Final report

1.1 Project details

Project title	ORACLE - Outdoor Reliable Application using CLean Energy
Project identification (program abbrev. and file)	Journal nummer 64011-0370
Name of the programme which has funded the project	**EUDP**
Project managing company/institution **(name and address)**	Nilfisk-Advance A/S (NA) Sognevej 25 2605 Brøndby Michael Gamtofte
Project partners	Aalborg University - Department of Energy Technology (AAU) Danish Power System (DPS) SerEnergy (SER) Nilfisk Outdoor Division (Nilfisk Egholm) (NOD)
CVR (central business register)	62572213
Date for submission	01.04.2015

Table of content

1.2 Short description of project objective and results

The purpose of the Oracle project is to develop a demonstrator (the ORACLE machine) to verify the advantages of fuel cell technology on tool carriers used on outdoor cleaning applications. Environmental advantages must be reached in comparison to existing diesel based solutions, and an improved efficiency must be gained to reduce energy consumption.

Results gained through the project:

- Energy optimization of the fan by using a high efficiency fan, up to 44 %. Partly demonstrated on the Oracle machine.
- Energy optimization of the suction nozzle by using a built-in tank close to street level and ECO-mode, up to 75%. Only the ECO-mode[1] demonstrated on the Oracle machine.
- Noise reduced from fan by using the "Bottle Principle", up to 3 dB (A). Demonstrated on the Oracle machine.
- A mathematical model of the power consumers on the vehicle.
- A model to optimize the efficiency and operational stability of fuel cell modules.
- MEA (Membrane Electrode Assembly) successfully integrated in the SerEnergy stack design. The performance and durability is now comparable with that of the BASF based MEA's. The cost targets specified in the project and the Danish Roadmap for HTPEM are fulfilled.
- Develop a 5kW Fuel cell module, suitable for at vehicle. Ensuring robustness and price compatible.
- Optimizing robustness for long term durability and start/stop of the system, a part of this is MEA optimization.
- Implementing fuel cell control in embedded controller.
- Developing power electronics for fuel module.
- Demonstrator build and tested.

1.2.1 Projektmål og -resultater

Formålet med Oracleprojektet er at udvikle en demonstrant (ORACLE maskinen) for at undersøge fordelene ved at anvende brændselscelleteknologi på redskabsbærere til udendøs regngøring. Miljømæssige fordele skal nås i forhold til eksisterende dieselløsninger, og en forbedret effektivitet skal opnås for at reducer energiforbruget.

Resultater opnået gennem projektet:

- Energioptimering af turbine[2] ved hjælp af en højeffektiv ventilator, op til 44%. Delvist demonstreret på Oracle maskinen.
- Energioptimering af mundstykke ved hjælp af en indbygget midletidig beholder tæt på gadeplan. Mundstykke og ECO-mode, sparer op til 75%. Kun ECO-mode er demonstreret på Oracle maskinen.
- Støj reduceret fan ved at bruge "Bottle Princip", op til 3 dB (A). Demonstreret på Oracle maskine.
- En matematisk model af elforbrugere på køretøjet.
- En model for at optimere effektiviteten og operationel stabilitet i brændselsceller.
- MEA (Membrane Electrode Assembly) er med succes integreret i SerEnergys stakdesign. Ydeevne og holdbarhed er nu sammenliglig med den BASF baserede MEA. Mål for omkostningerne, der er i projektet, og den danske køreplan for HTPEM, er opfyldt.
- Udvikle en 5kW brændselscellemodul som er egnet til køretøjet. Sikre robusthed og prismæssig konkurrenceevne.
- Optimering af robusthed på lang sigtet og start / stop af systemet (delvis omfattet af MEA optimeringen).
- Implementering af brændselscellestyring i embedded styrenhed.
- Udvikling af effektelektronik til brændstofmodul.
- Demonstrator bygget og testet.

[1] *ECO-mode is a condition, where the machine does not run full speed to save energy.*

[2] *Tubinen anvendes til at skabe sug.*

1.3 Executive summary

The main purpose of the Oracle project is to develop a demonstrator (the ORACLE machine) to verify the advantages of fuel cell technology on tool carriers used on outdoor cleaning applications.

Each company has their own objectives in the project and together we share the common objective to verify the advantages of fuel cell technology.

Danish Power System has optimized the MEAs, so the performance and durability is now comparable with that of the main competitor. The results will be implemented in the product portfolio of Danish Power System.

SerEnergy has developed a generic fuel cell module to be used in vehicles and other applications. The result will be implemented in the product portfolio of SerEnergy.

Nilfisk Advanced has made both energy and noise optimizations, that partly has been implemented on the Oracle Machine.

Nilfisk Outdoor Division has built a demonstrator, the Oracle Machine, where energy optimizations, noise optimizations and a fuel cell has been built in. The results will, in some degree, be implemented in the product portfolio of Nilfisk Outdoor Division.

There are both advantages and disadvantages by using fuel cell technology on a multifunctional tool carrier. The main disadvantages at the moment are the price, power output and reliability of the fuel cell compared with the application’s needs. However, we believe that the future development of the MEA´s, fuel cells and further optimization of the tool carrier can overcome these disadvantages.

1.4 Project objectives

1.4.1 Danish Power System

The participation in the Oracle project has provided important information about the Membrane Electrode Assembly (MEA) requirements and feedback from the integration into the stack design of SerEnergy. This have resulted in two new MEA products (Dapozol® 101 and Dapozol® 200), which are much easier to integrate into the SerEnergy stack design (joint Oracle and Cobra2 effort).

The focus on the operating conditions (as specified in the Oracle and Cobra2 projects) has resulted in a targeted MEA development towards fulfilling the durability and performance requirements. This has successfully been accomplished.

Furthermore, detailed cost analysis and optimisations have resulted in a fulfilment of the cost targets specified both in the Danish Roadmap for HTPEM as well as those specified in the Oracle and Cobra2 projects.

In conclusion, the objectives for DPS in the Oracle project are successfully completed.

1.4.2 SerEnergy

The goal of the project is to increase the development of a generic fuel cell module to be used in vehicles and other applications. The Fuel cell itself has to be able to handle the vibrations from a vehicle. This system is a Methanol to electrical power system including a methanol reformer and all that is needed for a complete system.

One challenge was to integrate all components into an 81 litre box. The mechanical work on this has some iterations before a decent result where achieved.

We did achieve all goals for this project, even if the integration of subcomponents inside the module, Software upgrades and Power electronics demanded a huge amount of work to get a stable revision.

1.4.3 Aalborg University - Department of Energy Technology

At Aalborg University a Ph.D. student has been employed on the ORACLE project full time. His work on the project had two objectives.

The first objective was to construct a mathematical model of the power consumers on the vehicle, based on assumptions about energy optimization made in cooperation with the project partners. The purpose of this model was to predict the performance of the street sweeper with different types and sizes of batteries and fuel cells. This objective was achieved and the model was used for the dimensioning of the battery-pack in the demonstration vehicle.

The second objective of AAU's part of the project was to experimentally analyze and model the Reformed Methanol Fuel Cell modules from Serenergy. The purpose of these models is to optimize the efficiency and operational stability of the modules. A series of experiments has been performed on a reformer system to assess and model the gas composition at different operating points. These models have been used to identify optimal operating points for the reformer system.

The Ph.D. student has spent 3½ months at University of the Western Cape in Cape Town, South Africa working with the local researchers. During this stay a model of the relationship between fuel cell current and module output current has been developed and used to develop an output current controller, which can make it easier to control the state of charge of the battery in the ORACLE vehicle. This controller has been tested on a scaled down version of the ORACLE drivetrain.

1.4.4 Nilfisk Advance

Nilfisk Advance has contributed to the project with knowledge about noise reduction and energy optimization. The two objectives for Nilfisk Advance are:

Lower the energy consumption
Lower the sound power

The first objective was to design a debris transportation system with lower energy consumption than the Nilfisk CR2250, which uses 7.5 kW of hydraulic power to drive the suction fan.

The second objective was to design a noise control system with lower sound power level than the Nilfisk CR2250, which has a level of around 104 dB(A) re 1 pW.

Both objectives were achieved and demonstrated on a mock up in Brøndby.

The machines used in the Oracle project are:

Figure 1.4.4.1 City Ranger 2250

Figure 1.4.4.2 City Ranger 3500.
Used as the base for the Oracle machine.

1.4.5 Nilfisk Outdoor Division

The main task for Nilfisk Outdoor Division was to design, build and test the ORACLE machine, but also to participate in the work with noise reduction and energy optimization.

The objectives for Nilfisk Outdoor Division are:

- Deliver a working demonstrator to the project
- Demonstrate the theoretical calculations of noise reduction and energy optimization on the Oracle machine
- Test the mathematical model of the power consumers on the vehicle

The objectives have been achieved:

- A working demonstrator has been designed, built and tested.
- The chosen solutions for noise reduction and energy optimization have been implemented in the Oracle machine:
    - An extension of the exhaust channel for the fan was built in.
    - The optimized fan was built in. To prove the energy optimization the optimized fan was compared with a CR 2250 fan.
    - ECO-mode was implemented in the control system and tested. The suction nozzle was not built in, as the concept was not completed and ready for field testing.
- The model has been used in choosing the size of the fuel cell/battery, and measurement on the demonstrator has shown the accuracy of the model.

See photos of the process building the Oracle machine in appendix 2.

1.5 Project results and dissemination of results

1.5.1 Optimizing the MEA

The objective was to optimize the MEA to meet the performance and cost targets for the preliminary markets as well as designing a development strategy to ensure continued focus on the key parameters enabling further market penetration.

The task was divided into the following:

1. Optimizing the MEA for the specific applications defined in the market analysis,
2. Optimizing in relation to platinum/catalyst content,
3. Optimizing economic model and cost,
4. Optimizing in relation to Methanol reformate and
5. Optimizing in relation to lifetime.

The performance and durability of the DPS MEA has been optimized. The following parameters have been optimized:

- Dry operation (both constant current and start/stop cycling)
- Wet fuels (constant current and start/stop operation)

The results of short stack testing at SerEnergy shows that the performance and durability are now comparable with that of the BASF based MEAs (See Figure 1.5.1.1).

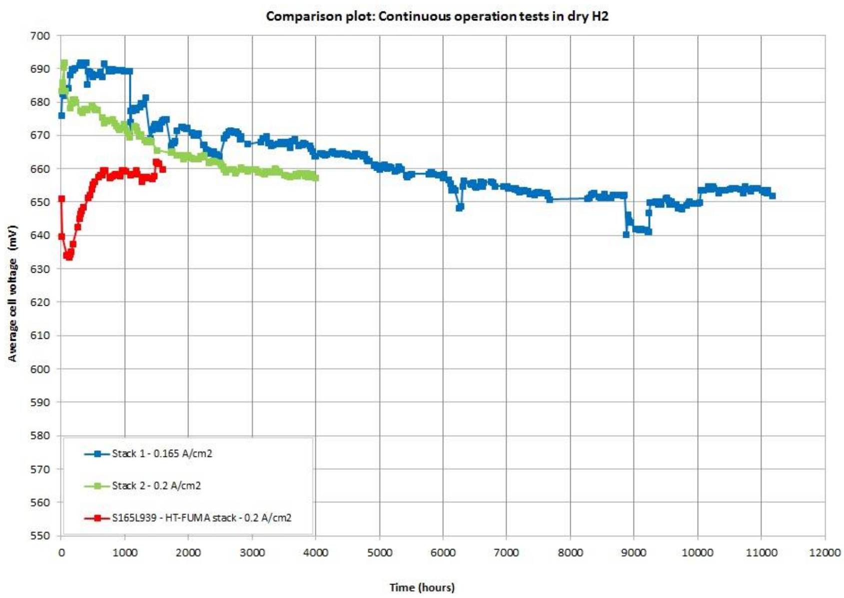


Figure 1.5.1.1 Results from MEA testing in short stacks at SerEnergy (10 MEAs pr. Stack). DPS Dapozol® 101 MEAs (red curve – the test is continuing) and BASF based MEAs (green and blue curves).

See appendix 1 for further details about the MEA testing at DPS.

The cost of the MEAs has been optimized and the key factors influencing the cost structure have been identified. The realized cost (2014) and the cost target for 2018 have been analyzed (See table 1.5.1.1). The cost prediction meets the targets specified in the roadmap for HTPEM (www.hydrogennet.dk).

	Today:	2018-2020:
MEA volume	**10 000/order** (400 kW)	**Large volumes**
MEA cost Performance	0.27 €/cm^2 0.22 W/cm^2	0.08 €/cm^2 0.40 W/cm^2
Cost	**1200 €/kW**	**200 €/kW**
Requirements:		Lower cost of components Recycling of Pt Larger MEAs Improved perf. and durability

Table 1.5.1.1 Results from cost analysis for 2014 (realized) and 2018-20 (Dapozol® 101)

DPS have developed two alternative MEA designs, namely Dapozol® 101 and Dapozol® 200, which shows much better compatibility with the SerEnergy stack design. However, it is only Dapozol® 101 can meet the cost target in the roadmap.

1.5.2 Optimizing the Fuel Cell

Optimizing the Fuel Cell
The Fuel cell module has goon trough a development phase in this project ensuring the usability in vehicles. The development is not finished, but a decent level of readiness has been proven. Here are the main objectives that have been the result of this project.

Results:
- Long-term durability test: more than 10000 hours on several fuel cells
- Simplified module complexity to be able to integrate all components into a box on 81 litres, hereby increasing the power density to be the world leading in this 5kw Class.
- Developing subcomponents ready for mass production.
- Developing an Embedded control platform for Fuel Cell module control.
- Developing Power electronics for fuel cell module.
- Including the possibility to use extern-cooling loop, hereby using heat for cabin heating.

Optimizing the control method of the combustion inside the fuel cell
The project team has been working on making the fuel cell module stable an reliable.
To be able to have a reliable system, it must be able to make start and stops fully automatically in any scenario.

Furthermore, the system must be able to deliver the requested output power, without damaging itself or the machine it is connected to. From this a safety handling system has been included into the platform.

As a service a remote support option has also been included into the system, for now it has been implemented using an external 3g router connected to the module, hereby the service department has the possibility to connect remotely to the module and update or look at the log files inside the system.

The area for optimizing the controllers and the features on the module are definitely ongoing, the better controllers the more reliable a system and the more useable features the more users are able to use and sell the systems.

Test results
Module effectivity from Fuel in to Power out:

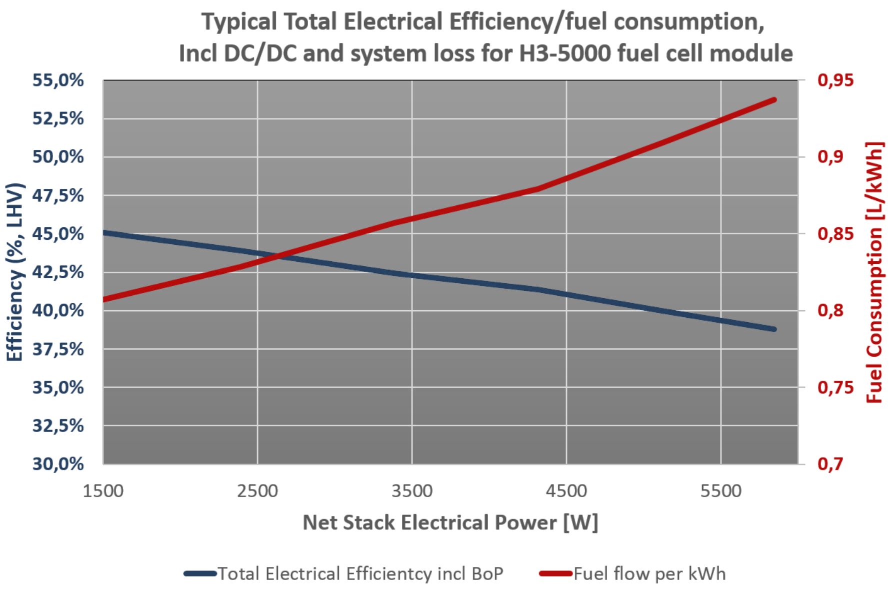


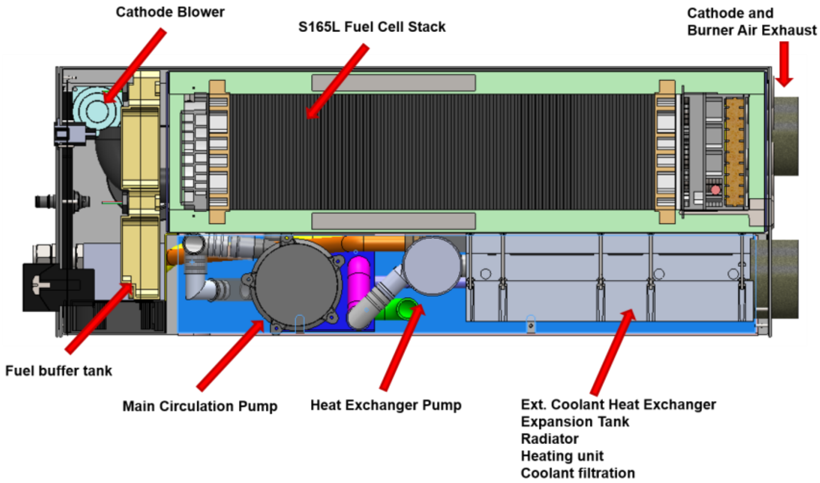
Figure 1.5.2.1 Electrical efficiency and fuel consumption

The efficiency of the fuel cell has been improved from near 30% to above 40%, the past two years.

- H3 5000 – Methanol Power system
- Electric power: 5kW
- Elec. efficiency(LHV): 40-50%
- Weight: 70kg
- Dimensions:
  - Width: 19”/430mm
  - Length: 700mm
  - Height (6U/253mm)
  - Volume: 77L
- DC/DC: integrated – bat charging capability
- Air cooling integrated – (liquid optional)
- Fuel pump + buffer tank integrated
- Output voltage: LV: 24/48/80 or HV: 350-600 VDC

Figure 1.5.2.2 H3 5000 module

On the following pictures/drawings it is possible to see how the module has been designed. On the drawing you can find descriptions of the different components.



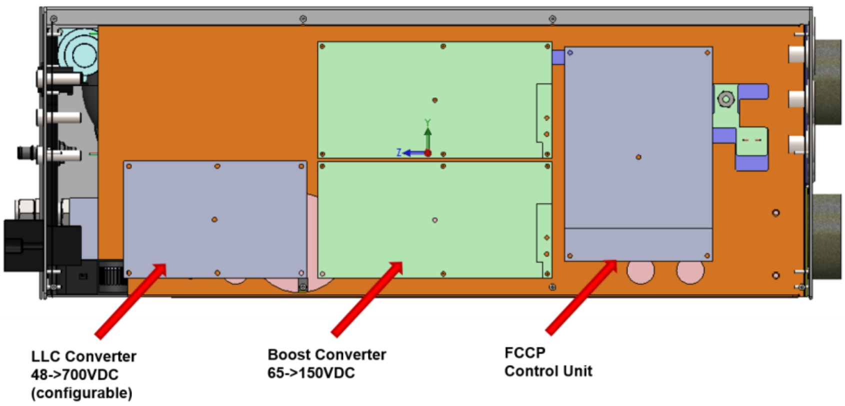


Figure 1.5.2.3 H3 5000 module

Power electronics are placed on one side of the module; the different components are all developed.

1.5.3 Developing a model of the vehicle

Here follows a description of the vehicle model developed at Aalborg University and the results obtained from it.

Vehicle model description

The purpose of the model is to predict the performance and battery state of charge during a working day using a defined operation cycle.

The model contains the following sub-models:

Mechanical model of the vehicles drivetrain: The model calculates the power consumption of the drivetrain based on the weight of the vehicle with a certain battery/fuel cell configuration, a simplified motor model and the incline of the road. This model can also be used for the development of speed controllers.

Models of consumers: Models of the primary consumers which are the brushes, suction fan and miscellaneous consumers such as the power steering, lights and data logging equipment.

High level model of fuel cell: Model of the fuel cell which calculates the efficiency and fuel consumption of the fuel cell module at the relevant power output.

High level model of the battery: Model of the battery's state of charge with current dependent efficiency.

Controllers for the fuel cell power output: Option to include charge controllers.
A diagram of the model can be seen in the figure below.

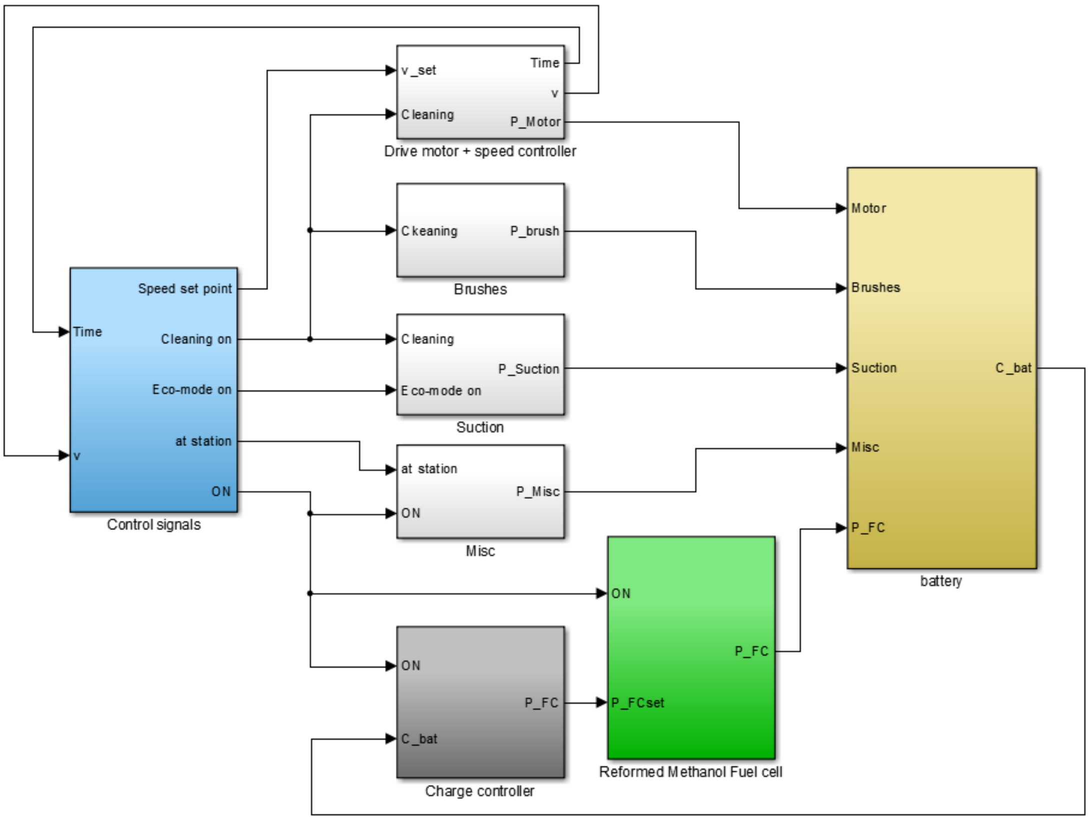


Figure 1.5.3.1 Diagram of fuel cell model

A drive cycle has been designed for the ORACLE project with the project partners, which is thought to be representative for a real world application for the vehicle. A more detailed description of the drive cycle can be found in section 1.5.7. This drive cycle consists of an 8 hour working day interrupted by 7 trips of 2000 meter to an emptying station and 100 second stops at red lights every ten minutes. The transport speed of the vehicle is 21 km/h and the cleaning speed is 5 km/h.

An ECO-mode has been included in the model, which assumes that the suction fan is operated on 60% power for 50 seconds followed by 10 seconds at full power. The figures below show the power consumption, vehicle speed and vehicle mode during a simulation in the model.

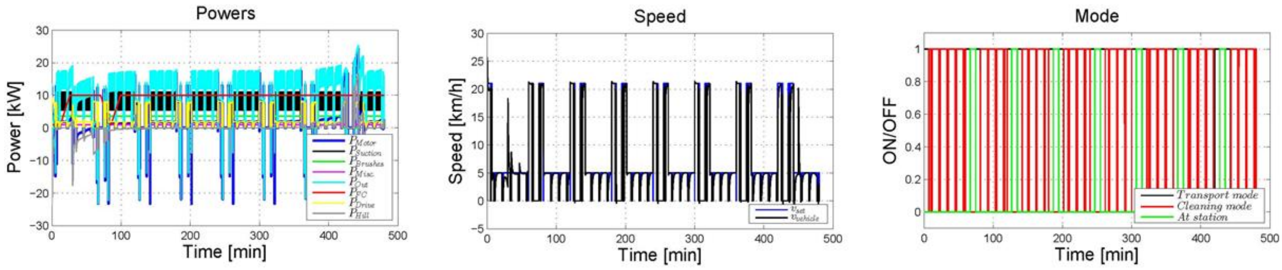


Figure 1.5.3.2 Power consumption, speed and mode

Based on an analysis of the diesel powered vehicle the following worst case values were used for the power consumers:

- Suction power = 8.6 kW
- Brush power = 4.9 kW
- Misc. power = 1 kW
- Friction coefficient = 0.05

Initial simulations

A series of simulations were performed to analyze the power consumption and battery state of charge during a working day. Based on these simulations it was chosen to use a lead acid battery with a capacity of 19.2 kWh in the prototype vehicle. This battery was chosen, because it is simple to implement and even without a fuel cell it is possible to test the vehicle. The battery will likely be changed to a more efficient, lighter but more complicated lithium-ion battery in a later production vehicle.

It was also concluded that a fuel cell size of 10 kW was necessary if the vehicle were to operate indefinitely. The following figures show battery capacity plots from the model of three scenarios where the vehicle is equipped with 0, 5 and 10 kW of fuel cell power. 5 and 10 kW is used, because it corresponds to 1 and 2 H3 5000 modules from Serenergy, which is to be used in the ORACLE prototype.

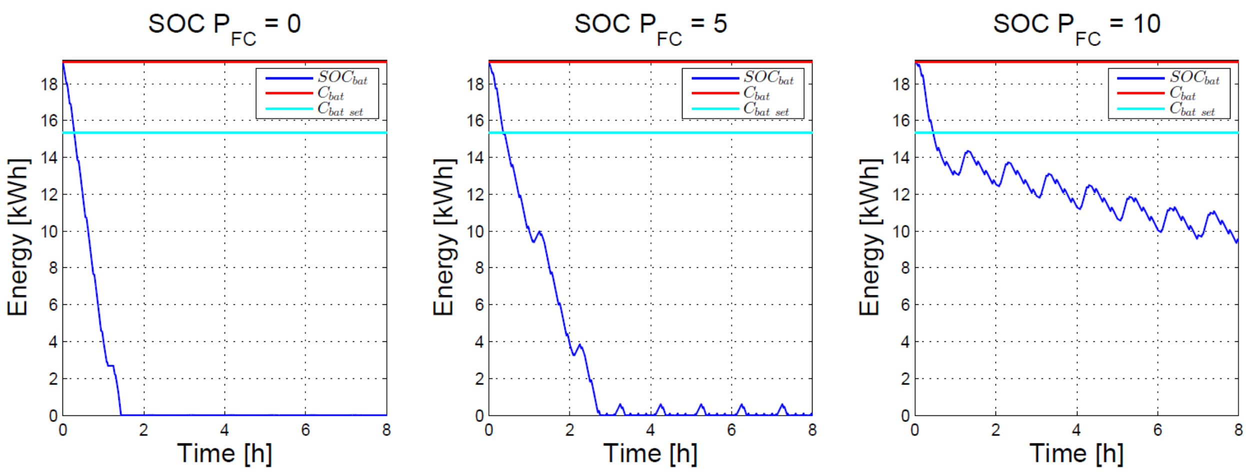


Figure 1.5.3.3 Battery capacity plots at different scenarios

In the last case, the average fuel cell power is 9.5 kW and the total methanol consumption is 83.5 liters of methanol, which is not quite enough to sustain the battery's state of charge.

To demonstrate the usefulness of the fuel cell in this application it is investigated how large the battery would have to be if it were to power the vehicle for a full 8 hour day.

As the next plot shows, the answer is 120 kWh corresponding to 5,000 kg of batteries, which is unrealistic on a 2,600 kg vehicle. The vehicle would also have to be off duty for recharging for a period of time after each 8 hour shift.

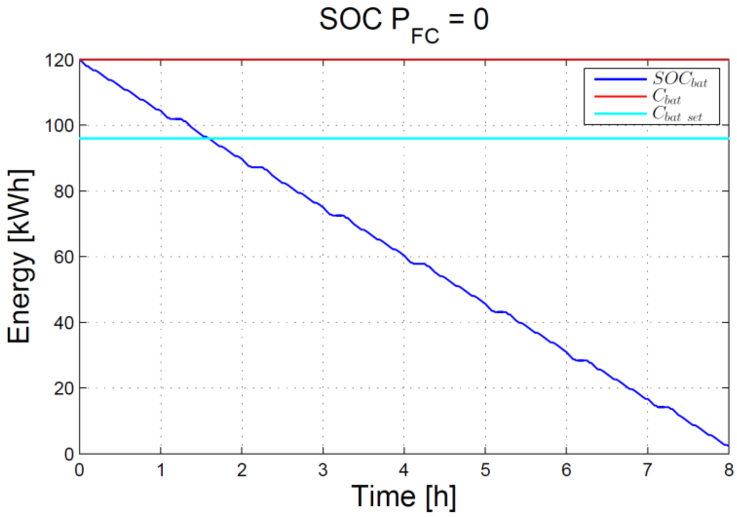


Figure 1.5.3.4 110 kWh battery and no fuel cell

Update of model constants and expectations after experiments
After the completion of the ORACLE prototype a series of experiments has been performed by Nilfisk Egholm. The constants in the model have been updated to the following values based on these experiments:

- Suction power = 8.7 kW
- Brush power = 1.4 kW
- Misc. power = 0.41 kW
- Friction coefficient = 0.03

It is worth noticing that the power for the brushes, misc. components and friction is much smaller than the conservative initial estimates. The figures below show plots of the battery capacity in simulations using these constants with a fuel cell power of 0, 5 and 10 kW.

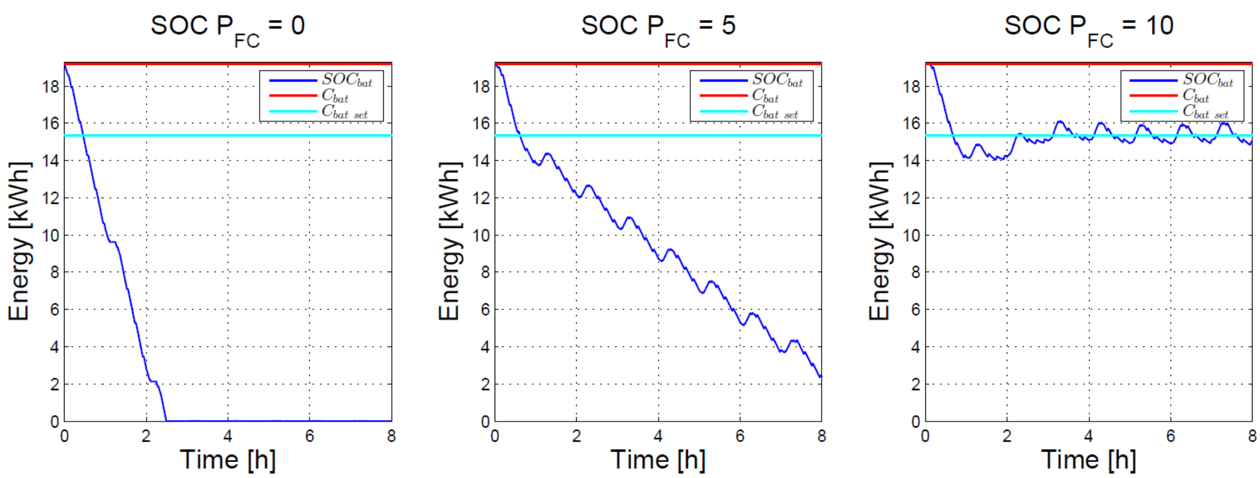


Figure 1.5.3.5 Battery capacity plots at different scenarios, revised constants

As the figures show, the 5 kW is now enough to make it through an 8 hour day if the user is willing to accept, that the battery is drained in the process. If the vehicle is to be ready for another shift right after the first one is over, a larger fuel cell stack is still needed. In the case with the 10 kW fuel cell system a PI controller is used to control the state of charge of the battery. Here an average fuel cell power of 6.3 kW is delivered and 54.6 liters of fuel is used.

1.5.4 Optimizing the control method of the combustion inside the fuel cell

Here follows a description of the work done at Aalborg University on the characterization of reformed methanol fuel cell systems in connection with the ORACLE project.

Characterization work done on Reformed Methanol Fuel Cell systems

Experiments have been performed on a reformer system from a H3 350 reformed methanol fuel cell module from SerEnergy to map its performance at different temperature set-points.

The output power of a H3 350 module is only 350 W, but the results obtained on this setup is thought to be scalable to the larger 5 kW modules, which is to be used on the ORACLE vehicle.

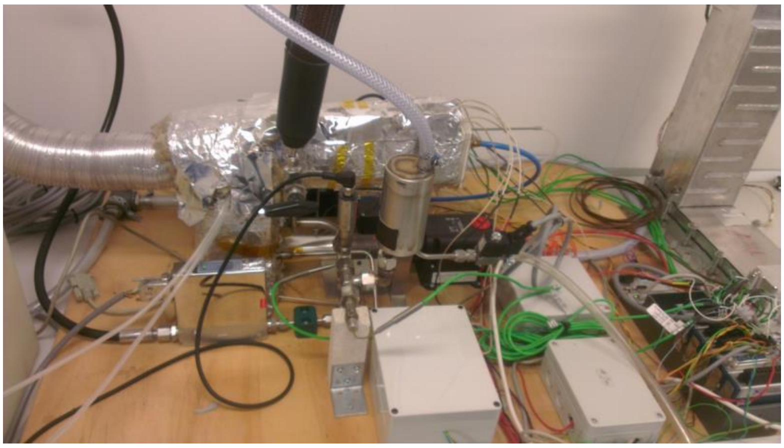


Figure 1.5.4.1 Picture of test setup

The setup is connected to a gas analyzer which measures the composition of the output gas of the reformer. These measurements include the content of hydrogen, carbon monoxide, carbon dioxide and methanol in the reformers output gas. The carbon monoxide content of the gas is important, because carbon monoxide works as a poisoning agent in the fuel cell, lowering the efficiency and decreasing the lifetime. The following figure shows a 3D plot of the carbon monoxide concentration in the reformers output gas at two different Steam To Carbon (STC) ratios.

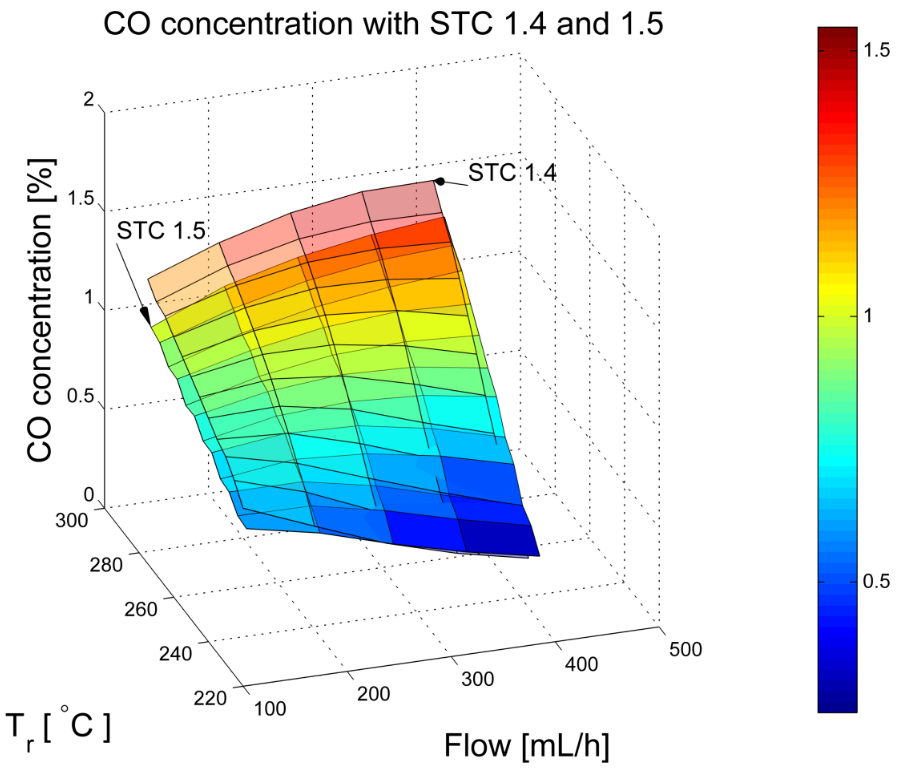


Figure 1.5.4.2 Carbon monoxide content

The figure shows that the carbon monoxide content is largest at high temperature and high flows and lowest at low temperatures and high flows. The content is lowest at STC = 1.5. The next figure shows a 3D plot of the hydrogen reforming efficiency at different reformer temperatures and STC.

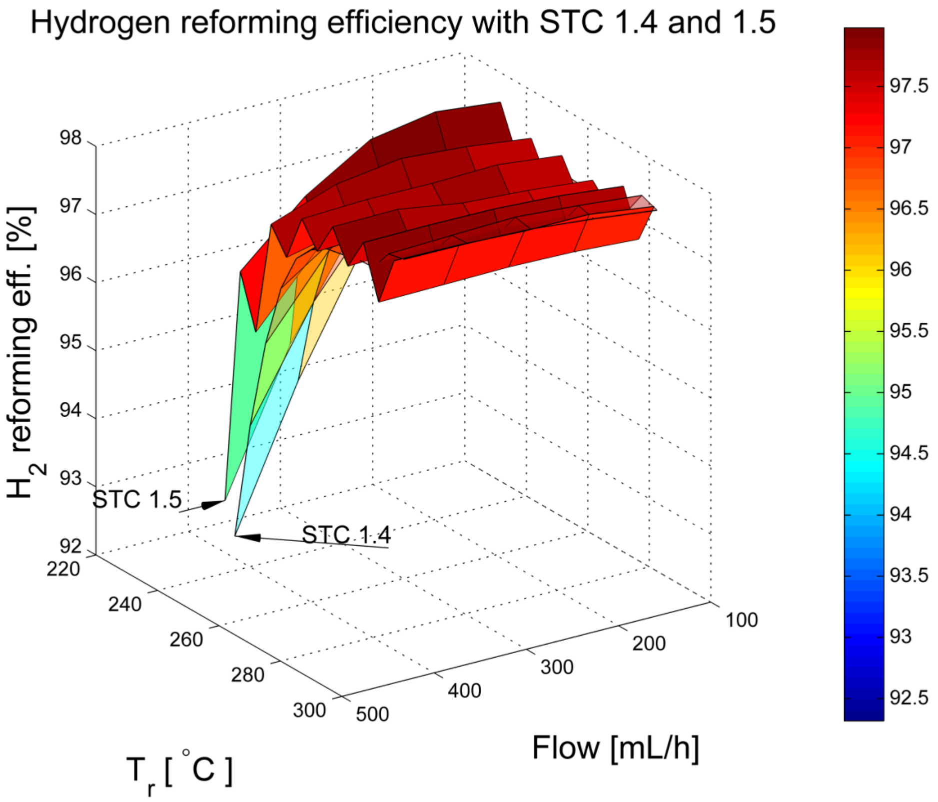


Figure 1.5.4.3 Reforming efficiency

Thus figure 1.5.4.3 shows that the reforming efficiency is highest at STC 1.5 and that higher temperatures generally give better efficiency. The optimal operating temperature will thus be a compromise between low carbon monoxide content and high reforming efficiency.

Based on measurements made by another Ph.D. student at Aalborg University a fuel cell model has been constructed using Adaptive Neuro-Fuzzy Inference Systems. The model is able to predict the fuel cell performance at different fuel cell temperatures and fuel gas carbon monoxide content. The following figure shows a plot of the performance of the fuel cell model at a fuel cell temperature of 170 degrees Celsius and varying carbon monoxide concentrations and fuel cell currents.

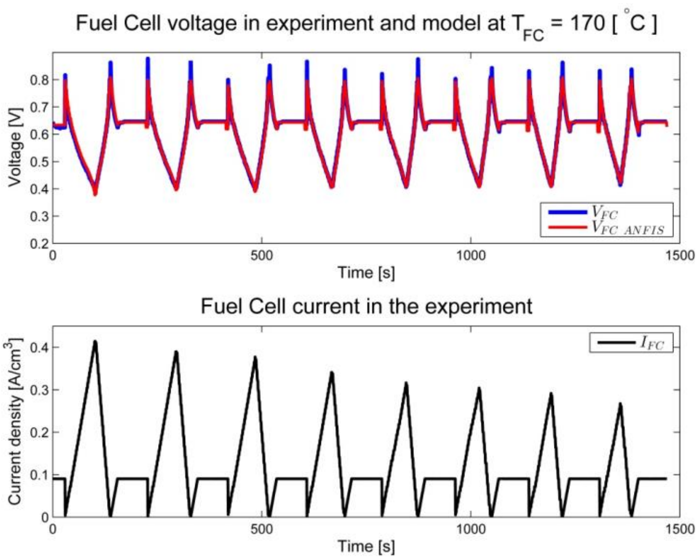


Figure 1.5.4.4

Similar model have been constructed of the reformers performance and the models have been combined to calculate the optimal reformer temperature at different fuel cell currents. A scientific paper is being produced, which demonstrates how this is done and the details of the calculation can therefore not be revealed here.

In cooperation with researchers at the University of the Western Cape a controller which can control the output current of a H3 350 module has been developed. This controller can ease the state of charge control of the batteries in the ORACLE vehicle, if they are rescaled to the larger modules on the vehicle. This controller and the dynamic model they were developed in will be the subject of a scientific paper, which is under development. The data produced using the reformer test setup will also be used to produce and tune a large dynamic model of a H3 350 module for control optimization purposes.

A test setup with a 5 kW reformer from SerEnergy is being constructed at AAU with the purpose of scaling the models and optimizations achieved in this project up.

1.5.5 Possible energy savings in a street sweeping machine

Regarding a Nilfisk CR2250 street sweeper, three basic functions consume energy. These functions are,

a. The forward drive of the machine.
b. The rotation of the brushes.
c. The suction of air used to transport debris from street level into the tank.

The forward drive of the machine

The power used to drive the machine forward during transport or sweeping depends very much on the climb and on the weight of the machine. The energy saving potential by construction here is to lower the weight and have a motor with a high efficiency.

The rotation of the brushes

The power used to drive the brushes depends of the number of brushes, type of brushes, and the weight applied to them.

The airflow used for transport of debris

The saving of energy in this field has a high potential. Therefore a detailed study of the system losses has been made on a Nilfisk CR2250 sweeper.

Nilfisk CR 2250

The study shows that the pressure loss in the complete flow system including filter and nozzle is p = 6.3 kPa at an airflow of Q = 1900 m3/h. This means that the fan is required to supply an air power of P = 3.3 kW to the flow. The distribution of pressure losses in the machine may be seen in figure 1.5.5.1. The pressure loss of the "filter and inlet grid" is found as a difference between the flow characteristics with and without the filter and grid, which gives some uncertainty.

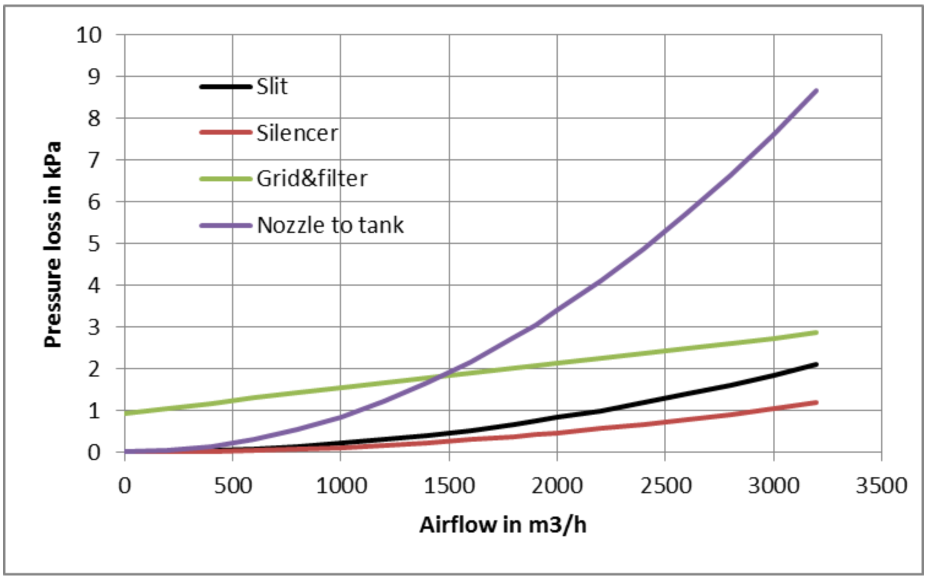


Figure 1.5.5.1 Distribution of pressure loss as a function of airflow for a CR2250. The "Slit" is the exhaust opening. (The non-zero value for the green curve at zero flow is due to the uncertainty of the measurements)

From figure 1.5.5.1 it may be seen that the highest loss is found in the inlet tube from nozzle to tank and the second highest in the inlet grid and filter upstream of the fan. In table 1.5.5.1 the curves from figure 1.5.5.1 are used to calculate the required powers to overcome the different losses at an airflow of Q = 1900 m3/h.

Element	Pressure loss in kPa	Power requirement in W	Rank
Inlet	3,05	1613	1
Filter	2,08	1096	2
Slit	0,74	392	3
Silencer	0,42	221	4
Fan to flow	6,29	3321	

Table 1.5.5.1 The required powers in a CR2250 to overcome the various losses at Q = 1900 m3/h.

Fan

The first step is to identify a more efficient fan with a performance similar to the performance of the fan in the CR2250. The PUNKER 1924 HL40 450 x 53-E, 5-2.5.2.25 with a maximum efficiency of around 66%.This fan has been installed in a wooden mock-up of a street sweeper with a new street nozzle and a new noise control system. A filtration system was not built into the mock-up, since the low loss water filtration system of the CR3500 has been selected for the ORACLE machine.

In the wooden mock-up the 400V 3-phase induction motor obtained P= 3270W at Q = 1900 m3/h, which is only 44% of the hydraulic power supplied to the hydraulic fan motor of the CR2250 of 7.5 kW.

Power consumption of ORACLE prototype (CR 3500)

In the CR3500 the original fan unit was replaced by the PUNKER fan with 3-phase induction motor and extra baffles were installed in the outlet from the fan (described later). Besides these changes the air paths of the CR3500 were not modified.

With these improvements the consumed power at 1900 m3/h was measured to 5.8 kW, which is 77% of the hydraulic power supplied to the hydraulic fan motor of the CR2250 of 7.5 kW. The extra power obtained by the ORACLE prototype, Compared with the wooden prototype 5.8 kW to 3.27 kW is believed to be due to flow loss in the exhaust duct of the ORACLE prototype.

Power saving potential - suction Nozzle

The new street nozzle is an innovative way to save power. The nozzle is a modified version of the CR2250 nozzle and has a built-in tank very close to street level. The advantage of the built-in tank is that only a small airflow in needed to transport debris from street level into the nozzle tank since most of the transport work is being done by brush inside the nozzle.

Figure 1.5.5.2.
Function model of the new street nozzle with built in-tank (white part to the right).
Flow of debris is from left to right.
The brush of the nozzle is driven by an electric power drill.

Experiments have shown that airflow of only 950 m3/h is needed to have a successful filling of the nozzle tank. Since the power requirement is quadratic only 480W is needed for the 950 m3/h. To this power must be added the power of rotating the brush inside the nozzle, which is 500 – 1000W depending on the type of debris and on the condition of the street.

The principle of operation is to have an intermediate cycle, where the small airflow of 950 m3/h is used most of the time. As soon as the nozzle tank is full the airflow is increased to 1900 m3/h in order to empty the nozzle tank. When to apply the high airflow may be controlled automatically by a level sensor in the nozzle tank.

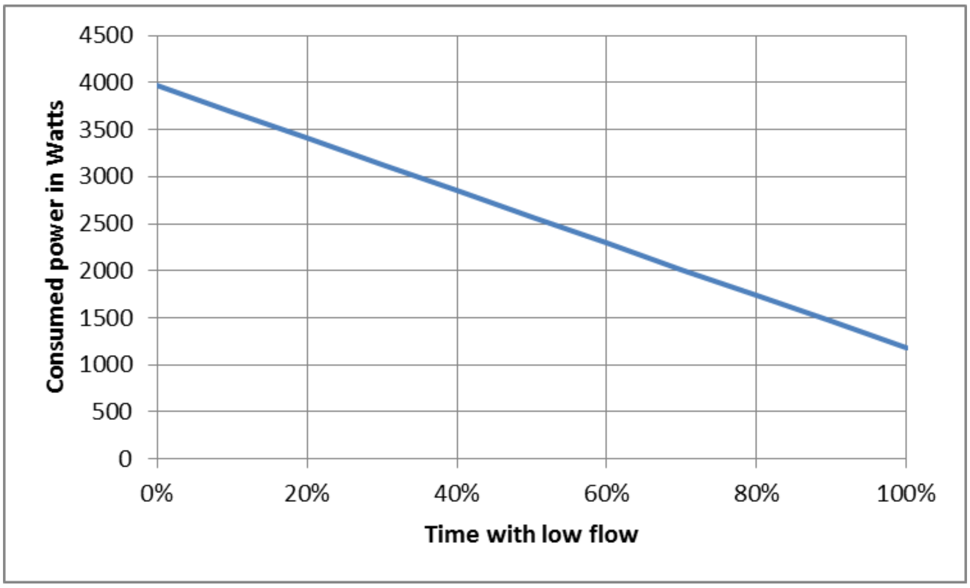


Figure 1.5.5.3. Power consumption of the transport system with the new street nozzle as a function of the percent of time the low airflow is used.

Power of nozzle brush is set to 700W.

As may be seen by figure 1.5.5.3, the power savings potentials are large and typically 50% or 2000W. Compared to the fan power consumption of the present CR2250 of 7.5 kW the intermediate airflow technique potentially saves 5.5 kW or 75 %!

Conclusion on energy saving

If the new nozzle is used together with the ORACLE prototype and we assume that the full airflow is needed 50% of the time, the power consumed by the fan motor drops to 4.3 kW or 57% of the power used on the present CR2250.

Following measurements are made with a flow of 1900m^3/t:

	Normal [kW]	New turbine [kW]	New nozzle* [kW]	Suction hose dia. [mm]
CR2250	7,5	-	-	150
Oracle	-	5,8	4,3	180
Mockup	-	3,27	2	160

*Figure 1.5.5.4 Measurements are made with a flow of 1900 m^3/t. *The cycle is as described in the text above.*

As each system setup is different to each other, each have a different resistance though out the system. Furthermore each system has a different diameter on the suction hose, because of the above mentioned reasons there should be made more tests to show how effective the solutions in fact are.

The mockup shows somewhat what is possible to reach with an optimized system. It cannot be directly implemented in reality, there are the following issues:

-There is no filtration system on the mockup.

-The placement of the element used for sound proofing is bad as it would get worn up over time. It would need to be shielded.

-The mock up is quite higher (165 mm) in size than the current one (90 mm). The extra space is used for air ducts.

1.5.6 Noise reduction

Noise control of street sweeper

The sources of noise in a typical street sweeping machine is in order of importance; the fan, the diesel engine, and the hydraulic system. In the ORACLE machine, the diesel engine and parts of the hydraulic system are missing.

In the aforementioned wooden mock-up of a street sweeper a low loss noise control system has been realized based on the so-called “Bottle Principle”, which works as an acoustic low pass filter damping noise at frequencies above the resonance frequency of the system. The resonance frequency shall be low, which is achieved by placing the fan in a large volume and let air and noise flow through a long and narrow exhaust duct.

The measured sound power level of the wooden mock-up at maximum airflow is 87.5 dB(A) re 1pW. This level is low and shall be compared to typical levels of street sweepers, which are 99 dB(A) and even higher.

Noise of ORACLE prototype (CR3500)

However, a perfect noise control system is difficult to realize in existing street sweepers due to space limitations. Furthermore, in order to focus on having a prototype of a fuel cell driven street sweeper in a short period of time, the CR3500 was selected as basis for the prototype. Consequently, the fully noise control system from the wooden model could not be implemented.

The noise control system of the CR3500 has been improved by extending the length of the exhaust duct. The extension was done by creating a labyrinth in the exhaust area.

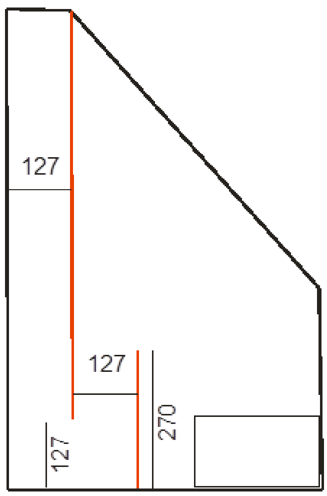


Figure 1.5.6.1.
The noise control labyrinth (red plates) created in the exhaust area of the CR3500. The exhaust of noise and air from the fan is the rectangle in the lower right hand part of the drawing.

The different of the added noise may be seen in table 1.5.6.1.

Configuration	**Change in sound power level**
ORACLE original compared with Oracle with modifications from figure 1.5.6.1	3,3 dB(A) less

Table 1.5.6.1 Fan running at n=4500rpm and Q = 2200m^3/h in the ORACLE prototype.

The cooling fans of the electrical parts are not estimated to contribute to the total sound of the ORACLE street sweeper.

Conclusion on noise
The noise control system of the wooden mock-up is designed without compromises, but in a real street sweeper this is not always possible due to the extra space obtained by the system. The sound absorbing rubber foam used in the exhaust duct may not be practical in a real street sweeper due to moist and abrasive particles in the air.

The sound reduction on the Oracle machine was according to the bottle principle and not focused on canceling out noise frequencies, which is also possible by applying the baffles. So there is still room for improvement.

The mock up showed how noise damping is a possibility and gave some good results.

1.5.7 Building the demonstrator – the Oracle Machine

The basic CR 3500 machine is driven by a 38 kW diesel engine which then drives the hydraulic pumps and a 12 V electrical generator. The hydraulic system handles the moving parts on the machine e.g. wheel motors and the steering cylinder. The standard CR 3500 street sweeper has furthermore two front brushes and a hopper tank with a build in suction fan. The fan and brush motors are also powered by hydraulic. The total weight of a CR 3500 street sweeper unit is 2600 kg without water in the hopper tank and 3040 kg with approximately 400 L water.

Building the Oracle machine

To build the Oracle machine the diesel engine was removed from the CR 3500. The diesel engine is one of the major noise sources. Furthermore most of the hydraulic system was removed as well. The few hydraulic parts that were kept were the steering cylinder, the hopper tank tipping cylinders, the brush movement cylinders and the cylinders for the suction nozzle. The reason to keep these hydraulic cylinders was mostly their low energy consumption which is a result of their periodic use. Another reason is the cost and the time to change these cylinders compared to the possible energy savings.

The fact that the CR 3500 and the Oracle machine have hydraulic steering means that the machine can be maneuvered without the electrical system or the diesel engine running. This is an important safety feature.

Hydraulic solution

A 2 kW DC motor drives the hydraulic pump in the Oracle machine. The motor is only running if a hydraulic function is active such as the tipping the tank, movement of brushes or the oil pressure in the buffer tank gets below 75 Bar.

The solution with a pressure tank as a buffer for the hydraulic system and a DC motor to make sure the pressure in the in tank is maintained is a decent solution. The motor and pump maintaining the pressure is quite noisy while building up pressure. While turning, if it’s not done continues it will make the machine move in bits and not continues and that will make the machine bounce a little.

There were a small problem with the compact DC motor for the hydraulic system which got to hot causing it to shut down. There was mounted a cupper heat sink and mounted a fan to increase the convection which solved the thermal issues. The cooling fan is a bit noisy.

The above described problems could be solved with having an electric actuator to steer the machine. Or an electric controlled motor which varies the speed according to the load and pressure.

Operating conditions

In order to correctly sizing the components for the Oracle machine the energy consumption of the existing CR 3500 has to be known. Furthermore the operating conditions for which machine have to be working and tested at has to be defined.

One cycle have duration of totally 60 min. 40 min of a cycle is used in working mode and another 10 min is used in transport mode. The last 10 min is used for emptying the hopper tank and refill it with water. Working mode is defined as driving with approximately 5 km/h and both fan and brushes is active. Transport mode is defined as only driving with 21 km/h. The average slope of the roads is assumed to be 0 %.

The cycle described in section 0 was used to simulate a full working day of 8 hours to determine the size of the battery but if this working day is split into 1 hour pieces it is almost similar to the cycle described above. The only differences are the use of ECO-mode and that the machine has to stop at red lights every 10 min.

An overview of the different modes can be seen in table 1.5.7.1 Cycle definitions and the standard test cycle for a sweeper unit is also shown in Figure 1.5.7.1.

Task	Time [min]	Speed [km/h]	Brushes & Suction fan
Work mode	40	5	On
Transport mode	10	21	Off
Emptying	10	0	Off

Tabel 1.5.7.1 Cycle definitions

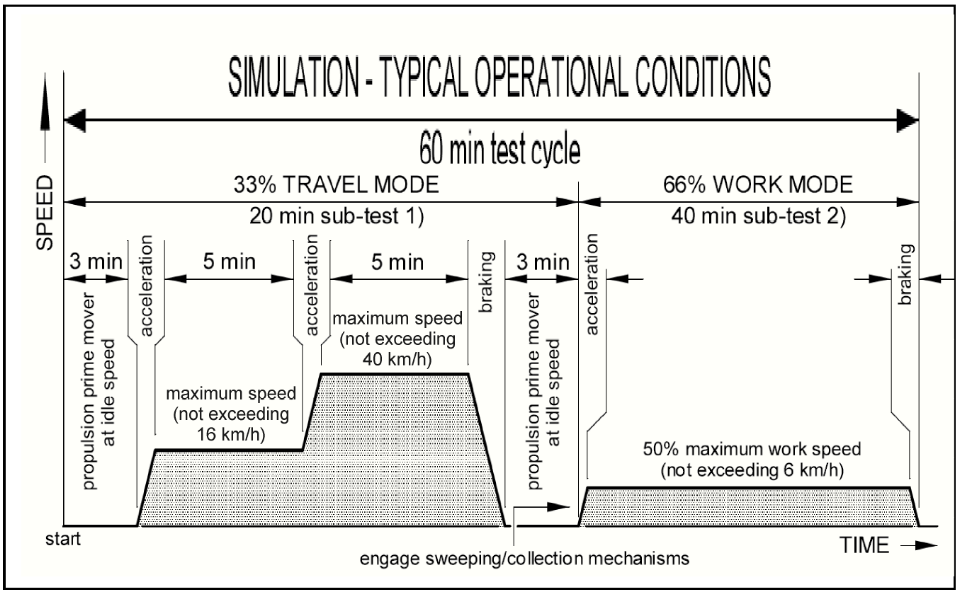


Figure 1.5.7.1 pr EN15429-2:2010(D) Definition of standard operational condition for a sweeper unit

The power consumption

Figure 1.5.7.2 shows the power usage for each hydraulic motor and cylinder in the CR 3500 in the different modes. The power is calculated from the measured oil flow and pressure difference. Each power data had to be obtained with individually test because it was not possible to measure pressure and flow at each motor and cylinder at the same time.

It is clearly the working mode which is the most energy consuming. Work mode total power is 15.9 kW and transport mode total power is only 7.2 kW.

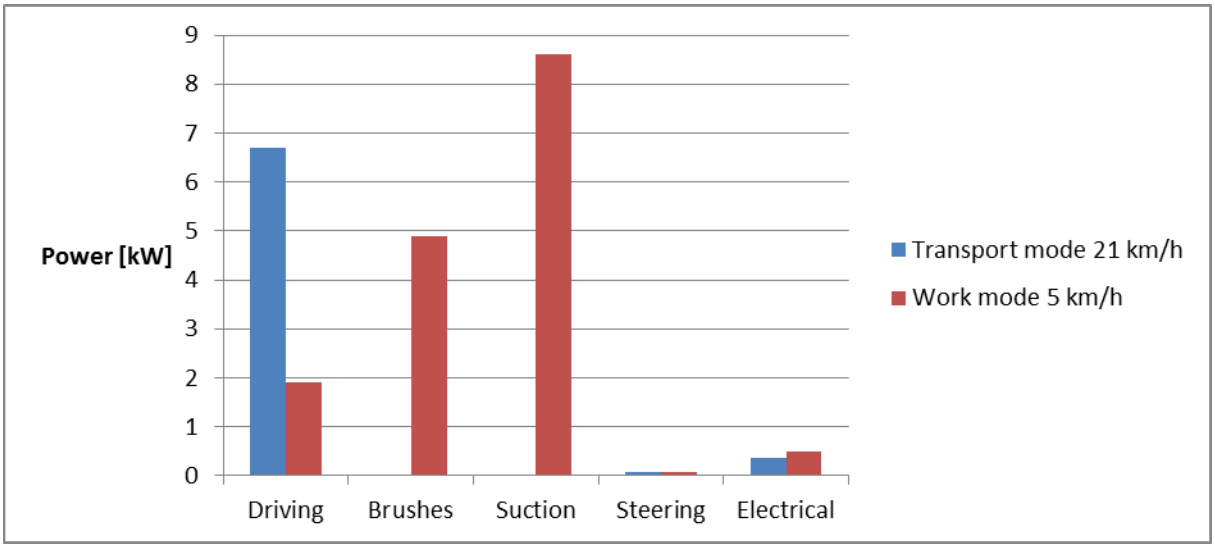


Figure 1.5.7.2 Power usage on a CR 3500

Mode	Speed [km/h]	Driving [kW]	Brushes [kW]	Suction [kW]	Steering [kW]	Tilt [kW]	Electrical [kW]	Total power [kW]
Work	5	1,9	4,9	8,6	0,06	0,02	0,49	15,9
Transport	21	6,7	0	0	0	0,02	0,37	7,2
Emptying	0	0	0	0	0	0,52	0,37	0,9

Table 1.5.7.2

Furthermore the machine was tested on a 10 % incline and the power consumption at 5 km/h was 9.0 kW and 24.5 kW at 21 km/h. The incline will only have an effect on the driving power. Some of the values in Table 1.5.7.2 were added to the mathematical based model of the vehicle made at Aalborg University. Based on this model and a minimum operation time requirement of 60 min for the machine, the battery capacity were determined.

Energy storage and generation

A lead-acid battery solution was chosen with a total capacity of 19.2 kWh combined with a 5 kW fuel cell. The main reason to choose the lead-acid over the lithium-ion is because it is a cheaper and easier to implement solution. Over the batteries total lifespan, the lithium-ion batteries are cheaper. Two clean water tanks on each side of the machine were removed to make space for the battery. This clean water is normally used for dust reduction at both brushes.

The charging of the battery is done in two ways. When Oracle machine is parked during the night the battery can be charged with an external charger. It takes roughly 12 hours to re-charge a fully depleted battery. During normal working operation the machine can be charged by the fuel cell if there is a surplus of energy. Even with a fuel cell that can supply the necessary power, there would still be the need for a small electrical buffer.

Lithium-ion batteries would technologically be the best solution because lead-acid batteries have some drawbacks in terms of higher weight and volume. For this project the price was rated higher than the weight and volume. Another downside from using lead-acid is only 70 % of the battery capacity can be used without permanently damage the battery and thus drastically reducing cycle life. This leaves only 13.4 kWh actual battery capacity available. Lithium-ion batteries can also be charged and discharge faster than lead-acid.

The fuel cell takes about 45-180 min[3] from the startup to be heated and fully functioning. Until it reaches the correct temperature it will not produce electrical energy to its full potential. After about 10 min. it starts being able to supply enough power to deliver some back to the system. The Oracle machine is still able to drive while the fuel cell is heating up, but the necessary energy will be drawn from the battery.

The fuel cell emits almost no noise while making electrical energy of the methanol, is not comparable to the noise the diesel combustion engine make in the CR3500. The only noise from it is a little fan cooling the fuel cell module. Also the fuel cell pollutes far less per kWh compared to the diesel engine, read more about this in the chapter 1.5.8.

Filter

The cooling channels in the fuel cell is quite small and to prevent them blocking, a filter is needed to filtrate dirt from the air flow. First a filter was chosen with the necessary filtration capability and a low pressure difference. Then the filter area was calculated to have the necessary air flow across the filter. Because of the size of the filter it was placed on top of the fuel cell and a vent was made from the filter to the air intake of the fuel cell.

By maintaining an area of the vent at least the size of the full cell opening for the air intake, the cross area of the vent shouldn’t create any pressure loss.

[3] The startup time depends of the configuration of the fuel cell e.g. the size of the blower.

Dampers

The dampers are mounted to protect the fuel cell from severe shaking from driving down curves or over road bumps. The dampers chosen are secured dampers meaning that there is a mechanical connection even if the damping part might break. The dampers have a combined strength of max. 240 kg which is about 3 times the weight of the fuel cell module.

The static weight of the module compresses the dampers 1,8 mm. At 180 kg the dampers reach their maximal deflection of 4 mm.

Motors and inverters

The hydraulic suction fan, traction and brush motors were replaced with 5 asynchronous AC motor. These motors were dimensioned according to the numbers in Figure 1.5.7.2 Power usage on a CR 3500. All AC motors is controlled by a separate inverter using Field Oriented Control (FOC) to give the best drive performance at all speed ranges.

When breaking or driving downhill the inverters will regenerate energy back to the battery. If the slope is too steep the voltage can increase beyond 62 V which will result in an emergency shutdown of the inverters, but as a safety measure the fan will start running to lower the voltage. An advantage from using electric motors is a higher starting torque meaning it’s having an easier time starting uphill or with a full load. Also with the inverters the foot pedal profile can be adjusted to give e.g. a more smooth driving experience or faster acceleration.

If nothing is activated on the CR 3500 the hydraulic pumps will keep circulating the oil back to the tank. This means energy is lost as heat. An electric system only uses energy when a function is active.

A 2x6 kW dual-drive motor solution was chosen for the traction although 24.5 kW is required for 21 km/h on a 10 % incline. If the traction motors were size according to the 24.5 kW the motors would be greatly oversized for most of the time and hence reducing the efficiency for most of the other operating conditions. Another reason is the physical size of the motors. The electric motor requires a reduction gear which the hydraulic motors didn’t. This further limits the space available for the general bigger electric motors in a narrow machine like the CR 3500.

With the traction system no longer being hydraulic there isn’t the hydraulic pressure in the system that makes the vehicle stop on a small incline, instead it will starting to roll down unless you hit the brakes.

The hydraulic suction fan motor uses 8.6 kW and with the possible energy optimization described in section 1.5.5 in mind only an 8 kW electric motor is chosen for the Oracle machine. 2900 rpm is nominal speed for the electric motor but the new suction unit for the Oracle machine needed to run at speeds above 4500 rpm to match the air flow from the CR 3500.

With a maximum airflow of 2200 m^3/h the Oracle machine cannot reach the airflow of the CR 3500 due to both thermal and torque limitations of the motor. At maximum airflow the power consumption is also 11.7 kW compared to only 8.6 kW on the CR3500. The higher power consumption on the Oracle machine is due to the fan was designed for a CR 2250 which means the fan is optimized for airflow of only 1900 m^3/h as described in section 1.5.5. At 1900 m^3/h the power usage is only 5.8 kW which is still an improvement compared to the CR 2250.

Because the fan was designed for a CR 2250 and can’t deliver airflow as the CR 3500 another way of testing is needed. Therefore on the Oracle machine the suction fan was adjusted to have the lowest possible airflow under normal sweeping conditions (ECO-mode) and could be boosted to 2200 m^3/h in case of mud or larger debris needed to be sucked up. This approach reduced the average fan power to 8.7 kW on the oracle machine.

From the power measurements on the CR 3500 a maximum of 4.9 kW is needed to rotate the brushes but this number is highly dependent on surface pressure and the rotational speed of the brushes. How the surface pressure is adjusted is reliant on the individual person operating the machine. Therefore 2x2.5 kW motors is chosen to cope with the worst case scenario. To reduce the rotational speed of the brushes a gear is needed which further adds weight to the suspension of the brushes. The brushes and the gears are placed in an exposed position when it comes to water, dust and crashing with objects. This means high IP classification and a mechanical sturdy construction is necessary.

When selecting components one should make sure they have the proper IP codes so they can handle the hostile watery and dusty environment in which they have to work. The weight of the Oracle machine after replacing the diesel and hydraulic motors with a lead-acid battery and electric AC motors is 3330 kg. With a full hopper tank the weight increases to 3480 kg comparing to the CR 3500 where the weight was only 3040 kg at the same condition.

Data log and control of the inverter and FC

To control and log data from the inverters and the fuel cell a small 7" touch panel PC with a LAN port and CAN-bus was added to the Oracle machine. The touch PC furthermore handles the digital inputs from the machine and measurement of the battery current to indicate the State of Charge (SoC). A big difference between the CR 3500 and the Oracle machine is that data can be logged for all motors and the fuel cell simultaneously.

The electrification has given possibilities to easier and more precise steering of the individual components. In some degree the same is possible with a variable pump; there is however no variable pumps on the CR3500.

The electrical generator on the CR 3500 has been replaced with a DC/DC converter in Oracle machine. This 700 W converter supplies the existing 12 V system in the machine. The power consumption in the 12 V system is mainly used for light and the hydraulic valves.

Test results

The totally energy consumption for a full working cycle is 9.58 kWh drawn from the battery and 6.42 kWh estimated on the axes. The calculated power on the axes is based on an estimated torque value therefore the axel power can vary up to ±10%. A static analysis of the data in steady-state points yields the following results:

Mode	Speed [km/h]	Traction [kW]	Fan [kW]	Brushes [kW]	Electrical [kW]	Total [kW]
Transport	21	6,0	0	0	0,35	6,4
Work	5	1,5	8,7	1,4	0,35	12,0

Table 1.5.7.3 Energy consumption in the Oracle Machine

The average power usage of the Oracle and CR 3500 is compared in Figure 1.5.7.3.

There can be observed a small improvement of the traction power although the weight has increased. The fan power has slightly increased on the oracle machine because the optimized fan was originally designed for a CR2250. But compared with a CR2250, see table 1.5.5.4, energy can be saved. There is seen a great reduction of the power for the brushes but this reduction is mainly caused by a much lower surface pressure.

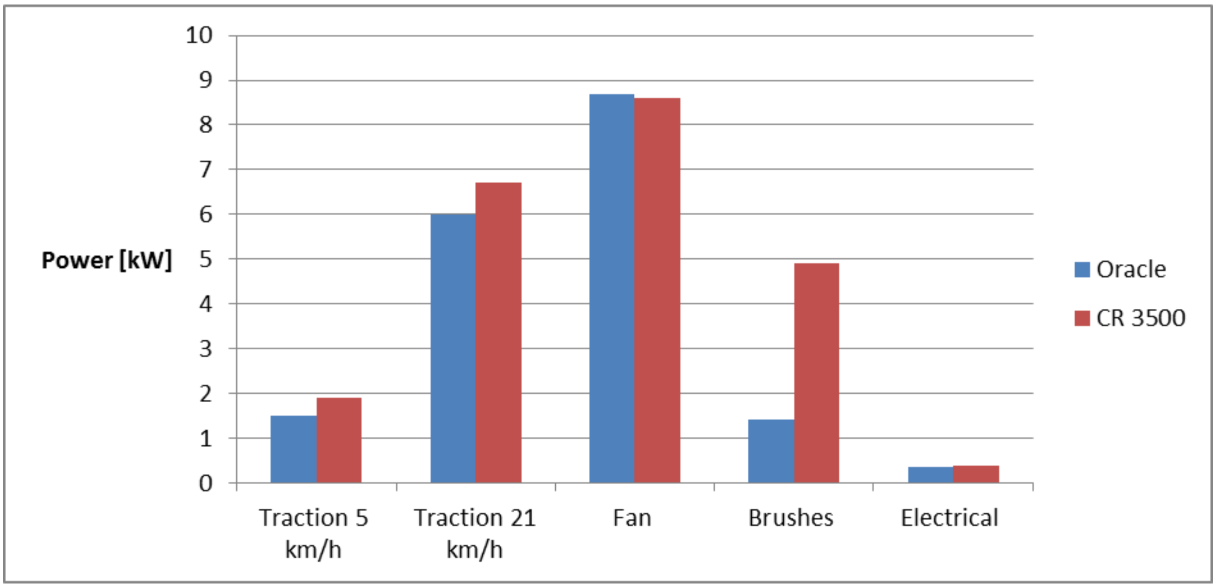


Figure 1.5.7.3 Power usage comparison of Oracle and CR 3500

Transport mode up a 10 % slope requires 19.1 kW and the speed will drop down to 12.6 km/h. The drop in speed is due to the chosen motor and inverter. In transport mode with an average speed of 15.2 km/h down a 10 % slope the traction motors will regenerated 6.8 kW which is send back to the battery. This regeneration was not possible with the CR 3500.

The energy capacity of the battery is 13.4 kWh at 70 % Depth of Discharge (DoD). This will give a maximum working time of approximately 80 minutes without fuel cell. According to the simulations in section 0 the maximum working time is approximately 100 minutes.

Physical dimensions

To make a simple illustration of the demand for re-designing the basic machine, two fuel cells have been drawn into a 3D model of the CR2250. Engines, placement of batteries etc. is not part of the illustration, but will contribute to the demand for a re-design.

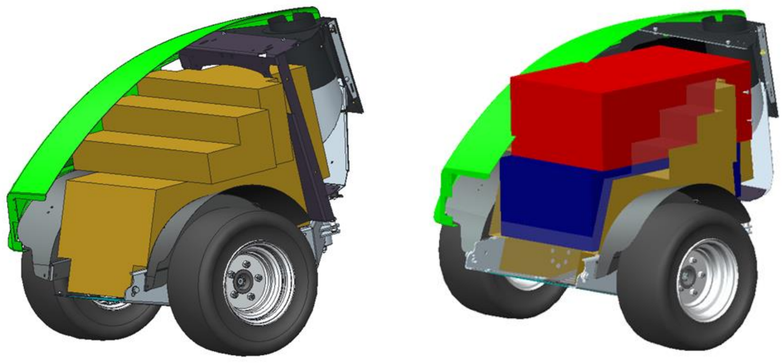


Figure 1.5.7.4 On the left is the available space, 0,19 m^3, shown as brown boxes. On the right the two fuels cells are place in the machine. The volume of a fuel cell is 0,081 m^3.

1.5.8 Comparison of emissions

Particles

The comparison of emission is based on the consumption of diesel in the drive cycle defined in figure 1.5.7.1 Consumption of diesel has been converted to Net Energy Production (kWh), which is the base for calculating emission.

The consumption of methanol is based on measurement of Net Energy Production on the CR 3500. The value from CR 3500 has been converted to CR2250 via an estimated conversion key.

	Liter/hour	Energy (kWh)	Efficiency	Net Energy Production (kWh)
Diesel	4,8	46,9	0,35	16,4
Methanol 60% /water	7,2	18,0	0,45	8,1

Table 1.5.8.1 Consumption of fuel per hour

	Diesel driven *3	**Methanol driven**
CO	1,885 g/kWh	Insignificant little.*2
HC+Nox	7,002 g/kWh	Insignificant little.*2
Particles	0,511 g/kWh	Insignificant little.*2
CO_2	2.690 g/l (2.690 g/l * 4,8 l/h)=> 12.900 g/h	544 g/kW *1 544 g/kW * 8,1 kWh = 4.406 g/h
Difference		-8.494 g/h 66 % less.

Table 1.5.8.2 Emission from a diesel driven machine, size CR2250 and methanol driven machine, size CR2250. In the figures for the fuel cell it is assumed all energy is provided by the fuel cell and no charging from the public electrical grid.

**1 Based on measurement on the 350 kW modules. SerEnergy expect the same level.*

**2 SerEnergy is getting measurement done by Dansk Teknologisk Institut, but no results available yet.*

**3 Data for "diesel driven" is based on diesel engine for CR2250.*

The table 1.5.8.2 shows there is 31% less CO_2 emission from the fuel cell machine compared with the diesel driven machine. Furthermore we expect the Methanol driven machine to have significant little emission of CO, HC+NOC and Particles.

Noise

The fuel cell itself is compared with the diesel engine much more silent. The fan is however so noisy, that we have not been able to measure a significant lower sound pressure when removing the engine. The total drop in sound pressure is due to:

- The labyrinth in the exhaust area
- Replacement of the diesel engine with the fuel cell.

Noise measurements have been done according to DS/EN ISO 374 2009[4]

[4] DS/EN ISO 374 2009: Acoustics – Determination of sound power levels of noise sources using sound pressure – Engineering method in an essentially free field over a reflecting plane.

1.5.9 Economics and marked

Customer
To make a fuel cell advantageous to the customers, it is necessary that the machine is not only a green alternative for the customers, but also is advantageous in terms of economic and performance

The price for fuel cells is still high, and the initial investment for the customer is significantly higher. Opposite is the cost of using the fuel cell vehicle lower than for the diesel machine, and that makes it interesting looking at the total cost of ownership.

In terms of money the fuel cell driven machine consume for around half the value of a diesel driven machine. This entails that a customer can pay the double initial for the fuel cell machine, and still after 8.000 hours have had the same total cost of ownership, as if he had bought a diesel driven machine.

The considerations above are only valid, when the machine is used around 1600 hours per year.

Nilfisk Outdoor Division
Whether it is advantageous for Nilfisk Outdoor Division or not to develop, produce and sell a fuel cell driven machine depends on several factors:

- The standard unit cost of the machine, where the price of the fuel cells and batteries is very important
- The general energy matureness of products in Nilfisk Outdoor Division, and there by the project cost. Reuse solutions from other machines and perhaps only rebuild an existing machine.
- Market potential, where the use pattern at the customers is important.

It is how ever under the right circumstances realistic to have a positive business case for a fuel cell solution.

Focused Nilfisk Outdoor Division marked analyze
A marked analyse conduct by Nilfisk Outdoor Division shows

- There are marked potential for non-diesel driven sweepers, and there is a trend were more cities and larger customers are going in direction non-diesel driven machines or hybrid machines.
- The marked analyse shows that the customers, that have interest in non-diesel driven sweepers, will operate their machine for more than 2.000 hours per year, which support a positive business case for the customer and there by Nilfisk Outdoor Division.

The opinion from marketing and sales is that the present solution in the Oracle machine is not strong enough for a product. But taken Time to Marked in consideration work must continue.

1.5.10 Business model for fuel cells

The business model by RMFC is quite simple and comparable example diesel engines.

The value (economic) is the reduction in fuel consumption / cost and less maintenance compared to a diesel engine. Due to a currently relatively higher purchase price will be a "Return on investment" ROI consideration - when an investment is worthwhile seen on operating costs.

Leasing in itself is not extra value, but may remove any risk about new technologies and their sustainability for the customer. Leasing can remove a barrier, but it does not make the basic economic consideration any different.

Due to the design of the fuel cell there is that after use (8000 t) still a high value in the system. Among others the platinum located in the MEA and recycling of flow plates and other components. If you swap a system you can get ~ 30% of its investment return.

1.5.11 Field test of the Oracle machine

Field test of the Oracle machine started up in the end of November 2014 and was completed start of March 2015**.**

Process
The process of getting the Oracle machine out running with fuel cell mounted is described in appendix 4 and in appendix 3 is the first test report from SerEnergy shown.

It took approximately 2½ months to get the fuel cell installed and started up on the Oracle machine. There were some mistakes and some adjustments on both the fuel cell and on the Oracle Machine. Mid-February was we ready to carry out Field test with at test driver.

Adjustments
The following adjustments have been carried out to get the Oracle Machine working:

- Software on both the fuel cell and the Oracle Machine has been adjusted.
- An expansion tank has been added to the Oracle Machine to prevent refrigerant to overflow.
- Http user interface and a 3G rooter installed, so SerEnergy can do long-distance support.
- The angel of the brushes and the suction mouth is adjusted a little bit.

1.5.12 Sum up on advantages and disadvantages on the Oracle machine

Working on Oracle project has elucidated the advantages and the disadvantages of using the fuel cell technology in a tool carrier. The list of advantages and disadvantages is based on the current state of the Oracle machine. Suggestions to repeal the disadvantages has been added to the list

Design - advantages

Programmable

Variable speeds are much easier to decide with a push on a button for the end-user.

Short overload period

Electric motors are able to peak at higher speeds and torques than their designed use.

Energy consumption

The hydraulic system cycles the oil through the pipes, even if a feature is not activated. The electrical system only uses power when it is needed.

The total energy consumption of the vehicle is lower on the Oracle machine than on the CR 3500 due to electrification and optimization of the fan[5].

When driving downhill we are able to regenerate energy to the battery.

Less noise emission

As the diesel engine has been removed, one of the major noise sources has been removed. Inserting plates to mute certain frequencies gave us approximately 3 dB (A).

Less emission

The Oracle machine emits less CO_2, CO, HC+Noc and particles then a CR 2250[6].

Greater torque

The torque on electrical motors is higher at low rpm, meaning the machine would have an easier time starting with a heavy load or uphill.

Design – problems and possible solutions

Fuel cell

There are 4 issues with the fuel cell.

- Startup time
- The necessity for an energy buffer
- Output
- The physical size

The startup time can be somewhat neglected with a timer set to start it up at a certain time on individual days. This can be done in advance.

Currently the fuel cell cannot change its output quick enough to follow the change in demand. To compensate there are added a battery to take these spikes. As the fuel cell delay gets smaller, the buffer can get smaller. An optimum between the size of batteries and fuel cell must be found.

[5] The fan in the Oracle machine is not optimized for CR 3500, but for CR 2250. The graph in figure 1.5.7.3 do not included the possible gain from an optimized fan. Table 1.5.5.4 shows the possible gain from an optimized fan.

[6] See chapter 1.4.8.

Currently the fuel cell module cannot deliver the necessary power to be the primary energy source to our system, which it was meant to. This has made the large amount of battery necessary. For a commercially viable machine it needs to be able to work for 8 hours consecutively.

- Further develop the fuel cell to give a larger electrical output.
- Further energy optimization of the vehicle to make the total necessary effect smaller.

It is not possible to fit a 10 kW fuel cell and batteries into a CR 2250. The physical size of the fuel cells needs to be reduced, together with another design of the vehicle

Battery options

In the project we had focus on Li-ion and lead-acid batteries. We have chosen lead-acid as they are cheaper to buy and they have the life time to prove this concept. If we had a product ready to commercialize the Li-ion seem to be a better choice because of a longer life time and seen over the life time they are cheaper.

The physical size of the chosen batteries is an issue, as water tanks have been removed from the Oracle machine to fit in the batteries. The Oracle machine cannot spray water on the brushes. Other type of batteries and a design dedicated to a fuel cell solution will help on this issue.

Maneuvering

The issue with the maneuvering is mostly when turning; instead of being smooth it's bumpy. It should be able to be improved with a better hydraulic system. With an electric actuator the problem would be solved, with the size needed it is however too expensive for this project.

Parking

The natural resistance on the hydraulic system is no longer present, which means that if you're not touching the gas or the brake, the machine will react as the ground beneath is leveled. The programming could how ever be changed to make the wheel engines keep the voltage on for longer, perhaps until the gas is touched again.

IP sealing

The IP sealing is an international standard and it is important to have in mind when choosing components to make sure they can handle the rough environment.

Engine and battery sizes/weight

The sizes of the available electric motors, at this time are quite big compared to the hydraulic engines and also quite heavier. The solution with 800 kg batteries is only a prototype worth solution. To have less battery on the machine, a greater output from the fuel cell is necessary.

The weight of the Oracle machine is higher than a CR 3500 due to the heavy batteries and choice of electrical component e.g. the brush engines. The choice of component and the use of electrical or hydraulic solutions must be carefully considered.

Climb ability

To have good climb ability the engines have to have a certain size to have the necessary torque, compact electric engines with high torque cost a lot. On this prototype we decided to be able to drive uphill with 12 km/h. Our solution to this issue is to recommend that the vehicle is only to be used in flat city environment with slopes of max 10%.

Cabin cooling

In the Oracle machine the air condition system is not working. The AC compressor is driven by the diesel engine, and we decided not to find another solution. The surplus of heat from the fuel cell can be used to heat up the cabin.

Cabin comfort

The "furnishing" of the cabin has not been optimized in the Oracle machine. Placement of e.g. screens can be improved.

Considerations for the design of a future machine

We recommend that a fuel cell product is developed with a certain use in mind. For instance to sweep streets in a somewhat flat city with slopes not greater than 10 % inclines. These tasks can be done with a relatively low amount of energy. That should make it easier to lower the overall weight and make the vehicle smaller/more compact. The lower weight benefits to the lower consumption quite a bit as it would influence the necessary effect whenever moving.

Performance of machine

Suction

The suction performance is poor, as expected due to the lower air flow.

Branches accumulate in the suction mouth / hose
Wet debris/dirt accumulate in the suction mouth / hose
Dry sand and dry materials can be collated from the ground (see also brushes)
Water is sucked up.

Boost function

The boost function is working fin and reduces energy consumption.

Brushes

The angel of the brushes was not right in the first place, and wet sand (15-20 cm out from the curb) was not removed but spread out on the road (the wide of the machine. After adjusting the brushes sand was gathered in front of suction mouth instead of spread out. The capability to gather sand etc. is ok.

DC engine for hydraulic

Got overheated. Cooling flanges and a fan were mounted and problem solved.

Flap by Suction Mouth

Not enough suction when driving with the lap open. Suction performance improved when it was closed, and only opened occasionally for lager items e.g. cola cans.

Driver comfort

The reduced noise level in the machine is very comfortable for the driver.

Operation hours

The operations time is approximate 1 hour when driving and sweeping. The fuel cell does only prolong the operations time very very little compared with operations on batteries alone.

Reliability

The fuel cell is not reliable, and there are many emergency shutdowns and errors.

Maneuvering

The machine is not easy to maneuver. Either is he turning wheel very heavy to turn, or the turning wheel bumps while driving.

Speed

Maximum speed on flat road:	21 km/h (OK – as designed for)
Maximum speed on inclination:	12 km/h (OK - as designed for) Søndergade in Lemvig, 10% inclination. The Oracle machine is designed to drive uphill for 2 minutes.

Energy consumption

The total energy of consumption for driving and working is on the Oracle machine 9,6 kWh for a full work cycle and for CR 3500 12,0 kWh for the same cycle.

Boost mode on the Oracle machine demands 11,5 kW.

Driving uphill a 10% inclination demands 9,1 kW and the speed drops to 12 km/h.

The Oracle machine is able to regenerate energy while driving downhill, estimated ~50%.

The energy consumption is measured with an insufficient airflow on the Oracle machine.

Status on the Oracle machine after test period

Output from fuel cell:	~2 kW in average in operation mode.
Batteries:	OK. Batteri kapacitet på 13,4 kWh ved 70% DoD.
Engine, brushes:	Operated OK in Danish winter, and no wear observed.
Wheel motors:	Operated OK in Danish winter, and no wear observed.
Inverter:	Operated fine in Danish winter, and no wear observed. The inverts shutdown when batteries were full loaded and the breaks were initiated. The inverters cannot handle the peak in voltage. The problem is due to the battery solution.

1.6 Utilization of project results

1.6.1 Danish Power System

The continued focus on reformate as fuel have resulted in two new MEA products targeted especially for reformate application. These two products will be marketed actively towards existing and new costumers having such applications. The new MEA products will also be used in the Cobra2 project as they are much easier to integrate in the SerEnergy stack design and shows excellent performance.

1.6.2 SerEnergy – Fuel Cell

The project has proven that an implementation of a methanol driven Fuel cell is obtainable. It has also shown that more output power is needed to be able to operate the vehicle 24-7. This has resulted in the first drafts of a 20kW module.

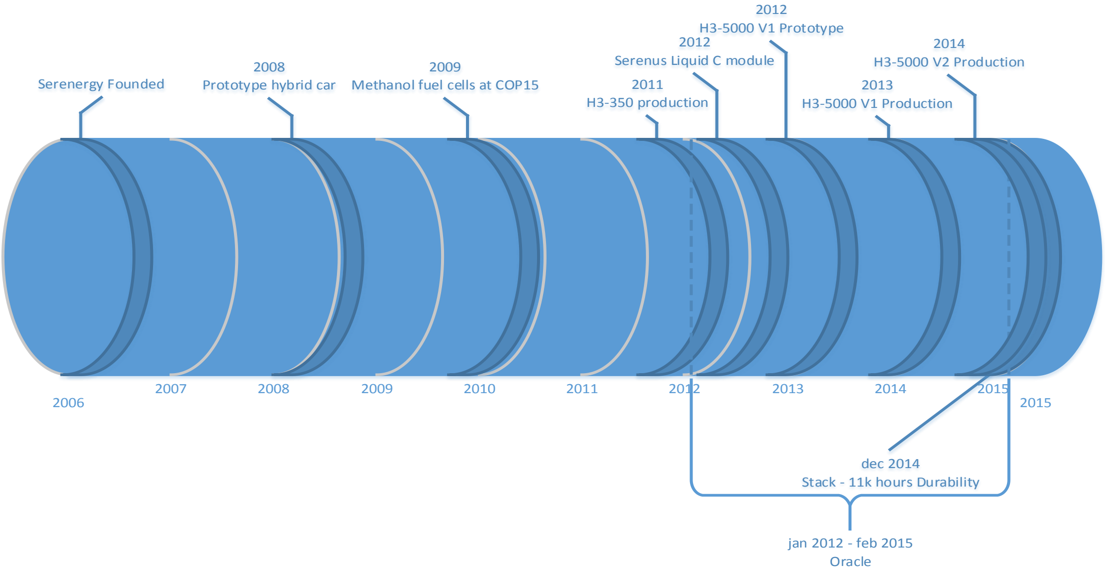


Figure 1.5.2.1 SerEnergy Timeline

As shown on Figure 1 the development at SerEnergy has changed from stack development more into system integration. The systems have increased in power density both by increasing the output power and by reducing the physical size.

The feedback from the user in field has additionally improved the robustness of the product by being able to implement these improvements in new releases. SerEnergy consider field test essential to be able to improve and ensure rapid development and hereby a solid, reliable and well adapted Reformed Methanol Fuel Cell system (RMFC)

The project has proven that an implementation of a Methanol driven Fuel cell is obtainable. It has also shown that more output power is needed before the vehicle is able to operate 24-7. This has resulted in the first draft of a 20kW system. The objective is to increase the power density by a factor 2 and reduce cost significantly.

Implementation and field test has provided vital feedback to development of H3-5000 V2 module, and also made it clear, that online external support of the fuel cell is necessary.

1.6.3 Aalborg University - Department of Energy Technology

The results of this research will be shared with the project partners and specific recommendations will be given for optimization of the reformed methanol fuel cell modules efficiency and stability.

The gas composition measurements where presented at the H2FC Technical School in Rethimon, Greece in June 2014 and the fuel cell model was presented at the Carisma 2014 conference in Cape Town, South Africa in December 2014. More results will be published in scientific papers in the months leading up to August 2014.

The vehicle model, and the results of the simulations performed in it, have been used during the dimensioning of the vehicles drivetrain and can be used in the future to design charge controllers and analyze different drive cycles.

1.6.4 Nilfisk-Advance and Nilfisk Outdoor Division

For Nilfisk Outdoor Division the obtained results can be divided into two:

- Technical improvements, energy and noise
- The ORACLE machine - knowledge about a future product

The technical improvements have during the product been evaluated and brought into ongoing products and projects. Methods to reduce noise and energy consumption can be transferred onto the machines produced today, and will contribute to more silent and energy optimized products.

By designing, building and testing the ORACLE machine valuable knowledge about the challenges in an electrical driven machine has been gained. One of the areas was the power balance in an electrical driven machine. How much power is consumed in the different engines; traction, suction turbine, brushes? Another area was the noise level, when the diesel engine no longer contributed to the noise image.

1.7 Project conclusion and perspective

As shown with the work carried out by the participants of the project it is possible to increase the efficiency of the fuel cell and it is possible to lower the energy consumption of the Oracle Machine.

Danish Power System
The Oracle project is a success on the MEA level. The project have made a significant contribution to the development of two new MEA products (Dapozol® 101 and Dapozol® 200), which are marketed directly for reformate fuelled HTPEM application. Especially Dapozol® 101 represent an interesting platform for further developments in the Cobra2 project (i.e. cost reductions related to a reduction in Pt loading and further improvements in performance and durability).

SerEnergy
As the development of MEA has progress so has the development of the fuel cell.

The H3-5000 system with full automatic Reformed Methanol Fuel Cell (RMFC) has been developed during the project:

Stack and reformer integrated in the module
Integrated embedded control and dual level safety system
Power electronics with possibilities for 48V dc battery charge or high voltage 375 / 750 V DC as output voltage

Furthermore the efficiency of the module has been optimizing. System efficiency has reached 88%, and not fully validated improvements show 94% is reachable.

Aalborg University - Department of Energy
Experiments have been performed on the gas composition of a H3 350 module from SerEnergy and models have been developed on the basis of these experiments. A fuel cell model has also been developed and an operating point optimization has been developed on the basis of these models.

A module output current controller has also been developed in cooperation with researchers at the University of the Western Cape. This controller will make it easier to control the state of charge of the battery in the ORACLE prototype vehicle when it is scaled up to the size of the fuel cell in the vehicle.

The vehicle model can be used in the future to analyze the impact of prospective power consumption optimizations before they are done, saving time and money.

Nilfisk Advance

Low energy consumption

A combination of a more efficient fan driven by an electric motor and a flow system with lower loss has led to an electric power requirement of 3.3 kW or 44% of the power consumed in the CR2250.

Further, a new street nozzle has been developed, which enables the suction system of the sweeper to run at a much lower airflow a great proportion of the time. If the high flow is only used for 50% of the time the power drops to 2.5 kW or 33% of the power currently used for the same job.

These results were achieved in a vehicle hopper tank designed from scratch, and built into the ORACLE vehicle (CR3500) only benefits from the effective fan and the new nozzle could be achieved, and not the benefits from the low loss design of the airways. Here the average power consumption props to 4.3 kW if the high flow is used 50% of the time or 57% of the power currently used for the same job.

Low noise level

In the CR2250 about 50% of the noise arises from the diesel engine, so by replacing this with an electric motor about 3 dB(A) has been gained. Further, a noise control system has been design including sound/vibration absorption and noise traps designed for the specific fan. Without causing any additional flow losses the system brings the sound power level down to dB(A) re 1pW. A reduction of 12.5 dB(A).

These results were achieved in a vehicle designed from scratch. Built into the ORACLE vehicle (CR3500) only minor improvements to the noise control could be made by extending the exhaust duct from the suction fan with baffles. By this design the sound power level was measured to 102,4 dB(A), i.e. 3 dB(A) reduction.

Nilfisk Outdoor Division

During design, building and testing the ORACLE machine we learned, that there were both advantages and disadvantages by using fuel cell technology on a multifunctional tool carrier. The main disadvantages at the moment are the price, reliability and power output of the fuel cell, compared with the application's needs. However, we believe that the future development of the MEA´s, fuel cells and further optimization of the tool carrier can overcome these disadvantages.

During the project we realized that it is important to configure a fuel cell driven vehicle correct. If a vehicle can be designed and dedicated to do relative low-power-demanding tasks, the vehicle will be a more environmentally friendly alternative to diesel driven vehicles. In this configuration the vehicle can be designed lighter and with a smaller power pack.

Future development

Among the participating companies there are planes to continue the work started in this project, and some of the learnings have already started to be implemented in products.

SerEnergy, in cooperation with Danish Power System will continue the work maturing the MEA´s and the fuel cells, and Nilfisk Outdoor Division will continue energy optimize the products, so that we hopefully are ready for step two in 2016-2017.

Annex

Add links to relevant documents, publications, home pages etc.

Aalborg University - Department of Energy Technology:	www.et.aau.dk
Danish Power System:	www.daposy.com
SerEnergy:	www.SerEnergy.com
Nilfisk-Advance:	www.nilfisk-advance.com
Nilfisk Outdoor Division:	www.nilfisk-outdoor.dk

1.8 Appendix 1 – MEA performance and durability results

The performance and durability of the DPS MEAs has been evaluated using single cell testing at various conditions:

Dry conditions (constant current and start/stop cycling)

Vet conditions (constant current and start/stop conditions)

The wet conditions simulate the most significant degradation mechanism when using reformate as fuel, namely the acid management in the MEA due to the presence of water. Water vapour increases the mobility of the phosphoric acid due to lower viscosity. Secondly, there is a potential risk of water condensation during the shutdown of the fuel cell stack. This can cause wash-out of the phosphoric acid, resulting in irreversible loss of performance.

The performance and durability of the Dapozol® 101 MEAs during constant current operation is shown in figure 1.8.1.

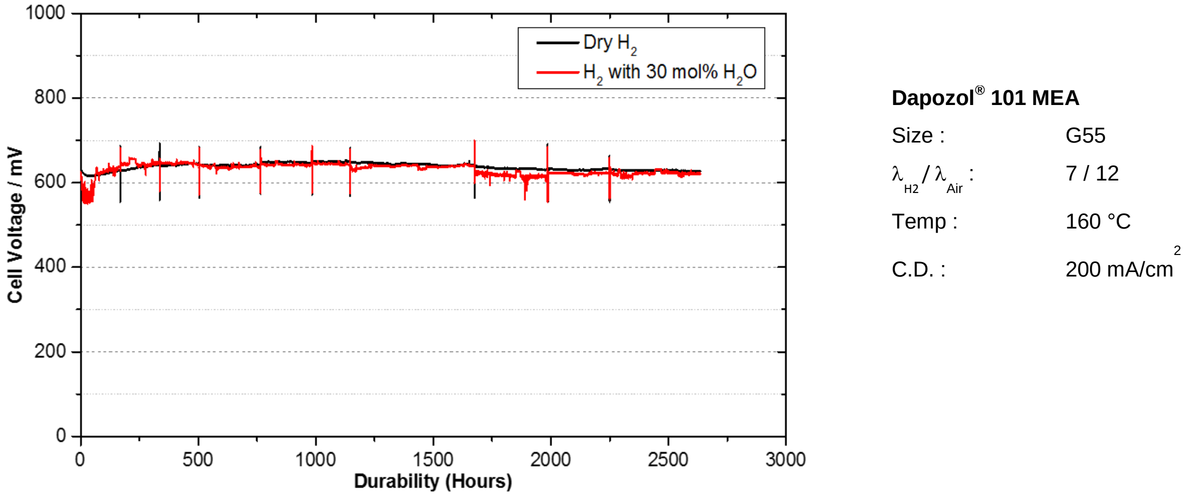


Figure 1.8.1: Performance and durability of the Dapozol® 101 at constant current operation using both dry and wet H_2. Active area: 25 cm^2.

The durability using wet H2 during start stop cycling is shown in figure 1.8.2.

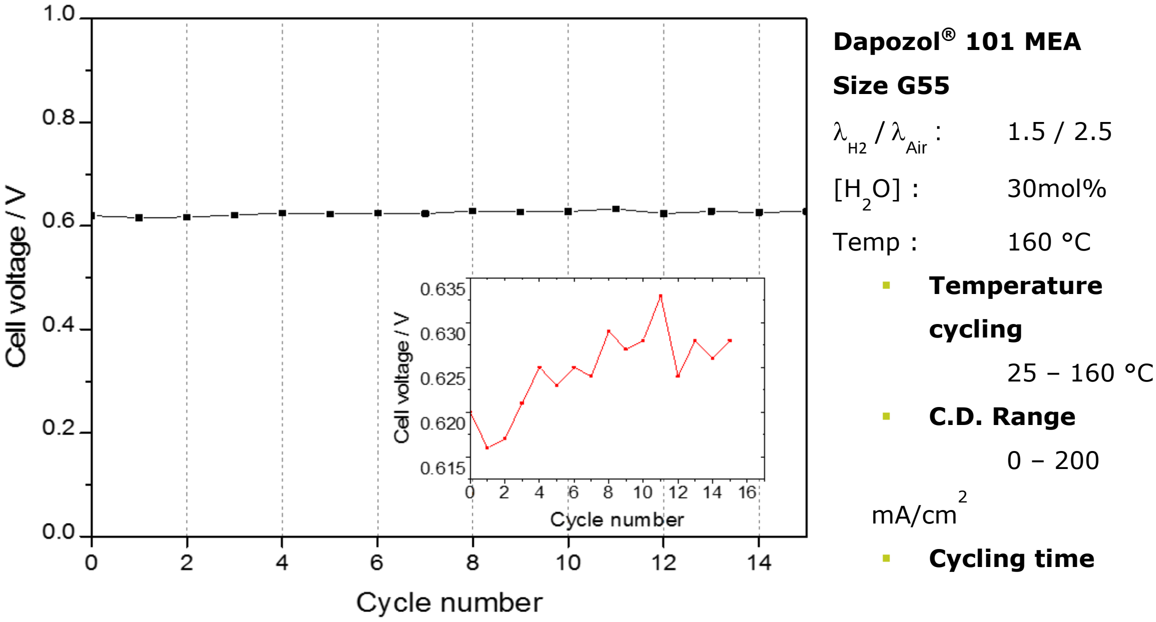
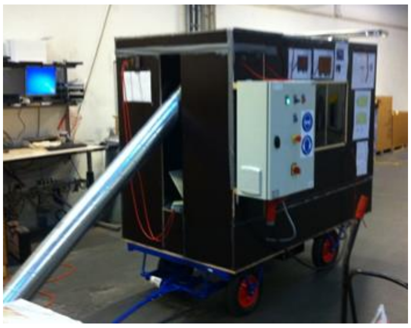


Figure 1.8.2: The durability of the Dapozol® 101 at start/stop cycling using wet H_2. Active area: 25 cm^2.

The results from start/stop cycling show no significant degradation as long as condensation of water is prevented by applying a suitable purging strategy during the shutdown.

1.9 Appendix 2 – Photos from the process of building the Oracle Machine



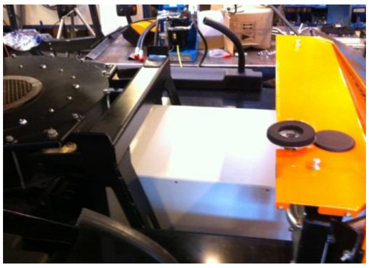
Test of fan, noise damping and suction mouth in Brøndby, December 2014

The wheels spinning for the first time after replacing the combustion engine with bat-teries

We can drive forward, but not backwards - yet

The Oracle machine drives out in the yard

Only a thermal switch was activated after the first speed test



Fuel cell mounted in the Oracle prototype

1.10 Appendix 3 – A section of SerEnergy Field report

Checking mechanical installation, very nice. Pictures will come later, at next visit.

FC has been installed on separate group, hereby possible to turn off all other equipment without disconnecting FC module. Only Emergency button and Power off FC module will cut power to FC module.

Update of software, by hand. New EXDC SW, SVC SW, CANManager, APCProgram (Rev 3.5), Config.xml, DataCore(Rev. 3.3).
After update all was working. Rev. 3,5
Filling MeOH on tank, approx. 18 liter filled on tank.

<u>Approx. 1 o´clock:</u>
Starting module, peek in voltage 110V at 45C fc temperature, dropped after 2-5 min to normal zero.

After 10-15 min strong smell from exhaust. Found ventilation system an mounted near exhaust. All seem ok, temperature on FC vent to 132 C, waiting on reformer temperature to go to 260C, but it stopped at 135 C.

Burner temperature peaked at 675 C and stabilized at approx. 580C.
Tried to find problem, increased burner fan to 80 %, system did make a response. Released to Auto did go to 20 %.

Still no temperature increase on Reformer.

Cheking Tacho FB on burner blower, this was zero.

System made Shutdown.

Alert list showed Tacho FB Error on Burner blower, and 15 sec later also a other Error.
Not sure with made the shutdown. Need to analyze log file to see.

Cooling down system: Fan still not able to run.

We decided to try to get the module out of vehicle; here I did see the reason for breakdown. The MeOH buffer tank ventilation was still blocked.

It is my mistake that I did not check this before starting module!!

We do need to have labels on module telling what the pipes are used for, and perhaps a nice label on the pipe blocking venting, "MUST BE REMOVED BEFORE INSTALLING!"

Module is send to SE as soon as possible, but Sonny will keep it until the parts for filter solution are installed on vehicle.

Decision to be made:
Do we install new Stack, in the module to have it perform more than 2 kW, nearly not enough to keep FC hot.

General issues

1. V1 pipes for venting of buffer tank and Coolant + Coolant filling must have labels!
2. The blocking we do for transport only must be labeled in a way that all will Remove before install!
3. A small how to make safe Commission.
    a. Check electrical install
    b. Check mechanical install

c. Check venting pipes.

Actions and Next Steps

	Responsible	Deadline
Decide if we will put in a new stack	MBF/MHS	
Repair module When we get it back	?	
Test module	?	
Send module	?	
Commission of module on site	SKI	10/12-2014

Conclusion of Visit

I made a commission Error, and the module was broken on this.
To ensure this will not happen ones more, see “General Issues”

1.11 Appendix 4 – Nilfisk Outdoor test log

November 2014	First installation	The basic Oracle machine is checked and the fuel cell is installed. Fuel cell is started up a meltdown happens inside the fuel cell due to a human error. The ventilation to the MeOH buffer tank was blocked. Fuel cell is returned to SerEnergy. See appendix 3 for test report
January 2015	Second Installation First start up	SerEnergy and NOD gets the fuel cell up running, but during shot down refrigerant/TEG starts to pourer out of the fuel cell. Probably due to water in the refrigerant. An expansion tank is installed on the Oracle machine.
January 2015	Second Installation Second start up	An error on the heater prevents the fuel cell to start up. Fuel cell is returned to SerEnergy. See appendix 4 for internal Nilfisk logbook
5th of February	Third Installation First start up	Heater replaced. Http user interface and a 3G rooter installed, so SerEnergy can do long-distance support. Settings in SW adjusted. Fuel cell up running. Deliver approximate 2,6 kW.
6th of February	Third Installation Second start up	Attempt to start up failed – probably due to water in the refrigerant + SW reset Tank indicator is not working with methanol and water.
9th – 13th of February	Third Installation Multiple start up	Touch PC SW update. Different errors/settings adjusted in fuel cell SW. When the breaks are activated to fast, the inverters closed down. Manual force of heat exchange pump necessary. Oracle ready for test driver.
20th of February	Field test	Peer test driving the Oracle machine with Sonny. Everything went OK <u>Feedback from Peer:</u> Very nice with no noise from engine. Asked for more automatically turn-on of brushes and fan. Asked for the possibility to lower one brush at the time

24th of February	Field test	Error on IntCoolant Pressure <u>Feedback from Peer:</u> Branches >20-30 cm is difficult to collect. Lack a camera at the suction mouth (Flaps)
25th of February	Field test	Everything went OK. FC working fine. <u>Feedback from Peer:</u> There might be an error on the suction mouth and with the air flow. The flow is not high enough.
26th of February	Field test	Filled 100-150 TEG in the expansion tank. Perhaps the explanation on the error on the 24th? FC working fine.
27th of February	Field test	Emergency break activated after 1 hour in the startup cycles. The persons though the machin was on fire, but it was only steam from the FC. Luckily no damage to the FC! Still error on IntCoolant Pressure. <u>Feedback from Peer:</u> Adjustment of the brushes has help on the cleaning performance, but wet debris is still not possible. Mud accumulates in the tube and in the suction mouth.
2nd of March	Field test	FC started up to verify heater and FC. FC does an emergency shutdown due to IntCoolantPressure 1½ hour after start up.
3rd of March	Field test	FC starts up and goes into operations mode, but takes a little longer to start up. FC working fine and machine is working fine. FC has downgraded due to an error in short down on the 2nd of March.
4th of March	Field test	FC makes a shutdown due to IntCoolantPressure before it even starts. Cannot connect to FV via WEB interface. FC restarted. Later FC makes an emergency shutdown. Water dripping into the cabin and the electronics.
5th of March	Field test	FC makes a shutdown due to IntCoolantPressure before it even starts. Still not able to connect to FV via WEB interface. FC error on IntCoolantPressure shortly after test-drive started.
6th of March	Field test	FC makes a shutdown due to IntCoolantPressure before it even starts. FC restarted and test-drive carried out. <u>Total Since 24/2</u> 158 hours 32 hours 53 km 33 km Suction performance is still pore.