around the world. However, as we believe it is of importance that the supplier is an active partner in project and in evaluations, the number of suppliers gets smaller.

The best supplier/"partner" would be **Haldor Topsoe**, due to all the earlier connections and the network established between LTH and Topsoe and due to their outspoken technological achievements. Stacks with a large number of cells have for instance shown good results at 750C. Further due to the recent co-operation agreement between Topsoe and Wärtsilä of Finland a very strong and broad consortium could be formed if also Wärtsilä would be engaged in the project. (See further details under 3.1.5 below)

Rolls Royce would be another alternative to deliver SOFC-stacks. However the impression is that Rolls Royce does not have as much resources for e.g. R&D and system integration as Topsoe has. Topsoe has since a long time established co-operation with Risoe and has own deep knowledge of fuel processing.

Regarding other companies/suppliers, e.g. **Global Thermoelectric** that has shown good performance on their stack characteristics, there will be potential co-operation hindrance due to the physical distance. The company has also recently been taken over by Fuel Cell Energy, which has its main business on Molten Cabonate Fuel Cells, MCFC. Today it is unclear to what extent they are willing to co-operate with other companies on SOFC-development as there has been a reduction of personnel at former Global Thermoelectric.

3.1.4 Meetings and discussions with potential suppliers and host of the pilot plant

The work in the pre-study has been concentrated to establish a strong Nordic industrial consortium consisting of;

- Wärtsilä as the system integrator,
- Haldor Topsoe as the producer of fuel cell stack, fuel processor and catalytic burner,
- ABB as the producer of process automation, electric converter and electric equipment for electric grid connection and
- Sydkraft as the owner of the field demonstrator.

LTH has been actively involved in this process and will have an active role in hosting and evaluation of the pilot plant.

Contacts with potential producers of other components of the fuel cell system have been done by telephone and E-mail contacts. A number of potential suppliers have been localized and some names are given in table 3 and 4. Some preliminary quotations have also been achieved. More research is to be made in next phase when also the knowledge from set-up at Espoo Finland is considered.

During the remaining part of this chapter the proposed main project members and their products are described. Sydkraft will become more actively involved in the project the closer one comes to the 50 kW field demo.

3.1.4.1 Wärtsilä/Haldor Topsoe cooperation

Haldor Topsoe has previously entered into an agreement with Wärtsilä to cooperate on fuel cell technology. The development program aims to bring to the market highly efficient, clean and cost competitive fuel cell products with power outputs above 200 kW for distributed power generation and marine applications.

The program combines the competence of both companies. Wärtsilä will apply its know-how in decentralised power plant applications and marine propulsion systems. Haldor Topsoe has long experience and a leading position in catalyst development for oil industry and in development of planar solid oxide fuel cell (SOFC) technology.

The fuel cell development program is part of Wärtsilä´s strategy to provide environmentally friendly solutions for customers with various power generation needs. SOFC technology will provide products for cogeneration applications with ultra-low emission levels, high efficiency and outstanding reliability.

Wärtsilä is the leading global ship power supplier and a major provider of solutions for decentralised power generation and of supporting services with its head office in Helsinki, Finland. Wärtsilä supplies engine room solutions, integrated propulsion systems, main and auxiliary engines and maintenance for all types of vessels. For the power generation market Wärtsilä delivers power plant solutions from 1 to 300 MW.

Haldor Topsoe is a global technology and catalyst company focused on heavy chemical, petrochemical, refinery, environmental and energy conversion related technologies, with its head office in Lyngby, Denmark. Topsoe has worked on the development of fuels cells and fuel processing systems for a number of fuel cell technologies for years. In the past five years, development has concentrated on solid oxide fuel cell (SOFC) technology. Topsoe's position within SOFC technology is to a significant degree based on 10 years participation, also financially, in the Danish SOFC Fuel Cell program led by the Danish National Laboratory at Risø and supported by the Danish government and the Danish energy sector.

Haldor Topsoe is now developing and plans to manufacture cells and stacks for all relevant applications and segments for SOFC systems.

3.1.4.2 ABB

Electric converters have very often been a problem in fuel cell development projects. Most resources have been put to the stack itself while converters have been neglected. This fact has been realized in the PEMFC-area where now the tendency is that the plant integrator makes their own, dedicated converter.

The Advanced Power Electronics department of ABB in Turgi has developed and tested converter-systems in field, from 80 kW and upwards, with very good results. The applications have been distributed power generation, power quality, different fuel cell technology power plants and battery storage. Converter efficiencies of as high as 98% have been verified. The efficiency target stated by Wärtsilä, > 95%, will according to ABB be no problem if a dedicated design is made of a specific power range ABB ensures that a converter with high efficiency and reliability can be designed as soon as the market asks for it. Time to market for a power electronic-system is approximately one year compared to ten years of a whole FC-system.

ABB has also a strong position in wind power and its integration to the grid, in sizes from 500kW and upwards. The production of converters for that business is in ABB DRIVES in Finland. Small 5kW converters could in principle also be used in the same platform as for wind applications with an addition of a chopper and some filters.

The Industrial^{IT} System 800xA by ABB could due to its scalability, flexibility and full redundancy very easily be used in the development stage, the discussed pilot plant at LTH, as well as in the pre- and the final commercial stage.

Electrical equipment for grid connections, safety equipment, breakers, monitoring, metering etc. are standard products with the ABB product range and all are compatible with the 800xA system.

In long term development projects the Research organization of ABB will coordinate the activities within the ABB group

3.1.4.3 Department of Heat and Power Engineering at LTH

Researchers at the Department of Heat and Power Engineering at LTH have found that the following questions would be answered with the use of the proposed 5 kW pilot plant:

Modeling:
Compared to the experimental data, from the pilot plant, are the developed mathematical models for the components for the system as well as for the control procedures reliable enough for system studies?

- Obtain/complete basic understanding of components performance and the system boundaries for development of reliable steady state physic based models.
- Obtain fundamental understanding of the components interactions, which will add to development of reliable dynamic models of the components & system that aid in control design and analysis.
- Obtain knowledge for interfaces between models at different scales/resolution (i.e. all components in the system do not necessary need to be described with high-order models. High order models can be combined with low order models. If enough performance data (experimental) exist for certain components consider use of empirical/semi-empirical models.)

Performance:
What is the optimal design and operation of kW size stationary SOFC systems?

- Can such system meet demand of energy and efficiency?
- Can such system meet dynamic load demands?
- What is the system ability to operate under off-design conditions?
- Based on the practical experience from the demo system operation can the configuration of the plant be improved?

Can **fuel processing** unit provide necessary service function to the stack?

- What are the key parameters for the reformer-stack integration? (start-up and shut-down procedures, range of operating parameters, pressure drop, thermal management)
- What is the transient characteristic of the fuel processing unit?
- Can the fuel processing unit provide the required amount of the fuel to meet the load and fuel utilization?
- Which problems occur with hydrocarbon operation of low-temperature stack, interaction issues stack-reformer?
- What is the multi-fuel capability of the system (different types of natural gas, biogas)?

Can **afterburning unit** provide necessary service to the system? (burning of the lean fuel with cathode gas recycle)

Power Conditioning issues:

- How to design cost effective inverters?
- What requirements are put on voltage stabilizers for SOFC systems?
- What requirements are put on transformers for SOFC systems?
- The interaction between the grid and the system.

Cleanup of Fuel, Air and Water issues:

- What are the lower limits for impurities of the gases/liquids fed into the stack? (Sulfur removal, deionization of water, particles in the air etc.)
- What is the lifetime of different components and can those components which are critical for the lifetime of the system be identified within short time demo projects? What is the long-term stability of sensors (H_2) in the system?
- What is the availability/reliability/maintenance/endurance of the plant?

Heat exchanger issues:

Heat exchangers play vital role in overall operation of a fuel cell plant. They are employed for heat and mass transfer in cooling of fuel cell stack, heating and cooling of fuel/oxidant and other auxiliary fluid streams, humidification and water removal and waste heat recovery. The heat and mass transfer devices for fuel cell systems require unique design and fabrication approaches due to stringent performance and durability and cost constraints. Compared to automotive, aerospace and other applications, design requirement for fuel cell heat exchangers are demanding and vary significantly due to different types of fuel cell systems which functions over wide range of operating conditions.

The close interaction of thermal hydraulic and thermal structural design with manufacturing engineering calls for integrated product development strategies. For high temperature application thermal radiation might be a key issue in the design process as well as material selection, corrosion and durability issues. Fouling might be another problem for non-clean gases. In any case the balancing between heat transfer and the pressure drop penalty has to be considered in selection and design of appropriate heat exchangers.

The access to a small scale SOFC demonstration and test facility, properly instrumented, offers unique opportunities to carry out experimental investigations on heat exchangers in fuel cell systems as validation and support for heat exchanger thermal design procedures and advanced numerical techniques such as CFD tools. Enhanced heat transfer topics and emerging design approaches such as microscale surfaces or devices should be included.

3.1.5 "Nordic SOFC-project"

End of April 2004 a meeting was arranged with representatives from Haldor Topsoe, Wärtsilä, ABB and LTH. Sydkraft was also invited but could not participate. However prior to the meeting there was a statement from Sydkraft that the company is willing to integrate a future SOFC field-demonstrator into their energy system, natural gas and electric distribution grid.

The result from that meeting, and a number of telephone-meetings in May, was that no direct hindrance was found to start a new common project with the object to develop the "Balance of Plant", BOP, of a future combined heat and power SOFC-system. In order to avoid double work, it was further decided that the experiences from the already ongoing development project run by Wärtsilä at Espoo ought to be used if a new project would be launched. All hardware has been installed and the experimental evaluation has started in August 2004.

Following preliminary "Nordic SOFC-project" plan was sketched.

I. Phase one, Detailed pre-engineering of a 5 kW atmospheric pilot plant.
Time: Q304-Q205.
Project leader: ABB; working parties: ABB, Wärtsilä, Haldor Topsoe and LTH.
Budget and finance: 1 MSEK from STEM/ELFORSK fuel cell program plus own work and expenses from Wärtsilä and Haldor Topsoe related to their in-put of experiences from the project at Espoo.

Activities and goals:
- Negotiation of a development agreement between all parties, including e.g. secrecy and finance of the whole project, and make it ready to be signed
- Adopt system design, component choice and evaluation program, see chapter 3.2 below, in accordance to the results from the ongoing prototype project at Espoo
- Get firm quotations from other component producers
- Simulation work of SOFC-hybrid run by LTH in co-operation with Wärtsilä and Haldor Topsoe , for details see chapter 3.3 below
- Define a simulation development project on integration of SOFC distribution generation plants into the established energy grids together with IEA-department at LTH, could be a common project together with researchers at VTT
- Initial market study, gather knowledge from the parties
- Detailed budget and time schedule for phase two

II. Phase two, Erection and evaluation of the 5 kW pilot plant

Time: Q305-Q406
Project leader: ABB; working parties: ABB, Wärtsilä, Haldor Topsoe and LTH.
Budget and finance: approximately 10 MSEK, financed by Nordic Energy Funds plus own work and expenses of industry parties.

Activities and goals:
- Purchase of components and assembly of 5 kW pilot plant at ABB Corporate Research in Västerås
- Transfer of plant to LTH and function test
- Evaluation of components and whole system of 5 kW pilot, LTH project leader of this part
- Simulation work on SOFC distribution generation plants into the established energy grids
- In parallel establish simulation work on HCCI (Homogenous Charge Combustion Ignition) as candidate for bottoming SOFC cycle. Perform experimental evaluation of HCCI engine fuelled with SOFC effluent (without direct HCCI-SOFC coupling; gas composition to HCCI is simulated from experimental results of 5 kW SOFC pilot.
- Summary of critical tasks to finalize a 50 kW field demonstrator
- Detailed budget and time schedule for phase three

III. Phase three, Detailed pre-engineering of a 50 kW field demonstrator
Time: Q107-Q407
Project leader: Wärtsilä; working parties: ABB, Wärtsilä, Haldor Topsoe, Sydkraft and LTH.
Budget and finance: approximately 5 MSEK, financed by Nordic Energy Funds plus own work and expenses of industry parties.

Activities and goals:
- 80 kW PEMFC converter by ABB and other critical components adopted to 50kW
- Detailed pre-engineering of field demonstrator
- Agreement with Sydkraft to test and evaluate field demonstrator
- Firm quotations from other component producers
- Continued market study
- Finance of phase four solved
- Detailed budget and time schedule for phase four

IV. Phase four, 50 kW field demonstrator
Time: Q108-Q209
Project leader: Sydkraft; working parties: ABB, Wärtsilä, Haldor Topsoe, and Sydkraft.
Budget and finance: approximately 15 MSEK, financed by Nordic Energy Funds plus own work and expenses of Sydkraft.

Activities and goals:
- Erection and evaluation of 50 kW field demonstrator

3.2 Test program of the atmospheric SOFC (activity 2)

3.2.1 Design of preliminary test program

The experimentation and operation program has been aimed at two different targets:

Target 1
To explore design needs and operation of the BOP equipment needed to carry out the service function of a 2-5 kWe stack and the stack interaction with the BOP system. Further, issues with the BOP system with scaling up the SOFC technology need to be identified. This target is set by stack supplier who needs to identify the problem areas to be resolved and make improvements in follow-on designs.

The following service functions must be provided to the stack and need to be demonstrated by the test rig:
- Heating up the stack to a temperature necessary for the reactions start.
- Heating up the process gases (air and fuel) to inlet temperatures.
- Maintaining the inlet gas temperatures at the inlet levels at all ranges of electric load.
- Altering the fuel and air supply to the stack in response to changes to electric load while maintaining inlet and outlet temperature constraints of the system.
- Providing the heat to the stack when it is not enough internally generated heat to maintain operating temperature.
- Providing the steam for the reforming reactions.
- Maintain certain fuel utilization.
- Burning off the non reacted fuel.
- Maintain the stack at hot-hold and standby conditions.

Target 2
The test rig will been designed to acquire the largest possible amount of experimental data, necessary for verification of computer simulation models being used in research. This target is set by model developers.

The experimental program includes investigation of:
- Designed/Proposed control strategy
  - Start-up from cold
  - Start-up from hot standby
  - Shut-down
- Predicted performance
  - Steady state operation
  - Load following and response to change in set points
- Fault conditions

3.2.2 Design of preliminary measurement system

Temperature measurement

Thermocouples and resistance temperature detectors (RTDs) are good sensors for monitoring both the stack temperature and the temperature of the incoming reactant gas streams. Characteristic points for the temperature measurement in the system are indicated with 'T' in the schematic (Figure 3).

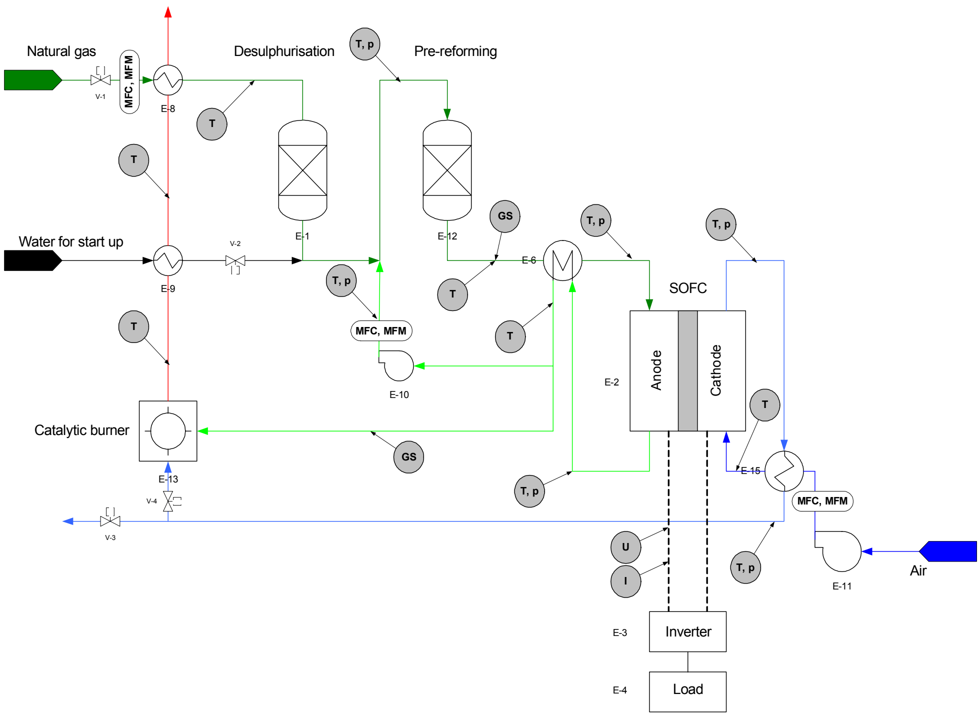

Figure 3: Measurement points specification for the system with anode recycle blower. (Similar points are valid for the system with anode recycle ejector.)

Pressure measurement

Pressure is measured with a pressure transducer and signal conditioning and the characteristic points in the system are indicated with 'P'.

Flow measurements

Fuel and airflow rates are typically measured with mass flow meters (indicated with 'MFM') that generate pulses at a rate proportional to the gas flow rate. These pulses are then monitored by a counter/timer board and scaled by software into a flow rate. Mass flow controllers (indicated with 'MFC') are used in the system for control of:

- Cathode air flow control. The main objective of this controller is to maintain the desired temperature gradient over the cell and maintain the stack operational temperature.

- Recycle flow control. The main objective of this controller is to maintain certain steam to carbon ratio necessary to prevent carbon deposition in the reformer.
- Anode flow control. The main objective of this controller is to maintain certain (constant) fuel utilization over variety of stack loads.

The gas analysis system
Gas samples ('GS') are taken from two points in the system, a point after the pre-reformer and a point after the fuel cell for analysis of the pre-reformed gas and the anodic exhaust.

Electrical test system
The electric test system consists of electronic load DC bank and voltage sensors. DC load bank can be set to draw a specific current from the stack and thus allows the power output of the stack to be varied. Voltage sensors record the voltage produced by each cell in the stack, with all voltages read to an electronic data logger. The combined system allows the current-voltage (I-U) characteristics of the stack to be measured.

3.2.3 Cost estimation for system operation and maintenance during the evaluation period

From the experiences of the PEFC-pilot plant in KTH one learned that the ownership of the unit as well as the maintenace and running costs have to be settled early in the project. A limited life-time of the pilot-plant ought to be defined and all the associated costs from planning, erection, evaluation, running and finally dismantling has to be budgeted. An alternative could be to sell the complete unit if an interested buyer would appear. The experiences are however that new technologies tend to develop so fast that a research pilot will very soon become too old to maintain.

3.3 Plan for the simulation project SOFC- hybrid (activity 3)

The purpose of this project is to develop a conceptual design for a power system that utilizes a hybrid cycle with solid oxide fuel cell, capable of achieving efficiencies higher than a conventional power system in the same power range. An adjunct objective is that the system yields a reduced cost-of-electricity (COE) relative to the COE for the conventional power system. To realize the project aims, the following work packages sequence are defined:

1. Definition of a bottoming cycle to SOFC. This first part of the project will consist of a literature search to identify different hybrid -cycles which had been considered for solid oxide fuel cells in previous reported work (with steam turbine, gas turbine, HCCI bottoming cycle etc.). This includes both theoretical studies and eventual demonstration units. Important input to this analysis will consist of the results from the evaluation of 5 kW demo units regarding the quality (composition, temperature) of the fuel cell exhaust gas which needs to be utilized in the bottoming cycle. A summary table with main system specifications (type of the bottoming technology, system power output, efficiencies, advantages, technological risks, etc.) will be populated for each system identified. Next step would be an evaluation of a system suitable for 'Proof of system' concept, where a system from the table will be either

accepted in its original design or design improvements will be made in order to simplify the concept for a future demo unit.

2. Model improvements for the system components and development of economic models. In order to further evaluate the thermodynamic performance of the chosen system, mathematical models of the components missing from the model library needs to be developed and the existing models needs to be completed to account for dynamic behavior. Both design and off-design models are under consideration. Economic models for system components need to be developed for evaluation of the systems cost.

3. In collaboration with industry model validation for the system components will be conducted.

4. Specification of the system size for demonstration. Based on the state-of-the-art technology and availability for the main components in the system a practical size of the system will be chosen.

5. Thermodynamic optimization and basic control design. The objective of this stage is to size the system components and to arrive at operating conditions required to unit to meet the preferred performance characteristics.

6. Preliminary evaluation of investment cost.

7. Draw up an outline system design for demo unit based on existing or pre-commercial technology.

8. Draw up a power system site arrangement.

9. Outline the basic control procedures for start-up, shut-down and identified possible failure modes.

3.4 Expectations of the project (activity 4)

Expectations from the industry of the proposed “Nordic SOFC-project” differs somewhat.

Sydkraft, representing the power industry, would like to:

- find out the maturity of the SOFC technology and learn if it could be an economic part of the future Swedish energy system as being the host of the proposed 50 kW CHP-unit
- learn the producers view of the technology
- understand how a SOFC-system interacts with its own infrastructure, power-, heating- and natural gas net
- get access to experimental verified models
- get access to a test facility to test own ideas and components
- become a member of a new net-work from producers to users

- get leverage on own R&D resource
- get contacts with future employees.

Wärtsilä, as the system integrator can with this project:

- find out the maturity of the SOFC technology
- to increase the experiences from various BoP components used in the system
- to learn about an alternative SOFC system compared to their own one
- to initiate SOFC focused development of power electronics, automation and BoP components
- to follow-up and co-operate around modelling activities at LTH
- in the long term to demonstrate own products on commercial bases
- learn critical component producers view of the technology
- understand how a SOFC-system works in a power and gas net
- get access to experimental verified models
- get access to a test facility to test own ideas and components
- become a member of a new net-work from producers to users (FMV, utilities)
- get help to market the technology (e.g. the ABB market channel)
- get leverage on own R&D resource
- get contacts with future employees.

Haldor Topsoe, as the deliverer of the critical SOFC-, reformer- and catalytic burner component will:

- find out the maturity of the SOFC technology,
- learn other critical component producers view of the technology, converters, heatexchangers, high temp. components, etc
- further the development of critical BOP components through establishment of an additional test rig
- deliver complete stack unit(s), desulfurisation and prereforming catalysts plus catalytic burner(s) to pilot and demo plants
- further strengthen existing collaboration with Wärtsilä and LTH
- learn about the capabilities of ABB within the field of instrumentation,electric converters, grid connection etc.
- enhance dialogue with the gas supliers and end users, in this case mainly Sydkraft.
- understand how a SOFC-system works in a power and gas net
- get access to experimental verified models
- get access to a test facility to test own ideas and components, stack, reformer, catalytic burner
- become a member of a new net-work from producers to users (FMV, utilities)
- get leverage on own R&D resource
- get contacts with future employees,

and finally will **ABB**, as a deliverer of other critical components:

- find out the maturity of the SOFC technology
- get deliveries of components, converter, control, other electrical equipment to pilot and demo plants

- learn other critical component producers view of the technology
- understand how a SOFC-system works in a power and gas net
- get access to experimental verified models
- get access to a test facility to test own ideas and components
- become a member of a new net-work, from producers to users
- get leverage on own R&D resource
- get contacts with future employees.

An expectation from the university side on the proposed "Nordic SOFC-project" also differs with respect to the different units engagement during the project. The university LTH will be the main academic partner and it will gain from this project mainly during the building and evaluation of the pilot-plant. Its involvement during the field demo phase will be settled during the run of the project. Most probably new academic project ideas will evolve, e.g. a pilot SOFC-hybrid.

LTH will, as being the host of the 5 kW atmospheric pilot plant:

- become an important R&D player of the SOFC-technology, it will cover the whole range from fundamental material research to applications
- get access to a test facility in which they can:
- verify experimentally dynamic and static system models
- verify experimentally heat- and mass transport models
- study interactions with the power net, strengthen their eu-deep membership
- test own new ideas
- use as a resource in future eg. EU-projects
- use in basic education
- attract new researchers
- become a member of a new net-work from producers to users

Academic networking.

Strong academic networking, with the goal to further strengthen the SOFC R&D in Nordic countries, is one of the results the research partners are expecting.

At LTH, three groups have been involved in the activity already in this pre-study and will be even more engaged in phase one. From the department of Heat and Power Engineering the two divisions *Thermal Power Engineering* and *Heat and Mass Transfer* have been actively involved. From the department of *Industrial Electrical Engineering and Automation (IEA*) an interest to work with power electronics and automation has been expressed.

LTH has also already started with a background work to identify and approach the research groups among the Nordic universities and research centres for discussions on the future collaboration. Several groups has been identified and contacted while meetings with some of them have been already held. Common project and publications have already been agreed with *Department of Energy and Process Engineering, NTNU, from Norway (Prof. Olav Boland),* on model benchmarking and dynamic modelling of

SOFC systems. This group will have an indirect access to the experimental data from this collaboration project.

Since 1998 collaboration already exists with *Risoe National Laboratory in Denmark and LTH* on SOFC modelling and it will continue exploring the possibility to connect to the Universities in Denmark this centre has strong relation to.

Department of Chemical Engineering and Technology at KTH in Sweden (Division of Energy Systems, Division of Applied electrochemistry and *Division of Chemical Reactor Engineering)* has already expressed interest in joint work on fuel cell system and component modelling as well as *Chalmers University of Technology (Prof. Bengt-Erik Mellander)*.

Through the collaboration with *Wärstilä in Finland (Masoud Rokni and Timo Kivisaari)* contact to *VTT* will be established as well as to the *University of Willmanstrand*, which already has joint project with the department IEA at LTH in the field of Power Electronic for distributed power.

This Nordic Academic Network is going to become strong and effective and an important partner to the Nordic Industrial Group active in the field of SOFC.

3.5 Finance and time plan (activity 5)

See chapter 3.1.5 above

3.6 State-of-the-art description (activity 6)

SOFC technology basic principle

In the SOFC, fuel and oxidant produce direct current by combining electrically across the solid oxide electrolyte. The basic principle is given in Figure 4. Oxygen fed to the cathode accepts the electrons from the external circuit to form oxygen ions. The oxygen ions are conducted through the electrolyte to the anode.

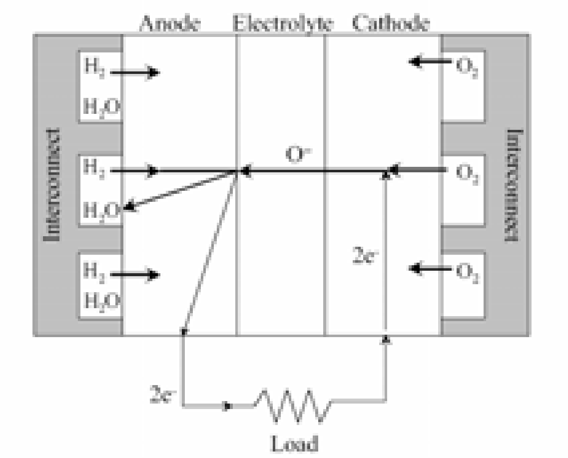

Figure 4: Basic principle of solid oxide fuel cell

At the anode, oxygen ions combine with hydrogen in the fuel to form water, liberating electrons. Electrons flow from the anode through the external circuit to the cathode. The water leaves the reaction vessel as steam, together with the excess oxygen and unused fuel.

Although the equilibrium potential of the fuel cell reaction ($H_2+O_2 \rightarrow H_2O$) may be more than 1V losses due to polarization and internal resistance in a typical operational system limit output to 0.7 – 0.8V. The performance will degrade subsequently to a small extent over the lifetime of the cell.

Features of fuel cells
Some general characteristics offered by fuel cells are:

- *Efficiency*: 40-65% electrical (fuel to electricity) efficiency in simple and hybrid combination and up to 85% (thermal) efficiency in combined heat and power applications.
- *Fuel Flexibility*: Uses commonly available liquid fuels such as gasoline, diesel, hydrogen, LNG, methanol, coal-gasified fuel as well as natural gas and propane.
- *Quiet operation*: No moving parts in the energy converter
- *Modularity*: The performance (efficiency) is unaffected by size of the system. The size of the system can easily be changed due to modular design of the power units.
- *Distributive Energy*: Makes electricity available very close to the load it serves and to remote locations with no access to the transmission grid. Avoids transmission line losses.
- *Environmental*: Avoids formation of nitrogen oxide NO_x, reduces emission of greenhouse gases particularly carbon dioxide (CO_2) thereby reducing global warming and air pollution.
- *Energy Security and Reliability*: Enables sitting flexibility, and alleviates transmission and distribution (T&D) grid congestion which reduces infrastructure vulnerability.
- *Power Generation Choices*: Makes available more power generation choices for residences and businesses. Grid integration and grid independence assists deregulation

Some general drawbacks of fuel cells include

- *Cost*: Market entry cost is at present to high.
- *Acceptance*: unfamiliar technology to the power industry
- *Infrastructure*: no infrastructure for fuel (except natural gas in some locations)

Properties of SOFC compared to other fuel cell technologies
For any fuel cell, compromises exist between achieving higher performance by operating at higher temperature or pressure and the problems associated with the stability/durability of cell components encountered at more severe operation conditions. Low temperature fuel cells (polymer electrolyte fuel cell, alkaline fuel cell, phosphoric acid fuel cell) require noble metal electrocatalysts to achieve practical reaction rates at the anode and cathode, and H_2 is the only acceptable fuel. With high-temperature fuel cells (molten carbonate fuel cell, intermediate temperature solid oxide fuel cell, solid

oxide fuel cell), the requirements for catalysis are relaxed and the number of potential fuels expands. The operating temperature above 800°C allows internal reforming, promotes rapid kinetics with non precious materials, and produces high quality byproduct heat for cogeneration or for use in a bottoming cycle.

The electrolyte is the predominant means of characterizing a fuel cell. In the SOFC (solid oxide fuel cell) there is no liquid electrolyte with its attendant material corrosion and electrolyte management problems. As with other cell types, it is necessary to stack the fuel cells in order to increase the voltage output. The solid-state character of all components means that, in principle, there is no restriction on the cell configuration. Cells are being developed in some different configurations; flat plane, tubular, flat tubular and monolithic. The flat plate, the tubular and flattened tubular configurations are shown in figure 5. Present SOFC designs make use of thin film concepts with the deposition of the components (electrode, electrolyte and interconnect material) one on another and sintered, forming the cell structure.

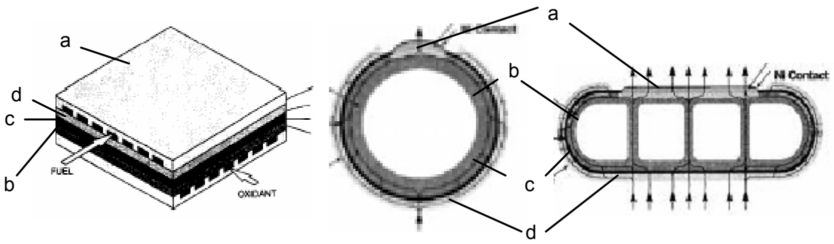

Figure 5. Flat, tubular and flat tubular configurations, with interconnect (a), air electrode (b), electrolyte (c), and fuel electrode (d). Reference [3] and [4]

The most developed SOFC is the Siemens Westinghouse Power Corporation (SWPC) tubular cell. A major advantage of this configuration is that relatively large tubular cells can be constructed in which the successive active layers can be deposited without chemical or material interference with the previously deposited layers. The support tube is closed at one end. This configuration results in eliminating seal problems between adjacent cells. However, because the current flows in the circumferential direction of the electrodes, a relatively large ohmic loss exist, which places an upper limit on the tube diameter. In a flattened tubular design, better performance has been achieved. In order to reduce the production costs SWPC focuses on cheaper methods for the preparation of powder and to develop alternative coating methods. The purpose of developing new coating methods is to avoid expensive electrochemical vapor deposition (EVD) and to use plasma spraying instead.

The flat (bipolar) plate configuration, permits a simple series electrical connection between cells without the need for external cell interconnections such as those used with the tubular configuration. Gas leaks with compressive seals are difficult to prevent and thermal stresses at the interfaces between dissimilar materials must be accommodated to prevent mechanical degradation of cell components. The production methods used today such as, “band” casting or strip rolling, are somewhat cheaper then those methods used for the tubular configuration. The interconnect is the most expensive component in the cell unit in a flat plate configuration. The demand that the interconnection must be impervious to fuel and oxidant gases and contain gas channels, makes this component to the thickest in the cell.

Another important distinction is the method used to produce hydrogen for the cell reaction. Hydrogen can be reformed from natural gas and steam in the presence of a catalyst starting at a temperature of 650°C. In SOFC (solid oxide fuel cell) operating temperatures are high enough that reforming reactions can occur within the cell, referred to as internal reforming. The cost of an external reformer is eliminated and system efficiency is improved because there is an effective transfer of heat from the exothermic cell reaction to satisfy the endothermic reforming reaction. But on the other hand a more complex cell configuration is needed and increased maintenance issues. This provides developers of SOFC the choice to use either an internal or external reforming approach. Carbon monoxide (CO), hydrogen gas (H_2) and hydrocarbons such as methane (CH_4) can be used as fuels in SOFC. It is feasible that the water gas shift involving CO ($CO + H_2O \rightarrow H_2 + CO_2$) occurs at high temperature environment of SOFCs to produce H_2, which is easily oxidized at the anode. The direct oxidation of CO in fuel cells is also well established. It seems that the reforming of CH_4 to hydrogen predominates in the present SOFCs ($CH_4 + H_2O \rightarrow 3H_2 + CO$).

The high working temperature in combination with a pressurized stack makes it possible to directly connect the SOFC to a gas turbine process. The stack replaces the burner. Very high efficiencies can be achieved in this way. The high operation temperature of the SOFC places stringent requirements on its materials. The materials used in the cell components need to be chemically stable in oxidizing and reducing environments, conductive and thermo mechanically compatible. The thermal expansion coefficients of the individual cell components must be closely matched to reduce stresses arising from thermal expansion. The development of suitable low cost materials and the low cost fabrication of ceramic structures are presently the key technical challenges for the SOFC technology. Table 5 provides a brief description of the different components, their respective function, and the materials used in the currently most developed SOFC (tubular configuration).

Field of application and economic prerequisites of the SOFC technology

The major applications for fuel cells are as stationary electric power plants including cogeneration units, as motive power for vehicles, as on-board electric power for space vehicles or other closed environments. A higher electricity price can be accepted by markets such as hospitals, central computer processing units, hotels and universities which need reliable back-up power (“premium power”). But for a broader market introduction, a decrease of the fuel cell system cost is necessary. A large part of the investment cost consists of the manufacturing cost which in turn depends on the manufacturing method and the design of the system.

Table 5. Components, properties and the materials used in the SOFC tubular configuration of Siemens Westinghouse. EVD=electrochemical vapor deposition Resistivities at 1000°C

Component	Properties	Current Status
Anode	High electronic conductivity	Ni/Y2O3 stabilized ZrO2 cermet
(fuel electrode)		~150 μm thickness
	Mass transport of reactant and product gases	20-40% porosity
		3×10-6 Ω cm (electronic resistivity)
		12.5×10-6 cm/cm°C
		Deposit slurry, EVD fixed
Cathode	High electronic conductivity	Doped LaMnO3
(air electrode)	Mass transport of reactant and product gases	~2 mm thickness
		0.01 Ω cm (electronic resistivity)
		30-40% porosity
		11×10-6 cm/cm°C
		Extrusion, sintering
Electrolyte	High conductivity of O2-	Y2O3 (8 mol%) stabilized ZrO2
	Low electronic conductivity	30-40 μm thickness
	Thin to avoid ohmic losses	10 Ω cm (ionic resistivity)
		10.5×10-6 cm/cm°C
		EVD
Cell interconnect	High electronic conductivity	doped LaCrO3
		~100 μm thickness
		1 Ω cm (electronic resistivity)
		10×10-6 cm/cm°C
		Plasma spray

Potential fields of application for the SOFC and the SOFC/GT technologies are mainly for small scale power heat generation up to 1 MW and decentralized power heat generation between 1-30 MW. The larger market of power heat generation between 30 MW and several hundred MW is estimated to be out of reach today, due to that conventional technologies (larger gas turbines, natural gas heated combined cycle power plants, coal fired condensing power plants etc.) result in high enough efficiencies and are less expensive. Gas cleaning is also more economically defendable for larger conventional power plants.

Industrial gas engines and small gas turbines have been identified as the main competitors to SOFC. The advantages of micro turbine generators (small gas turbines with high speed generators) compared to SOFC are their compactness and lower cost. A comparison between SOFC, micro turbines and gas engines (up to 1 MW) is shown in Table 6. The specific volume of the fuel cell is expected to decrease in the future due to

an improved electrode performance, resulting in a decreased cell area and an increased effect density (kW/m^2)

the development of an alternative interconnect-design. The interconnect in the planar configuration is the main contributor to the cell volume.

that a successful application of pressure of the cells would result in improved performance of the electrodes which would make possible to make smaller cells.

It is also important to note that the outlet temperature of the Topsoe stack is said to be as low as 750 C, which open up the possibilities to build a more cost effective power unit.

Table 6. Comparison between SOFC, micro turbines and gas engines.
Reference: [4]

	SOFC	Gas turbine	Gas engine
Effect$_{out}$	100-1000 kW		
Efficiency$_{el}$	47-60%	25-35%	30-40%
Specific cost	Goal: 1500-1000 $/kW	1200-800 $/kW Goal: <500 $/kW	1200-600 $/kW
Emissions	NO_x <1 ppm CO <1 ppm	NO_x <25 ppm CO <240 ppm	NO_x <115 ppm CO <195 ppm
Noise	<60 dB	<65 dB	<103 dB
Outlet heat	<1000°C	<700°C	<300°C
Specific volume	800 L/kW	30 L/kW	50 L/kW
Status	Demonstrations	Prototypes and first products available	Products are established

Capacities above 1 MW up to 30 MW is assessed to be the most interesting field of application for SOFC due to that the competition from conventional technology is lower. The interesting applications within this size are different district heating and district cooling projects, power plants for isolated and rural areas and decentralized power heat production. Many power producing companies have realized the advantages of placing the power heat generation near the load by achieving a decreased cost related to transmission and distribution. The dominating technologies within this field are larger gas engines and gas turbines. A typical investment cost for a gas engine is about 1000 $/kW. Gas engines can reach efficiencies from 40% to more than 45%. If heat energy is recovered 50% efficiency can be reached. The performance can decrease a few % as actions are taken to reduce emissions. Advantages with gas engines compared to SOFC are longer lifetime, fuel flexibility, and low investment and maintenance costs. The disadvantages with gas engines compared to SOFC are relatively high emissions and slightly lower efficiencies. Gas turbines of these sizes have developed very fast lately and continue to do so. Efficiencies between 25-38 % have been reported (ref 17 in [4]). The most important progress is related to environmental performance. Emission reduction of NO_x can be achieved by water and steam injection into the burning chamber (<25 ppm), selective catalytic reduction (<25 ppm), "dry low NO_x" combustion system (<10 ppm) and catalytic combustion (<10 ppm). With a further development of the catalytic combustion technology the NOx emissions can be reduced to levels characteristic for fuel cells (~ 1 ppm).

A combination of SOFC and micro turbine (SOFC/GT hybrid), results in both increased efficiency and lower emissions. The efficiency is assessed to be two times higher than for a micro turbine. The manufacturing costs of a SOFC/GT hybrid (size 2-5 MW) and a stand alone SOFC (size 5 kW) is assessed to 700-1000 $/kW and 350 to 600 $/kW, respectively (ref 36 in [4]). The investment costs of both SOFC and SOFC/GT are still too high as compared to the conventional techniques used today.

National and international activities

The SOFCs have been developed and demonstrated during more than 10 years but have not yet been commercialized. The development is going on in many different places USA, EU, Australia and Japan. USA is leading. The SOFC technology is far away from fully developed. There are many possibilities to choose between: the flat, the tubular and the flat tubular configuration. A summary of developers are given in figure 6.

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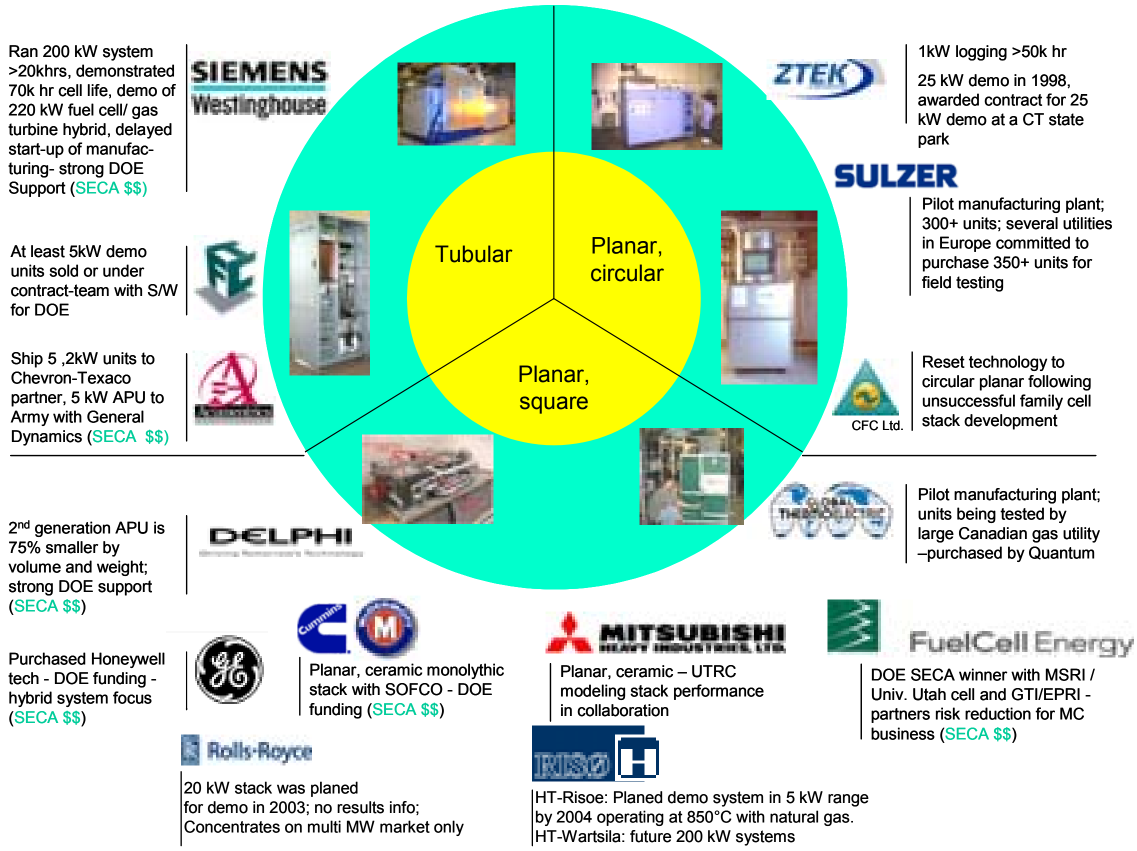

Figure 6: SOFC developers around the world

Solid State Energy Conversion Alliance (SECA) - USA

The Solid State Energy Conversion Alliance (SECA) was initiated in 1999 as a unique alliance between government, industry, and the scientific community. SECA's goal is to accelerate the commercialization of low-cost ($400/kW) SOFCs in 3kW – 10kW range as quickly as possible over the next decade. It is a collaborative effort coordinated by two of the U. S. Department of Energy's national laboratories – the National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL) – supported by the DOE's Office of Fossil Energy, NETL's Strategic Center for Natural Gas, and other government agencies. The industrial teams are Acumentrics (10 kW module for residential markets, military applications, broad-band communication networks and as auxiliary power units for heavy-duty trucks), Cummins

Power Generation (10-kW net generator system for use in recreational vehicles, commercial vehicles and telecommunications emergency power applications using propane and natural gas as the fuel), Delphi Automotive Systems (5 kW system for distributed power generation and automotive auxiliary power units), Fuel Cell Energy (10 kW, low temperature SOFC for transport, military and stationary applications), General Electric Power Systems (low-cost, high-performance 3 to 10 kW SOFC system suitable for a broad spectrum of power generation applications) and Siemens Westinghouse Power Corporation (7-10 kW combined heat and power system for residential applications and auxiliary power units 3-10 kW for transportation applications).

Siemens Westinghouse (USA/Germany) is the company which has worked the longest time period with SOFC and is considered to be leading. Siemens Westinghouse worked originally with the tubular configuration which successively was developed to the flat tubular configuration, called High Power Density (HPD) tubes.
Siemens Westinghouse has delivered about ten test- and demonstration plants between 1 to 200 kW. The 200 kW plant is also the first hybrid plant with integrated micro turbine. The hybrid system has been tested being tested at the National Fuel Cell Research Center in Irvine, California. Siemens Westinghouse's plan to build a new FC-factory with 500 employees have failed due to technical problems and failing FC-market.

Acumetrics (USA), with the three strong owners Texaco, NiSource (the second largest natural gas distributor in the USA) and Northeast Utilities has delivered two 5 kW SOFC to General Dynamics (APU) and Texaco (UPS). The most nearby plans are focused on typical APU and UPS systems up to 100 kW but for the future there are ambitions for stationary systems for DG applications.

CFCL, Ceramic Fuel Cells Limited, (Australia) is owned by some of the greatest power companies in Australia. CFCL has chosen a planar configuration for their SOFCs and a suitable size of 40 kW (20 pieces of 2 kW all-ceramic SOFC stacks with internal reforming) for a future Australian market introduction initially aimed at stand-alone systems. Recently the company had excellent results with test runs on its technology. The building of a manufacturing plant is planned to be established in 2004 and a market introduction is planned to 2005.

FCT, Fuel Cell Technologies, (Canada) is involved in some development of the SOFC technology but has so far mainly worked with SOFC on the system level using stacks from Siemens Westinghouse. The ambition of FCT is to deliver systems with sizes between 1-50 kW, i.e. smaller systems than Siemens Westinghouse. The first prototype was taken under operation in 2002. FCT is a leading developer of small-scale power systems (1 kW to 50 kW) that provide on-site generation of electricity. They have contracts for about 20 systems for field tests which were due to be delivered in 2003. Several of them were delivered but two of them which were aimed for Hammarby Sjöstad has so far not been delivered. One so called beta-unit has been delivered to an outside customer.

FCT and Siemens Westinghouse Power Corporation (SWPC) have a joint development agreement. The goal the two corporations set is to produce 5-kW fuel cell units that provide electricity and heat for homes, farms, and commercial buildings in both remote and urban locations.

The collaboration between FCT and Ford has resulted in an industrial application of solid oxide fuel cell (SOFC) technology that transforms a waste into useful energy. The pilot system consumes emissions from Ford's vehicle paint shop and turns them into electrical energy and heat for the facility.

The delivery of reliable power from fuel cells was demonstrated in Canada. FCT reports that "FCT keeps lights on during power blackout. We believe that in future there will be many more fuel cell systems similar to this operating in Canada," said company spokesperson Barbara Haines. "This was a visible demonstration of the potential for FCT's fuel cell products. We have to get the costs down and the availability of product up. Then this technology becomes a viable option for homeowners and commercial enterprises for reliable power," she said.

Global Thermoelectric, GT, (Canada) aims at the small-scale power heat market (residential fuels cells) but is also interested in remote power. GT uses the flat configuration with very thin film of electrolyte in order to reach operation temperatures of 700°C where metallic materials can be used. GT has recently finished a manufacturing plant where cells corresponding to 70 MW can be produced. Some prototype systems have been tested on the laboratory. Some field systems of sizes 2-5 kW were planned to be tested in 2003. GT recently announced that the first systems were under delivery to Enbridge, the largest natural gas distributor in Canada.

Rolls-Royce, RR, (Great Britain) has developed a configuration in between planar and tubular which they call Integrated Planar Solid Oxide Fuel Cell (IP-SOFC). RR focuses on low costs and electricity generation. They work mainly with hybrid systems with an integrated gas turbine. They believe that costs of 2000 $/kW soon can be reached and for a long term perspective that 1000 $/kW can be reached. Systems of the sizes 500 W are being tested in the laboratory. A 20 kW system was planned for 2003 and a first pressurized system expected for 2004. If everything pursues as planned, a 1 MW hybrid system (800 kW fuel cells + 200 kW gas turbine) could be realized in 2006.

Sulzer-Hexis, S-H, (Switzerland) works with the concept "residential fuel cells" of 1 kW_e for the building sector. S-H is one of few companies which have achieved testing of their systems on field. They have a pre-commercial system called "HXS 1000 Premiere". The "HXS 1000 Premiere" has an electrical efficiency of 30% and a total efficiency of 85%. In a new version "Gallileo", a new design, for instance a new reformer, will be used in order to reduce costs. Gallileo is planned to be introduced on the market in 2005.

The New Energy and Industrial Technology Development Organization, **NEDO, (Japan).** Several companies have been involved in the NEDO programs. Mitsubishi Heavy Industries and Kansai Power Company seem to be strong actors of SOFC in

Japan. The extent of SOFC work has increased lately compared to MCFC. Both flat and tubular configurations of SOFC are developed. For the tubular configuration, they are aiming at pressurized plants for gas turbine combinations. A pressurized 10 kW tubular system was tested in 1998 for totally 7000 hours. A pressurized tubular system (10 kW) with internal reforming was tested for 750 hours in 2001. Several different designs are studied for the flat configuration. The most interesting is the so called MOLB (Mono Layer Built). The cell material has a three dimensional structure which creates a large active surface as well as acts as flowing channels for air and fuel. Several prototypes of 10 kW has been built and tested for 7000 hours.

Haldor Topsoe A/S, HTAS, (Denmark) has worked on the development of a number of fuel cell technologies and fuel processing systems for years. In the past five years, the development has been concentrated on the SOFC technology (planar configuration). HTAS's position within the SOFC technology is to a significant degree based on 10 years participation in the Danish SOFC Fuel Cell programme led by the Danish National Laboratory at Risö, supported by the Danish government and the Danish energy sector. A pilot plant for production of anode supported cells has been established within the HTAS and Risoe National Lab consortium (ref. [1]). The pilot plant has been in operation for more than a year. An atmospheric SOFC system (250 kW) based on HTAS/Risö cell and stack technology has been analyzed. The commercialization of products is planned for at the end of this decade. The road to commercialization will go through tests of larger stacks, a 5 kW pilot system, a 50 kW prototype system and finally a 250 kW demonstration unit. A hybrid, i.e. a SOFC in combination with a heat engine will be investigated and pursued if cost and risk analysis is in favor. In 2002 HTAS and Wärtsilä announced a common development work of SOFC for stationary and marine applications (200+ kW). Wärtsilä will apply its know-how in decentralized power plant applications and marine propulsion systems. Wärtsilä is the leading global ship power supplier and a major provider of solutions for decentralized power generation and of supporting services.

3.6.1 Usefulness

Summary of Swedish and international market conditions of the SOFC technology (reference [2])
The fuel cell market is expected to grow as the technology matures and the cost decreases. The fuel cell technology is considered to be one of the future technologies for electricity and heat production. The international market is expected to be extensive and especially if hydrogen gas can be produced in a competitive and renewable way. The technology is expected to have a break through with complete competitiveness in 2020 (ref. [5]). If the cost of electricity in Sweden continues to be low, the technology may not result in a large impact in the Swedish energy system. However, the Swedish industry can still be an important manufacturer of surrounding equipment for fuel cell systems.

How well a SOFC plant can systematically fit into an energy supply system? (Ref. [2])
The profit and degree of complication achieved with a plant included in the central electricity network compared to driven stand alone.

Due to the fact that the fuel cell systems today are not designed to fulfill the building's demand of heat and power instantly, either energy storage or grid connections are required together with the fuel cell systems. Normally additional burners and electricity trading with the power grid, or use of batteries for stand alone applications solve this. The heat demand of a residential building is very much dependent on the outdoor temperature and therefore varies over the year. The electricity demand varies only slightly over the year but varies more during the day and night. For office buildings the major electricity demand is during the day and for residential buildings the demand is highest during the morning and the evening. A typical residential building in the south of Sweden has an annual electricity and heat demand of 5000 kWh_{el} and 20000 kWh_{heat}, respectively. The relation between the amount of electricity and heat produced from a SOFC fuel cell system is about 2.2/1 (el/heat).

A fuel cell system connected to the power grid could possibly be used as a frequency regulator or for voltage control.

How the heat energy generated from the system is best gained, if the heat need varies greatly over the year/ day and night

A lower fuel cell system cost is achieved (Swedish circumstances; low electricity cost, much higher heat need compared to electricity need, high investment cost, high natural gas cost) if the system is dimensioned to satisfy the need of electricity and not the need of heat.

Where does decentralized electricity and heat production fit in and how is it administrated/ controlled? For which niche applications can this technology be interesting? In an industrial perspective, the Swedish market is small. Therefore the analysis should be broadened to also include at least Scandinavia or Europe.

For customers

- who need extremely high availability of electricity (Peak power and Premium power)
- who need low emissions and independence is highly valued
- at locations where the power grid is weak and there are high risks for disturbance in the electricity delivery
- without connection to the power grid (islands or isolated cottages)(Remote power)

Examples: applications military, telecommunication, supervision.

To what extent can a SOFC plant serve as reserve power/ emergency power with the expected start times? What fuels are necessary under these circumstances?

The response time is too long for fuel cell systems with fuel reforming in order to momentarily adjust to large electricity load changes. This can be solved by the use of hydrogen storage or storing electricity in flywheel or super capacitors.

4 Proposals for continuation, summary

A general conclusion is that a demonstration of 5 kW SOFC-system is feasible/realistic within 2 years, based on the findings of this study (maturity of the SOFC technology and BoP components). There is further a strong interest from Nordic industry in conducting a larger scale demo unit. Therefore we suggest the following plan:

During the first phase, 12 months, a detailed engineering study of a 5 kW pilot plant is suggested. An industrial consortia agreement including project finance of the whole project will be finalized. Binding quotations from subcontractors, preferentially Nordic industry will be negotiated. Estimated cost 1 MSEK, financed by Elforsk. Topsoe and Wärtsilä will at own costs, estimated to 200 kSEK, give in-put to this phase based on the experiences from the ongoing project at Espoo.

If a positive result is got from phase one the pilot plant will be built and placed in the Department of Heat and Power Engineering at LTH. Including evaluation this phase will take 18 months and will cost approximately 10 MSEK. Finance by Nordic Energy Funds is suggested.

In phase three critical components for a 50 kW demo plant will be developed. The finance and ownership of the demo plant will be finally settled. The cost of this 12 months phase is estimated to be 5 MSEK. Finance by Nordic Energy Funds is suggested.

In phase four the 50 kW demo plant will be built and evaluated in 18 months to a cost of approximately 15 MSEK. Finance by Nordic Energy Funds is suggested.

4.1 Test sites

According to discussions with Sydkraft/Sydgas a test site within its distribution grid is possible for the 50 kW demo plant.

Vattenfall has decided to concentrate its fuel cell development work in Germany.

5 Administration of this pre-study

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Economy:

Department of Heat and Power Engineering, LTH	100 kSEK
ABB AB, Corporate Research	300 kSEK

6 References

Reference: [1] J. Palsson, J.B. Hansen, N. Christiansen, J. U. Nielsen, S. Kristensen, Solid Oxide Fuel Cells – Assessment of the Technology from an Industrial Perspective, Risoe International Energy Conference, 19-21 May 2003, Denmark)

Reference [2]. Bränsleceller för småhus Sverige. Teknik, ekonomi och miljöaspekter, Elforsk rapport 03:04, Bengt Ridell, Cecilia Wallmark, Kjell Jonasson, Urban Axelsson, Anders Holm, Anders Johnsson, Jonas Greberg, 2003.

Reference [3]. Fuel Cell Handbook, EG&G Services Parsons Inc. Science Applications International Corporation, 2000

Reference [4]. Statusrapport År 2000: Teknik, Mognad, Ekonomi för SOFC och Hybrid SOFC/GT System, Jens Pålsson och Azra Selimovic

Reference [5]. Forskning och utveckling inom energiområdet, Resultatredovisning 2003, Energimyndigheten

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