ETC
Battery and FuelCells Sweden AB

A technical report from the pilot study

Environmentally Adapted Power Production Onboard Ships

- A pilot fuel cell system with a 50 kW capacity

Matilda Sjöholm

December 2005

Abstract

The main idea in this pre-study is to look at the option to replace the combustion diesels engines for electricity production with fuel cells, when the ship Stena Jutlandica is in Gothenburg harbour. This to prepare for a potential second phase were such a system may be built. The electricity is needed for lamps, air-condition and other necessary functions in the boat, but also for running the fans during on and off loading.

In this study the main goal is to achieve a description of a possible fuel cell system; how it functions, how it can be adjusted to the boat application and what such a system might cost. The project is carried out by Swedish partners and as the fuel cell technology is still quite new most of the system projecting work is done for the first time in Sweden.

There are several partners involved in this technical part of the project. AGA is projecting the gas distribution and the adjustment of the gases to the fuel cell system. Stena is adjusting the fuel cell system to the boat. PowerCell is a potential fuel cell supplier and contributes to the project with a specification of the fuel cell stack. Processkontroll AB is a potential supplier for the complete system. They have contributed with a tender and a timetable for the construction of the fuel cell system. ETC Battery and FuelCells Sweden AB has served as the project manager. These companies has contributed with there knowledge in this project, which is summarised in this report.

The fuel cell type that is considered is called PEM (Proton Exchange Membrane) or PEFC (Polymer Electrolyte Fuel Cell). It's a fuel cell type that operates between room temperature and 90 ^{o}C. The hydrogen reacts with oxygen within the fuel cell. The emission is hydrogen, oxygen plus water generated in the process which is led out together with the oxygen. The system has a closed system of cooling water which removes the waste heat.

Because of the large amount of hydrogen required and the safety of the system, the choice of putting a hydrogen container next to a container for the fuel cell system was made. They are assumed to be placed on the weather deck. The fuel cell container is a 40'' ISO container which consists of three separate rooms with gas tight walls between them, the fuel cell room, the electricity room and the auxiliary system room.

The estimated investment cost for the suggested system is SEK 12 400 000. This includes the fuel cell container with its contents, hydrogen and air regulation and software to control the system. As this is a first prototype system many steps are done for the first time. Therefore the cost for the same system will decreases a lot after the first system is delivered. The cost for gases per year is SEK 946 000

which includes gases, gas transport and rent of gas container. If the gas is estimated as the only operation cost the variable cost for the produced electricity is SEK 6.30 per kWh.

The system efficiency is assumed to be 50-55 %. The fuel cell itself has an efficiency of 55-60 % then there are small losses for the DC/AC-conversion and the electricity the system required is drawn off.

Table of contents

1. Introduction 1
1.1. An introduction to fuel cells and the fuel cell system 2
2. A system adjusted to power production onboard ships 4
2.1. Specification of the fuel cell stack...4
2.2. The design of the fuel cell system 6
2.2.1. The fuel cell container 6
2.2.2. The water system 6
2.2.3. The gas system...7
2.2.4. The air system..7
2.2.5. The electrical system 8
2.3. Integration of the system onboard 8
2.4. Hydrogen distribution...9
2.5. System efficiency 11
2.6. The endurance of the system 12
2.7. Time table for constructing the system...12
2.8. The maintaining of the system...12
2.9. Safety and approval issues, rules and regulations 12
3. Cost estimation 14
3.1. The construction of a full 50 kW system...14
3.2. The cost to integrate the system to the system onboard 15
3.3. The operation cost 15
3.3.1. Cost for the hydrogen consumption...15
3.3.2. Cost for the nitrogen consumption 16
3.4. The total investment required and estimated operation cost 16
3.5. The system cost when more systems are ordered...16
4. Discussion...18

1. Introduction

In the pilot study, Environmentally Adapted Power Production Onboard Ships, one of the main goals is to achieve a description of a fuel cell system; how it functions, how it can be adjusted to the boat application and what such a system might cost. The project is adjusted to Swedish partners and as the fuel cell technique is quite new in Sweden most of the system projecting work is done for the first time. Adjusting the system to auxiliary power unit onboard boats is a quite new application, also from an international point of view.

The aim of this report is to deliver a good description of how such a system can be designed, what the time plan is and what service the system requires. This work is made to prepare for a second phase, when the system is going to be built. The paper also includes price estimation for the suggested system. This price is for a first prototype and includes all the planning and projecting expenses. To look at this project from an economic side, it is recommended to read the complete project report which includes a business plan is recommended to read.

When this work started a likely system design including necessary components was made. One of the first tasks was to find companies that were interested to participate in this pre-study as well as in a second phase. These companies has contributed with there knowledge in this project, which is summarised in this report.

There are several partners in this technical part of the project. AGA is projecting the gas distribution and the adjustment of the gases to the fuel cell system. Stena is adjusting the fuel cell system to the boat. PowerCell is a potential fuel cell stack supplier and contributes to the project with a specification of their stack. Processkontroll AB is a potential supplier for the complete system. They have contributed with a budget tenders and a timetable for the constructing of the fuel cell system. ETC Battery and FuelCells Sweden AB has served as the project manager.

The report starts with a small introduction of what a fuel cell is and the basic system that it requires. After that the results of this project is presented which includes information from the different partners. There is a specification of the fuel cell stack, the system, the fuel cell container and the hydrogen distribution. After that cost estimation is presented and than follows a discussion about this pilot fuel cell system that is adjusted to generate electricity onboard the ship Stena Jutlandica.

1.1. An introduction to fuel cells and the fuel cell system

A fuel cell is an energy converter that needs fuel to generate electricity. In this case the fuel required is hydrogen. When the hydrogen reacts with oxygen within the fuel cell the chemical energy in the fuel converts to electricity and heat. A basic system is shown in Figure 1.

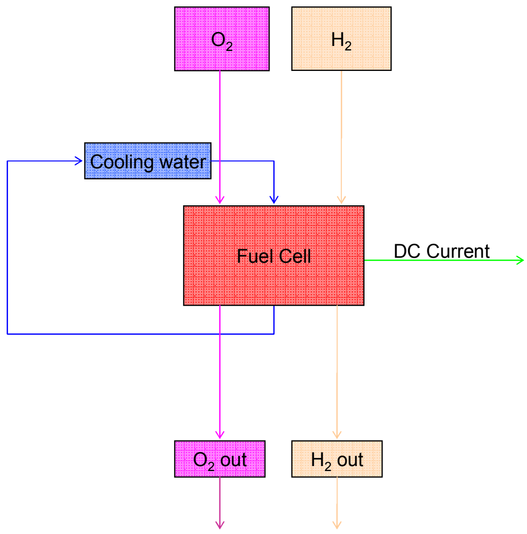

Figure 1 A basic illustration of a fuel cell system. The hydrogen reacts with oxygen within the fuel cell. The emission is hydrogen, oxygen plus the water generated in the process which is led out together with the oxygen. The system has a closed system of cooling water which removes the waist heat

The fuel cell type that is of topic here is called PEFC, Polymer Electrolyte Fuel Cell, also called PEMFC. It's a fuel cell type that operates between room temperature and 90 ^{o}C. Thanks to its low temperature there is no need of expensive materials that is obligated for the high temperature fuel cells. The working temperature area is also the reason why this fuel cell type is suited for applications with short start up time. But low working temperature also has its drawbacks. It makes the PEFC sensitive to impurity in the fuel. The purity of fuel, air and water is therefore of great importance.

The PEFC needs a moisturised membrane to obtain good ion conductivity and thereby generate a high amount of current. The fuel cell produces water at the cathode but this isn't enough to keep the membrane moisturised. A common method is to vaporise the gases before entering the stack.

For the fuel cell stack to achieve good performance the regulation of temperature within the stack is important. The amount of heat produced is in the same order as the electricity generated, as the electrical efficiency of the fuel cell is approximately 50 %. The heat is removed by cooling water circulating within the stack. The heat can than be removed with for example a heat exchanger.

Another thing that is of high importance in a fuel cell system is the regulation. The most obvious regulation required is the flow of the reactants. The amount of fuel is proportional to the current so when the load is change the flow must be adjusted. Other thinks such as the flow of the cooling water, measurements to contain good safety and on and off routines is also regulated within the system.

2. A system adjusted to power production onboard ships

The main idea in this project is to replace the combustion diesel engine for electricity production when the ship is in the harbour. The electricity is needed for lamps, air-condition and other necessary functions in the boat, but also for running the fans during on and of loading.

The technology part of this pre-study is adjusted to a 50 kW fuel cell system. According to Stena, the full power required is 1,500 kW. Even this is not enough during peak load but enough to generate APU for 95 % of the time. During peak load a combustion engine may contribute to the power production.

The ship Stena Jutlandica is in Gothenburg harbour for a period of 45 minutes at the time and returns there 3 times a day. This is the most important time for a non emission electricity production. It is also of interest to use the fuel cell during the passage into Gothenburg harbour. This adds 60 minutes each way. The time to aim at is therefore 8 h and 15 min per day. During this estimation only time spent in Swedish water has been taking under consideration. This choice is made because of the limit in hydrogen storage and the fact that this is a Swedish pilot project.

Because of the large amount of hydrogen required and the safety of the system, the choice of putting a hydrogen container next to a container for the fuel cell system was made. They are assumed to be placed on Stena Jutlandicas weather deck.

2.1. Specification of the fuel cell stack

The fuel cell type of interest is the PEFC. A potential supplier of such a fuel cell stack is PowerCell. Pictures of fuel cell stacks made by PowerCell can be seen in Figure 2.

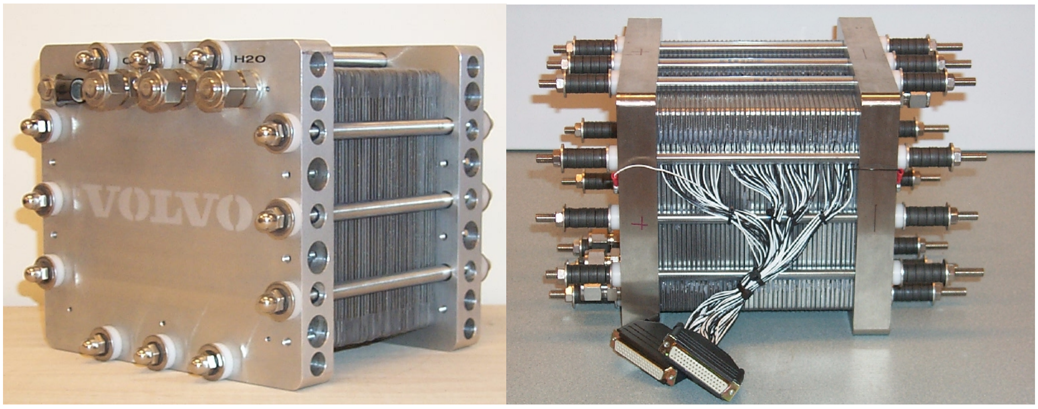

Figure 2 The fuel cell stack delivered by PowerCell. Five fuel cell stacks, 10 kW each, is connected in series to deliver the aimed 50 kW.

The specification of their stack can be seen in Appendix 1. A summery of the most relevant information is show in Table 1. The specification includes some physical data like the amount of cells and the active area of the cells. But most of the information relates to the required operating conditions. It carries information of what the fuel cell generates and what it requires for functioning. It also gives information of which safety measurements that are necessary.

Table 1 Selected data from the fuel cell stack specification sheet made by PowerCell. The complete specification is in Swedish and can be seen in Appendix 1.

Nominal Power	50 kW
Nominal Voltage	280 V
Nominal Current	188 A
Number of Cells	400
Number of Stacks	5 (10 kW each)
Stack Temperature	75 ^{o}C
Pressure Anode	3 bar (g)
Pressure Cathode	3 bar (g)
Stoichiometry Anode (H_2)	1.1
Stoichiometry Cathode (Air)	1.8
Water Content Anode	100 % RH
Water Content Cathode	100 % RH
Flow H_2	577 Nl/min (at 0^{o}C and 1 atm)
Flow Air	12 82 Nl/min (at 0^{o}C and 1 atm)
Flow N_2	500 Nl/min (at 0^{o}C and 1 atm)
Flushing time N_2	approximately 1 min
Pressure Cooling water	$\leq P_{Anode}$ and $P_{Cathode}$
Flow Cooling water	150-200 l/min (or 30-40 l/min/stack)

2.2. The design of the fuel cell system

The work of designing a fuel cell system adjusted for this application has been done together with the company Processkontroll AB. They are a potential supplier of the system if the project reaches a second phase. Their task has been to take care of the complete fuel cell system, with other words deliver a fuel cell container. Their work is based on the specification of the fuel cell stack from PowerCell and on a preliminary flow chart maintained during the process of this project.

2.2.1. The fuel cell container

The building is a 40’’ ISO container which consists of three separate rooms with gas tight walls between them. The rooms are: the fuel cell room, the electricity room and the auxiliary system room. All rooms have electrical lightning and temperature regulation.

The fuel cell room is entirety ex-classed and is primary reserved to the fuel cell stacks and the hydrogen system. The room is provided with gas alerting system and forced ventilation. All wall entrance through connections for cables etc. between this room and other arias is made with gas tight inlets.

The electricity room is a separate room, not ex-classed, which holds the entire regulation system including an office place to serve as operation station. All the electrical power components are within this room, for example the DC/AC converter.

The auxiliary system room is not ex-classed and holds the cooling system, compressed air manufacturing devices etc.

2.2.2. The water system

The cooling system consists of a joint centrifugal pump that pumps the water to the stacks where the flow is split parallel. Each stack has its own regulation valves and temperature transmitters on both inlets and outlets.

The cooling system is a closed system. It contains de-ionizing filters and a flat heat exchanger that is connected to the water system on the boat. The pump is regulated by a static frequency changer and is controlled by a pressure transmitter and two temperature transmitters, one on each side of the heat exchanger.

The water used to moisturise the gases is generated by deionization equipment connected to the fresh water system on the boat.

2.2.3. The gas system

The hydrogen gas system is installed in the same room as the fuel cell stacks. The incoming gas is heated to 75 ^{o}C and is than moisten with a moisturiser. After that the dew point of the gas is measured and the gas is split up to parallel systems to the five fuel cell stacks. Each system is equipped with a mass flow meter, regulation valve, two pressure transmitters, and two temperature transmitters. Analogue signals are sent to the controlling system giving pressure and temperature at inlet/outlet on both the anode and cathode sides. All gas pipes located after the moisturiser is heated with electricity and isolated.

After each stack the gas system is reconnected and rests, by a clack valve and a safety valve, against a joint back pressure valve that is maintaining a constant pressure over the fuel cell stacks.

After the gas pressure has been reduced to atmospheric pressure the gas leads through a separator where the condense water is removed. The rest of the gas is released from the system by a high funnel, the same funnel as the safety valves leads to.

2.2.4. The air system

The air system is very similar to the gas system but the system is placed in the area that isn't ex-classed to reduce the cost of the components.

The incoming air is heated to 75 ^{o}C and is moisten with a moisturiser. After that the dew point of the gas is measured and the gas is split up to parallel systems to the five fuel cell stacks. Each system is equipped with a mass flow meter, regulation valve, two pressure transmitters, and two temperature transmitters.

After each stack the gas system is reconnected and rests, by a clack valve and a safety valve, against a joint back pressure valve that is maintaining a constant pressure over the fuel cell stacks. The air is than released trough a funnel.

2.2.5. The electrical system

The regulation system that is projected here is delivered complete from ABB and contains controller and I/O modules for approximately 600 signals. Each cell voltage is measured individually. ABB has experience of projection, constructing and programming fuel cells from previous Swedish projects.

The DC/AC converter that is made by ABB is a special made converter that delivers 3-phace 380 A AC with software included.

2.3. Integration of the system onboard

Because of the hazards with hydrogen in closed areas and because of the quite large space that the complete system required, the fuel cell and hydrogen container is planned to be placed on deck five, on the weather deck. An illustration of the fuel cell system can be seen in Figure 3**.** As the fuel cell system is in need of air, electricity and water from the ship, it is important to know the condition on the boat.

The compressed air on the boat has a pressure of 6-7 bar and is generated by Ventax compressor. The compressor has a capacity of 6900 l/min. It is therefore possible to use the air in the fuel cell.

The water on the boat has a pressure of three bars on deck five. Next to the pump, at deck one, the pressure is 4.5 bar but the pressure decreases with the deck number. The capacity of the pump is 2.3 l/min. Water temperature changes with season and has a temperature around 10 ^{o}C during summer and 15^{o} C during winter.

Power is needed in the fuel cell container, both for regulation and measurements and for heating elements, lamps and fans. The required power can be taken from the electrical system on the ship.

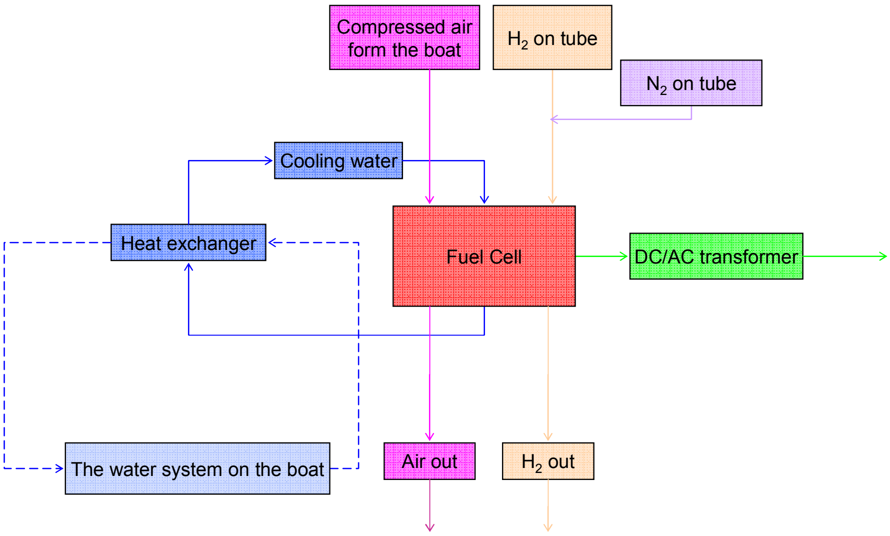

Figure 3 A summery of the fuel cell system required. Air and water is taken form the system onboard the ship.

The use of nitrogen is chosen as safety precaution. The gas will be used to flush the hydrogen areas before and after the fuel cell is in use. This precaution is for eliminating the risk of having oxygen in the hydrogen system.

2.4. Hydrogen distribution

The hydrogen used is stored in a container of dimension 6.5 m x 2.5 m. It contains 1470 Nm^3 of gas in 147 gas bottles, se Figure 4. The container is replaced when the gas is used.

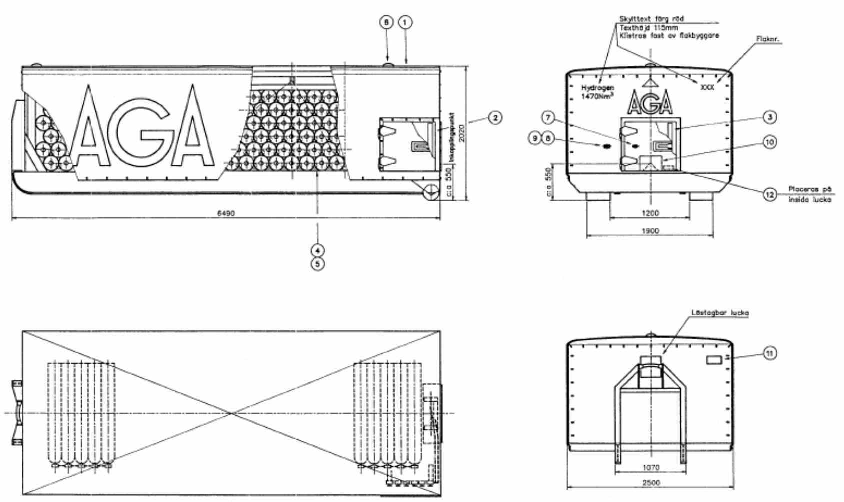

Figure 4 The hydrogen storage consists of a container filled with 200-bar gas bottles. It holds 1470 Nm^3 gas stored in 147 bottles. The container is replaced when the gas is consumed.

A flexible tube goes from the hydrogen storage to the fuel cell container where a panel of regulators, se Figure 5, decreases the pressure to three bars overpressure. Outside of the fuel cell container, 12 bottles of nitrogen are attached are to the container wall. The nitrogen is used to flush the hydrogen system clean from reactants in a start/stop procedure. It may also be of interest to place a few bottles of hydrogen outside the wall so the fuel cell can run while the hydrogen container is replaced. This is yet not included in Figure 5.

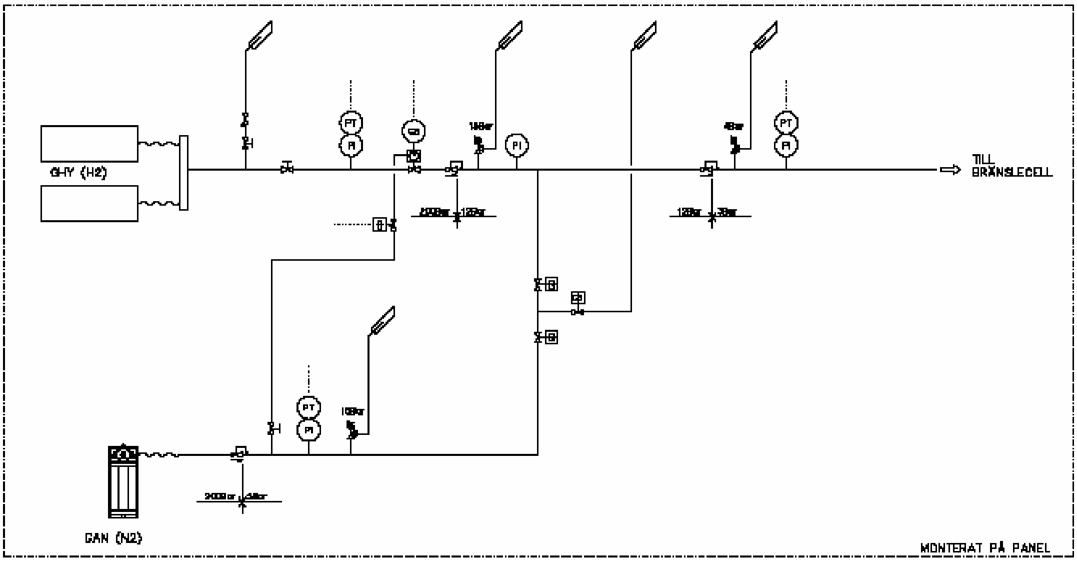

Figure 5 The figure illustrates the regulation of hydrogen before the fuel enters the fuel cell system. At left hand the hydrogen storage, a container, is shown and at the right hand the pressure has been decreased to the desired pressure and the gas is led into the fuel cell system. At the lower part of the blue print a regulation system for nitrogen is illustrated. This gas shall be used during the start/stop procedure to clear the hydrogen system.

The elementary task for the system above is to lower the pressure and to lead the gas safely into the fuel cell container. The suggestion includes several pressure transmitters to detect the gas, regulators to decrease the pressure and safety valves to ensure safety. The valve pressure relievers lead the gas to a funnel if the pressure is too high. Some of the components are hand operated and some emits or receive signals from the regulation system.

The nitrogen distribution is integrated in the hydrogen system. Both gases have the same inlet in the fuel cell stack. The amount of nitrogen consumed in the process is a lot less than the amount of hydrogen or air as it’s only used in the start/stop procedure and not during run. The nitrogen part of the system doesn’t have the same component requirements since the nitrogen is neither a reactive, explosive or poisonous gas. The components in this part of the system is therefore less expensive and fewer.

The fuel cell also needs oxygen to produce electricity and in this suggestion the oxygen is fetched from the onboard compressed air on the ship. Though the instrument air is higher than three bars overpressure the pressure has to be decreased. This is done in a way shown in Figure 6.

The components is made in stainless steel and is therefore of benefit if the system will be displayed.

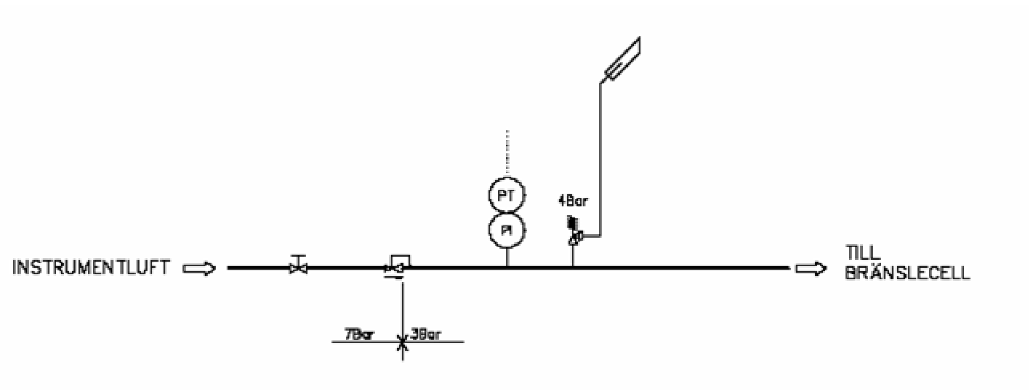

Figure 6 The figure shows an illustration of how the pressure of the air is decreased before it enters the fuel cell system. Here the instrument air pressure is decreased to three bar overpressure as the fuel cell stack requires.

2.5. System efficiency

The fuel cell is optimised to deliver 50 kW of electricity. This amount does not reach the boat as the electricity needs to be transformed to AC-current. The transformation is not completely reversible and gives therefore rise to energy loss.

The fuel cell system also needs electricity to work. This amount has to be taking into account when looking at the system efficiency. During run the fuel cell system requires approximately 2 kW. The fuel cell itself has an efficiency of 55-60 % according to PowerCell.

When putting this together the system efficiency is around 50-55 %. In practice the efficiency also depends on the operating cycle because the system requires electricity even though it isn’t running. This is not included in the figures above.

2.6. The endurance of the system

The endurance of the system is dependent of the fuel cell stack endurance since this is the weakest link. No other component is exposed to large wear. The endurance of the rest of the system is at least 20 years with some small maintenance like filter change, renovation of values etc.

2.7. Time table for constructing the system

The fuel cell system is ready for programming and testing eight months after order. Some of the programming work can be done parallel but when the system is constructed there is a need of extensive testing. The test period starts with a cool test, when all the signals are tested together with the regulation system. Time for this is approximately eight weeks. After that the testing with hydrogen starts and this is estimated to take 12 weeks more.

The total period from order is than approximately 13 month if everything goes according to plan.

2.8. The maintaining of the system

The system is design to work by it self. The water and air is connected to the boat so there is no need of filling that up. The only things that need refilling regularly are hydrogen and nitrogen.

As long as the system is working as planed the only maintaining that is required is ordinary service of the system like filter changing etc.

If the system doesn't work as planed and the system shuts of, the service work will be more extensive. The work load is in that case hard to estimate. The staff on the ship therefore needs to be educated to serve the system if needed.

2.9. Safety and approval issues, rules and regulations

The following land based authority approvals are required for handling hydrogen:

1. Approved storage site. Decision by local Byggnadsnämnd (Construction Committee) with input from local Fire Authorities and Räddningsverket (Swedish Rescue Services Agency).

2. Permit to handle flammable substances. Decision by Räddningsverket (Swedish Rescue Services Agency) with input from local Rescue Service and local Fire Authorities with regards to evacuation, etc. An explosionsskyddsdokument (explosion protection document) among others is needed.

All equipment needs to be CE and ADR approved.

For shipboard systems it is necessary also to have approvals from the ship´s Flag State authority and Classification Society. The Swedish National Marine Administration as of yet have no regulations in place for hydrogen handling, however indicate that such rules for the future will be based on regulations for handling of Natural Gas. The Classification Society det Norske Veritas (DNV) plan to issue a draft set of class rules for hydrogen and fuel cell systems by mid 2006.

3. Cost estimation

One of the goals in this study is to find possible suppliers for the system. The suppliers have in this section estimated the cost for the system, both for constructing the system and for adjusting the system onboard the boat. There is also a cost approximation for the fuel that is required during use.

3.1. The construction of a full 50 kW system

This section includes the regulation of the gases/air before entering the fuel cell system and the cost of the fuel cell system it self. The results are seen below. All prices are in Swedish Krona (SEK) and excludes tax.

Hydrogen, air and nitrogen regulation before entering the fuel cell system
Excl. gas. Supplier: AGA

Total cost, gas regulation:	**100 000 - 120 000:-**

The fuel cell system
Excl. the fuel cell stacks. Supplier: Processkontroll AB

Hardware:	4 000 000
Projection:	1 150 000
Construction:	1 210 000
Programming of the controlling system:	600 000
Testing:	275 000
Classification:	65 000
Total cost, system:	**7 300 000**

The fuel cell stacks
5 *10 kW. Supplier: PowerCell

Total cost, stacks:	**5 000 000**

This gives an estimated investment cost of SEK **12 400 000**.

3.2. The cost to integrate the system to the system onboard

Stena Line intends to connect water and air provisionally as a start. This means no expense for the project.

3.3. The operation cost

The cost for operating the system is very hard to estimate and is therefore not done in it's full in this stage. If the system runs as planned the operation cost is fairly low and mainly consists of hydrogen cost. The system is design to operate by it self as much as possible and this leads to a low operation cost when it comes to man hours. Even though, their may be a need of a part time job onboard the ship to control the system during the project time.

3.3.1. Cost for the hydrogen consumption

In a scenario where AGA produces the hydrogen through electrolyses in Fagersta the estimated consumption cost is:

Hydrogen:	SEK 10 000 per container
Transport:	SEK 5 000 per container (this figure may decreased with collective driving)
Renting of container:	SEK 10 000 per month

Another option is to collaborate with The Petrochemical Industry in Stenungsund. They are producing approximately 1000 kg hydrogen per hour (11 000 Nm^3/h) as by-product. At present the hydrogen is combusted for heat but the companies has offered to sell it to pilot projects for an equivalent amount of natural gas energy as replacement in the heating process. For this opportunity to take place some investments are required. For example there is a need of a fuelling station, a compressor to raise the pressure and piping to transport the hydrogen. This is therefore an option of interest if the quantities are right, not for a single small scale project.

3.3.2. Cost for the nitrogen consumption

If the fuel cell is run three times each day as discussed earlier than the hydrogen system needs to be flushed with nitrogen six times, each start and stop. The consumption of nitrogen is than 3 Nm^3 per day.

Thus it's not easy to deliver nitrogen together with the hydrogen container as the hydrogen is delivered with its own car; AGA suggests that nitrogen is delivered in a racket with 12 bottles (120 m^3). This rocket is than replaced ones a month.

If this nitrogen is delivered from AGA the price assumption is

Nitrogen:	SEK 150 per bottle
Transport:	SEK 1000 per time
Renting of bottles:	SEK 1000 per month

3.4. The total investment required and estimated operation cost

The figures mentioned in this section are approximate figures. They will most probably be adjusted when the investments take place in the beginning of a phase two.

Investment cost:	
The system:	12 400 000
Total investment cost:	**12 400 000**

Operating cost per year:	
Hydrogen:	900 000
Nitrogen:	45 600
Total cost for gases per year:	**945 600**

If only the cost for gas is considered, the price tag for the electrical energy is SEK 6.30 per kWh.

3.5. The system cost when more systems are ordered

The cost for the systems will decrease a lot after the first system is build. The cost for programming is a one time cost and will be left out for later systems. The cost for projecting, classification and testing will decrease with approximately 90 % as much of the work already is done. The construction cost is also decreased with approximately 50 % after the pilot system is completed.

The difficult part is to estimate the hardware cost. The numbers of instrument may be lowered when the system is used and optimised. This will alone lower the cost. Another thing that is of relevance is that some of the components is customised built for this specific project. The DC/AC converter cost today SEK 500 000 because there is no previous developed product in the market. A more fare price for a commercialised DC/AC converter is at tops SEK 50 000, that is 90 % lower.

4. Discussion

This pre-study is performed as a preparation for a potential second phase, where a fuel cell system is intended to be built and put in use. Further planning has to be done before such a system is actually built, however this project has gathered companies with the interest and the competence to successfully conduct a second phase if such a decision is made.

This system is designed with the same preferences as most pilot systems. It is built with the knowledge that the requirements of the components aren't completely established. During time the design won't only be more adjusted to the specific fuel cell stack and the application, but also the cost will be optimised during the following process.

This pilot study is trying to do something new and therefore the cost for generating the product might be large. Much of the cost is for generating the knowledge that has to be gathered. Examples for this is the projection cost, components that has to be customised build and the testing and programming that has to be done for the first and only time.

But this knowledge doesn't end to exist after the fuel cell system is put in use. Hopefully this is just the first of a long series of similar systems that will be built, not only in Sweden but also in the rest of the world. In time, when the fuel cell technology gradually becomes more commercially viable, this pilot project have hopefully contributed to Swedish industry having the knowledge necessary for creating new business in this area.