SINTEF RAPPORT

SINTEF Fiskeri og havbruk AS
Fiskeriteknologi

Postadresse: 7465 Trondheim
Besøksadresse:
SINTEF Sealab
Brattørkaia 17B

Telefon: 4000 5350
Telefaks: 932 70 701

E-post: fish@sintef.no
Internet: www.sintef.no

Foretaksregisteret: NO 980 478 270 MV

TITTEL

Bruk av brenselceller om bord i fiskefartøy.

FORFATTER(E)

Knut Tore Aurdal /Håvard Røsvik

OPPDRAGSGIVER(E)

Norges Fiskarlag, Teknologiforum / FHF

RAPPORTNR.	GRADERING	OPPDRAGSGIVERS REF.	
	Åpen	Joakim Martinssen	
GRADER. DENNE SIDE	**ISBN**	**PROSJEKTNR.**	**ANTALL SIDER OG BILAG**
Åpen	978-82-14-04630-4	830194	76
ELEKTRONISK ARKIVKODE		**PROSJEKTLEDER (NAVN, SIGN.)**	**VERIFISERT AV (NAVN, SIGN.)**
Brennselcelle-rapport.doc		Håvard Røsvik	Harald Ellingsen
ARKIVKODE	**DATO**	**GODKJENT AV (NAVN, STILLING, SIGN.)**	
SFH80 A083044	17/10 2008	Vegar Johansen, Forskningssjef	

SAMMENDRAG

Rapporten summerer opp resultatene fra forprosjektet Bruk av brenselceller om bord i fiskefartøy. I prosjektperioden ble det innledet et nært samarbeid med NTNU som medførte en grundig gjennomgang av alt som har med brenselceller og dagens status innen bruk av denne teknologien inn mot fiskeflåten å gjøre. Arbeidet endte opp med en omfattende rapport som student Knut Tore Aurdal skrev i forbindelse med sin prosjektoppgave. Denne rapporten er vedlagt som fagrapport.

Hovedkonklusjonen etter dette arbeidet er at det foregår svært mye interessant angående utvikling av brenselceller, men med dagens priser på utstyret er dette for kostbart til å anvendes i fiskeflåten.
Den mest nærliggende anvendelsen av brenselceller vil være å bruke disse for dekning av hjelpekraft (strømproduksjon) om bord i fiskefartøy som i dag anvender dieselaggregat.

Et annen mulighet er å bygge et mindre fiskefartøy (sjark) for å teste ut muligheten for å anvende en standard hydrogenbasert brenselcelle. Dette er tidligere beskrevet og Norges forskningsråd innvilget prosjekt på temaet. Dette prosjektet kom ikke i gang på grunn av at kravet til egenfinansiering var for høyt. Da dette prosjektet ble foreslått skulle det kobles til Utsiraprosjektet der de skulle produsere hydrogen fra kraft generert av vindmøller.

STIKKORD	NORSK	ENGELSK
GRUPPE 1	Fartøy	Vessel
GRUPPE 2	Brenselceller	Fuel cells
EGENVALGTE	Fiskefartøy	Fishing vessels

INNHOLDSFORTEGNELSE

Sluttrapport

Prosjekt
Bruk av brenselceller om bord i fiskefartøy

1 Prosjektansvarlig/institusjon
SINTEF Fiskeri og havbruk AS

2 Prosjektleder/utøvende institusjon
Prosjektleder: Håvard Røsvik
Utøvende institusjon: SINTEF Fiskeri og havbruk AS samt NTNU

2.1 Måloppnåelse
Prosjektet hadde som mål å finne ut om brenselceller kunne anvendes om bord i fiskefartøy. Det skulle også undersøkes om en kunne starte et hovedprosjekt hvor slik teknologi skulle testes ut.

Etter å ha foretatt en grundig kartlegging og gjennomgang av det stadiet teknologiutviklingen er kommet til, ble det klart at det er for tidlig å gjennomføre implementeringsprosjekter i fiskeflåten. Dette bør først komme når en del andre industrier har prøvd ut teknologien. Det nærmeste vil være å teste teknologi for hjelpekraftproduksjon om bord i mindre fiskefartøy. Det forventes at firmaet Powercell vil ha klart et utstyr som kan produsere ca 5 KW fra en installasjon som konverterer diesel til hydrogen, og deretter kjører hydrogenet over en brenselcelle. Dette utstyret ventes å være produksjonsklart i 2011 (se omtale i fagrapporten side 43). Det bør også tas kontakt med de tidligere aktørene som var med på søknaden om hydrogendrevet sjark og forsøke å gjenoppta dette prosjektet.

2.2 Er målsettingen målbar?
Målsettingen med å lage en gjennomgang av brenselcelleteknologien og vurdere om dette kunne videreføres i et hovedprosjekt ble oppnådd.

2.3 Er aktivitetene gjennomført som planlagt i prosjektbeskrivelsen?
Aktivitetene er gjennomført etter det som var beskrevet i prosjektbeskrivelsen. Det er laget en svært grundig rapport som kan være nyttig å bruke inn mot andre brenselcelleprosjekter etter hvert som teknologiutviklingen gjør det mulig å anvende dette om bord.

2.4 Er fremdriftsplanen fulgt?
Fremdriftsplanen når det gjelder gjennomføringen av prosjektet ble i all hovedsak fulgt. Sluttrapporteringen er dessverre noe forsinket, men dette er avklart med oppdragsgiver.

2.5 Har prosjektet hatt styringsgruppe/referansegruppe?
Prosjektet var for lite til å ha en egen styringsgruppe.

2.6 Er spesifisert regnskap iht. budsjett levert?

Revisorbekreftet regnskap vil bli oversendt i forbindelse med sluttrapporteringen.

2.7 Hvordan er resultatene fra prosjektet formidlet?

Resultatene vil bli formidlet gjennom FHFs hjemmeside og prosjektdatabase.

2.8 Kan/bør vi gjøre noe mer?

Prosjektet bør videreføres når det foreligger teknologi som er utviklet for andre næringer. Det nærmeste er å teste ut løsningen fra Powercell som primært utvikles for lastebilnæringen. En annen mulighet er å gå for et demoprosjekt der en bygger et fartøy som går på ren hydrogen. Dette er mulig med dagens teknologi, men er for dyrt til å være bedriftsøkonomisk lønnsomt.

2.9 Oppsummering av hovedresultatene på norsk

Her er en oppsummering på norsk av hovedresultatene i prosjektet. Dette kan også med fordel leses på engelsk i fagrapporten.

Den norske fiskeflåten sammen med resten av verden merker utfordringene med fokus på global oppvarming. Dette har ført til en fornyet interesse for å innføre reguleringer og avgifter som kan få fiskeflåten til å anvende mindre energi og eventuelt skifte til energibærere som slipper ut mindre drivhusgasser i atmosfæren. Hovedhensikten med dette prosjektet var å få en oversikt over hvilke muligheter det er til å anvende brenselceller i fiskeflåten. For å gjøre dette har dagens teknologi blitt sammenlignet med dagens brenselceller og den teknologien som er under utvikling i pågående prosjekter. Dette har avdekket en rekke muligheter og utfordringer når det gjelder å ta brenselceller i bruk.

En brenselcelle er en elektro-kjemisk innretning som konverterer kjemisk energi til elektrisitet. En vanlig celle bruker hydrogen som brensel. Dette foregår ved at protonene i hydrogengassen får passere gjennom en membran mens elektronene går gjennom en ytre sløyfe der de produserer elektrisitet. Etter å ha gått gjennom denne sløyfen reagerer hydrogenet med oksygen og vann blir produsert. Vannet er eneste utslippet fra denne prosessen. Med en slik hydrogendrevet brenselcelle er det mulig å produsere stille, vibrasjonsfri energi som kan være en ideell energikilde for fiskefartøy.

Siden det er mange forskjellige former for teknologi som anvender brenselceller med en stor bredde i levert ytelse, kan det være mange forskjellige løsninger som kan være av interesse for den norske flåten.

Det er klart at null utslipp, stille og vibrasjonsfri energiproduksjon vil være ideelt for fiskeflåten. Dette vil gi både miljøvennlige skip samt båter som har et godt arbeidsmiljø om bord. Den klart største ulempen ved brenselceller er prisen.

Prisen for brenselceller er i dag tre til ti ganger dyrere enn eksisterende dieselaggregat. Teknologien er dessuten ikke så robust og brukervennlig ennå at en kan stole på dette som eneste energiprodusent i for eksempel et fartøy. Dette gjør at brenselceller har et stort potensial uten at teknologien har fått sitt gjennombrudd ennå.

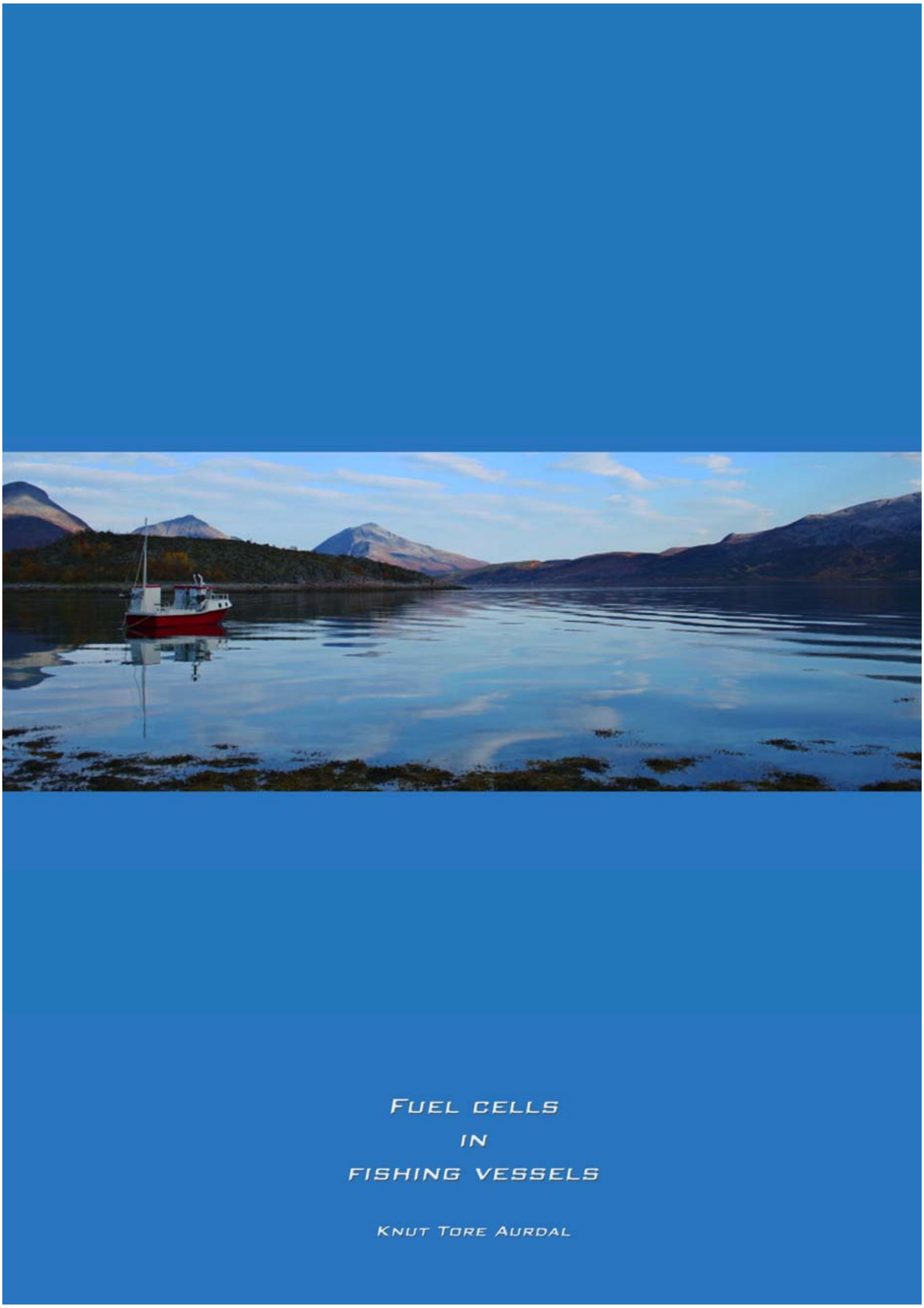
Prisen på brenselceller er på vei nedover. Samtidig har vi opplevd svært høye oljepriser, og dette har gitt deler av fiskeflåten svært høye operasjonskostnader. Til sammen gjør dette at kostnadene på brenselceller etter hvert nærmer seg et leie der det kan være interessant å anvende dem. I følge representanter for Wärtsilä vil dette kunne skje i løpet av en tiårs periode.

Ved en overgang til bruk av brenselceller vil en også få andre utfordringer som ikke er direkte koblet til teknologien, som for eksempel hydrogeninfrastruktur og mulighetene til å lagre hydrogen. Dette vil særlig være en utfordring for de minste fartøyene langs kysten. De større fiskefartøyene kan bruke celler som kan anvende LNG, mens de mindre må bruke hydrogen som drivstoff siden de har så lite lagringsplass. En mulig løsning kan være bruk av celler som konverterer fossilt brensel om bord og brenner hydrogenet i brenselcelle. To firma som arbeider med løsninger for dette er Powercell og Voller Energy som stort sett ser for seg et marked innen hjelpestrømsproduksjon.

Mange forskere er enig om at hydrogen kan være drivstoffet for fremtiden og at brenselceller kan være fremtidens motorer. Når dette vil skje er uklart. Derfor er det viktig å følge med i utviklingen og ta teknologien i bruk når den er moden. Man kan også se for seg koblinger mellom f.eks. sjarker med brenselcelleteknologi og Utsiraprosjektet slik at vindkraft kan utnyttes som primærkilde til energiforbruket.

I den følgende rapporten på engelsk vil dette bli gjennomgått i mer detalj.

Fag rapport



Preface

The life on earth as we know it today is changing and we are dependent of finding new energy sources in the future. Norway wants to have one of the world's most environmental friendly industries. This policy is already affecting the Norwegian fisheries through the NOx–fee. The domestic shipping industry and fisheries are one of the main contributors to especially NOx emissions, and new, more energy efficient vessels are needed in the years to come.

The project is done in co-operation with SINTEF – Fisheries and aquaculture, which is the Norwegian fisheries' largest in-dependent researching institution. To develop the future's energy efficient and environmentally friendly vessels you need new technologies. This project's purpose is to map the possibilities for using fuel cells as a power source in fishing vessels.

Fuel cells are electro-chemical devices that transform chemical energy into electricity without emitting greenhouse gases. Since the fuel cells do not run on fossil fuels, it seems like a perfect solution for any application that needs electricity. However, fuel cell technology is quite young, and still under development.

The project is divided in three parts. The first part is describing the fuel cell technology and will give the reader a basic understanding of a rather large variety of technologies. The next part is looking at existing and on going projects, and hopes to emphasize the technology's possibilities and limitations. The last part is determining the technology's challenges and limitations for use in the Norwegian fisheries. The report is hoped to be used as a basis by SINTEF Fisheries and Aquaculture when they develop more definite fuel cell projects in the future.

I would like to thank Håvard Røsvik, my advisor at SINTEF, and Harald Ellingsen, my advisor at NTNU for their help and good feedback. I will also like to thank all the other, helpful people that have been kind and willing to answer my questions. That has really meant a lot to me.

Finally, I hope you will enjoy the report and I hope that it can be helpful in some way.

Knut Tore Aurdal

Trondheim, 19.12.2007

Content

Figures:

Tables:

3

Summary

The Norwegian fishing fleet is together with the rest of the world facing new challenges as a result of global warming. The new, strict environmental politics are forcing the fleet to evolve in a more environmentally friendly direction. The purpose of this project, in co-operation with SINTEF Fisheries and aquaculture, was to map the possibilities for the use of fuel cells in the fishing fleet. To do this, today's technology has been compared with today's fuel cell powered applications and ongoing projects. Hence, many of the challenges and possibilities with today's technology has been unveiled

Fuel cells are electro-chemical devices that convert chemical energy from a fuel into electricity. A basic fuel cell is using hydrogen as fuel. While the protons in the hydrogen gas are allowed to pass through a membrane, the electrons are forced into an outer circuit to produce electricity. On the other side of the circuit, the electrons merge with the protons before reacting with oxygen to produce water, which is the fuel cell's only "waste". This way a fuel cell is capable of producing zero-emission, silent and vibration-free power, which would be ideal for a fishing vessel.

There is a large diversity of fuel cell technologies. Some technologies are suitable for smaller, portable applications >100 kW, and others are more suitable for stationary applications, like power stations < 25 MW. The Norwegian fishing fleet also have a large diversity of different ship types, thus many different technologies can be of interest.

With their zero-emission, silent and vibration-free power supply, fuel cells seems ideal for use in fishing vessels. You will get both an environmentally friendly ship and a very good work environment on board. However, there is still one major disadvantage with the fuel cell: Price. Fuel cell prices are today three to ten times as expensive as an equivalent diesel generator. At the same time, the technology is so far not good enough to satisfy our standards. This leaves the fuel cell with a huge potential that not yet have the ability to break through.

Today, the fuel cell prices are slowly decreasing, while the fleet's running expenses are increasing due to the high oil price. This means that we are approaching that point in time where fuel cells are becoming a better investment than today's applications. It is hard to predict when we will reach this cross-over point, but according to Wärtsila's predictions, it might happen as soon as within ten years.

If using fuel cells in the fishing fleet, you will also be facing some challenges that isn't directly attached to the fuel cell technology; Hydrogen infrastructure and hydrogen storing. This is mainly a problem for the local, smaller fisheries along the coast. While larger vessels can use fuel cells that run on LNG, smaller fishing vessels have to use fuel cells powered by pure hydrogen due to the limited space available. The answer to this question might be to reform fossil fuels on board and burn the hydrogen in the fuel cell. PowerCell and Voller Energy are two companies that are developing such applications for use as auxiliary power units.

Most scientists agree that hydrogen will be the fuel of the future, and thus fuel cells will be tomorrow's engines. It is hard to predict when this will happen, but one thing is for certain: Hundred years from now, our fishing vessels won't be powered of conventional diesel engines as today. Thus, SINTEF Fisheries and Aquaculture should, keep track of the fuel cell technology development and build competence within the field. An interesting idea is to outfit a smaller fishing vessel at Utsira, "The world's first hydrogen society" with a fuel cell. This will in fact be the first wind-powered fishing vessel without a sail.

4 Introduction

The world is facing one of its largest challenges ever. It is getting more and more obvious that the climate changes we see today are manmade. The utilization of fossil fuels has exploded in the last century, resulting in not only a huge economical growth, but also the largest environmental threat ever. Emissions from power plants, cars, airplanes and ships increases the density of greenhouse gases in the atmosphere and contribute to the phenomenon known as global warming. This global warming will affect our planet as we know it today. The ice at the poles is melting, sea levels are rising, ocean -currents are turning and our daily life as we know it today is many places threatened.

Fossil fuels are a limited resource. The world's reserves of oil are believed to last for no more than 50 to 100 years. The natural gas reserves are believed to last a little longer, but it is time to look around for new technologies that can replace oil and gas as the world's most important energy source. Fuel cells are one of the most viable alternatives. Already, the world's largest car producers are testing cars driven on hydrogen powered fuel cells. The maritime industry, however, is starting to lag behind. This report are trying to map what has been done with fuel cells in maritime applications so far, and also try to lay open which possibilities fuel cells have for applications in the Norwegian fisheries.

A lot of scientists believe that hydrogen is the fuel of the future, strictly because there are no obvious side effects on the environment. For the Norwegian fisheries, the need for a more environmental friendly fleet is becoming more and more necessary. Norway has international commitments in terms of the Kyoto and Gothenburg agreements, and the fishing fleet is one of the industries that contribute the most negative, in special within NOx emissions. Thus, the authorities have recently placed a fee on NOx emissions for the maritime industry, among others. This fee is striking the fishing fleet hard, and we will probably see a restructuring in different segments within the fleet. An assumed persisting high fuel price in the years to come will also be a big challenge for the fleet. Thus, the need for new energy solutions, that reduces the emissions of greenhouse gases at a reasonable price, is getting stronger.

Fuel cells are believed to be one of the most important features in the hydrogen society of the future, because it can be a solution to all the mentioned problems above. The report is written in co-operation with SINTEF – Fisheries and aquaculture and is supposed to help them with ideas for futuristic projects containing fuel cells in fishing vessels. The report is divided into three parts. The first part is describing fuel cell technology and different reasons that explain why fuel cells are so interesting. The next part is describing different examples of finished and ongoing fuel cell projects both on land and at sea. The last part shall, based on the other two, try to describe different challenges and possibilities for the use of fuel cells in the Norwegian fishing fleet. At the same time it will launch ideas for futuristic fields of development.

The project is supposed to count for a quarter of the semester credits (7.5 points), but the effort put into it has unquestionably exceeded this description.

5 Background

Why fuel cells?

The world is facing challenges like never before. The greenhouse effect and global warming is resulting in climate changes. These changes might be a threat to life as we know it today. So should we maintain our quality of life, we will eventually have to come up with answers to these challenges. And it might even be too late. From the writers point of view there are basically two main reasons that directly or indirectly are attached to these challenges.

1. Emissions from burning fossil fuels. The burning of fossil fuels are producing greenhouse gases, which reduce the reflection of sunlight back into space, resulting in global warming.
2. The limitation of fossil fuels. Fossil fuels are a limited resource that gradually is being emptied. This limitation is forcing us to look for new renewable energy sources in the future.

These two reasons will be explained in detail later, where the focus is on the challenges in Norway, and in the Norwegian fisheries.

But why fuel cells? Fuel cells can be the answer to both main challenges, if the technology is used correctly. Hence, the question is not; “Why fuel cells?”, but “Why not?”

Norway has through the Kyoto- and Gothenburg Protocol promised to reduce their emissions of greenhouse gases. Within 2010, certain goals are set to reduce the amount of greenhouse gases shown in table 1.

Table 1 - Emissions in Norway 2006 compared to the goals from the Gothenburg protocol. [1]

Component	Emission 1990	Emission 2006	Goal 2010	Necessary reduction 2006-2010
Nitrogen Oxides (NOX)	212 524	194 506	156 000	39 000 ton (20 percent)
NMVOC	294 875	196 345	195 000	1 000 ton (1 percent)
Ammonia (NH3)	20 375	22 610	23 000	Emission goal reached

5.1

5.2 Emissions in Norway

5.2.1 NOx - Emissions

The Norwegian emissions of NO_X were 195 000 tons in 2006. The NOx emissions are reduced with 8.5 percent since 1990, but the emissions have to be reduced with further 20 percent within 2010 for Norway to fulfil their commitment given in Gothenburg-protocol. [1]

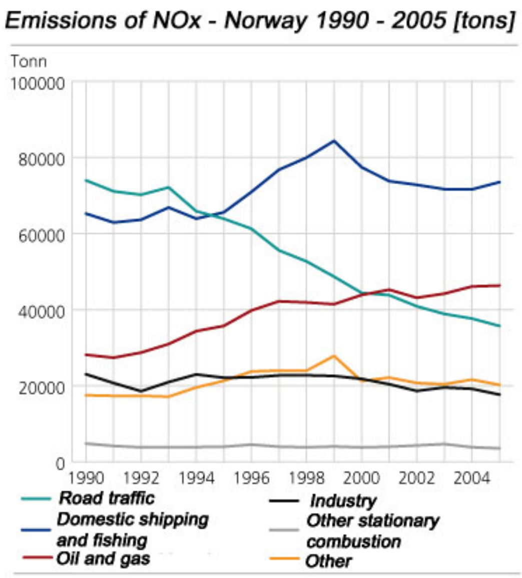


Figure 1 - NOx emissions in Norway, by industries. 1990 - 2005 [1]

Domestic shipping and fisheries, the oil and gas business and the road traffic are in total responsible for 80 percent of Norway's NOx emissions. Domestic shipping and fishing is the biggest contributor to the emissions. In 2005, 73 000 tons or 37 percent of Norway's total NOx - emissions came from this industry. The emissions have increased since 1990, and they are now 13 percent above the 1990 level, where 30 % of NOx emissions came from domestic shipping and fisheries. Today the emissions from this business are almost 38 percent. In other words, the Norwegian domestic fleet is the slow learner in Norway in terms of NOx emissions.

23 000 tons of the emissions comes from the fishing fleet. That is 11.8 percent of Norway's total emissions of NOx. This means that the Norwegian fishing fleet is one of the main contributors to the NOx emissions in Norway. Thus, a more environmental fishing fleet would be very helpful for Norway to reach their climate goals.

The Norwegian government introduced a NOx fee in January 2007, which aims to reduce NOx emissions. The fee is 15 NOK per emitted kg of NOx, and prevails for domestic ships and fishing vessels, aviation, diesel-powered railroads and motors, boilers and turbines from power stations. The fee is including about 55 percent of the total NOx emissions in Norway.

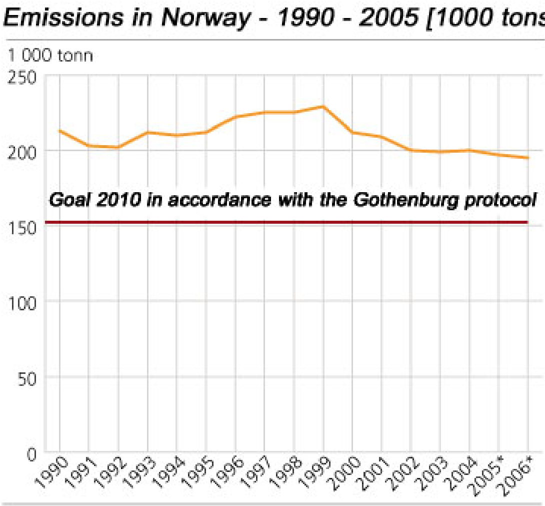


Figure 2 - NOx emissions compared to the Gothenburg agreement

The SSB (Statistics Norway) in Norway is mentioning exhaust gas purification and motor technical re buildings as measures to reduce the NOx emissions in the fishing fleet.

The fee is geographical limited in accordance with the Gothenburg protocol. This means that e.g. emissions from abroad shipping and aviation is not comprised by the fee. [1]

5.2.2 CO2 - emissions

Today, CO2 is the greenhouse gas that gets the most attentions from the media. The reduction of all greenhouse gas emissions are agreed upon in the Kyoto-agreement and ratified by 171 of the world's countries (6th May 2007), also including Norway. Fossil fuels are the main contribution for Norway's CO2 emissions, and if Norway shall keep up with their promises in the Kyoto agreement, some actions have to be done. The figure below shows that CO2 is the most emitted greenhouse gas in Norway. If Norway shall reach their Kyoto goal, the easiest way to do that is to reduce the amount of CO2. [1, 2]

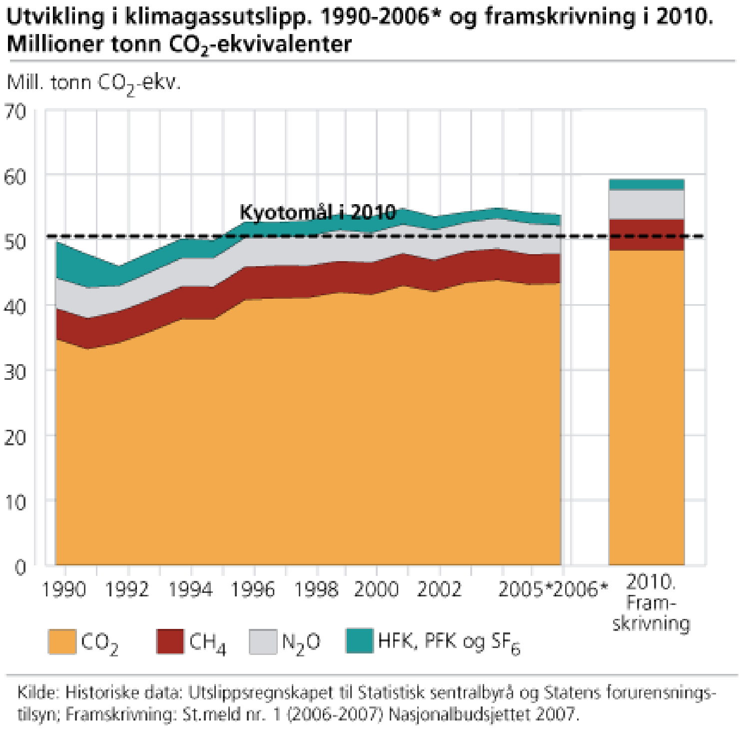


Figure 3 - Norway's CO_2 emissions in relation to the Kyoto goals [2]

Figure 4 shows us that the Norwegian domestic shipping and fishing fleet is a rather small contributor to Norway's total CO_2 emissions, with its annual emissions of approximately 4 million tons. The percent of CO_2 emissions is in other words just a fraction of what it is for the NOx. But even though the fishing fleet isn't the main contributor to the CO_2 emissions, the amount of CO_2 is still high, and should not be forgotten when we are designing the vessels for the future. [2]

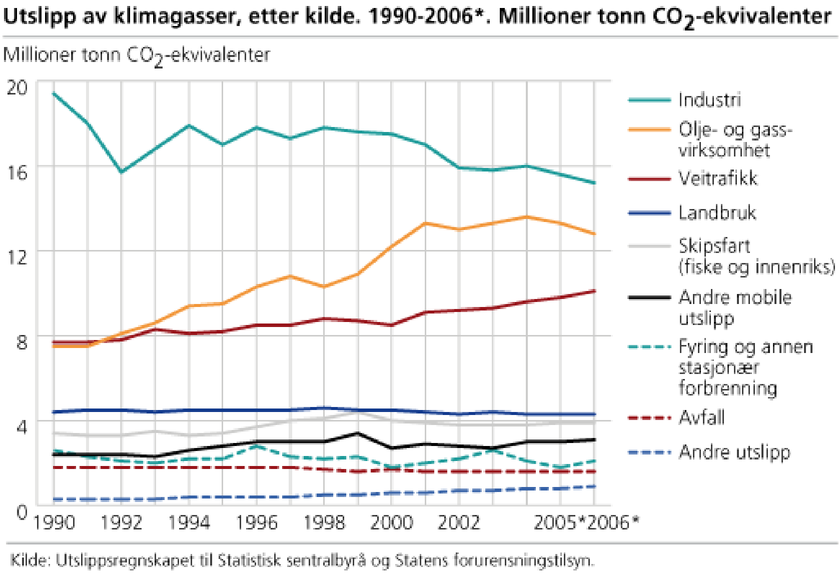


Figure 4 - CO2 emissions by type of industry [2]

5.3 Fossil fuels in the future

The world's fossil fuels are a limited resource at the same time as it is the biggest cause to global warming and climate changes. There are many different predictions of when the world's oil and gas reservoirs are emptied, but a common suggestion is that we will have oil in approximately 50 more years, gas in almost 100 years and coal in approximately 250 years. [3] In 2004, it was estimated that 86 % of the human-produced energy come from burning of fossil fuels [4]. This means that we are facing a huge challenge in the future when converting our fossil fuel society.

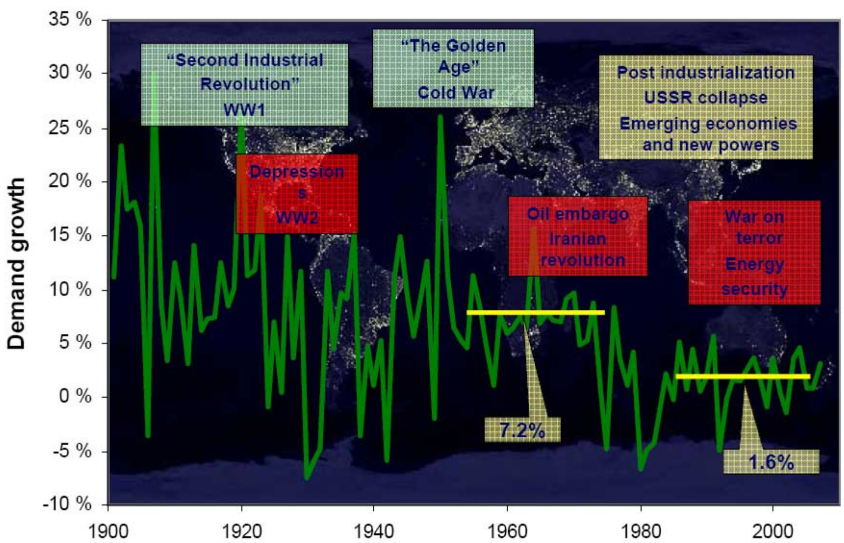


Figure 5 - Energy demand growth in the world [5]

The duration of oil supply is very dependent of the oil prices and the demand for fossil fuels. At the moment, the world's oil producers are able to deliver the demand, but this will soon change. In the latest years, the demand for oil has increased with an annual 1.6 percent. [5] When the oil production is decreasing in the same period, due to less new oil discoveries and smaller reserves, it is obvious that we are approaching a point in time, when the world no longer can deliver the demand for oil. [5]

In later years, the oil price has increased rapidly from as low as 15 $ per barrel in 1999 to almost 90 $ today (October 2008). This rapid increase is mainly caused by the continuously increasing demand. Today the world's oil producers produce as much as they are capable to produce, to deliver the demand. This means that the oil prices will stay on a high level in the years to come, and it is not likely that we will se oil prices of $ 15 pr. barrel again. [6]

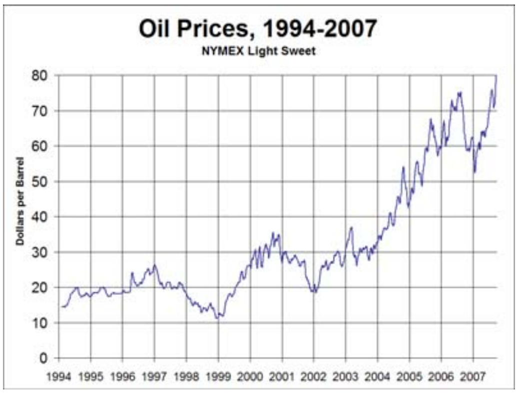


Figure 6 - The development of the oil price 1994-2007 [6]

As mentioned, the oil supply will soon not be able to meet the demand. What will happen then? Probably the prices will increase even more, to levels that we in Norway only could dream of only five years ago. There have been done some analyses of when we reach this point in time. The figure below is showing StatoilHydro's predictions.

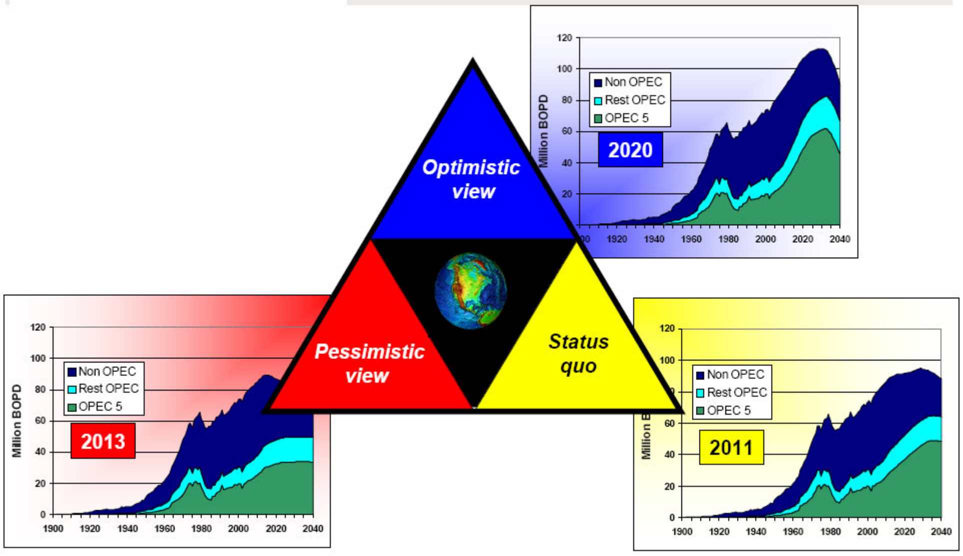


Figure 7 - The oil supply will soon not be able to fulfil the demand. StatoilHydro [5]

Figure 7 shows that this point in time is highly dependent on a few Middle East countries, (The OPEC – countries), and mainly on their outtake growth in existing, developed fields. If there are no changes, we can see from the figure 7 that the supply will reach the demand already 2011. However, it is assumed that the market forces and the high oil price will contribute to delay this point. A pessimistic scenario, that takes these predictions in to account tells us that the cross over point will be in 2013, while an optimistic suggestion suggests 2020. In any case, this point will be reached within the next 5 to 15 years, forcing us to reduce our energy consumption or to find new energy sources. [5]

5.3.1 The challenges in the Norwegian fishing fleet

In the Norwegian fisheries we have already seen political actions through the NOx emission fee to reduce emissions. It is plausible that there are coming more emission fees in the future on other sorts of emissions, such as CO2, SOx, and particles, to reduce the emissions and the global warming. At the same time, the oil prices are high and will probably maintain on high level, and even increase in the future. This means that the operating costs in the fishing fleet will increase in the future if we are using the machinery and the technology that are installed today. These facts might be a threat to the whole Norwegian fishing fleet and it is necessary to look at alternatives for the future. Because one thing is certain, hundred years from now, Norwegian fishing vessels will not run on the diesel engines we have today.

Fuel cells seem to be a good alternative. With fuel cells, the emissions of greenhouse gases disappear or get strongly reduced. Further, there is no longer need for hydrocarbon fuels, even though that also can be used in fuel cells (If we do not extract hydrogen out of natural gas, which today, is the cheapest way to produce hydrogen)

"The Stone Age did not end because of lack of stones and the oil age will not end because of lack of oil" is a slogan you often hear, also from people in the oil business. This might very well be true if the hydrogen technology develops further at the same times as the oil prices continue to raise. [7]

Fuel Cells

5.3.2 What is a fuel cell?

Fuel cells are electrochemical devices that convert chemical energy of the reactants directly into electricity and heat with high efficiency. [8, chapter. 1.1]. In other words, a fuel cell is simply an energy conversion device for power generation. Basically hydrogen is the fuel used in fuel cells, but there are also other chemical compounds containing hydrogen used as fuel.

The chemical equation for the reaction in a traditional fuel cell is

5.3.2.1.1.1.1 2 H2 + O2 → 2 H2O + energy (1.1)

Another importing feature with this reaction is that it works both ways. If you supply energy in form of electricity to the water, you can split the water into hydrogen and oxygen through a process called electrolysis (see the hydrogen chapter). The hydrogen can then be stored until you once again need the electrical energy. Then you let your hydrogen react with oxygen, and you get the water and the electrical energy back. With a fuel cell you can control this energy. [9]

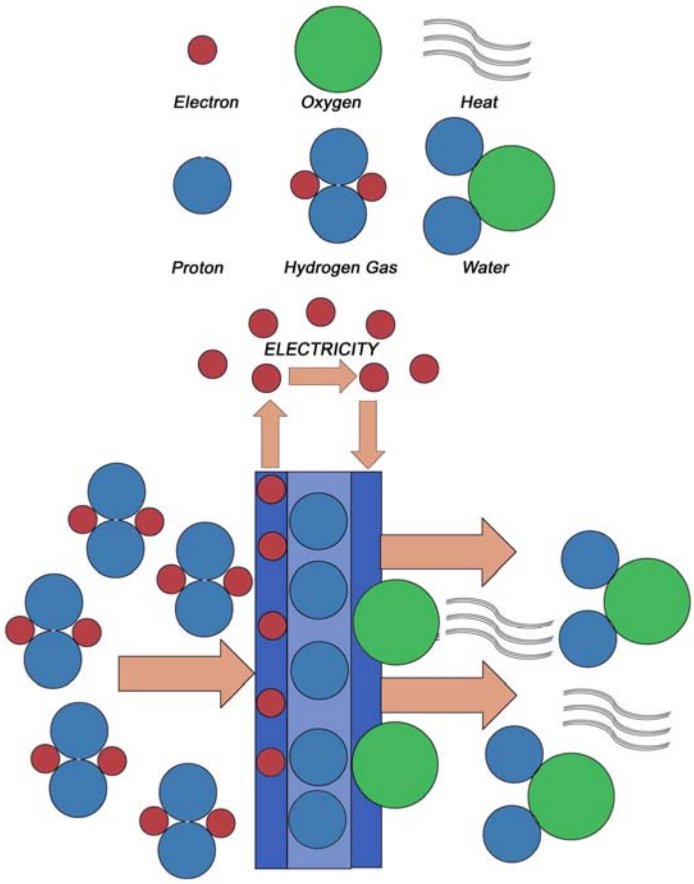


Figure 8 – The basic principle in a Fuel Cell (PEM).

In a typical fuel cell, hydrogen (H_2) is fed continuously to the anode (the negative electrode which is the dark blue staff on the left in figure 8) while an oxidant (oxygen from the air) is fed continuously to the cathode (the positive electrode, which is the dark blue staff on the right in figure 8). Electrochemical reactions take place at the electrodes to produce the electrical current. Between the electrodes there is an electrolyte, which works like a membrane that just is allowing the positive protons to pass. This membrane forces the electrons to run in an outer circuit, and an electrical current is created. The result is energy where the only "waste" is pure water. [8, 9]

Colleen Spiegel, the founder of Clean Fuel Cell Energy, LLC, has in her book, *Designing and building fuel cells [8]*, listed some advantages and disadvantages for fuel cell systems.

5.3.3 Advantages of a fuel cell system

- Fuel cells have the potential for a high operating efficiency that is not a strong function of system size.
- Fuel cells have a highly scalable design.
- Numerous types of potential fuel sources are available
- Fuel cells produce zero or near-zero greenhouse emissions. (When we don't take the production of hydrogen in to account. This will be discussed later)
- Fuel Cells have no moving parts (other than pumps or compressors in some fuel cell plant subsystems.) This provides for stealthy, vibration free, highly reliable operations.
- Fuel cells provide nearly instantaneous recharge capability when compared to batteries.

5.3.4 Problems and disadvantages with fuel cell systems

- Fuel cells are still very expensive.
- Hydrogen. To mass produce hydrogen is cost effective and there is many challenges attached to the storing and delivering of hydrogen.
- If pure fuels are not used, fuel reformation technology needs to be taken in to account.
- If fuels other then pure hydrogen are used, then the fuel cell performance gradually decreases over time due to catalyst degradation and electrolyte poisoning.
- Hydrogen also has a low volumetric energy density (if not liquefied or stored with extremely high pressures). This will be a problem for ships that needs large operating ranges such as larger trawlers.[8]

Fuel cells have another efficiency characteristic than a diesel engine. While a diesel engine is most effective when running at approximately 80 % of its capacity, a fuel cell gets more efficient at low power outputs. An oversized fuel cell is in other words a good thing. However it takes up more space and costs more. This makes the calculations to find the optimal fuel cell more complex then for finding an optimal diesel engine.

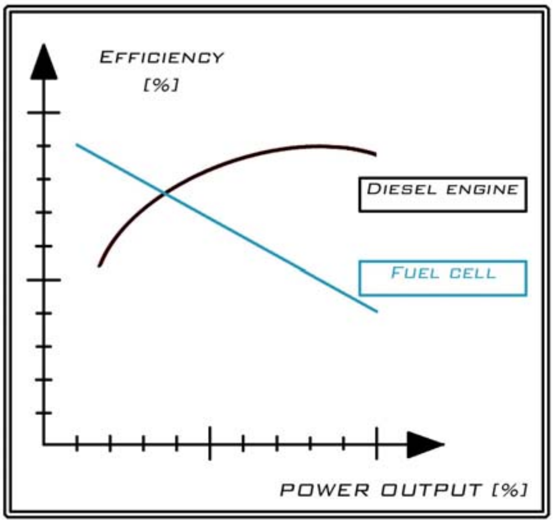


Figure 9 - Efficiency characteristics is different for a fuel cell then a diesel generator.

5.4 Hydrogen

“For without coal there would be no machinery, and without machinery there would be no railways, no steamers, no manufactories, nothing of that which is indispensable to modern civilization!"

"And what will they burn instead of coal?"

"Water," replied Harding, but water decomposed into its primitive elements, and decomposed doubtless, by electricity, which will then have become a powerful and manageable force… “Yes, my friends, I believe that water, and hydrogen and oxygen which constitute it, will one day be employed as fuel, “I believe, then, that when the deposits of coal are exhausted we shall heat and warm ourselves with water. Water will be the coal of the future."[10]

This conversation from the French author Jules Verne’s book “The mysterious Island”, written in 1874 tells us that the idea of using hydrogen as fuel is very old. The positive thing about hydrogen is that there are unlimited amounts of it on the planet, but a negative fact is that it always appears in combination with other elements, so that it has to be isolated before being used as a fuel. However there are so many positive aspects for the use of hydrogen as fuel that most scientists today are not wandering: “When does the hydrogen age come?”, but “Does it come to late?” [11] The following part will discuss possibilities and challenges with the use of hydrogen as fuel.

5.4.1 Hydrogen basics

Hydrogen is the simplest and lightest element, and is found in unlimited amounts on earth and in space. It has to be generated, with the use energy, from a hydrogen-bearing chemical compounds. Such chemical compounds are everywhere on the planet, e.g. in every organic matter, in biomass and hydrocarbons, but the most common compound is water. Hydrogen can be used in the same way as other conventional fuels. It can be burned in boilers or engines to create heat and power, or it can react with oxygen in a fuel cell to produce electricity directly. Combustion in air with high temperatures will result in some NOx emissions to the air, but if the reaction happens in lower temperatures or in a fuel cell, the only waste product is pure water. Hence, we get a “hydrogen cycle”, that won’t be any environmental problem. [7]

Table 2 - Hydrogen basics, compared to other fuels

	Hydrogen	Naturgass	Bensin
Nedre brennverdi (MJ/kg)	120,00	50,00	44.5
Selvantennelsestemperatur (oC)	585,00	540,00	228-501
Flammetemperatur (oC)	2045,00	1875,00	2200,00
Antennelsesgrenser i luft (vol. %)	4 % - 75 %	5,3 % - 15 %	1.0 % - 7.6 %
Minimum antennelsesenergi (uJ)	20,00	290,00	240,00
Detonasjonsgrenser i luft (vol. %)	18 % - 59 %	6,3 - 13,5 %	1.1 % - 3.3 %
Teoretisk eksplosjonsenergi, (kgTNT/m3 gass)	2,02	7,03	44.22
Diffusjonskoeffisient i luft (cm2/s)	0,61	0,16	0,05

5.4.2 How is hydrogen produced?

There are several ways of producing hydrogen, but today's most common way is extracting hydrogen from natural gas. Some production does also come from coal and oil, but in total, approximately 90 percent of today's hydrogen production comes from refining fossil fuels.

Steam reforming:

The most frequent used process is called steam reforming and can be described as:

$$CH4 + 2H_2O \rightarrow 4H_2 + CO_2 \quad (1.2)$$

Here methane, CH_4, is the main component in natural gas. Water is then added in form of steam, and pure hydrogen and CO_2 are extracted. The process has in fact two raw materials, natural gas and water, but needs energy that is obtained by for instance burning natural gas. So even though hydrogen is a pure fuel that does not give environmentally unfriendly emissions, there will be emissions of CO_2 at the production phase. [7]

CO_2 emissions from hydrogen production versus diesel:

When looking at the steam reforming- (1.2) and the fuel cell process (1.1) combined, you can see that there are produced one mole of CO_2 (from 1.2), for every four moles of water (waste, 1.1). In number this means that there are produced approximately 5.5 tons of CO_2 for every ton of H_2 in the steam reforming process, if we do not take the energy needed to run the process into account. You can also look at it in another way: For every ton of CO_2 produced in the production of hydrogen, 1.63 tons of water is "emitted" from the fuel cell using the hydrogen.

Looking at diesel, it is found that a combustion engine operating at it's natural state will discharge in total 3.0 kg CO2 pr. litre, where 2.7 kg are direct emissions, while 0.3 kg are indirect emissions, from refining, etc. [12]. Assuming a density of 0.84 [kg/m3], we get that 1 kg of diesel will lead to 3.6 kg of CO_2. Thus, use of hydrogen from steam reforming will produce 50 % more CO_2 then a diesel engine, when it comes to the fuel's weight.

However, this comparison does not take the matters of energy density in to account. If we divide the relative emission on the respectively lower heat value for each fuel, we get.

Diesel: $$\frac{CO_2 Emission}{H(x)_{Diesel}} = \frac{3.6 \, {}^{tonCO_2}\!/_{tonDiesel}}{44MJ} = 0.08181 \, {}^{tonCO_2}\!/_{tonDiesel \times MJ}$$

Hydrogen: $$\frac{CO_2 Emission}{H(x)_{Hydrogen}} = \frac{5.5 \, {}^{tonCO_2}\!/_{tonH_2}}{120MJ} = 0.0458 \, {}^{tonCO_2}\!/_{tonH_2 \times MJ}$$

So when comparing the two fuels, taking the energy in to account, we get:

$$\frac{X_{Diesel}}{X_{Hydrogen}} = \frac{0.0818}{0.0453} = 1.785$$, where x is the emission per energy unit

This means that there is produced 78.5 % more CO_2 per unit of energy from a diesel engine compared to a fuel cell running on steam reformed hydrogen. The fact that you will get some CO_2 emissions when adding energy to the steam reforming process is not taken into account here.

Electrolysis:

Electrolysis is a way of separating water inn to hydrogen and oxygen in a way Jules Verne thought of 130 years ago. An electrolysis machine is in many ways the opposite of a fuel cell, where the chemical reaction runs the other way

Fuel cells:	$H_2 + 1/2\ O_2$	$\rightarrow H_2O$ + energy	(1.2)
Electrolysis:	H_2O + energy	$\rightarrow H_2 + 1/2\ O_2$	(1.3)

Water electrolysis is a process where energy in form of electricity is added to the water in an electrolysis machine, containing the same main components as a fuel cell, e.g. anode, cathode and an electrolyte (often KOH). Basically, the fuel cell process is run backwards producing pure oxygen and hydrogen. [7]

In Norway, Norsk Hydro has produced hydrogen through electrolysis, at their facility Vemork at Rjukan since the late 1920s, using hydroelectric power.

The two processes mentioned above are the two commercialized ways of producing hydrogen, but a lot of research is done in other production methods. Some of these are:

Thermolysis:

It is possible to split water into pure hydrogen and oxygen using heat, but very high temperatures are needed. These temperatures, above 2000 ^oC, can be achieved when concentrating sunlight. Still there is a problem separating the hydrogen and oxygen at these temperatures. If the separation is not done immediately, the hydrogen and oxygen will react back into water when the temperature drops. There is still a long way to go before this technology will have any practical meaning, but recent experiments have given positive results. [7]

Photolysis:

In photolysis, the light's photon energy is used. This can be used in several ways but we can distinguish between photo chemical, photo electrolytic and photo biological methods. These methods will here not be described in any detail, but it can be mention that the biological method is using bacteria and micro organisms to produce hydrogen. These bacteria and algae are producing organic matter using sunlight, hydrogen from the water and CO2 from the air. [7]

5.4.3 Hydrogen as fuel

Advantages

The main advantage by using hydrogen as fuel is that there are no emissions of greenhouse gases and pollutants as long as it is produced from renewable energy sources (i.e. electrolysis). At the same time, the use of hydrogen will give us a sustainable energy situation. When we today get almost 90 % of our energy from fossil fuels, we have an unbalanced energy situation. An introduction of hydrogen will however balance this situation as shown in figure 9 below.
Today, most of the use of hydrogen is not sustainable since it is created from natural gas, which is a fossil fuel. In the future, we are depending on renewable energy sources to reach our goal of a zero-emission society.

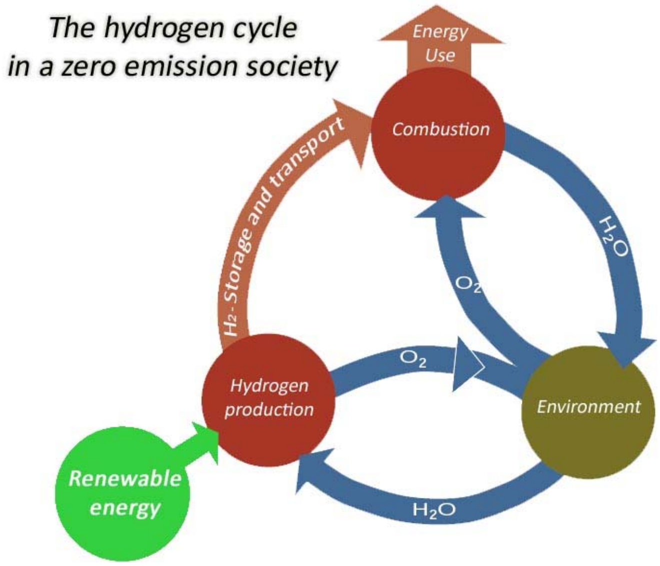


Figure 10 - Hydrogen Cycle in a zero emission society

5.4.4 Problems and challenges

Infrastructure:

The perhaps greatest challenge for the introduction of hydrogen as a fuel is that there is very little hydrogen infrastructure. Hydrogen can not be the most important energy source as long as just a few people have access to it. The hydrogen infrastructure will be developed in the years to come, but it will take time. For the Norwegian fisheries, who's base often are in smaller, less populated communities, the access to pure hydrogen will be a large problem in many years to come.

Volumetric energy density:

Hydrogen has three times the energy density of gasoline when it comes to weight, see table 2, but it is however quite hard to liquefy. Thus, the easiest and cheapest way to store hydrogen is as compressed gas. When stored as gas, the volumetric energy density strongly decreases. This is the reason why hydrogen-fuelled vehicles' have strictly reduced operating ranges compared to conventional gasoline-fuelled vehicles.

The diagram in figure 10 shows that the hydrogen has to be compressed to 3500(!!) bars to have the same volumetric energy density as regular fuel oil. The assumptions done here will not describe the correct picture, in special for higher pressures, but it shows us that hydrogen's volumetric energy density is really low compared to fuel oil. At 250 bars, the volumetric energy density is approximately 7 % compared with fuel oil, while 14.5 % percent at 500 bars. Most hydrogen powered vehicles usually store their compressed hydrogen at 250-350 bars. In this calculation the gas constant is set constant for every pressure and the temperature is set to 20 ^{O}C.

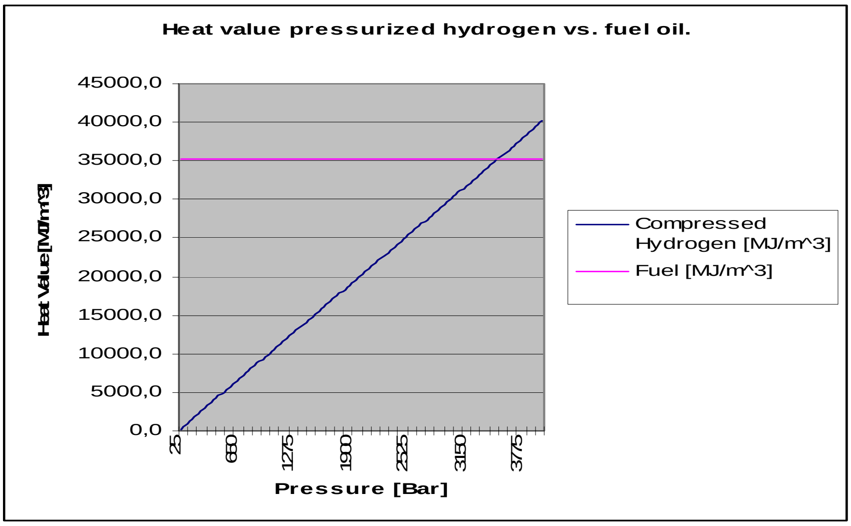


Figure 11 - Heat value for pressurized hydrogen compared to fuel oil.

Hydrogen safety features

One of the critical issues with the use of hydrogen as fuel is safety. In fishing vessels there will specially be problems with the storing of hydrogen. Hydrogen gas is both colour-free and odour-free, but is not considered as poisonous. The gas has stronger demands for compact pipes and equipment to avoid leakage, due to the very small hydrogen atoms. Hydrogen will tend to leak through holes or joints of low pressure fuel lines 1.26 to 2.8 times faster than natural gas leaks through the same hole [14]. It is important to remember that hydrogen is reacting with steel and other materials inducing reduced material strength. Further, hydrogen has a lower density then air, which make a leakage of hydrogen raise to the roof. Thus, it is important that the roof contains good ventilation at the highest point.

Other security facts:

- Hydrogen burns in air concentrations between 4 % and 75 % (volumetric), while gasoline burns from 2 %.
- The hydrogen's ignition temperature is twice as high as for gasoline.
- Almost every spark will ignite hydrogen, including sparks from static electricity.
- Hydrogen burns with an almost invisible flame.
- A hydrogen concentration of 18 % in air causes a danger of explosion.
- Hydrogen mixes very fast with air, so that concentrations get safe. Experiments carried out tell that an emission of 2000 litres of liquefied hydrogen will vaporize and mix with the air so that the concentrations are safe within a minute.
- Equipment that contains hydrogen should be outfitted with a hydrogen detector that warns if there are leakages.

The conclusion is that hydrogen is not very dangerous compared to other fuels as long as you are aware of its properties. However, the use of hydrogen requires adapted technology. [8], [13]

5.5 The fuel cell history

The fuel cell is not a new invention. Already in 1839, Sir William Robert Grove, a Welsh judge, inventor and physicist realized that if electrolysis, using electricity, could split water into hydrogen and oxygen then the opposite would also be true. Combining hydrogen and oxygen, with the correct method, would produce electricity. To test his reasoning, Sir William Robert Grove built a device that would combine hydrogen and oxygen to produce electricity. Grove called his invention *the world's first gas battery. [23]*

In 1889, the term "fuel cell" was first adapted by Ludwig Mond and Charles Langer, who attempted to build a working fuel cell using air and industrial coal gas. Another source states that it was William White Jacques who first coined the term "fuel cell." Jacques was also the first researcher to use phosphoric acid in the electrolyte bath. *[24]*

Friedrich Wilhelm Ostwald, a founder of the field of physical chemistry, provided much of the theoretical understanding of how fuel cells operate. In 1893, he experimentally determined the interconnected roles of the various components of the fuel cell: electrodes, electrolyte, oxidizing and reducing agents, anions, and cations. *[25]*

Francis Thomas Bacon (1904 -1992) began researching alkali electrolyte fuel cells in the late 1930s. Early cell designers used porous platinum electrodes and sulphuric acid as the electrolyte bath. Using platinum was expansive and using sulphuric acid was corrosive. Bacon improved on the expensive platinum catalysts with a hydrogen and oxygen cell using a less corrosive alkaline electrolyte and inexpensive nickel electrodes. In 1939, he built a cell that used nickel gauze electrodes and operated under pressure as high as 3000 psi. It took Bacon until 1959 to perfect his design, when he demonstrated a five-kilowatt fuel cell that could power a welding machine. Francis T. Bacon named his famous fuel cell design the "Bacon Cell." [24]

In October of 1959, Harry Karl Ihrig, an engineer for the Allis - Chalmers Manufacturing Company, demonstrated a 20-horsepower tractor that was the first vehicle ever powered by a fuel cell [24]

In the 1960s, the race for the moon forced USA to research a broad scope of new technologies. The fuel cell became the technological solution to NASA's dilemma of how to provide power for extended missions to space. The earlier problems of cost and fuel supplies that plagued fuel cells became irrelevant as the spacecraft was already carrying liquid hydrogen and oxygen. An additional benefit of fuel cells over other technology was that the astronauts could consume the fuel cell's by-product, water. On the early missions powered by fuel cells, there were problems with the systems that required attention. On each subsequent mission the fuel cells became increasingly reliable and today NASA's space shuttle relies on fuel cells for electricity and drinking water. NASA has funded more than 200 research contracts exploring fuel-cell technology, bringing the technology to a level now viable for the private sector.

The first bus powered by a fuel cell was completed in 1993, and several fuel-cell cars are now being built in Europe and in the United States. Daimler Benz and Toyota launched prototype fuel-cell powered cars in 1997. [24}

Different types of fuel cells

There is a large diversity of different fuel cell technologies. The principle is the same as shown earlier, but there are several types of fuels, electrodes and electrolytes used, depending on the fuel cell's purpose. Following is a description of the most frequent used fuel cell technologies.

5.5.1 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

Proton exchange membrane (PEM) fuel cells work with a polymer electrolyte in the form of a thin, electrically conductive carbon paper. [8] The standard electrolyte material currently used in the PEM fuel cells is a fully fluorinated Teflon – based material produced by DuPont for space applications in the 1960s. The DuPont electrolytes have the generic name Tafion. This membrane is small and light, and it works at low temperatures (about 80 ^{o}C). Other electrolytes require temperatures as high as 1000 ^{o}C. Efficiency for a PEM cell reaches about 40 to 50 percent and an external reformer is required to convert fuels such as methanol or gasoline to hydrogen, because the electrolyte does not handle impure fuels very well. [15]

PEM fuel cells are the most researched and used fuel cells for smaller and portable applications. The car industry is mainly developing PEM fuel cells for they vehicles, (Some also look into DMFCs), mainly because they are compact and relatively light.

Research is being done to raise the fuel cells operating temperature to perhaps 120 ^{o}C. This will give an even more efficient fuel cell

- Small and compact
- Efficient, high power density
- Has been researched a lot
- Low operating temperatures
- Zero emissions when pure hydrogen is used as fuel
- Mass production will probably make the prices affordable
- Fast start-up time
- Low sensitivity to orientation
- Favourable power-to-weight ratio [8] , [15] , [16]

- Requires pure hydrogen. Reformer needed when using other fuels.
- Cost of production still very high
- Further research is needed to optimize the design [8] , [15] , [16]

5.5.2 Alkaline Fuel Cells (AFCs)

Alkaline fuel cells operate on compressed hydrogen and oxygen and generally use a solution of potassium hydroxide in water as their electrolyte. The operating temperature of these cells is in the range between room temperature and 250 ^{o}C [17]. Alkali fuel cells operate at efficiencies up to 70 percent and like other fuel cells they create little pollution. Because they produce pure water in addition to electricity, they have been a logical choice for spacecrafts and have been used by NASA since the Apollo program. So fuel cells have already been to the moon. AFCs typically have a cell output from 300 watts to 5 kW [18], but the technology should be quite easy to scale. AFCs' high performance is due to the rate at which chemical reactions take place in the cell.

An advantage of the AFCs is the material's low cost. A disadvantage of AFCs is that pure hydrogen and oxygen have to be fed into the fuel cell because it can not tolerate the small amounts of CO2 in the atmosphere. The carbon dioxide will degrade the electrolyte and shorten the AFCs lifetime drastically. Due to these tolerance limitations the AFCs are not used in many power applications today [8], [19]

- Very high efficiencies
- Low material costs
- Relatively good operating temperatures
- Zero Emissions

- Requires pure hydrogen and oxygen. You have to bring both.
- Small market gives high prices.
- The purification of hydrogen and oxygen needs costly equipment
- Low lifetimes. Around 8000 hrs.

5.5.3 Phosphoric Acid Fuel Cells (PAFCs)

The phosphoric acid fuel cell is one of the few commercially available fuel cells. Several hundred fuel cell systems have been tested and these fuel cells have been installed all over the world. Most of the PAFC plants that have been built are in the range from 50 to 200 kW, but larger plants of 1MW and 5MW also have been built. The largest plant tested today achieved 11 MW. [17]

PAFCs have alone an efficiency of 37-42 % percent efficiency. This is only slightly more efficient than combustion-based power plants, which typically operate at 33 to 35 percent efficiency. However, the efficiency can be as high as 85 percent if the steam produced by the PAFCs is used for cogeneration. Operating temperatures are in the range from 150°C to 220°C. At lower temperatures, PAFCs have a poor ionic conductor and emissions of carbon monoxide (CO) and poisoning of the platinum catalyst in the anode can become severe.
PAFCs currently require an extended warm-up period, making them quite useless in portable applications. Hence, PAFCs are so far most suited for stationary applications. However, PAFCs were tested in buses in the US in the 1990s. [8]

- Very efficient with cogeneration of the steam produced, (up to 85 %)
- CO tolerant at higher temperatures. Approx. 1.5 % at 200 °C
- Possibilities for high power outputs
- Operating temperatures above water's boiling point in spite of acid electrolyte
- Tolerant for different fuels, but this shortens the cell's lifetime.

- Long start up time
- Low CO tolerance at low temperatures reduces lifetime
- Large size and weight. Less powerful then other fuel cells, compared by weight
- In general, low currents a produced
- Expensive due to the use of platinum catalyst. [8], [15], [19]

5.5.4 Solid Oxide Fuel Cells (SOFC)

Solid Oxide Fuel cells seems promising for large, high-power applications such as industrial and large-scale central electricity generating stations. Some developers also see potential for SOFCs for use in motor vehicles and are developing fuel cell auxiliary power units (APUs). Wärtsila is basing their fuel cell engines for ship on SOFCs, and is currently testing APUs with this technology. [20]

The operating temperature of SOFCs can reach 1000 °C and the power efficiency could reach 60 to 85 percent with cogeneration. Tubular SOFC technology has produced as much as 220 kW. In Japan there are two 25 kW units online, while a 100 kW plant is being tested in Europe. [18] High operating temperatures have disadvantages. It results in a slow start-up and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications. The high operating temperatures also place stringent durability requirements on materials. However, SOFCs coupled with a small gas turbine, to benefit the heat, are high-efficiency systems that can have a combined output in the range of 250 kW to 25 MW, and are expected to fit into grid support quite soon. These fuel cells could potentially compete head-on with today's power sources. [17], [8]

+

- High efficiencies with cogeneration (60 to 85 %)
- Can use a large variety of fuels due to the high operating temperature
- Can give high power outputs
- Can in time become cost effective
- There is no need for an external reformer

÷

- High operating temperatures gives large structures and safety zones
- Slow response time due to the high operating temperatures
- The high operating temperature place stringent durability requirements on materials

5.5.5 Molten-Carbonate Fuel Cells (MCFCs)

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. The project Fellowship that will be mentioned in more detail later is also a MCFC project. MCFCs have high fuel to electricity efficiencies rating from 60 to 85 percent with cogeneration, and operate at about 620-660 ^{o}C [17]. The high operating temperature is a big advantage because it enables a higher efficiency and fuel flexibility. Thus, fuels such as LNG can be used together with inexpensive catalysts. MCFCs producing in the range from 10 kW to 2 MW have been tested throughout the world with a large variety of fuels, but are so far primarily targeted to electrical utility applications. This technology has potential to also power larger portable applications, such as ships in the future.

+

- Molten carbonate fuel cells can run on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel and coal gasification products, without need for an external reformer.
- The tolerance for different fuel types makes the MCFCs very interesting for the marine business since no hydrogen infrastructure is needed.

÷

- The high temperature in the fuel cells enhances corrosion and breakdown of cell components, resulting in shorter lifetimes then other fuel cells.
- The use of fuels containing carbon will result in CO_2 emissions.
- Liquid electrolyte (Carbonate salts melts at operating temperatures to drive the fuel cell) in stead of solid electrolyte as we have in the SOFCs.

5.5.6 Direct methanol Fuel Cells (DMFCs)

The large potential for fuel cells in portable applications has generated a strong interest in fuel cells that can run directly on methanol. Operating on liquid fuel would reduce the risk of transporting high - pressure hydrogen at the same time as the refuelling becomes easier. The DMFCs use the same electrolyte membrane as the PEM fuel cells, but the fuel is methanol and not hydrogen. Although methanol only has a fifth of the energy density of hydrogen by weight, it offers more than four times the energy per volume when compared to hydrogen at 250 bars since it is liquid [21]

A major issue with the DMFCs is that the oxidation of methanol produces intermediate hydrocarbons, which poisons the electrode. There is also the problem of high crossover of the methanol through the electrolyte (the fuel molecules diffuse directly through the electrolyte to the oxygen electrode). Thus, power is severely reduced since almost 30 percent of the methanol can be lost this way. [22]

The efficiency of DMFCs is of about 40 percent. The fuel cell would typically operate at a temperature from room temperature to about 100 ^{o}C. This is a relatively low temperature range, which makes this fuel cell technology very attractive for smaller applications, such as for instance cars. Military forces around the world are researching a lot on these fuel cells, since they are very suitable for field equipment. [8]

+

- Easy refuelling and development of infrastructure
- Higher volumetric energy density then hydrogen
- Easy storage
- Small operating temperatures make the DMFCs very suitable for smaller, portable applications.

–

- Relative low efficiency due to diffusion of methanol through the electrolyte
- The oxidation of methanol of methanol produces intermediate hydrocarbons, which poisons the electrode and result in short lifetimes.
- The new technology lays 3-4 years behind other fuel cell technologies [19]

5.5.7 Zinc Air fuel cells (ZAFCs)

ZAFCs are often referred to as “regenerative” fuel cells. A regenerative fuel cell system is a system where no fuel is added, and none of the products or by-products is wasted. The fuel cell works a lot like a battery. ZAFCs contain a zinc “fuel tank” that automatically regenerates the fuel. Zinc fuel is in the form of small pellets, and is consumed before releasing electrons that drive a load. The efficiency is 30 to 50 percent for a zinc regenerative fuel cell system. [8]
The zinc-air fuel cell technology is classified under the fuel cells and batteries. The main advantage zinc-air technology has over battery technology is its high specific energy. ZAFCs have been used to power electronic vehicles, and have been proven to deliver longer driving distances between refuelling then any battery in vehicles of similar weight. The material costs for ZAFCs and zinc-air batteries are low because the abundance of zinc as an element. Due to this, zinc-air technology can be potentially used for a wide range of applications, such as electronic vehicles and military applications. [8]

5.5.8 Comparison of Fuel Cell Technologies and summary

There is a huge scope of different fuel cell technologies. Research is being done on a very wide perspective and it could seem a little difficult to see the possibilities for the different technologies. While the fuel cells that are mention above are being further researched, new technologies such as *Protonic Ceramic Fuel Cells, and Biological Fuel Cells* are developed.

The main principle is the same for all fuel cell technologies, but still there are huge differences. The fuel cells are mainly differentiated from one another based upon electrolyte and fuel type. These differences lead to important characteristics, advantages and disadvantages of each fuel cell type.

All fuel cells can run on pure hydrogen gas, but high temperature fuel cells can also use hydrocarbon fuels or carbon monoxide (CO). Out of all fuel cell types being researched today, the PEMFCs seems to currently be the best suited fuel cell for portable, backup and transportation purposes, while SOFCs and MCFCs seems to be the best suited for larger-scale stationary applications.

Because of this huge variety, it is important to have an overview of the different fuel cell characteristics when starting up fuel cell researching projects. The different technologies have different operating scopes and a good basic knowledge of the different technologies is essential to find the best solutions, either you are looking on a car or a fishing vessel.

It might me important to notice, that the technology for use in larger power applications in ships possibly is quite different from the one used in road vehicles. Table 3 below is the US department of energies comparison of fuel cell technologies [19]

Table 3 – Comparison of fuel cell technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Efficiency Electrical	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C 122 - 212°F	<1kW – 250kW	53-58% (transportation) 25-35% (stationary)	•Backup power •Portable power •Small distributed generation •Transportation	•Solid electrolyte reduces corrosion & electrolyte management problems •Low temperature •Quick start-up	•Requires expensive catalysts •High sensitivity to fuel impurities •Low temperature waste heat •Waste heat temperature not suitable for combined heat and power (CHP)
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C 194 - 212°F	10kW – 100kW	60%	•Military •Space	•Cathode reaction faster in alkaline electrolyte, higher performance	•Expensive removal of CO_2 from fuel and air streams required (CO_2 degrades the electrolyte)
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C 302 - 392°F	50kW – 1MW (250kW module typical)	32-38%	•Distributed generation	•Higher overall efficiency with CHP •Increased tolerance to impurities in hydrogen	•Requires expensive platinum catalysts •Low current and power •Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C 1112 - 1292°F	<1kW – 1MW (250kW module typical)	45-47%	•Electric utility •Large distributed generation	•High efficiency •Fuel flexibility •Can use a variety of catalysts •Suitable for CHP	•High temperature speeds corrosion and breakdown of cell components •Complex electrolyte management •Slow start-up
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of Yttria is added	650 - 1000°C 1202 - 1832°F	5kW – 3MW	35-43%	•Auxiliary power •Electric utility •Large distributed generation	•High efficiency •Fuel flexibility •Can use a variety of catalysts •Solid electrolyte reduces electrolyte management problems •Suitable for CHP • Hybrid/GT cycle	•High temperature enhances corrosion and breakdown of cell components •Slow start-up •Brittleness of ceramic electrolyte with thermal cycling

6 Fuel Cells Today

6.1 Land-based applications

6.1.1 Portable fuel cell applications

Fuel cells have already been used in a wide scope of applications. What is important to remember is that different kind of fuel cell technology is used in different types of applications. Small portable devises are usually outfitted with smaller PEM fuel cell, while larger stationary fuel cells usually have a higher operation temperature, making the use of more impure fuels such as LNG possible. Fuel cells such as SOFC, MCFC and PAFC are used for these stationary applications with higher power outputs.

Fuel cells are believed to be an alternative for all applications that are using electricity today. Even though many of the examples have no relation to fisheries, they are included to show the variety of possibilities for fuel cells. In the following, some examples of fuel cell applications in land-based applications are explained.

Camcorders:

Figure 12- US President George W. Bush testing fuel cell powered camcorder from Jadoo Powersystems [26]

This professional camcorder is powered by a PEM fuel cell system developed by Jadoo Power Systems. Broadcasters never know when or where news will break, so having reliable power in the field that lasts as long as the story does is essential. [26]. Here the camcorder is tried out of President Bush in February 2003. A fuel cell can strongly extend camcorders durability in isolated areas when compared to a regular camcorder.

Desktops:

Figure 13 - Fuel cell powered desktop from Fujitsu Laboratories, 2004

A lot of companies have developed portable computers running on fuel cells. The computer shown in the picture above was presented by Fujitsu Laboratories in January 2004 and runs on a DMFC fuel cell. The fuel cell technology enables the use of 30% methanol as a fuel source. [27]

Portable power generators:

Figure 14 - Portable 1kW power generator from Ballard [27]

Figure 13 shows a portable *Ballard fuel cell generator* developed by the Canadian well known fuel cell producer Ballard. The generator is capable of producing 1 kW, and is a fully automated power system which converts hydrogen fuel and oxygen directly from the air into DC electricity. Water is the only “waste product” of the reaction. This fuel cell generator which operates at low pressures is supposed to *provide reliable, clean, quiet and efficient power,* according to the producer. It is small enough to be carried to wherever power is needed. [27]

6.1.2 Examples of fuel cells in transportation applications:

Buses

Figure 15 - Fuel cell powered bus in the CUTE - project, developed by DaimlerChrysler

The CUTE project is called the most important fuel cell project so far. 27 fuel cell powered buses, developed by Daimler Chrysler were tested in nine European cities. The project started in 2003 and lasted until 2006 and was characterized as a major step in European fuel cell development.
The partners received European financial assistance of 18.5 million euros, and all the cities involved had to build up refuelling stations and hydrogen infrastructure. The conclusion of the project was that we need greater efficiency, i.e. longer lifetime, reduced fuel consumption and a lower price per vehicle. DaimlerChrysler is now developing the next generation of fuel cell busses, with PEM cell outputs at almost 300 kW. [8], [28]

Cars

Most automobile manufacturers have been developing fuel cell vehicles for at least a decade, and have demonstrated at least one prototype vehicle. The major reason for developing automotive fuel cells are their efficiency, low or zero - emissions, and fuel that could be reproduced from local sources rather then imported. [8] Some car producers, such as General Motors, Toyota and Honda, are working on their own fuel cell technology, while other manufacturers are buying the fuel cell technology from fuel cell developing companies, such as Ballard, DeNora and UTC fuel cells. Ford, Mazda, DaimlerChrysler, Hyundai and Volkswagen are among these manufacturers.

Many of the automobile manufacturers demonstrated their first fuel cell vehicle in the late 1990s. The most common fuel type is compressed hydrogen, but some producers have also demonstrated alternative fuel types such a methanol. Thus, the most common automotive fuel cells are PEMFCs and DMFCs.

Automotive fuel cells can have one or more of the following characteristics.

- A fuel cell is sized to provide all power to a vehicle. A battery might be present for start-up.
- A fuel cell typically supplies a constant amount of power, so for acceleration and other power peaks, additional devices such as a batteries are switched on.
- Sometimes fuel cells are used as the secondary power source. A system is set up where batteries power the vehicle while the fuel cell is just recharging the batteries [8]

The latest fuel cell vehicles have a power output up to 100 kW and as an example Honda's newest fuel cell vehicle will be presented to show how good the automobile industry's technology is.

November 14, 2007–Honda unveiled the FCX Clarity fuel cell vehicle at the Los Angeles Auto Show, announcing plans to begin limited retail marketing of the vehicle in the US the summer 2008. [29]

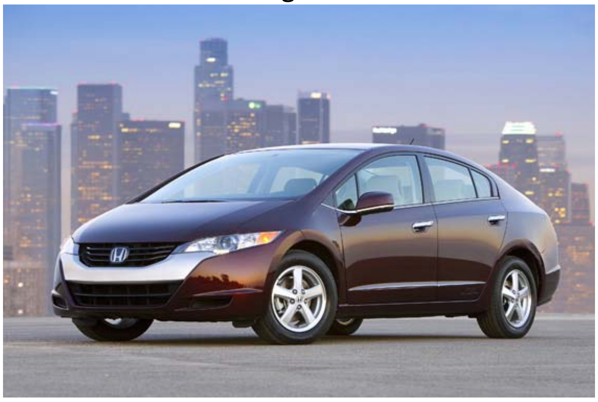


Figure 16 - Honda FCX Clarity fuel cell vehicle - 100kW [29]

"*Taking advantage of a completely new cell configuration, the vertically-oriented stack achieves an output of 100 kilowatts (kW) (versus 86kW in the current Honda FC stack) with a 50 percent increase in output density by volume (67 percent by mass*)"- Honda Motors

The car's new fuel cell stack increases the vehicle range to approximately 430 km, and gives the vehicle a 20 percent increase in fuel economy compared to the old prototype. The compressed hydrogen is placed under the backseat with a pressure of approximately 350 bars. This can be seen in figure 16

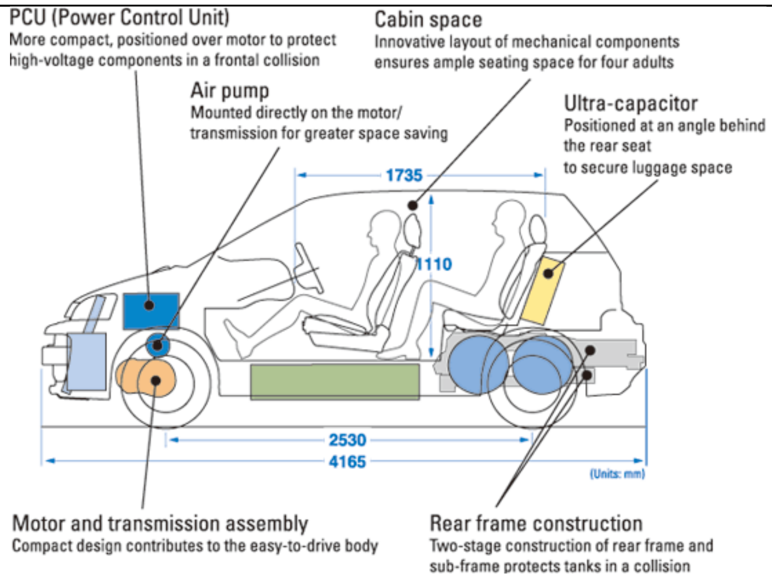


Figure 17 - Honda FCX clarity fuel cell vehicle - Fuel cell system description

Hydrogen-powered vehicles are also found in Norway. Through the HyNor project, (which will be mentioned later) hydrogen infrastructure is being developed with hydrogen refuelling stations. The two first hydrogen stations are already build in Stavanger and Grenland and hydrogen-powered cars are tested together with these stations. Mazda will in the years to come test their fuel cell vehicles on the HyNor road.

FYK

FYK is a sports car developed by the Norwegian company Aetek AS. The car is not running on fuel cells, but is included in this report to show other possibilities for the use of hydrogen as fuel.

Figure 18 - FYK is a Norwegian developed sports car, running on HCNG[30]

The car is powered by NaturalHy (hydrogen compressed natural gas) which consists of 8-20% hydrogen and 92-80 % compressed natural gas. The fuel is burned in a combustion engine. Hence, the car still emits greenhouse gases. However, the emissions are strongly reduced compared to other sports cars.

"Using cutting edge wireless communications solutions from Norwegian IT-companies, the FYK concept car will exceed consumer expectations for a 'normal' sports car" – [30]

And the latest prototype has sports car characteristics. The car is powered by a HCNG 3.0 l V8 engine with a power output of 300 hp. It does 0-100 km/t in 4 seconds and does not weigh more then 800 kg. The operating range is 350 km, but most importantly, the car emits just a small fraction of greenhouse gases when compared to every other sports car. [30], [31]

6.2 Maritime projects

6.2.1 Examples of fuels cells in marine applications today

There are a few projects that are using fuel cells as an energy source in marine applications. The most of these applications are so far smaller leisure boat models that are not put into mass production. The vessels are all below 40 feet and they are mainly using PEM fuel cells and hydrogen as fuel. In the following some of these concepts will be presented to show some fuel cell ideas in the maritime business.

Xperiance from Ecofys in Netherland:

Length:	**7 m**
Type of fuel cell:	**PEM**
Fuel:	**Hydrogen**

The Hydrogen Xperiance is developed by the Dutch company Ecofys in collaboration with Ganita Shipyard and the Knowledge centre of Yacht building. According to Robert van der Hoed of Ecofys, the Xperiance will be able to travel for two or three days without refuelling. Besides, the hydrogen powered boat can be refuelled in 15 minutes rather then 4-6 hours for an electrical powered boat. [32]

Figure 19 - The Hydrogen Xperience [33]

Ecofys claim that the boat is very cost effective compared to similar projects. They have managed to produce the fuel cell system that powers the vessel for 40,000 euros. The development had a cost of 200,000 euros, which was done with help of Dutch national and regional authorities. The cost of the fuel cells should go down to 10,000 euros when the boat is produced on a larger scale.

The boat will still have to rely on subsidies to compete on the market. But while similar vessels so far needed subsidies equal to 80-90% of their production costs, for the Xperiance this will be 20-30%, according the designers. [33]

Ecofys is a leading company in the field of sustainable energy and energy saving. More than 350 employees in thirteen countries deliver sustainable energy services and innovations. Ecofys is part of the Econcern group, one of Europe's 500 fastest-growing companies with the mission to ensure a sustainable energy supply for everyone. [34]

Zebotech

The Cobalt 233 ZET with Zero Emission Technology has been developed of the German company Zebotech GmbH, located in Koblenz together with Brunnert-Grimm AG from Gottlieben in Switzerland. The boat is shown in figure 19, at the "Innerboot" in Friedrichhafen in September 2007. The designers, located far from the sea in Germany and Switzerland has designed the boat for lakes such as the Bodensee.

Figure 20 - Zebotech - Electrical powered boat, with fuel cells to extend the operating range. [35] , [36]

Already in the year 2000, Brunnert-Grimm AG built and tested a runabout running on an electric motor. The motor had a capacity of 50 kW and the energy was supplied entirely from batteries. The testing demonstrated the feasibility of such a concept but also highlighted requirements for further technical development. The two main problems were the low range and the weight, two significant limitations of a battery system. [35]

With these problems in mind, the decision was to implement fuel cell technology in the further development of the boat. So using a commercially available runabout, the two companies mentioned have developed a hybrid drive consisting of electric motors, fuel cells, hydrogen tanks and a battery only for peak power requirements.

According to the designers, the system optimization ensures that the different features of each technology are exploited to a maximum and shall be capable of reaching 40 km/t or above 20 knots. The boat is operated like any "normal" runabout.

Three hydrogen tanks that can be filled to a pressure of 350 bars shall provide sufficient fuel to travel across the entire Bodensee – quietly, smoothly and without any emissions. [36]

The fuel cell boat Cobalt 233ZET, is built according to the guidelines of Germanischen Lloyd (GL) and will shortly receive the "GL Certification for Fuel Cell Boats". First deliveries are planned for the European season 2008. Prices for a Cobalt runabout with hybrid drive will be available in November 2007.

H2Yacht

H2 Yacht is a German based company that has developed two PEM fuel cell leisure boats on a typical traditional German design for use in channels and sheltered waters. The two designs have already been tested and are now possible to order from the shipbuilders in Germany. In the following some specifications of the designs will be presented

Figure 21 - H2Yacht 540 (right) and H2Yacht 650 (left)

H2Yacht 540

Dimensions:	
Length, (LOA):	5.80 m
Length (LPP):	5.40 m
Breadth:	2.10 m
Draught.(w/ 0 persons):	0.40 m
Draught (w/ 5 persons):	0.47 m
Machinery:	
PEM fuel cell:	24 V / 1.2kW
Cooling:	Air
Buffer battery:	24 V / 90 Ah
Fuel:	Hydrogen
Fuel capacity:	8 Nm^3
Electrical power output:	2 x 672 W = 1.34 kW

H2 Yacht 650:

Dimensions:	
Length, (LOA):	6.75 m
Length (LPP):	6.75 m
Breadth:	2.44 m
Draught:	0.57 m
Machinery:	
PEM fuel cell:	2 x (24 V / 1.2kW) = 2,4 kW
Cooling:	Water
Buffer battery:	24 V / 225 Ah
Fuel:	Hydrogen
Fuel capacity:	15 Nm^3
Electrical power output:	2 x = 1.34 kW

Urashima:

Already in the year 2000, The Japan Marine Science and Technology Centre (JAMSTEC) unveiled its deep-sea cruising explorer "Urashima”.

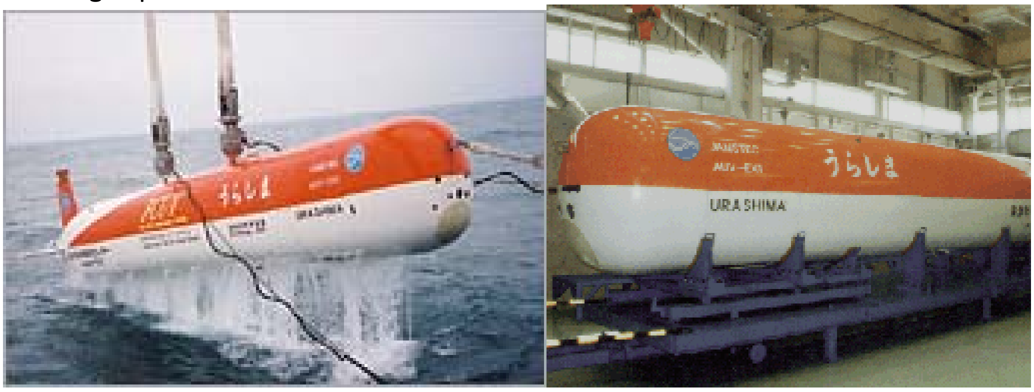


Figure 22 - Urashima - Japanese fuel cell and battery powered ROV[38] (left), [39] (right)

The vessel is a deep-sea exploration robot which was developed by JAMSTEC since 1998. The vessel is able to determine its own location and follow predefined courses configured in its onboard computer. On February 28, 2005 *“Urashima”* succeeded to complete the world-record, 317-km continuous cruise.

Urashima is able to automatically collect oceanographic data (such as salinity, water temperature and dissolved oxygen) required to clarify the mechanisms of global warming over an extensive area. The vessel is also able to cruise along the seafloor in order to acquire extremely high-resolution seafloor topography and sub-bottom structure. The vessel is navigated by program put into its computer, which means that it can perform surveys over a particular fixed location or up and down a defined narrow path or range. [38]

Specifications: [37]

Dimensions:

Length, (LOA):	approx. 10 m
Breadth:	approx. 1.3 m
Height	approx. 1.5 m
Weight in air (With battery):	approx. 8 ton
Weight in air (With fuel cell):	approx. 10 ton
Maximal depth capacity:	3500 m
Cruising range (battery):	100 km
Cruising range (Fuel cell):	300 km
Cruising speed:	3-4 knots

Machinery:

Fuel cell or Lithium-ion battery

PEM fuel cell:	2kw x 2 Stacks = 4kW
Operating temperature (FC):	60 °C
Generation efficiency(FC):	54%
Fuel:	Pure hydrogen and oxygen

Duffy Boat

In this Californian project, four 1.5 kW PEM fuel cells are placed in the Duffy-Herreshoff 30 to produce electricity to charge the boat's batteries. The batteries are in the next phase producing electricity to the boats 20 hp electrical motor. The boat's top speed is 8 knots, and it has an operating range of 350 km, (at 4.5 knots). The boat is 30 feet and has a capacity of 18 passengers. The fuel cell system weighs only 27 kg.[40]

It is the storing of hydrogen which makes this project quite interesting. That is because the hydrogen is stored in a liquid form within sodium borohydride. A Millennium Cell Hydrogen storage and delivery system is installed in to the boat and this system is run by the fuel cells. The Millennium Cell will be explained in more detail later. [41]

Figure 23 - Duffy boat with fuel cell powered by The Millennium Cell - Hydrogen on demand system [42]

The Millennium cell

"A critical barrier to the wide-spread use of hydrogen is how to effectively store hydrogen for various energy applications. Chemical hydrogen storage—in particular through the use of sodium borohydride ($NaBH_4$)—is a way to combine high energy density and ease of hydrogen release. These characteristics are essential for any near-term commercial opportunities of hydrogen power sources". [43]

The millennium cell storing and delivery system is a system that is extracting hydrogen from $NaBH_4$ and delivers it to the fuel cell stack. This way, hydrogen can be stored in a liquid so that the volumetric energy density strongly increases when compared to hydrogen in form of compressed gas. As table 4 shows, sodium borohydride ($NaBH_4$) has 50 % better volumetric energy density compared to methanol, which makes this a very interesting alternative. [44]

Feature	Sodium Borohydride	Methanol
Gravimetric Energy Density	7100 Wh/kg	6000 Wh/kg
Volumetric Energy Density	7314 Wh/l	4800 Wh/l
Power Source	The Hydrogen Battery	Direct Methanol Fuel Cell (DMFC) or Reformed Methanol Fuel Cell (RMFC)

Table 4 - Volumetric energy density of $NaBH_4$

The chemical process in the Millennium Cell is described in figure 23. Water is added to the liquefied sodium borohydride and with the help of a catalyst pure hydrogen is extracted and can be fed to the fuel cell. The waste from this process is NaBO2, which can be stored aboard and recycled back into NaBH4 later on.

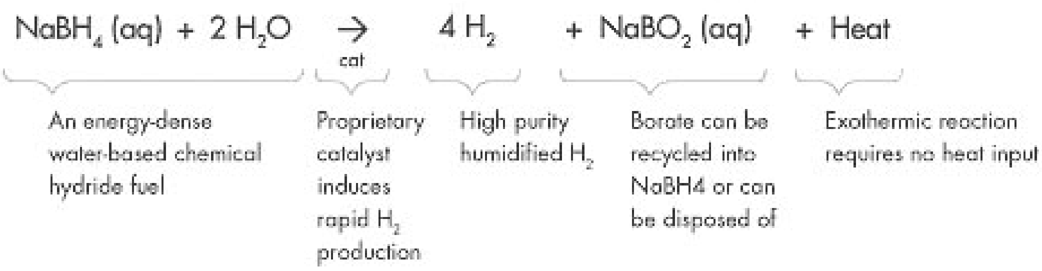


Figure 24 - The chemical process in a millennium cell [45]

This way, the millennium cell becomes a so-called hydrogen battery. Compared to a regular battery, a hydrogen battery is not a closed system, and it can be recharged simply by adding fuel in the form of sodium borohydride. The millennium cell has demonstrated a minimum efficiency of 40 %, and the reactor temperature can reach 90 °C.

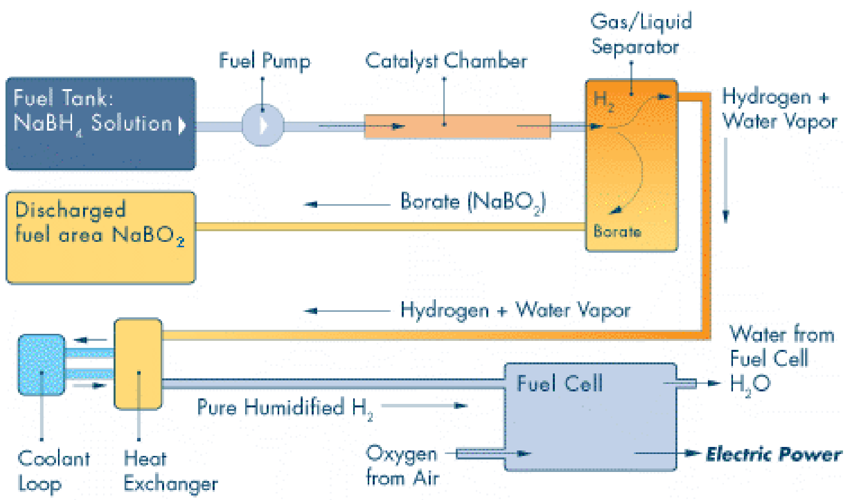


Figure 25 - The millennium cell principle [45]

Why a hydrogen battery?

The main reason is the increase in volumetric energy density you get while storing the hydrogen in a liquefied form. At the same time you will not need any reformers of any sort since the hydrogen extracted from the sodium borohydride is very pure. Further, the system is quite simple and does not rely on complex controls or sensors for efficient operation. Another important issue is safety. Liquid solutions of sodium borohydride are non-flammable which results in a good overall system safety. $NaBH_4$'s stability in air also makes it a much safer choice than its metal hydride counterpart. The system has also a slow start-up time of less then 30 seconds due to the low operating temperatures. [43]

The biggest problem with the Millennium Cell is the price of the system and the price of the $NaBH_4$. But since the waste $NaBO_2$ can be stored and "recharged" back into $NaBH_4$, the system can be lucrative in the long run. It might however be mentioned that you will be requiring a lot of space for both the fuel and the waste. At the same time $NaBH_4$ is lighter then $NaBO_2$, so that if such a system is installed in a ship, the weight of the total fuel and waste will increase during a trip. You are in other words adding weight to the ship. For many fisheries, this weight development can be unwanted.

Hydroxy 3000 from EIDV in Switzerland

The IESE Institute at the (EIVD) Ecole d'ingenieurs du Canton de Vaud (University of Engineering, Vaud) started working on fuel cells in 1998 by developing a small boat, the Hydroxy100, which was the first boat in Switzerland of this type powered by a 100W PEM fuel cell. The EIVD then decided to develop a second prototype, the Hydroxy300 with a 300W PEM fuel cell. These achievements have given the institute experience in the fields of fuel cells and boats which has resulted in the latest development, the Hydroxy3000 (3kW PEM) which allows the transport of passengers. [50]

Figure 26 - Hydroxy 3000 - Developed by EIDV in Switzerland [46]

The Hydroxy3000 is a catamaran with a length of 7 m, a width of 2.5 m, and a weight of 1.5 t. Both hull parts are equipped with a 3 kW electric motor. The fuel cell is the main source of energy. Batteries balance the energy supply and serve as an energy reserve in case of problems. The boat can carry seven passengers and travel at a speed of approx. 11 km/h. [46]

The fuel cell is supplied from a 76-liter (200 bars) hydrogen bottle. It drives two propellers via two 48 V DC motors that are electronically controlled from the bridge. Since each hull is equipped with a control system, the boat is exceptionally manoeuvrable. The hydrogen bottle and the fuel cell are located in separate, naturally ventilated compartments. Vibration and hydrogen sensors can shut down the hydrogen system in the event of problems. In such an emergency, auxiliary batteries ensure that the boat remains manoeuvrable and can return to its base.

The water-cooled 3 kW fuel cell consists of 73 individual cells supplying about 60 A at a variable voltage between 40 and 60 V. A heat exchanger dissipates the heat from the primary cooling system to the lake via a secondary system. [46]

6.3 Larger, Ongoing maritime Projects

6.3.1 FellowSHIP

Fellowship (Fuel Cells for Low Emissions Ships) is a project with collaborating companies from Norway and Germany. They are on track for the demonstration of a 320 kW MCFC auxiliary power unit in an offshore supply vessel. The FellowSHIP team consists of:

- Det Norske Veritas (DNV)
- Eidesvik Offshore
- MTU CFC Solutions
- Vik-Sandvik
- Wärtisila Automation Norway

Phase 1, containing a feasibility study, ran from 2003 to 2005. In the ongoing second phase, which started in 2005, the meaning is to fabricate and test the fuel cell in M/S Viking Avant, owned by Eidesvik Offshore. The testing is supposed to start in the first part of 2008. The project's budget from 2003 to 2008 is approx. 110 millions. [48]

Figure 27 - M/S Viking Avant, owned by Eidesvik will be powered by a 320 kW molten-carbonate fuel cell[49]

The Principle:

MTU CFC Solutions in Germany is providing a “Hot Module” fuel cell stack. In the “Hot Module”, incoming liquefied natural gas (the LNG - fuel gas in this case) is fed to the vertically-installed flow channels of the anodes via a gas distribution device. The horizontal fuel cell stack is sealed below through gravity. At a temperature of about 650 °C, the natural gas and steam split off the hydrogen needed on the anodes (internal reforming). The principle is shown in the figure below: [52]

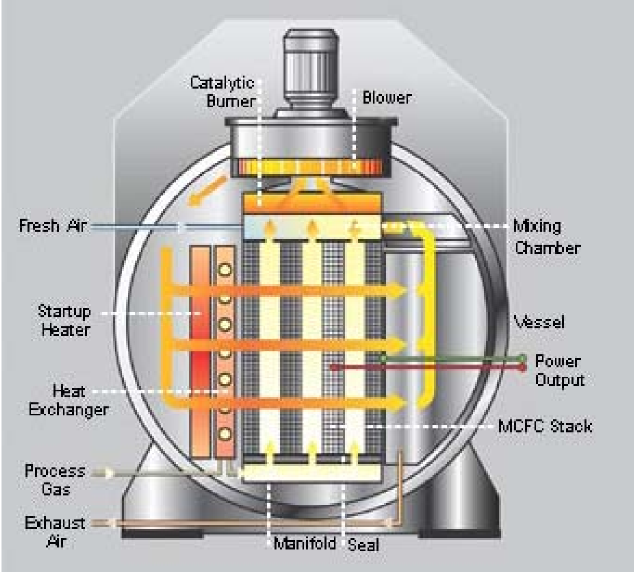


Figure 28 - Internal reforming of LNG in the "Hot Module" - molten carbonate fuel cell, [51]

“This technology can be up to 50% more efficient than today’s diesel engines and at the same time open up for ultra clean ships,” says FellowSHIP’s project manager Tomas Tronstad of DNV. [53]

According DNV, which is the project leader in Fellowship, the use of fuel cells in an offshore supply vessel will result in the following yearly emission reductions when run on LNG as main machinery: [40]

- 180 tons of NOx - (Equal to the emissions of 20 000 cars)
- 33 tons of SO2
- 4 tons of particles
- 4755 tons of CO2

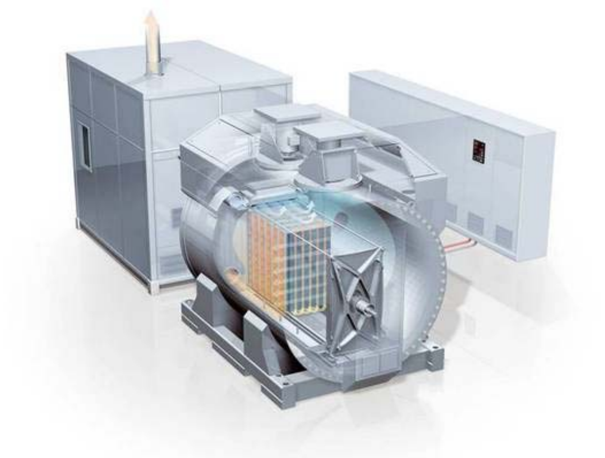


Figure 29 - The "Hot Module MCFC that's being put into M/S Viking Avant [51]

Technical Data:

The “Hot Module” fuel cell is a Molten Carbonate Fuel Cell that is supposed to be used as an auxiliary power unit in the supply vessel. The Fuel cell has a power output of 320 kW and is approximately the same size as a 20 feet container. The different parts can however, to some extend, be put where they fit. The fuel cell is operating in temperatures around 650 ^{o}C and will have an efficiency of about 50 % (from fuel to shaft). The initial project will not take advantage of the heat produced from the fuel cell reaction. However, Fellowship has patented systems where they with a steam turbine use surplus heat energy to increase the total system's efficiency. Such systems will increase the total efficiency of the fuel cell system with approx. 7- 8 percent. [47]

Today's challenges:

Emissions:
The fact that the fuel cell are using LNG result in emissions of CO_2, but the emissions are reduced with about 45 % percent when compared to a corresponding diesel engine, without no extra handling of the CO_2 . The emissions of NOx, SOx, and particles disappear.

Costs:
A fuel cell system is a lot more expensive than a corresponding diesel engine system. An estimate stated from Tomas Tronstad in DNV [47], says that the cost of this system is approximately 6 times the cost of a corresponding diesel engine system in 2010.

Lifetime:
The lifetime for a "Hot Module" is actually demonstrated to approx. 30- 35.000 hours. This is closed to an industry standard, but dynamic problems in the system will considerably reduce the lifetime.

Dynamic problems:
Heating and cool downs from starting, stopping and large load variations is problematic, especially for the materials inside the fuel cell. Thermal stresses will occur in the cell materials, leading to cracks and fractures. To avoid this problem, the response time have to be very long for the fuel cell. Dynamic forces from the electrical system can also become a problem for the fuel cell. These dynamic problems are the main reason why the use of MCFCs as main machinery is still far from being a reality [47]

Maintenance:
There is no need for more complicated work on a fuel cell stack then for a diesel engine, but having to change a fuel cell stack is expensive.

Reliability:
The reliability of fuel cells is in general not on an industrial standard yet. [47]

Other Challenges:
The waste from the fuel cell is steam, and in cold environments, this might be a problem. The wastewater is resulting in quite a lot of fog in the exhaust outlet. However, this problem is believed to be solved.

The response time for such fuel cells is quite long. This is a problem that they have decided to live with in this initial project.

Other information:
A design study, looking at the fuel cell's performance in the harsh conditions of the North Sea has been done. The conclusion was that is absolutely should be possible to operate in these kind of conditions. [47]

6.3.2 PowerCell – A fuel cell APU for use in long-distance trucks

PoweCell was founded in 2005 as a joint venture project between Volvo and Statoil, with the objective of bringing fuel cell technology to full commercialization. The initial PowerCell project is a 5 kW fuel cell generator for auxiliary power supply for heavy-duty trucks. The primary objective is to replace power supply from the main engine with fuel cell energy when the truck is parked. [56]

PowerCell is hoping to launch their first unit on the American truck marked within 2011. This marked will be the main objective marked for PowerCell, because of several reasons. Today there are 2.3 million long distance trucks in the USA, and among these, approximately 600 000 are equipped with a so called “sleeper”. The drivers of these trucks usually sleep in the truck. This means that the “sleepers” are equipped with everything from refrigerators to TVs, and thus they require a lot of electrical power. Today this power is made from a generator set on the idling main diesel engine. This results in a very low efficiency and a lot of noise. The PowerCell split the diesel into carbon and hydrogen before feeding the hydrogen to a PEM fuel cell, eliminating most of the emissions and, increase the efficiency and reduce the noise [54]

It has been calculated that one single truck outfitted with a “sleeper” is running on no load 1800 hours, or almost 11 weeks every year. This means that an annual 11 million tons of CO emissions comes from long distance trucks running on no load. When many states within the USA now are talking of forbid no-load running, then PowerCell has an enormous marked for their product, but how are they going to make it happen. [54]

The PowerCell Principle

The idea of the PowerCell is to extract the energy from the diesel in a much more environmentally friendly and efficient way. The first step of this process is to separate the hydrogen atoms from the diesel molecules. This is done in a reforming process with the use of heat, where all carbon molecules left over is burned to run the process. The hydrogen is then fed into a PEM fuel cell, where it reacts with the oxygen molecules in the air and produces energy. Pure water is the only “waste” from the reaction in the fuel cell, but there are some emissions of CO_2 in the reforming phase. [58]

The fuel cell

The PEM fuel cell is designed to deliver 5 kW of electric energy. The reason why this cell is chosen in stead of SOFCs and MCFCs is because of the short response time. While a SOFC perhaps would have a response time of 3 hours, the PEM cell is aiming for three minutes. This is mainly because of the low operation temperatures between 60 and 80 ^{o}C. [58]

The low operating temperatures are also a challenge because it makes the fuel cell quite sensitive for impure fuels. Comparing it with other PEM fuel cells, PowerCell has managed to increase the tolerance of CO five times, but this is still a challenge for the lifetime and reliability of the fuel cell. However, PowerCell aim to let the service interval of the fuel cell coincide with the service interval of the vehicle. [55] , [58]

The reformer

In the reformer, the diesel fuel is reformed into pure hydrogen gas. In the first phase, the diesel fuel is vaporized at 800 ^{o}C with the use of air and steam. With the help of a catalyst, the fuel is split into mainly pure hydrogen, CO and CO_2. Further the hydrogen is isolated from the carbon monoxide (CO) in two steps. The amount of CO must be below 100 pps before the hydrogen can be fed into the fuel cell. Sulphur is also captured before the hydrogen enters the fuel cell. The reformer is quite silent, but compressors and the diesel pump make some noise. [55]

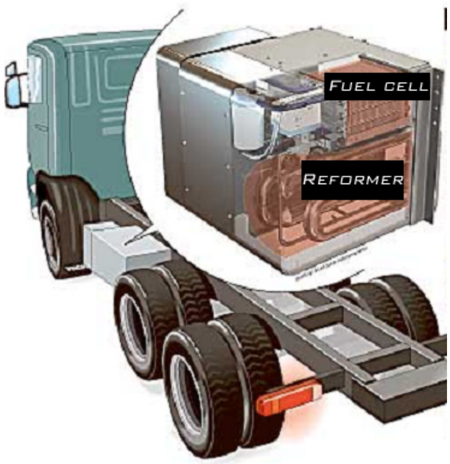


Figure 30 - PowerCell and reformer in actual size on a truck. [55]

Challenges:

The PowerCell is hoping to be launched on the American marked during 2011. Even if the project's financial structure now is under reconsideration, PowerCell state that this still is their goal. This means that PowerCell within three years shall have a competitive product. Testing is now being done, but there are still some challenges to be solved.

Costs:

The plan is that the fuel cell system shall compete with today's diesel generators. PowerCell has still a long way to go before they have reached this goal. The price will of course decrease strongly when the mass production of fuel cells begins, but there is still more development to be done before this goal can be achieved. Thus, PowerCell will probably in the first phase be dependent on commercial measures such as "green taxes" to achieve their goal. A completely installed 5 kW diesel generator today cost 40000-50000 NOK in a smaller fishing vessel. [58] The cost for an equivalent application in an American truck is probably cheaper.

Lifetime:

The reformer will not be able to provide completely pure hydrogen. Thus, small amounts of CO will come in to the fuel cell and degenerate the electrolytes and reduce the fuel cell's lifetime. However, this problem is believed to be feasible and PoweCell's goal is to let the fuel cell and the vehicle's maintenance interval coincide.

Dynamic problems:

When compared to the FellowSHIP's MCFC, the PowerCell do not have the same dynamic problems. This is because the operating temperatures in the fuel cell are so low. However, the reformer will be more exposed for material weaknesses due to thermal tensions.

Reliability:

PowerCell aims to be as good as any corresponding diesel generator. Thus, the reliability also has to be on the same level.

Efficiencies:
PowerCell aims to reach an average efficiency of 30%, but this is of course highly dependent on the state of operation. Unlike a diesel generator, a fuel cell's efficiency increases when the power output is reduced, see figure 9. Hence, a fuel cell can be better than a diesel generator at small power outputs, but worse at higher power outputs. This is a challenge for every fuel cell designer and is strictly dependent of the application and the operational state. PowerCell has still not been able to reach the 30 % efficiency goal, and further development has to be done. However, the PowerCell has better efficiencies than large diesel engines running on no load.

Why is a PowerCell interesting for smaller fishing vessels?

Some smaller fishing vessels have quite similar operating profiles when they are compared to long-distanced trucks. They are fishing during the day, and are often spending the night in the harbour without a shore connection. Thus, generation of electricity has to be done on board. So if the PowerCell is suitable for trucks, it should also be suitable for a smaller fishing vessel.
At the same time, the fuel cell provides silent energy supply, which might have a value for many fishermen. Further, the PowerCell do not emit any other waste then some CO_2 and water, which makes it a much better environmental alternative. The emissions of NOx are discussed in two examples in the next chapter. The NOx-fee only applies for ships with more then 750 kW installed power [59]. Thus it does not apply for most of the smaller fishing vessels, but the emissions have been calculated to see how much the PowerCell can reduce the total emissions from the fisheries. Another very good thing about the PowerCell is that you do not have to carry compressed hydrogen as fuel. The system runs on marine diesel oil and a development of hydrogen infrastructure is unnecessary.

In some areas the PowerCell can be better suited for fishing vessels then trucks. One thing is that we in a boat have much better possibilities for cooling. On the other side, the salt content in the air has to be dealt with. [56], [57]

Ferryboat in Bergen

The idea behind this project is to outfit the ferryboat, ”MF Vågen”, which is bringing passengers to Akvariet in Bergen, with a PEM fuel cell. Prototech AS, a Bergen based company developing fuel cell technology is the project leader. Both SOFCs for stationary power generating and PEMFCs for smaller applications for such as cars and space travelling are being produced by Prototech.

Figure 31 - Prototech AS is installing a PEM fuel cell in "M/S Vågen"

The project, which started August 2007 has a budget of 16 million NOK and has received economical support from the research council of Norway, among others. The project is divided into two parts where the first phase, which includes development, design and installation, will cost 12 million NOK and is scheduled to finish within May 2008. The last phase, which is including testing and demonstration, is scheduled to finish within September 2009. The project is financed with 6 million NOK from NFR, 8 million NOK from the shipping business and 2 million NOK from the project participants. [40]

Challenges:
The fuel cell system will be designed and installed by Prototech AS. Following is a list of challenges they have described.

- Control of the temperature and the moisture (water level) in the fuel cell stack
- Effects of air with a high content of salt inside the system. Methods to handle these effects.
- Compact and safe storage of hydrogen on board.
- Refuelling hydrogen
- Classification and approval from national authorities
- Public acceptance for the use of hydrogen and fuel cells in a passenger vessel.
-

The project is just started and according to partner Asle Lygre, the project is so far on budget and schedule, and hopefully the boat is ready to be tested next summer. [40]

Participants:

- *Prototech AS* - Bergen based fuel cell designing company.
- *Umoe Mandal AS* - Producer of tanks and storing systems for natural gas and hydrogen
- *Vågen Fergeselskap* – The owner of MF Vågen, where the fuel cell will be installed.
- *Maritime Engineering AS* – Ship consultant and Design Company.
- *Mundal Båt AS* – Shipyard located in Hordaland with relations to Maritime Engineering.
- *Gexcon AS* – Bergen based consultants with expertise in safety development. Good knowledge to gas handling safety with practical and experimental experience in use and storing of hydrogen.
- *Yara* – International supplier of hydrogen[40]

6.3.3 The Voller Emerald System

The Voller Energy group is a British company which was founded in 2002. They have developed The Voller Emerald, an application quite similar to the PowerCell. The Voller Emerald also has an effect of 5 kW, but unlike the PowerCell, the Voller Emerald runs on LPG or propane in stead of diesel fuel. The Emerald is also especially constructed as a marine application, and is being tested on Voller Energy's own sailing yacht at the moment.[60]

The Voller Emerald

As mentioned, the Voller Emerald is a 5 kW fuel cell system that reforms LPG in a similar way that the PowerCell reforms diesel fuel, before feeding the isolated hydrogen to a PEM fuel cell. As well as power, the Emerald also provides hot water and space-heating and can even support an air conditioning system. According to the designers, The Emerald provides all your energy needs in a quiet, compact and vibration-free generator. [61]

The system works by constantly monitoring boat's batteries and automatically recharging them when required. The life of these batteries is also extended by providing constant on-demand charging, avoiding the damaging power surges caused by conventional diesel generator systems. [61]

Figure 32 - The Voller Emerald

The Emerald will provide a pure electrical efficiency of 25 % and a combined power and heat efficiencies of more then 60 %. This is a powerful and portable alternative to the traditional diesel generator. With the Emerald, power fridges, TVs and major applications such as washing machines can be powered.

According to Jeoff Carr at Voller Energy, the Emerald will be available for commercial use by April 2008. The price of the application is not yet published, but it is assumed to be two to three times the price of an equivalent diesel generator. Further it will have the dimensions 800 x 600 x 600 mm and weigh approximately 140 kg. [62]

The fuel cell is today tuned to run on LPG/propane, but an LNG reformer will probably be included in the next phase of the development.

Testing of the Emerald

The Voller Energy group has outfitted a sailing yacht with a Voller Emerald fuel cell. A lot of power hungry devices that you can expect to find in a yacht today are placed in the yacht to be power by the fuel cell. Throughout the day, the power delivered by the batteries will change, but the Voller Emerald fuel cell works with the batteries to supply the boat's average consumption of electricity, unlike a generator, which is constantly reacting to every small change in consumption and in some cases over supply.

Figure 33 - The Voller sailing yacht, equipped with the Voller Emerald Fuel Cell System [63]

These days, the Voller Yacht is sailing the Atlantic Rally for Cruisers (ARC). This race is the largest and most popular Transocean sailing event in the world. The race starts in Las Palmas, Grand Canaria and finishes in the Caribbean island of St. Lucia. When Jeoff Carr at Voller got the question: “And is the Emerald working perfectly?” he answered “Ahh…It’s working. But it’s a test!”[62]

Why is the Emerald interesting for Norwegian fisheries?

The Voller Emerald is quite similar to the PowerCell. It produces the same amount of energy and could be installed in the same type of vessels, (see the PowerCell chapter). When comparing the two different solutions, the Emerald is produced especially for marine environments, which is good. Further, the application will be commercial available already next year while the PowerCell will not be available before 2011. On the other side, the Voller Emerald runs on propane. Since propane is denser then air, a leakage of propane will stay within the boat and not disappear, which seems quite unsafe. When Voller Energy is commercializing the product next year, they must have taken care of the worst safety problems. However, there are some safety challenges that have to be solved before the Emerald can be placed in a fishing vessel. Propane is easily available and could seem like a quite suitable energy source for fishing vessels based in smaller Norwegian communities. But today there are no bunkering possibilities at the harbours as there are for diesel oil. [64] If the Emerald was running on LNG, which it might do after more development, then both the safety problem and the bunkering problem would be partially solved.

6.3.4 Fuel cells in submarines

U212

The German shipbuilding companies, HDW (Howaldtswerke) and TNSW (Nordseewerke) have since 1987 developed the submarine U212 together with the German navy. This submarine runs on a so called AIP (Air independent propulsion system), which is the world's first mass-produced fuel cell system for ships [40]. The U212 combines the air-independent propulsion system (for silent slow cruising), a conventional diesel generator with a lead acid battery and a fuel cell equipped with pure oxygen and hydrogen storage. The system, which is delivered by Siemens, consists of nine PEM fuel cells, providing between 30 and 50kW each. For higher speeds, a connection is made to the high-performance lead acid battery. [65]

Figure 34 - The fuel cell powered submarine U212 - "Salvatore" at Fincontieri

There are so far build six U212 submarines. Four is built at HDW ("U31" (okt05), "U32" (okt05), "U33" (apr06) and "U34" (okt06)) for the German navy, while two are built at Fincontieri in Italy ("Salvatore" (jun05), "Scire" (may06)) for the Italian navy [40]. The U212 has an operating range of 670 km when diving. No other submarines, except nuclear submarines, have such long operating ranges.

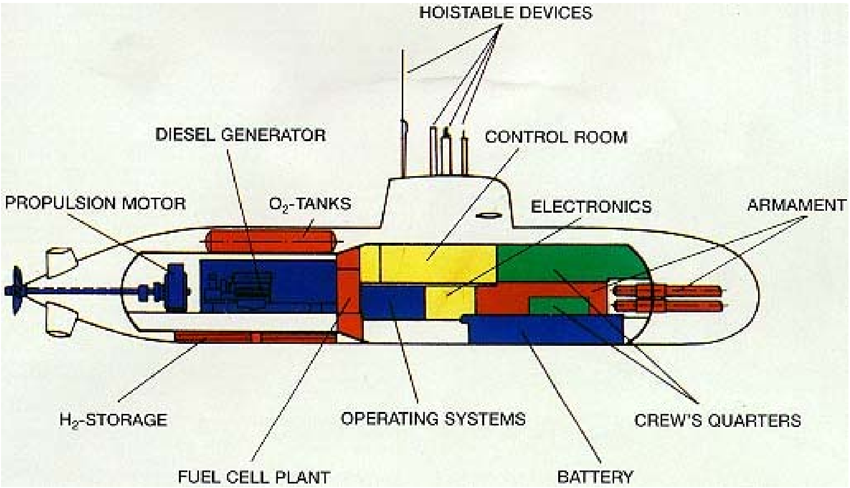


Figure 35 - The U212s main systems [66]

U214

U212s big brother; The U214 is being developed and is already sold to the Greek navy. The propulsion is provided by a Siemens Permasyn engine which draws its power supply either from the fuel cells or from batteries which are fed by a diesel generator. Performance of the AIP system has been increased with two Siemens PEM fuel cells, which produce 120kW per module and will give the submarine an underwater endurance of two weeks. [65]

Why is fuel cells interesting for submarines?

The main reason why fuel cells will be popular in submarines in the years to come is because they provide silent, vibration-free power. Norwegian submarines are for instance equipped with a diesel engine. This engine is only used to charge the submarine's batteries when it is surfacing. When ever the submarine is on diving missions, the batteries are providing all the power and the diesel generator is never used. This is because the sounds and vibrations from it make the submarine easily detectable and the diving operating range becomes small.

With a fuel cell, you can charge the batteries without making much noise. Thus, when bringing pure hydrogen and oxygen, the submarine can also charge its batteries when diving without getting detected. This strongly increases the vessels operating range.

6.3.5 METAPHU

Wärtsila, Wallenius Marine, The University of Genoa, DnV and L'loyds Register is the partners in this project that will last for 2 ½ year, starting December 2006. The project is so far divided into two parallel phases. In the first phase a 20 kW methanol powered SOFC, designed by Wärtsila will be installed and tested in one of Wallenius Willhelmsen's ships. In parallel with this project, a 250 kW SOFC designed by Wärtsila is going to be modified for a marine environment. The review of this new 250 kW fuel cell is supposed to be done within September 2008. [67]

The total costs for the first phase is NOK 15 mill, and the project is getting economical support from the European Union. [40]

Figure 36 - The METHAPU-project will install a 20 kW SOFC APU in one of Wallenius Willhelmsen's ships [68]

6.3.6 ZEMSHIPS

A PEM fuel cell, powered by pure hydrogen will be installed and tested in an “Alsterdampfer” with room for 100 passengers. The project started in 2006, and will last for 3 ½ year. The project is a co-operation with local partners where Proton Motor Fuel Cell is providing the fuel cell technology. A couple of companies from the Czech Republic are also involved together with Germanischer Lloyd.

The vessel will operate on the river of Alster in Hamburg and will be powered by a 100 kW PEM fuel cell system that is indicated to cost NOK 20 mill. The project has a total budget of NOK 40 million. Hence, the fuel cell system constitutes half of the project’s total cost.

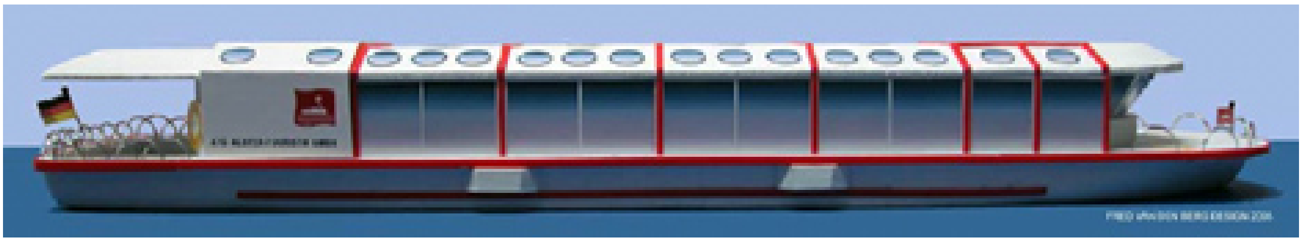


Figure 37 - An "Alsterdampfer” will by 2008 be outfitted with a 100kW PEM fuel cell

The “Alsterdampfer”, which is scheduled to start operating in the middle of 2008, will be much more environmental friendly than today’s alternatives. The emissions will be reduced by an annual 1000 kg NOx, 72500 kg CO2, 220 kg SOx, and 40 kg particles. [40]

6.4 Hydrogen infrastructure in Norway

6.4.1 HyNor

HyNor is a national project to develop a hydrogen infrastructure for the Norwegian transportation sector by building up a hydrogen infrastructure between Oslo and Stavanger.

Within 2009, it shall be possible to drive from Oslo to Stavanger, a distance of 580 kilometres, in hydrogen-powered vehicles, when refuelling in hydrogen along the way. To reach this goal, HyNor has to build sufficient production- and refuelling infrastructure along the way. [69]

Figure 38 - Norway's first hydrogen refuelling station in Stavanger [69]

"Through this project, the new hydrogen infrastructure shall present alternative distribution methods, Norwegian technology and Norwegian competence" – HyNor.no.

At the same time, the project will present participants that are expected to be central in the development of hydrogen solutions for the Norwegian transportation business. Further, new solutions within safety, quality and design are expected to be developed.

Figure 39 - Hydrogen Station in Grenland, Norway [70]

The project is currently running according to schedule, and the first hydrogen station opened in Stavanger, 23th August 2006 (Figure 39). 12th June 2007, the second stationed opened in Grenland (Figure 40). In addition to these stations, stations are planed in Drammen, Lyngdal, Kristiansand, Romerrike and Bergen. Within the project is also the goal to produce all the hydrogen with zero emissions. The hydrogen station at Herøya, which Hydro recently opened, gets surplus hydrogen from the salt water electrolyses at the chloride production at Rafnes. The energy source is hydroelectric power and there is enough surplus hydrogen to cover the need of more then 100 000 road vehicles. [69]

Within the project, hydrogen vehicles are bought to be using the hydrogen stations. In Grenland, nine vehicles are driving around and need to refuel at the station every 200 kilometres. In Stavanger there are also some vehicles that are bought to use the station. In addition to this, HyNor has recently signed an agreement with Mazda, which says that Mazda will test 30 to 40 of their hydrogen vehicles on the Norwegian “Hydrogen road”. The first vehicle is coming during 2008, while a lot more are coming in 2009. [71]

Figure 40 - Mazda will test 30-40 fuel cell vehicles on the HyNor road, starting in 2008. [71]

6.4.2 The Utsira Project

Statoilhydro is the provider of the world’s first hydrogen society at Utsira. The project was finished in 2004, but further development is being considered. Two wind mills, both with an effect of 600 kW are through electrolyses producing hydrogen. This hydrogen is being stored in a 2400 Nm3 tank on 200 bars. [72] Through a 55 kW hydrogen engine and a fuel cell system, the hydrogen is turned back into electricity when needed, supplying ten households. Since the hydrogen works as an energy-storage, the system provides electricity independent of the wind situation. This way, an isolated island community such as Utsira can strictly be powered with wind energy without the need of a connection to shore.

The power system had of course had some problems during the start-up period, but is today working as it should. It is specially the fuel cell that has been causing trouble while being integrated into the system. At the same time, the hydrogen engine has a quite low efficiency. Some energy is also being lost in the electrolysis process when the hydrogen is generated from the wind energy. [72], [73]

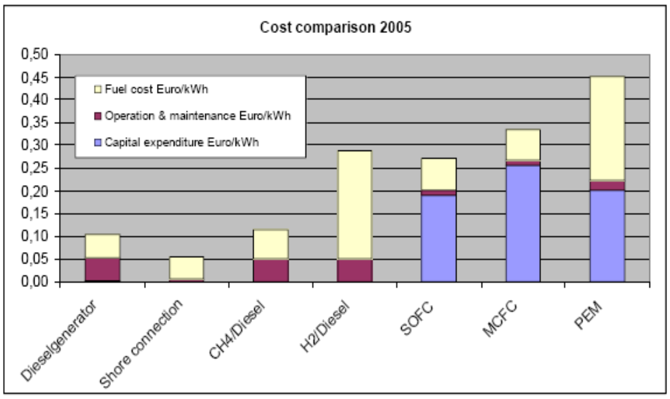
Calculations shows that such a system within five to ten years can be economical sustainable for isolated communities. [72] If the project at Utsira is developed further, 100 households will get its power this way, and such a pioneer project might be path-breaking for the development our futuristic hydrogen society. However a lot of improvements are yet to be done.

Today's Challenges

6.5 Price

The main challenge when starting a fuel cell project is the fuel cell prices. Fuel cell power units are in general several times more expensive then conventional diesel generators and other power sources. The auxiliary power unit that is being installed in M/S Viking Avant is indicated to cost six times more than a diesel application. The Voller Emerald is estimated to cost two to three times more. In all the other projects, the fuel cells are still quite expensive. In other words, the price is a big challenge.

The high price is in strong relation with the amounts of fuel cells produced. When fuel cells are starting to be mass produced instead of being "handmade" as today, the prices will drop rapidly. For instance the PowerCell has a goal of not being more expensive then the competing diesel generators. Now, the PowerCell is a PEM fuel cell, which today is the technology which is the most developed and also the cheapest, but there are possibilities that more fuel cell applications will reach reasonable prices within five to ten years. This is indicated by figure 33 below, which shows Wärtsila's estimated price development.



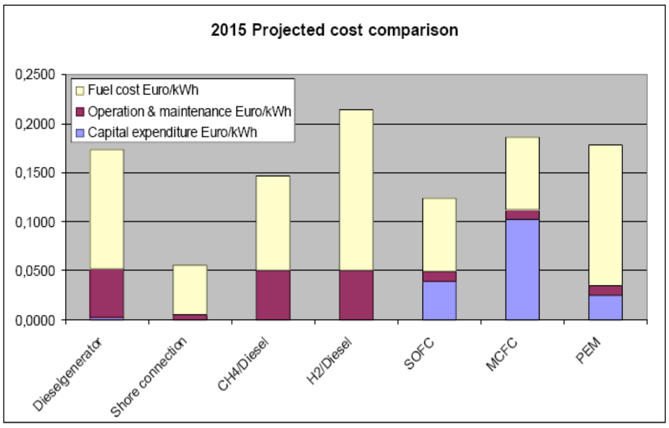


Figure 41 - Fuel cell price development - Prices per kWh for a ship in port for different power sources. Estimated prices in 2005 and 2010, by Wärtsila 2005[40]

Wärtsila has estimated the price of power from fuel cells compared to other power sources in 2015. This comparison is showing the price for power generation of ships in port in Euro per kWh (Figure37). This is of course just an estimate where the underlying information has been impossible to get, but it shows how Wärtsila, which is investing huge amounts in the development of fuel cells, is predicting the future. According to Wärtsila, most fuel cells will already in 2015 be as cost effective as a regular diesel generator. The fuel cell type which is predicted to be the cheapest is the SOFC, which is the type of fuel cell that Wärtsila now is developing for ships, and that they will install in the METHAPU project (See page 49). Probably, Wärtsila's focus on SOFCs is based on these predictions.

The diagrams in figure 37 show that fuel cells today are 2.5 to 4.5 times more expensive per produced kWh than a regular diesel generator. However, within 2015, this price difference will have vanished due to increasing oil prices and lower production costs for the fuel cells. The reason why Wärtsila believes in SOFCs rather than PEMFCs is that they predict that the price of natural gas as fuel will be a lot cheaper then for pure hydrogen.

6.6 Operational state

There are still some concerns when it comes to fuel cells' state of operation in maritime applications. As seen from the FellowSHIP project, no fuel cells are today as reliable as a diesel generator, but new technologies are starting to close that gap.

Rough sea conditions

There have been some concerns due to high waves and rough seas in locations such as the North Sea. FellowSHIP has carried out a design study of their MCFCs performance in rough conditions, and they mean that operating in rough conditions is absolutely feasible. The fuel cell in it self contains no loose parts, which reduces the risk for fatigue and perhaps is an advantage for the fuel cell compared to today's engines and turbines. So as long as you can provide a steady flow of fuel into the fuel cell, rough sea conditions should not be a problem, in most cases.

Salinity

A perhaps bigger concern is the salt content in the air. As mentioned earlier most fuel cells are using the oxygen from the air directly to run the chemical reaction in the fuel cell. For some fuel cells, salt from the air will have a bad corrosive effect on the fuel cell's electrolyte. This result in a reduction in the amount of positive ions getting through the electrolyte, leading to reduced power-outputs from the fuel cell and thus also reduced lifetime. This problem is biggest for the fuel cells with small operating temperatures such as PEM and AFC, while fuel cells such as SOFCs and MCFCs are less vulnerable for this problem. Anyway, a desalinating devise for the incoming air might be added.

Cold conditions

The waste from a fuel cell is pure water, which we all know freezes at 0 ^{o}C. In cold Norwegian conditions during the winter, this must be taken into consideration. The FellowSHIP project mentioned that they had experienced a lot of mist at their exhaust duct while testing, but they believed that they would come up with a feasible solution for this problem.

While operating at sea in cold conditions, the sea's temperature is always above 0 ^{o}C. From the writer's point of view, the discharging of the water has to be below the waterline. To reduce the amount of mist further, the water, or the water vapour from high-temperature fuel cells, like MCFCs, has to be cooled and condensed on board before being discharged. This could be done through heating deck area or other areas onboard. If the fuel cell is installed in a fishing vessel, it will be important that the discharged water below the waterline not is interfering with the ship's fish-finding equipment.

Dynamic problems

Specially, for the high-temperature operating fuel cells like SOFCs and MCFCs, the dynamic loads due to warm-ups and cool-downs result in problems. For instance, the FellowSHIP project is experiencing such problems. At first, the system's response time severally increases with long warm-up and cool-down times. For the MCFCs this might result in a response time as long as three hours. In other words, this type of fuel cells is today mostly suited for applications with a relatively low variation in power output. Thus, these fuel cells might be more suited for trawlers then for long liners and purse seiners. The other problem is the tensions that the high temperature variations induce into the porous fuel cell material. This severally shortens the fuel cell's lifetime and is one of the greatest concerns FellowSHIP has in their project.

6.7 Emissions

As seen earlier, fuel cells are strongly reducing the emissions of environmentally unfriendly gases. The only problem with some fuel cells is the emissions of CO_2. Figure 38 below is made by Wärtsila and shows the emissions from a ship in port using different kinds of power sources.

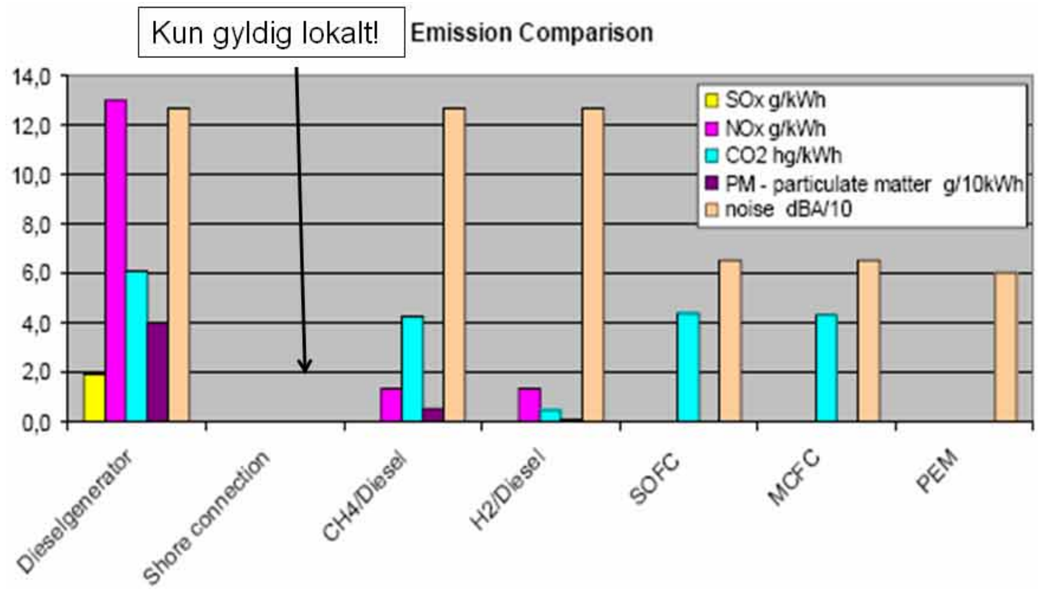


Figure 42 - Emissions of greenhouse gases from a ship in port. Estimates by Wärtsila, 2005[40]

The figure shows that the fuel cells don't emit SOx and NOx, but the SOFCs and MCFCs are emitting some CO_2 due to their use of LNG as fuel. For these fuel cells to be completely emission-free, the CO_2 has to be handled separately. It shall be mentioned that according to this investigation, fuel cells emit 20-30 % less CO_2 then a corresponding diesel generator. PEM fuel cells will not have any emissions except water since they are running on pure hydrogen. When this is mentioned, you should remember that the production of pure hydrogen usually lead to emissions of CO_2, through the steam reforming process.

Another very important fact from the figure is the low noise level from the fuel cells. This will be a great advantage both for the on board crew and the surrounding environment.

Summarizing, there are no environmentally challenges with the use of fuel cells, except some emissions of CO_2. However, it should be mentioned, that while being discharged, the fuel cells are containing a lot of quite unusual materials, like platinum and nickel electrodes, that might class the fuel cell as a special waste.

6.8 Lifetime

The fuel cells lifetime is still not on today's industrial standard. [47] If again using FellowSHIP as an example, the Hot Moduel – MCFC that they are using has an expected lifetime of 30000-35000 hrs. This is close to today's industrial standard, but when being installed on a ship, the dynamic forces from continuously heating and cooling the fuel cell, will strongly reduce its lifetime. At the same time, the air's high content of salt onboard a ship will also affect the fuel cell's lifetime negatively.

6.9 Reliability

The fuel cell's reliability is another problematic issue, which holds different opinions within the business. Tomas Tronstad, [47] project leader for Fellowship, means that there are no fuel cells today which can match the reliability of a diesel generator. On the other side, according to the Voller Energy's advertising film: "The Emerald is more reliable then today's diesel generators. Together with cheaper fuel, this is reducing your operating costs." [61] At last, PowerCell aim to let the fuel cell's maintenance interval coincide with the vehicles maintenance interval.

There are a lot of different opinions surrounding this issue, and it is hard to know what's correct. However, it could seem that the business is handling this problem and is giving us reliable fuel cells sometime soon. Despite the fuel cell's problem with corrosive electrolytes, compared to a diesel engine, it has very few moveable parts which usually are the reason for brake-downs in mechanical components. With this in mind, fuel cells have a potential of being highly reliable in the future.

6.10 Infrastructure

For the Norwegian fisheries, the hydrogen infrastructure is still far away. The Aynor's "Hydrogen road" has so far not taken the shipping business into consideration. At the same time, most of the Norwegian fishing fleet is located in quite small, isolated communities.

As described earlier, some types of fuel cells do not need to run on pure hydrogen, but can for instance run on LNG. The problem with these fuel cells is that they are quite big (Fellowship's 320 kW MCFC unit is the size of a 20 feet container). For bigger fishing vessels like trawlers and bigger purse seiners, LNG powered fuel cells such as SOFCs and MCFCs are a possibility. However, for smaller fishing vessels along the cost smaller, more compact fuel cells with lower operating temperatures, such as PEMFCs are needed. The problem with these fuel cells is that they still only run on pure hydrogen. Along our Norwegian coast, it will take a long time to build up an infrastructure that can provide smaller vessels with hydrogen. Thus, this vessel group has to look on alternative ways to get hydrogen if they will use fuel cells as an energy source. Earlier in the report, we have seen a couple of other projects that can solve this problem.

The reforming of fossil fuels onboard is one way to get hydrogen to run a PEM fuel cell. Both the PowerCell and the Voller Emerald project mentioned earlier are using this principle. The PowerCell is using diesel and the Emerald is using LPG or propane. These systems will quite easily be put into smaller fishing vessels and produce power. The problem so far is that these applications have quite small effects (5kW) and can today only be used as auxiliary power units. The technology should however be quite easy to scale, thus larger applications of these units could be on the marked within five years.

Another possibility is to produce the hydrogen ashore through systems like the one at Utsira. This introduces yet another problem, when the hydrogen is needed to be stored on board. This problem is solved in smaller scales in many of the projects that are mentioned earlier and further development of the storing technology might result in a good, completely emission-free solution for smaller fishing vessels.

6.11 Fuel cell in fishing vessels – Some examples

Some scenario examples of fuel cells will be given in the following. The fuel cell applications that are most likely to be tested first are the smaller auxiliary power units such as the Power cell and the Voller Emerald. These units could be outfitted as APUs in smaller fishing vessels, and the following examples will discuss the fuel cell's abilities in fishing vessels in the group from 10 to 15 meters.

Example 1 - PowerCell or Voller Emerald for use in 14.95 meter multipurpose fishing vessel

This example is based on an existing 14.95 meter long multipurpose fishing vessel. The vessel's name will however not be given in this report. [75]

The vessel is outfitted with a diesel generator, capable of producing 46 hp or 33 kW. In this particular vessel, the diesel generator is continuously running to produce electricity and heat. This is not too usual in such vessels since newer vessels are outfitted with a heating boiler or a diesel burner. From the fisherman's point of view, the noise from the diesel generator is not bothersome, but it is noticeable. [74]
The diesel generator is running continuously, except when the boat is ashore with access to a shore connection. Thus, the diesel generator can be assumed to run approximately 3000 hours pr. year. Another important comment from the fisherman was that the diesel generator seldom utilizes more then half of the maximum effect. When every electrical device was turned on, there was need for approximately 20 kW. This is a scenario that in reality never occurs, and it seems that this generator is strongly oversized. For a diesel generator that runs on low loads, its efficiency decreases. Thus, it is assumed that the diesel-to-electricity efficiency is approximately 25 % (35% when operating on optimal load), which is the same as assumed for the fuel cell systems.(see Voller Emerald Chapter) Further it is assumed that the diesel generator is running on an average of 40 % of its load (33.8 kW x 0.4 = 13.5 kW).

As shown earlier (Emissions in Norway), today's NOx emissions are one of the Norwegian fisheries' greatest challenges, and the NOx fee can have a large economical impact on many fishing vessels. Hence, mapping of the auxiliary power unit's NOx emissions will be done.

According to Imp's regulations [75], the NOx emissions from a power unit exceeding 2000 rpm shall be below 9.8 g / kWh. This is of course a maximum limitation, but since our diesel generator is only utilizing 40 % of the maximum effect, this number will be assumed. NOx emissions are dependent on the engines operational state and a low efficiency leads to high NOx emissions.

Total amount of kWh pr. Year

kWh_{annual} = 13.5kWh*3000hrs/year = 40500 kWh/year

NOx emissions in kg pr. Year

0.0098 g/kWh*40500 kWh/year = 397 kg

This vessel will in this scenario emit an annual of 400 kg NOx. This is however a worst case scenario since most vessels like these are outfitted with smaller generators and heating boilers. On the other side, the example shows the magnitude of the reductions that can be made.

Example 2 – 5 kW APU in 12.99 m Liner/Netter

Another existing vessel is the 12.99 m liner/netter that will be evaluated in this experiment. This vessel is perhaps has perhaps a little more common APU, which has an effect of 5 kW. Compared to the vessel in example 1, this vessel is outfitted with a heating boiler and a diesel burner. This ship only uses the diesel generator when in harbour without access to a shore connection. According to the skipper, this is no more then approximately 200 hours per. year. [58] When operating, the generator utilize approximately 4.3 kW or 80% of the accessible effect, which gives the generator a very good efficiency of approximately 35%. With the same assumptions for emissions as in example 1, we get:

Total amount of kWh pr. Year:

kWh_{annual} = 4.3kWh*200hrs/year = 860 kWh/year

NOx emissions in kg pr. Year:

0.0098 g/kWh*860 kWh/year = 8.4 kg

If a PowerCell or a Voller Emerald system is installed in these vessels, the NOx emissions would disappear.
The examples show that even if the boats are quite equal, the NOx emissions are very different. The internal difference in this group of vessels is very high, and several more examples are needed to be done, if a good picture of this group of vessels should be made.
However, these examples represent the extreme point of the group and do show which magnitudes the emissions have.

Assume that a vessel in the group from 10 to 15 meters emit the average of these two examples ((397+8)/2=202.5 kg/year). The emission savings for the whole group can be calculated as:

Total emissions of NOx = 202.5 kg/vessel*1872 vessels [76] = 379 tons

If the whole group is outfitted with a PowerCell or an equivalent system for auxiliary power generation, the total NOx emissions would be reduced with 380 tons. In total the Norwegian fisheries emit 23000 tons (See, Emissions in Norway). So even if the whole group of vessels between 10 and 15 meters convert to fuel cell systems like these, the Norwegian fisheries will only reduce their total NOx emissions with 1.65 %. Thus, there have to be other reasons why such fuel cell systems should be of interest in the future.

Will such fuel cell systems be profitable today?

As long as the vessels with less then 750 kW for propulsion don't need to pay the NOx-fee [59], the installing of a PowerCell or Emerald will not in any way be profitable. A diesel generator has a better efficiency and costs less. Hence, the only reason of buying a fuel cell system is that it provides silent power. However, the fishermen talked to in this report are not willing to pay that much for that privilege. Therefore, no calculations of profitability have been done in this project.

7 Fuel Cells – A solution for the near future?

Fuel cells provide zero-emission, silent and vibration-free power. This will both make the ship more environmentally friendly and improve the work environment aboard. In addition a more silent ship might increase the effect of the fish finding equipment. Thus, using fuel cells as a power source could also increase the boat's fishing efficiency.

A fuel cell won't emit anything except pure water, if it is running on pure hydrogen. Hence, there won't be any NOx fees or any other climate fees for ships powered by fuel cells. This will strongly reduce the running expenses for larger fishing vessels. There are in other words many reasons to test fuel cells in fishing vessels.

There is however a large variety of problems combined with the fuel cell technology. Every investment is dependent on costs, and today's fuel cell prices make them quite bad investments when compared to other power sources. For fuel cells to be profitable, the fuel cell prices will have to decrease, or the running expenses of today's diesel engines have to increase. What we see today, both of these scenarios are occurring. Mass production of fuel cells will lower the prices, and the high demand for oil increases the diesel price and thus also the running expenses for a fishing vessel. These two factors are heading towards each other, meaning that we are approaching the point in time where fuel cell investments are more profitable then for other power sources. Due to factors like the oil price, which is quite hard to predict, it is hard to predict when this cross-over point in time will be. According to Wärtsila's predictions, the point might be reached within ten years, but there is as mentioned many unpredictable factors.

Even if the fuel cells become as cheap as a diesel generator, the technology has to be good enough. Today, the technology is not quite as good as our expected standards. Especially for fishing vessels, there are some problems that need to be solved before the fuel cell technology can be applied. High contents of salt in the air, bad hydrogen infrastructure and reduced lifetimes are among these problems. There are plans and solutions for most of these problems, but these solutions make the fuel cell even more expensive. Most solutions also need more development before being applied.

The two main challenges for the smaller Norwegian fisheries are: hydrogen infrastructure and onboard storing. As shown earlier, there are ideas and plans to also solve these problems, but there is still a long way to go. Interesting ideas like the PowerCell, which solves the infrastructure problem, and the Millennium cell, which can be a solution for the storing problem, are all still very small systems. From the calculation examples on page 58 and 59, the conclusion could be that these systems still are too small to have a commercial future in fishing vessels since the savings of installing them becomes so small. This is however a quite easily scalable technology, and more powerful, better solutions will probably emerge soon.

For larger applications, for use in larger fishing vessels there are also a lot of problems. Many of these problems are described in the FellowSHIP project (page). Here, both the infrastructure and storing problem is solved by using LNG as fuel, but other problems like low lifetime and long response times are big challenges. Still, these problems are more distinct and perhaps easier to solve. Thus, it can seem that this fuel cell technology is the closest to a commercialized breakthrough.

One thing common in the fuel cell technology and the Norwegian fishing fleet, is the diversity. In the same way that there are fishing vessels for different types of fish, there are fuel cells for different types of applications. You do not fish herring with a long line, and you do not power a desktop with a Solid Oxide fuel cell. Therefore it can be interesting to see how different fuel cell technologies suits different fishing vessels. First, larger fishing vessels are considered.

SOFCs and MCFCs are the fuel cells that are best for bigger power outputs. The problems with these cells are the response time due to the high operating temperatures. Thus, these fuel cells are most suited for applications with continuous power supply. Larger trawlers are the type of fishing vessels which has the most continuous power demand. Some years from now, when the fuel cell technology has been further developed, it will not be unlikely to put a SOFC or MCFC as a trawler’s main machinery. The peak loads will then have to be handled by other fuel cells, i.e. PEMFCs, or other energy sources. However, there will be a problem with the trawler’s operating range when operating on LNG.

Long liners and purse seiners do not have this continuous power demand, and the characteristics of SOFCs don’t fit that good. However, it should be possible to fit these types of fuel cells in a hybrid energy system.

For smaller fishing vessels, today’s SOFCs and MCFCs are too big. If we use today’s technology as a basis, PEM fuel cells are the most likely to fit the varying power demands of this group of vessels. The only problem is that they require pure hydrogen, and this has to be stored aboard in one of the ways mentioned earlier. Using fossil fuels and a large reformer might also be a possibility. Honda is today outfitting quite small cars with 100 kW fuel cell systems [29], so it should absolutely be possible to outfit a smaller fishing vessel with this technology, some years from now. PEM fuel cells can also become popular as auxiliary power units in larger fishing vessels.

8 Conclusion

There are a lot of possible features with fuel cells that make them very attractive for the use in fishing vessels. The fuel cell will provide zero-emission, silent and vibration-free power. In fact, fuel cells could be the ultimate power source for a fishing vessel, but there is one major disadvantage: Price. The fuel cells are still to expensive and the technology is not yet good enough for fully commercialization. Fuel cell prices are today three to ten times higher than for an equivalent diesel generator. At the same time, the technology is so far not good enough to satisfy our standards, but it seems like this is about to change.

For the fisheries there are also some problems that are not directly attached to the fuel cell technology. The problems of hydrogen infrastructure and hydrogen storing need to be solved before fuel cells can be a hit. This problem is especially for the smaller fishing vessels that are located in smaller, isolated areas. Larger vessels can use other types of fuel cell technology that runs on fuels like LNG. For these applications, the main problems are mainly attached to the fuel cell technology. Today, the SOFC and MCFC used in larger power applications have bad response times and are quite big.

Today, the fuel cell prices are slowly decreasing, while the fleet’s running expenses are increasing due to the high oil price. This means that we are approaching that point in time where fuel cells are becoming a better investment than today’s applications. It is hard to predict when we will reach this cross-over point, but according to Wärtsila’s predictions, it might happen as soon as within ten years.

From the author’s point of view, there is no better alternative power source for a fishing vessel then fuel cells. It will however take years before the fuel cell prices are down at a reasonable level and the technology is up on today’s standards.

The world’s fossil fuels are about to be emptied, and the need for new energy sources and power applications is increasing. Most scientists agree that hydrogen will be the fuel of the future, and thus fuel cells will be tomorrow’s engines. It is hard to predict when this will happen. But one thing is for certain: Hundred years from now, our fishing vessels won’t be powered of conventional diesel engines as today.

Thus, Sintef Fisheries and Aquaculture should, from my point of view, keep track of the fuel cell technology development and build competence within the field. The diversity in the fishing fleet and within the field of fuel cells makes it hard to know which fields that should be researched. In the following there is a small list of projects I believe could be possible to launch to build competence within the field.

8.1 Where do we go next?

Sintef – Fisheries and Aquaculture is a very important institution for the Norwegian Fisheries. It is expected that SINTEF F&A has some competence on any new technology that is being introduced to the market. Still there are some years before fuel cells can be introduced into fishing vessels, but when the technology further develops, fuel cells will play an important role in the futuristic Norwegian fisheries. Thus, Sintef should from my point of view, through attending in fuel cell development projects for, build competence in the field, so that you are prepared when the fuel cell era begins.

There are today quite large amounts invested in the fuel cell projects. For instance, FellowSHIP has a total budget of NOK 110 million. So what kind of projects Sintef engages in is highly dependent on the financial supports. Following are some project ideas.

1. Outfitting of smaller fishing vessel with a PEM fuel cell at Utsira.

Utsira is the “world’s first hydrogen community”. Isolated communities like these are found all over the world, and often fishing is the main profession for the people living there.

At Utsira, hydrogen is produced by two wind mills (page 53). A fuel cell powered fishing vessel could refuel hydrogen produced from these windmills when operating. Then you would get a completely new type of “wind powered” vessels that captures fish, completely without emitting greenhouse gases. With today’s technology, this project should absolutely be feasible and it should be a project that easily gathers publicity all over the world. StatoilHydro who owns today’s establishment can be a possible partner.

2. PowerCell or Voller Emerald in smaller fishing vessel.

A PowerCell or a Voller Emerald fuel cell system can be installed in a smaller fishing vessel as an auxiliary power unit. The PowerCell, which is powered by diesel, is not expected on the marked before 2011. This fuel cell system will provide silent, vibration-free power which can be a great advantage for ships in ports without access to a shore connection.

The Voller Emerald is supposed to be launched April next year. Thus, a project containing this application can probably be started earlier then a project with the PowerCell. However, the Voller Emerald runs on LPG, which will make the project a little more complex due to safety issues.

3. Installation of SOFC or MCFC as APU in larger fishing vessel

Since SOFC and MCFC are believed to be the first technologies to have a commercialized breakthrough in the fisheries, this would be an interesting project. However, it will probably be quite costly, and it could be smart to evaluate the FellowSHIP- and the METHAPU project before starting a corresponding project in a fishing vessel

4. Develop onboard equipment for use in fishing vessels.

There are possibilities to use fuel cell to power all kinds of electrical equipment in a fishing vessel. Everything from heating equipment on one side to cranes and winches on the other side might be of interest.

9 References

[1] **Ssb.no**. *Statistisk sentralbyrå*. [Online] [Accessed: 15.09.2007] http://www.ssb.no/emner/01/04/10/agassn/

[2] **Ssb.no**. *Statistisk sentralbyrå*. [Online] [Accessed: 16.09.2007] http://www.ssb.no/emner/01/04/10/klimagassn/

[3] **James Larminie, Andrew Dicks**, *Fuel Cell Systems Explained*, 1st edition. Chichester: Wiley, 2000

[4] **Wikipedia.org**. *Wikipedia*. [Online] [Accessed: 25.09.2007] http://en.wikipedia.org/wiki/Fossil_fuel

[5] **Meling, Leif Magne** - *The origin of Challenge – Oil supply and demand – A pragmatic evaluation of critical issues*. Paper presented at the international student conference (ISC07), Trondheim, Norway, 9th October 2007.

[6] **Wikipedia.org**. *Wikipedia*. [Online] [Accessed: 15.12.2007] http://en.wikipedia.org/wiki/Oil_price

[7] **Hydrogen.no**. *Norsk Hydrogen Forum. Brochure. "Hydrogen – Ren energi".* [Online] [Accessed 19.12.2007] http://www.hydrogen.no/hydrogen/hydrogen-ren-energi/

[8] **Spiegel, Colleen S**. *Designing and building fuel cells*, 1st edition. New York: McGraw Hill book company, Inc, 2007

[9] **Turid Knutsen**, 2005. *Brenselceller – Hvordan virker de og hvorfor kan de bli så viktige for oss?* [Online] Poole: Cappellen Fysikk – RSTnett [Accessed 10.09.2007] Available from: rstnett-r94.cappelen.no/manus/brenselsceller.pdf

[10] **Verne, Jules**. *The mysterious Island*. First printed 1874

[11] **Tvedt, Terje**. TV2. *En reise I vannets fremtid*. Tv-program. 11.11.2007.

[12] **Nrk.no**. *Norsk Riks Kringkastning*. [online] [Accessed: 16.09.2007] http://www20.nrk.no/kalkulatorer/forurensingskalkulator.aspx?t=forklaring&sti=fbi

[13] **Hydrogen.no**. *Norsk Hydrogen Forum*. [online] [Accessed 26.10.2007] http://www.hydrogen.no/hydrogen/hydrogensikkerhet?set_language=no

[14] **Barbir, Franco.** *PEM fuel cells: Theory and Practice,* 2005. Amsterdam: Elsevier Academic Press.

[15] **Americanhistory.si.edu**. *National museum of American History*. [online] [Accessed 16.12.2007] http://americanhistory.si.edu/fuelcells/pem/pemmain.htm

[16] **Uaf.edu**. *University of Alaska Fairbanks*. [online]. [Accessed 15.10.2007] http://www.uaf.edu/ine/erc/proton.html

[17] **C Rossi, D Estéve, N Fabre, T Do Conto, V Conédéra**. *A New generation of MEMS based Microthrusters for Microspacecraft Applications*. Proc. Micronanotechnology for space applications. Vol.1. April 1999

[18] **Fuelcell.org**. Fuel Cell Basics [online] [Accessed 12.09.2006] http://www.fuelcells.org/basics/how.html

[19] **www1.eere.energy.gov. US Department of energy**. *Energy efficiency and renewable energy*. [online] [Accessed 16.12.2007] http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

[20] **Stenersen, Dag**. Personal communication. 05.11.2007

[21] **Lin, Bruce**. ”Conceptual Design and Modelling of a Fuel Cell Scooter for Urban Asia.” Princeton university, Masters Thesis, 1999.

[22] **Hirschenhofer, J. H., Stauffer, D. B., Engleman, R. R. and Klett, M. G**. *The fuel cell handbook*, 4th ed. 1998. Reading, PA: Parsons Corporation.

[23] **Fuelcellstore.com**. *Fuelcellstore.com* [online] [accessed 05.11.2007] http://www.fuelcellstore.com/cgi-bin/fuelweb/view=NavPage/cat=1007

[24] **About.com**. *About.com* [online] [Accessed 05.11.2007]
http://inventors.about.com/od/fstartinventions/a/Fuel_Cells.htm

[25] **www.princeton.edu**. *University of Princeton*. [online] [Accessed 05.11.2007] http://www.princeton.edu/~chm333/2002/spring/FuelCells/fuel_cells-history

[26] **Jadoopower.com**. *Jadoo Power*. [online] [Accessed 15.09.2007] http://www.jadoopower.com/

[27] **Fuelcellstoday.com**. *Fuel Cell Today – Fuel cell news*. [online] [Accessed 15.09.2007] http://www.fuelcellstoday.com/

[28] **www.cute-hamburg.motum.revorm.com**. *Cute congress. Press release: CUTE: Success through team spirit*, Hamburg May 2006 [online] [Accessed 05.11.2007] www.cute-hamburg.motum.revorm.com/download/motum_CUTE _Nachbericht_eng_2006-05-11.pdf

[29] **Honda.com**. *Honda Motors. Press release*: Los Angeles, 14.11.2007. [Online] [Accessed 13.12.2007] http://world.honda.com/news/2007/4071114All-New-FCX/

[30] **fyk.no**. *FYK*. [online] [Accessed 13.12.2007] http://www.fyk.no/pressimages/1883.jpg

[31] **Statoilhydro.com**. *StatoilHydro*. [online] [Accessed 13.12.2007] http://www.statoilhydro.com/no/TechnologyInnovation/NewEnergyAndRenewables/Hydrogen/Pages/SportsbilenFYK%E2%80%93moderneogkul.aspx

[32] **Fuelcellstoday.com**. *Fuel Cell Today – Fuel cell news*. [online] [Accessed 14.12.2007] http://www.fuelcelltoday.com/online/news/articles/2006-05/First-Dutch-fuel-cell-boat-intro

[33] **Edie.net**. *Edie*. [online] [Accessed 18.11.2007]
http://www.edie.net/news/news_story.asp?id=11491&channel=0

[34] **Ecofys.com**. *Ecofys. Press release*: 07.11.2007 [online] [Accessed 18.11.2007]
http://www.ecofys.com/com/news/pressreleases2006/
pressreleasefuelcell.htm

[35] **Evworld.com**. *EV World*. [online] [accessed 18.11.2007]
http://www.evworld.com/news.cfm?newsid=16388

[36] **Zebotech.de**. *Zebotech* [online] accessed 18.11.2007]
http://www.zebotec.de/front_content.php?client=1&changelang=3&idart=133

[37] **mhi.co.jp**. *Mitshubishi Heavy Industries*. [online] [accessed 18.11.2007]
http://www.mhi.co.jp/power/e_power/topics/2004/july_04.html

[38] **jamstec.go.jp**. *Japan agency for marine earth science and technology*. [online] [Accessed 19.11.2007]
http://www.jamstec.go.jp/e/about/equipment/ships/urashima.html

[39] **www.maxt.go.jp**. *The Japanese Ministry of Education, Culture, Sports, Science and Technology*. [online] [Accessed 19.11.2007]
http://www.mext.go.jp/english/news/2000/05/h000501.htm

[40] **Lygre, Asle**. *Brenselceller I skip – Status og muligheter*. Paper presented at the University in Bergen Universitetet i Bergen, 15th November 2006

[41] **fuelcellsworks.com**. *FuelCellWorks News and information portal.* [online] [Accessed 19.11.2007]
http://www.fuelcellsworks.com/InsidetheindustryOct19-03.html

[42] **Power and motor yacht**. [Online] [access 19.11.2007]
http://www.powerandmotoryacht.com/boattests/0104duffy/index6.aspx

[43] **Millennium fuel cell**. [online] [Accessed 13.12.2007]
www.millenniumcell.com

[44] **Millennium fuel cell**. [online] [Accessed 13.12.2007]
http://www.millenniumcell.com/fw/main/Technology_Advantages-28.html

[45] **Millennium fuel cell**. [online] [Accessed 13.12.2007]
http://www.millenniumcell.com/fw/main/How_it_Works-31.html

[46] **Haute Ecole d'ingenierie et de Gestion de Canton de Vaud -Brochure** – Electric boat features hydrogen fuel cell.

[47] **Tronstad, Tomas**. Personal communication, 23.10.2007

[48] **tu.no. Teknisk ukeblad** [online] [Accessed 19.11.2007]
http://www.tu.no/offshore/article105624.ece

[49] **Eidesvik.no**. [online] [accessed 19.11.2007]
http://www.eidesvik.no/pictures/news/viking_avant_i_barentshavet.jpg

[50] **Engineering talk**. [online] [Accessed 19.11.2007]
http://www.engineeringtalk.com/news/hay/hay144.html

[51] **Green car congress**. [online] [Accessed 19.11.2007]
http://www.greencarcongress.com/2007/08/hydrogen-fuel-c.html#more

[52] **CFC solutions** [online] [Accessed 19.11.2007]
http://www.cfc-solutions.com/en/cfct/cfct.htm

[53] **Leirgulen, Svein Inge**, 2006. Dnv.co.uk. *Fuel cell technology introduces ultra clean ships*. [online] [Accessed 19.11.2007]
http://www.dnv.co.uk/press/Fuelcelltechnologyintroducesultracleanships.asp

[54] **Lövgren, Stephan**, 2006. *Göteborgs Posten. Ny motor stoppar tomgångskörning* [online]. [Accessed 23.11.2007]

[55] **Alpman, Marie**, 2006. *Nyteknik.se. Volvos nya kraftpaket är skonsamt mot miljön* [online] [Accessed 23.11.2007]

[56] **PowerCell.se** – *Company presentation*. [Online] [Accessed 18.12.2007]
http://www.powercell.se/news_media.htm

[57] **Sivertsen, Børge**. *StatoilHydro – New Energy*. Personal communication, 30.10.2007

[58] **Kristiansen, Bjørn Kåre** – *Fisherman* – Personal communication, 11.12.2007

[59] **Toll og avgifts direktoratet**. *Avgift på Utslipp av NOx, 2007. Rundskriv nr. 14/2007 S. Oslo*. 12.01.2007

[60] **Voller Energy Group** [online] [Accessed 18.12.2007]
http://www.voller-energy.com/company.asp

[61] **Voller Energy Group** [online] [Accessed 18.12.2007]
http://www.voller-energy.com/applications_mar.asp#

[62] **Carr, Jeoff**. *Voller Energy Group*. Personal communication, 11.12.2007

[63] **MyMarina.co.uk**. *MyMarina* [online] [accessed 18.12.2007]
http://www.mymarina.co.uk/gfx/mygreenboating/news/18/1.jpg

[64] **Skjervheim, Aksel**. *GasNor*. Personal Communication, 08.12.2007

[65] **Gizmag.com** [online] [accessed 18.12.2007]
http://www.gizmag.com/go/3434/

[66] **Naval-Technology.com** [online] [accessed 18.12.2007]
http://www.naval-technology.com/projects/type_212/

[67] **www.METHAPU.com**. *General presentation*. [online] [Accessed 18.12.2007]
http://www.methapu.com/File.ashx?mode=file&file=///Presentations/
METHAPU_general_presentation.pdf

[68] **Wallenius Marine**. [online] [Accessed 18.12.2007]
http://www.walleniuslines.com/the_fleet.jsp?art_id=76&shp_id=16

[69] **HyNor.no**. *HyNor prosjektet*, 2006. [online] [accessed 18.12.2007] http://www.hynor.no/prosjektet

[70] **Zero.no.** *Zero Emission Resource Organisation* [online] [accessed 13.12.2007] http://www.zero.no/transport/hydrogen/bilder/apning-av-hydrogenstasjonen-i-grenland

[71] **HyNor.no**. *HyNor*. [online] [accessed 13.12.2007 http://www.hynor.no/nyheter/jubel-for-mazda-prosjekt/image/image_view_fullscreen

[72] **StatoilHydro.no**, 2007. *Det første hydrogensamfunn*. [online] [accessed 13.12.2007] http://www.statoilhydro.com/no/NewsAndMedia/Multimedia/features/Pages/HydrogenSociety.aspx

[73] **Utsira Kommune**, 2007. *Historien bak vindmøllene*. [online] [accessed 13.12.2007] http://turist.utsira.kommune.no/severdigheter/hydro/historie

[74] **Leinebø, Gunnar Martin**. *Fisherman*. Personal communication [11.12.2007]

[75] **IMO**. *International Maritime organization. Regulation. Marpol 78/73 – AnnexVI – Paragraph 13 (NOx Emissions)*.

[76] **The Norwegian directorate of fisheries**. *www.fiskedir.no*. [online] [accessed 14.12.2007] http://www.fiskeridir.no/fiskeridir/english/statistics/norwegian_fisheries/norwegian_fishing_vessels_fishermen_and_licenses