**WP 5 Final report**

# Improving technical performance of RES-FCHS

**This work package is organized as follows:**

**5.1.0 The objectives of this study and the general overview regarding the lessons learned from previous work packages and the conclusions that have allowed the project to narrow the focus somewhat.**
**5.1.1 A rather detailed original study of some aspects of decentralised electrolysis of water.**
**5.2 The various pathways to reductions, starting with electrolysis and then turning into the primary pathway of producing biogas, methanol.**

**5.2.2 Fuel cell systems and the potential reduction possibilities in their design, production and operation.**
**5.3 Smarter use of materials and other technology growth areas**
**5.4 The cost of inverter electronics**
**5.5. A comment on alkaline and direct methanol fuel cells**
**5.6 The effect of mass production**
**5.7 Fuel cell systems**
**5.8 The lessons learned from the Danish wind generator industry.**
**5.9 What can be learned for RES-FCSH systems technology and market development from the technology and market development of wind energy?**
**5.10 The cost reduction of pathways of methanol**
**5.11 Concluding remarks by Work Package leader,**

## 5.1.0 The Objectives of this work

- Objectives:
- To obtain technical and thereby economic improvements of RES-FCHS through utilization of experiences with similar technologies where good results have been obtained.
- Improvements defined as of:
    - Specific RES-FCHS solutions of biogas, methanol and wind/$H_2$
    - Fuel Cell technologies, including systems of converters etc. and electrolysers

In our studies so far we have gradually become capable of narrowing down the areas within which it is interesting and relevant to look closer in the search for cost reductions and improved performance of the FCHS systems.

Due to the decision in WP2 to focus on LT PEM, a systems design with central hydrogen production has so far been the primary area of investigation. This was chosen, so that the same LT PEM CHP system could be used across the three renewable energy routes, and we thereby could achieve significant economics of scale via establishment of joint purchasing. That massive cost reduction can be achieved via joint purchasing of the micro CHP was one of the important conclusions of WP4.

In the wind/$H_2$ scenario the optimum solution for a FCHS system is:

1. To purchase electricity, run the electrolyser and store electricity in the form of Hydrogen when the electricity is cheap. This will primarily occur at night and when it is very windy.

2. When the price of electricity is high, we use the stored Hydrogen in the fuel cells, and produce heat and electricity for the household.

Re 1:
As the individual household is also connected to the electricity grid they off course draw power directly from the grid in these periods.

Re 2:
It is very important to note that, when we are talking about the fuel cell part of the system, the point of reference, when deciding whether or not to use Hydrogen and run the fuel cell, is the heating requirement/possibility of heat storage. This is the case because the overall energy efficiency of the system becomes to low and thus uneconomically, if we don't use the heat generated from the fuel cells.

The energy efficiency of the system (with LT PEM) is 67% if we utilize the excess heat from the electrolyser. If the heat can not be utilized the overall energy efficiency drops to 51%.

With regards to the other hydrogen carriers, several factors speak in favour of choosing an overall system design with a decentralised reforming unit. When working with decentralised reforming as opposed to central reforming we:

- Can much more easily utilize the “waste heat” from the reformer
- Do not need to establish a local hydrogen grid
- Can in the biogas/natural gas case connect directly to the existing natural gas network

Regarding the biogas scenario the renewable energy route involves biogas upgrading, distribution through the natural gas grid, reforming and use of the hydrogen gas in LT PEM fuel cells. Due to the above reasons and our preliminary conclusion that natural gas reformers cannot be purchased in a size that is suitable for the identified clusters in our project, decentralized reforming is the systems design we continue to work with.

The renewable energy route has an overall energy efficiency of 0.77 (loss in upgrading) * 0.85 (LT PEM with decentralized reforming and heat recovery) which give a total efficiency of 65% (30 % electricity and 35% heat).

The traditional use of biogas has an efficiency of approximately 40% electricity and roughly 20-25% non process heat which can be utilized externally through a district heating network. Since the latter route at the moment is significantly cheaper than upgrading and installation of fuel cell systems this route will be the obvious choice in locations with district heating networks.

However, taking regional perspectives into account, there are several areas in Europe with rising biogas production and no district heating - but with natural gas grids where it is an obvious and energy efficient choice to experiment with biogas upgrading and use of the upgraded gas in FCHS with decentralized reforming.

Regarding methanol, then methanol is one of the most traded and easily accessible chemicals worldwide. The pathway from biomass to bio methanol is still in a development phase, but the cost projections are encouraging and both Germany and Denmark has pilot plants in operation. There is not yet a market for bio methanol - but it is coming, and since methanol is an easily distributed fuel, and cracking of methanol into hydrogen is a relatively easy process the FCHS producers find it to be a very promising fuel for FCHS in areas with no district heating or natural gas network. Due to the obvious advantages of methanol we therefore suggest to use fossil produced methanol in FCHS in a transitional period in order to kick start the market for this most promising technology – and then shift the methanol supply to renewable methanol when it becomes available.

In a central methanol reforming unit we loose roughly 18.5% of the energy content in the methanol (based on LHV). Combined with the energy loss in the fuel cells a total systems efficiency of 0.815*0.85= 69.2% can be obtained (39% electricity + 30% heat)

Choosing the decentralized reforming unit will according to the latest figures from Dantherm Power yield a total energy efficiency of 85% (40% electricity and 45% heat).

Choosing decentralized reforming will not necessarily affect the possibility of using the same core system across the 3 different hydrogen carriers. The reforming unit can be made as a plug on unit and the core of the system therefore remains the same – and the sought-after cost reductions due to economics of scale can still be obtained. Furthermore the FCHS with decentralized reforming has the advantage that it can be implemented directly in existing individual households, and no cluster of houses has to agree upon investments in centralized and shared reforming facilities.

In WP5 we look only at improvements of the system from the point where we have the fuel available (except with regards to electrolysis where the input is electricity) – meaning that we no longer discuss the renewable path of the hydrogen or hydrogen carrier.

In WP5 we continue to work with an electricity grid connected system, where the operation strategy of the FCHS is to run the fuel cells according to heat demand/possibility of heat storage. This strategy is chosen to maximize energy efficiency and the marginal costs of operating the system. Furthermore the size of the fuel cells in the individual houses is dimensioned to come close to an annual electricity import/export balance of zero. Regarding the sizing of the fuel cell systems across regions and hydrogen carriers the results received from the partners so far indicates that a 100 $m^2$ passive house (4 persons) can have their heat and electricity needs covered by a 0.75 $kW_e$ FCHS (LT PEM) system in the wind (pure $H_2$ case) and by a 0.5 $kW_e$ FCHS when using methanol or bio/natural gas as hydrogen carriers.

It might, however, be possible to use the same size of fuel cell in all applications. This is the case because a 0.5 kWel cell can function as a 0.75 $kW_e$ cell if we choose to operate it harder. This will however make the system a bit less efficient but most importantly it will effect the lifetime of the fuel cell system negatively.

Another opportunity which has been discussed with the FCHS suppliers within the project, is to design and build a modular system etc. a 0.5 kWe base module and 0.25 or 0.5 $kW_e$ add on modules. Which option is the most viable will be looked further into in WP5.2.

The decision to focus upon decentralized reforming combined with a much faster development of the HT PEM and DMFC technology than anticipated earlier in this study it suddenly becomes relevant to look into these technologies in the search for overall systems efficiency improvements and cost reductions.

By shifting from LT PEM to HT PEM it is possible to build a modular system capable of using both pure $H_2$ and reformats without extensive cleaning – due to the higher operating temperature and tolerance towards impurities in a HT PEM system. Furthermore, the balance of plant is much simpler and easier in a HT PEM system because the higher temperature makes it possible to work with an air cooled system instead of the complicated water cooled system that is necessary in a LT PEM system.

The (re) introduction of DMFC in the study would imply (if we conclude to use DMFC in our pooled order) that the total number of identical units in the joint order decreases which will have a negative effect on the FCHS prices that can be obtained. However, if the longer term possibilities embedded within the technology for FCHS use seem very good – the negative short term cost effect can be justified in order to pull yet another new technology promising to the market.

The introduction of these two new technologies in the study means that we from now focus upon the following scenarios:

1. Wind -> $H_2$->LT PEM
2. Wind -> $H_2$->HT PEM
3. Methanol->decentralized reforming->cleaning ->LT PEM
4. Methanol->decentralized reforming->HT PEM
5. Methanol->DMFC
6. Upgraded biogas/NG->decentralized reforming->$H_2$->HT PEM
7. Upgraded biogas/NG->decentralized reforming->$H_2$->LT PEM

Before embarking on the general improvements found by this study, the report will address the important area of electrolysis of water and the technological improvements on electrolysers that could, for example, make the pathway of utilising wind energy more feasible.

### 5.1.1

# Technological improvements on electrolysers

## The hydrogen system setup and the control strategy

**Electrolysers**
**Decentralised electrolysers – perspectives and possibilities**

In the earlier WPs centralised electrolysers were chosen for hydrogen supply of the CHPs. The choice was made due to the fact that electrolyser plants in the kW size cost about ten times as much pr. kW as plants in the 100 kW size. See figure below.

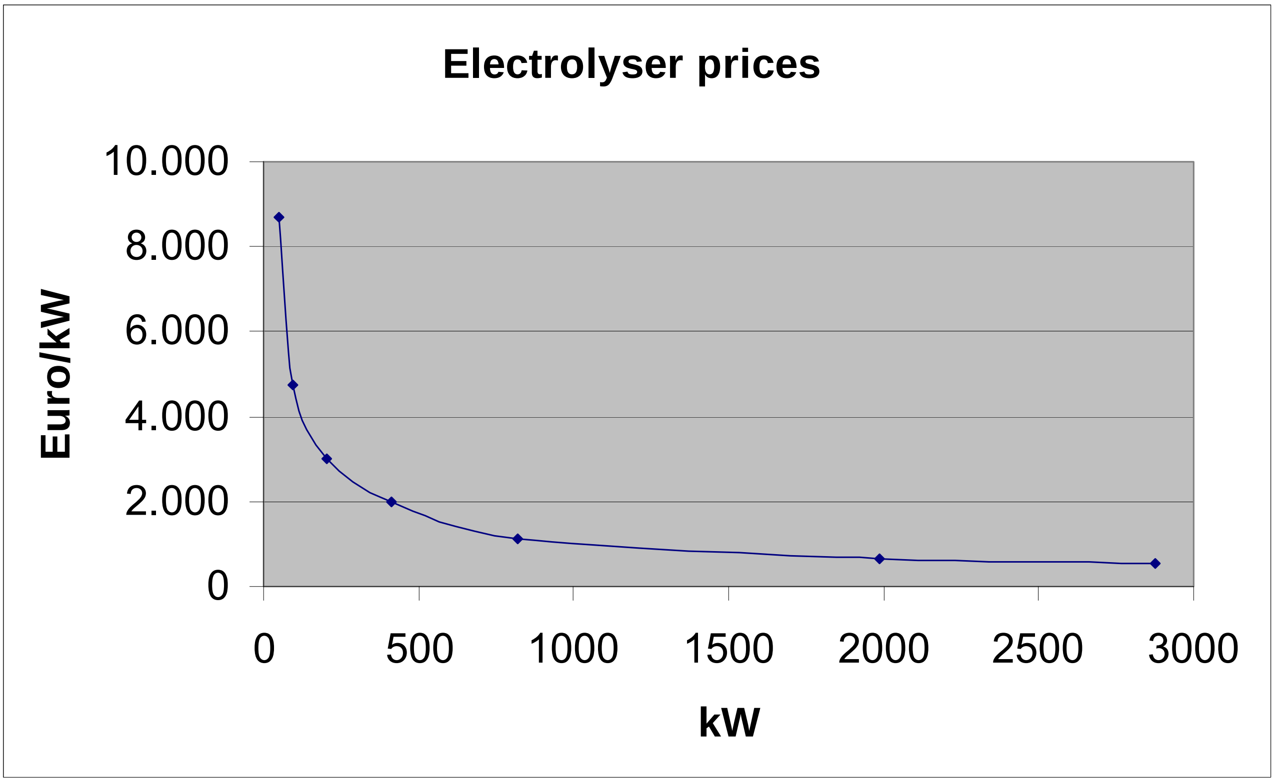
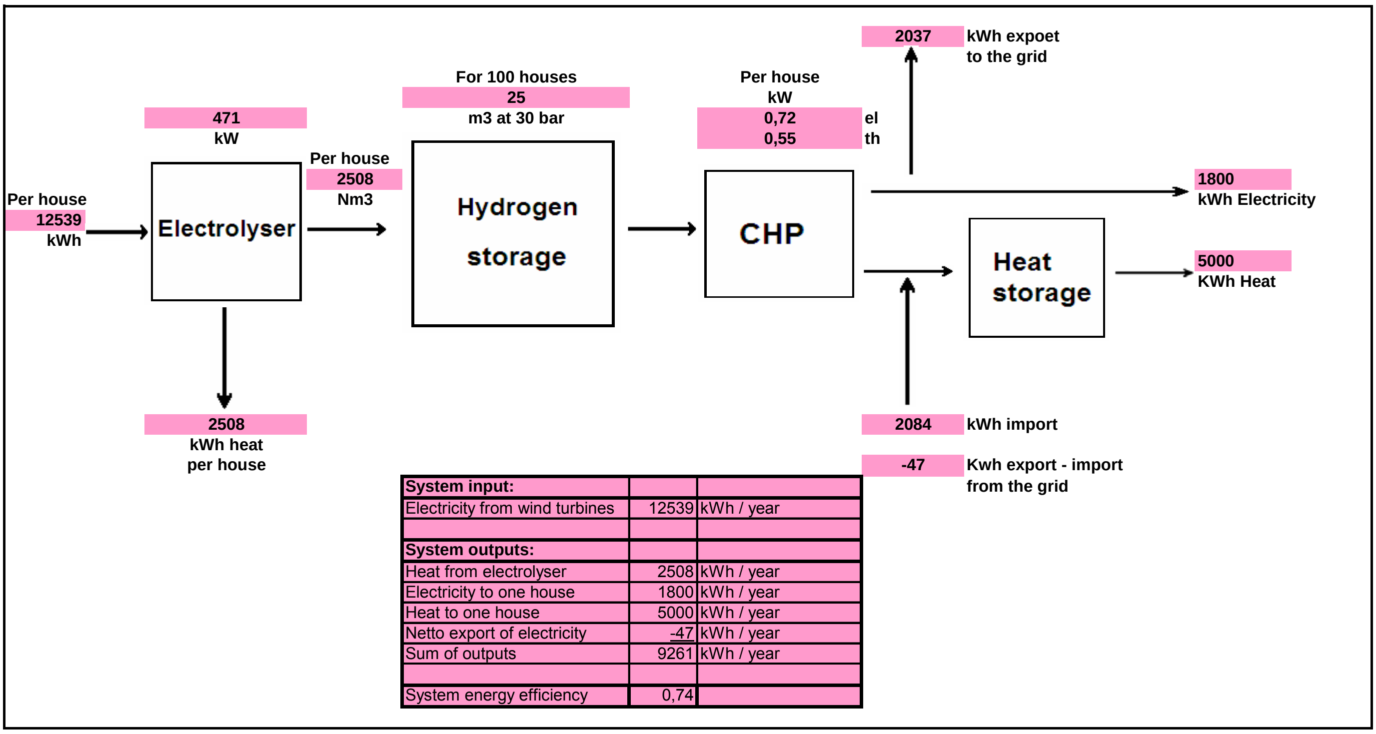


Fig. 5.1.1: Pieces of electrolysers per kW.

The market for small electrolyser plants is very limited because hydrogen delivered in bottles is much cheaper. Plants in the size of around 1 kW are used for production of hydrogen for labs, and plants in the size of a few kW are used for production of hydrogen for weather balloons.

The relatively steep decrease in prices is therefore not only due to a scale factor of size but also due to a factor of market size.

The disadvantage of a centralised electrolyser is that a consumer for the excess heat must be found. About 20% of the electrolyser electricity consumption ends up as heat that has to be used in a sensible way. From a system point of view the heat production from the electrolyser makes up about one third of the total heat production from the electrolyser and the fuel cell together in the system case where the heat production from the electrolyser is not utilised and the CHP is operated according to the need for heat for room and hot water heating. See figure below.



| System input: | | |
|---|---|---|
| Electricity from wind turbines | 12539 | kWh / year |
| | | |
| System outputs: | | |
| Heat from electrolyser | 2508 | kWh / year |
| Electricity to one house | 1800 | kWh / year |
| Heat to one house | 5000 | kWh / year |
| Netto export of electricity | -47 | kWh / year |
| Sum of outputs | 9261 | kWh / year |
| | | |
| System energy efficiency | 0,74 | |

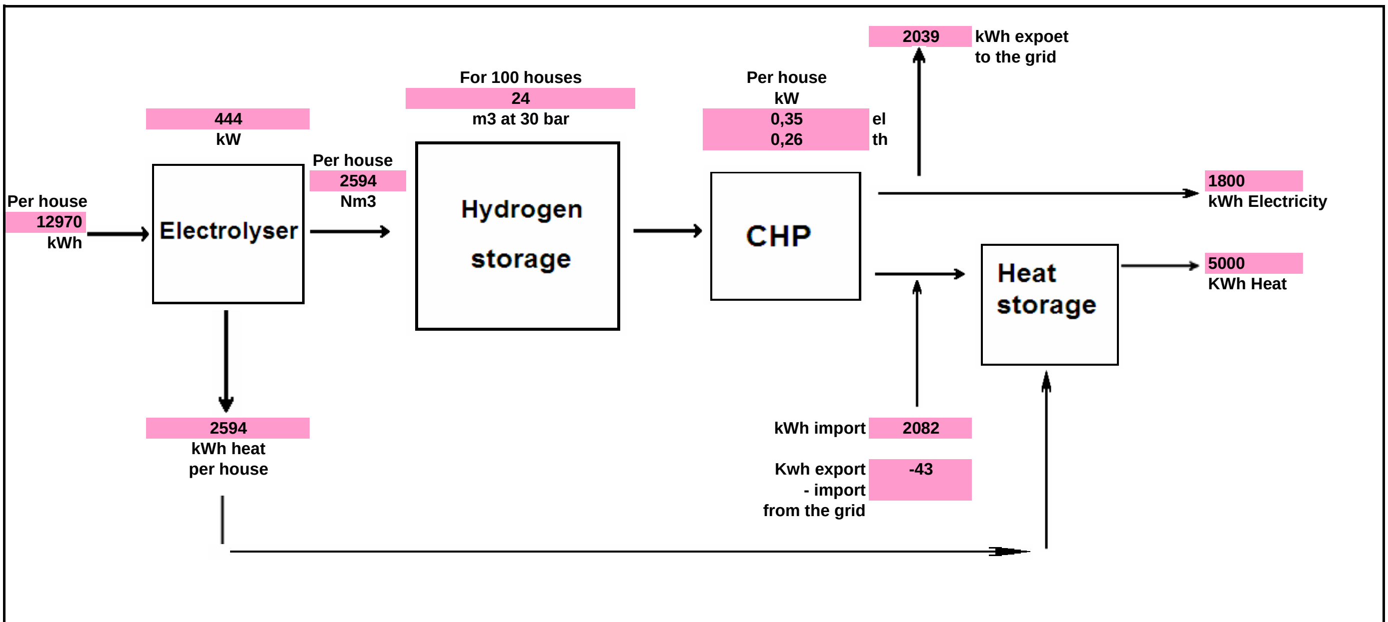
Fig.5.1.2: Energy balance for a hydrogen system with a central electrolyser.

If the heat production from the electrolyser can be used in the same system as the CHP, then the CHP can be downscaled to around half the size because the electrolyser takes over some of the heat supply from the CHP.

When the power of the CHP becomes smaller the number of operation hours increases in order to be able to deliver the same amount of electricity.

In both cases the CHP is controlled by the total heat demand and the size of the CHP is chosen so that the export and import of electricity to and from the grid, as far as possible, balance each other on a yearly basis. See figure below.

The size of the electrolyser is calculated to 471 kW for 100 houses. Therefore, if a decentralised electrolyser is to be used in each house, each decentralised electrolyser should have a size of 471/ 100 = 4.71 kW if operated for 8 hours each night.



| System input: | | |
|---|---|---|
| Electricity from wind turbines | 12970 | kWh / year |
| | | |
| **System outputs:** | | |
| Heat from electrolyser | 2594 | kWh / year |
| Electricity to one house | 1800 | kWh / year |
| Electricity for room heating | 0 | kWh / year |
| Heat to one house | 5000 | kWh / year |
| Netto export of electricity | -43 | kWh / year |
| Sum of outputs | 9351 | kWh / year |
| | | |
| System energy efficiency | 0,72 | |

Fig.
5.1.3: Energy balance for a hydrogen system with decentralised electrolyser.

There is a trade off between the size of the electrolyser and the CHP determined by the number of operation hours of the electrolyser. Few operation hours for the electrolyser require a larger plant, since the same amount of hydrogen has to be produced. At the same tine fewer operation hours for the electrolyser per night leaves more hours for the CHP to operate, since the CHP and the electrolyser are not allowed to operate at the same time. More operation hours for the CHP mean that a plant of less power can be used because it has more hours to produce the needed energy.

From the calculations showed in fig.1 and 2 it can be seen that the size of the CHP is reduced from 0.72 kW to 0.35 kW if a decentralised electrolyser is used and its heat production is utilised to cover a part of the heat demand of the house.

### Development potential of traditional alkaline electrolysers

All traditional alkaline electrolysers use the so called zero gap design. In this design the anode and the cathode are placed at zero gap on each site of a diaphragm, which acts as a filter that prevents mixing of the oxygen and the hydrogen.

There are two arguments for this construction. First, by placing the two electrodes as close as possible to each other, the ohm loss in the electrolyte is reduced. Second, when the gas bobbles are produced, they will be transported to the rear site of the electrodes through holes in the perforated electrodes and thus not block the current of ions between the two electrodes.

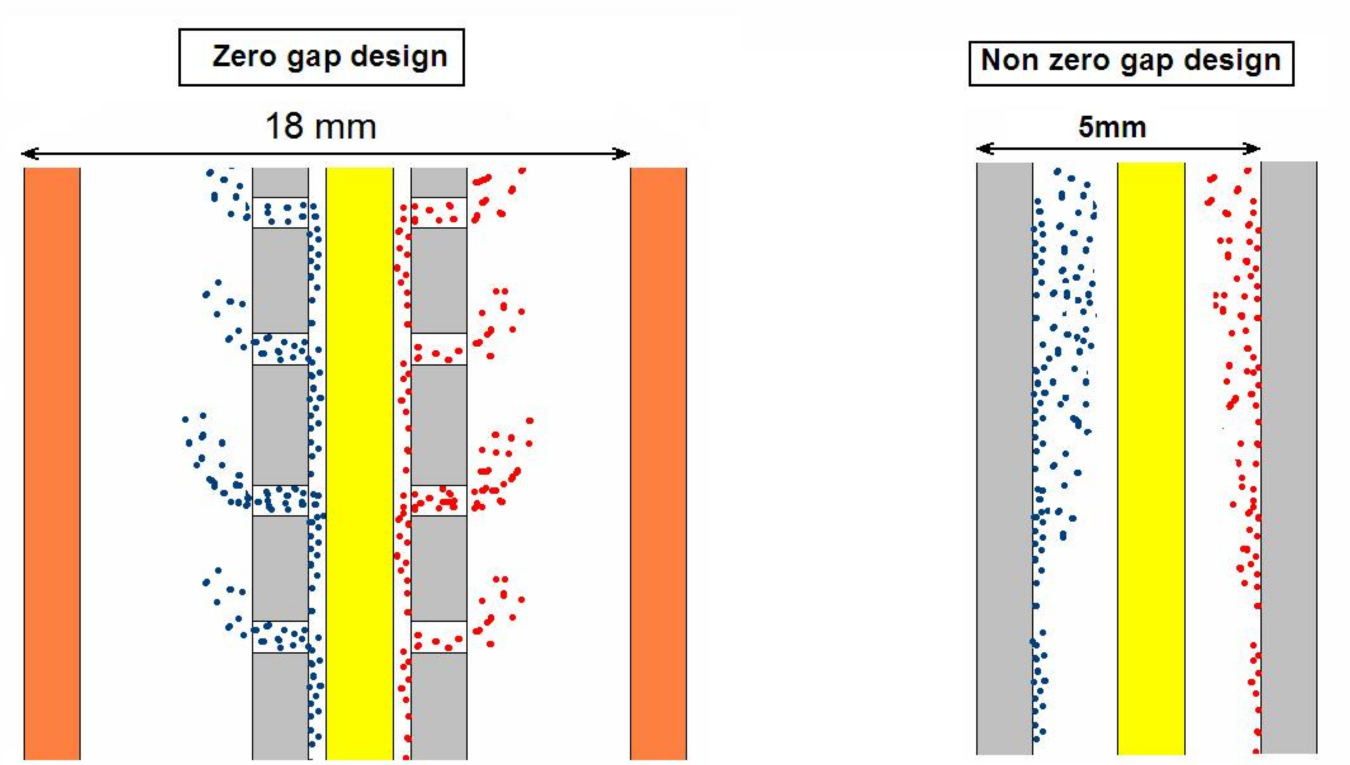


Fig.5.1.4: Zero and non zero gap electrolyser cells

The zero gap-concept is so obvious that no one seems to have questioned it. New research on gas bubbles made by N. Nagai and M. Takeuchi from Department of Mechanical Engineering, Fukui University, Japan and M. Nakao from Graduate School of Engineering, Fukui University, Japan, indicates that the influence of gas bubbles on the ion current is overestimated, which opens up for new materials and time saving designs.

By the use of photographs the research team investigated the hydrogen and oxygen evolution on two non zero gap electrodes as showed below.

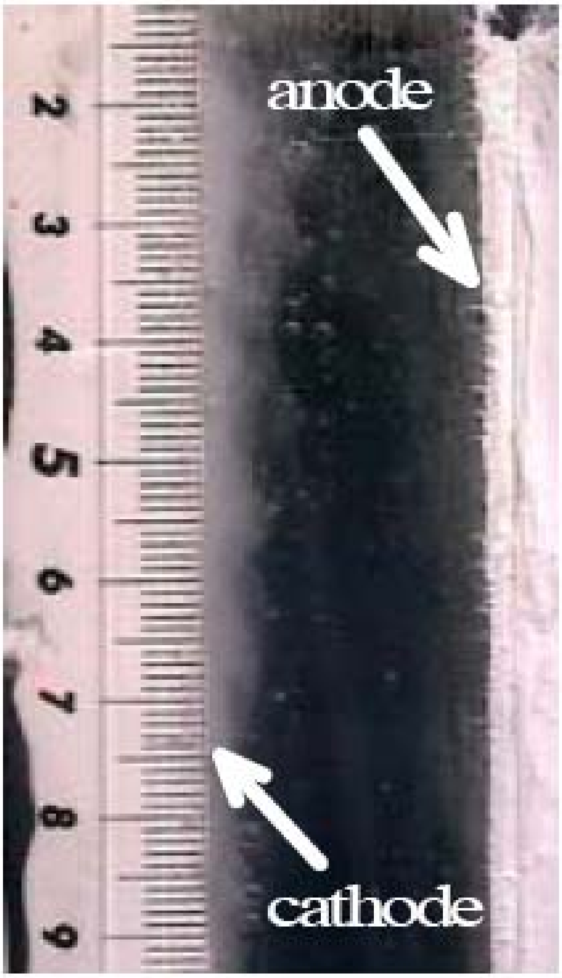


Fig.3 Two phase flow pattern between electrodes
($\Phi$=1.0A/cm$^2$, T=40°C, C=40%)

Fig.5.1.5: Hydrogen and oxygen gas evolution in a non zero gap cell.

Experiments in the lab revealed that there is an optimum electrode distance where the cell voltage is minimal for a given current density. This optimum distance is most pronounced at high current densities. For a current density of 0.1 A/cm$^2$ the curve was linear without a pronounced minimum.

The experiments also revealed an electrode distance, where the gas evolution stopped, and this distance was not very far from the optimum distance. See the graph below.

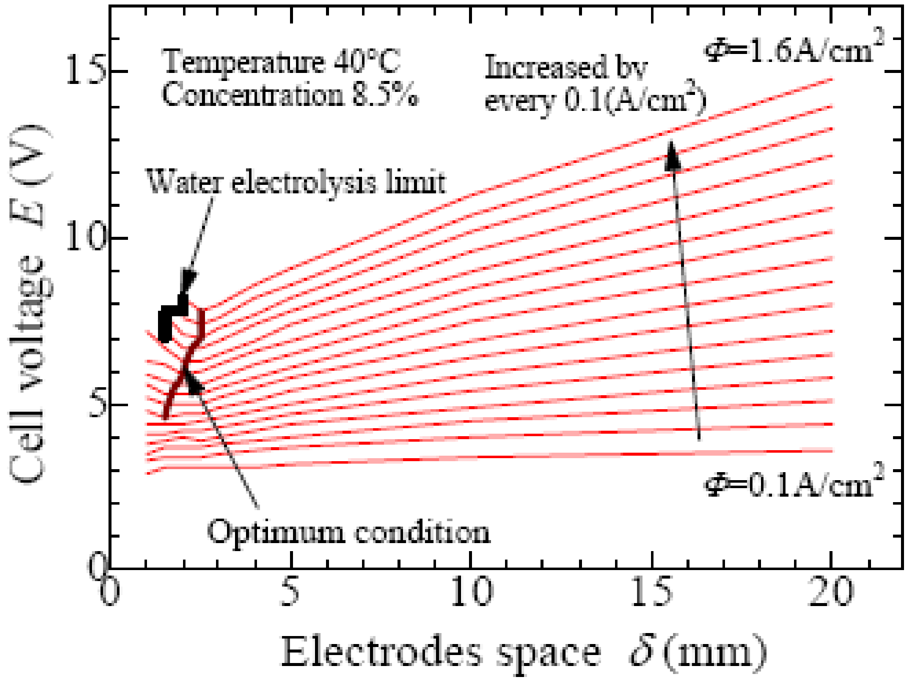


Fig.5 Relation between cell voltage and electrodes space (optimum condition and water electrolysis limit)

Fig.5.1.6: Optimum electrode distance.

The team also elaborated a mathematical model for calculation of the optimal electrode distance. In the spread sheet below a calculation for a 10 cm high cell with a current density of 0.1 A/cm$^2$ is shown.

| **Electrode space at optimum condition** | | | | **d= 1,271*RTH?  / FPu =** | | **0,0007** | **m** |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| R | Gas constant | | 8,3143 | J/mol K | | | |
| T | System temperature | | 40 | Celcius | | | |
| H | Electrode hight | | 0,1 | m | | | |
| ? | Mean current density | | 1000 | A/m2 | | | |
| F | Faraday constant | | 96500 | C/mol | | | |
| P | Systempressure | | 100000 | Pa | | | |
| u | Bubble rising velocity | | 0,05 | m/s | | | |

Surprisingly the optimal distance is only 0.7 mm. This distance has to be divided into two. One distance is from the cathode to the diaphragm and another distance is between the anode and the other side of the diaphragm. Since the volume of the hydrogen evolution is the double of that of the oxygen, the distance from the cathode to the diaphragm must be the double of the distance from the anode to the diaphragm.

### Cell design

The non zero gap cell consists of one sheet of metal, where one side acts as cathode and the other as anode, plus the diaphragm.

The zero gap cell is made of three sheets of metal - one bipolar plate and two perforated electrodes mounted on the bipolar plate by spacers.

Since the zero gap cell has a bipolar and a electrode plate extra compared to the non zero gap cell, it will be two dimensions thicker.

The cell space for the gas bubbles is determined by the height of the cell, because a higher electrode produces more gas bubbles, which needs more space in order not to block the ion current. So high cells are thicker than low cells.

If the thickness of the bipolar and the electrode plates are constant, the difference in the thickness of the zero gap and the non zero gap cells will be more pronounced for the smaller cells.

In order to investigate the price ratio between the zero and non zero gap electrolyser a spread sheet has been elaborated, where prices for material and labour for assembling for electrolysers of 2, 20 and 200 kW were used. See below.

It is important to mention that the calculations do not provide an exact price for the different stacks, but just a rough estimate. But since the same conditions (design criteria, material and labour prices) are used, it is reasonable to use the calculated prices to find the price ratio between the two designs.

From the second last line in the spreadsheet it can be seen that the relative savings are independent of the size of the stack and amount to about 2/3, ore in other words, the zero gap stack costs three time as much as the non zero gap stack.

| **Electrolyser** | kW | **2** | **2** | **20** | **20** | **200** | **200** |
|---|---|---|---|---|---|---|---|
| | | Zero gap | Non zero gap | Zero gap | Non zero gap | Zero gap | Non zero gap |
| Current density | mA/cm2 | 200 | 200 | 200 | 200 | 200 | 200 |
| Cell voltage | Volt | 2 | 2 | 2 | 2 | 2 | 2 |
| **Cell thickness** | **mm** | **4,0** | **3,0** | **6,2** | **5,2** | **13,0** | **12,0** |
| Power density | kW/m2 | 4 | 4 | 4 | 4 | 4 | 4 |
| **Power density** | **kW/m3** | **1000** | **1333** | **649** | **775** | **308** | **333** |
| Electrode area | cm2 | 100 | 100 | 1000 | 1000 | 10000 | 10000 |
| Electrode height | cm2 | 10 | 10 | 32 | 32 | 100 | 100 |
| **Plus electrode thickness** | **mm** | **0,5** | **0,25** | **0,5** | **0,25** | **0,5** | **0,25** |
| **Minus electrode thickness** | **mm** | **0,5** | **0,25** | **0,5** | **0,25** | **0,5** | **0,25** |
| **Bipolar plate thickness** | **mm** | **0,5** | **0** | **0,5** | **0** | **0,5** | **0** |
| Diaphragm thickness | mm | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 |
| Gaskets thickness per cell | mm | 4,0 | 3,0 | 6,2 | 5,2 | 13,0 | 12,0 |
| Gasket width | mm | 10 | 10 | 10 | 10 | 10 | 10 |
| Gasket circumference per cell | mm | 40 | 40 | 126 | 126 | 400 | 400 |
| Gaskets volume per cell | mm3 | 1600 | 1200 | 7795 | 6530 | 52000 | 48000 |
| Number of cells | | 50 | 50 | 50 | 50 | 50 | 50 |
| Nickel volume | cm3 | 750 | 250 | 7500 | 2500 | 75000 | 25000 |
| **Nickel weight** | **kg** | **6,8** | **2,25** | **68** | **22,5** | **675** | **225** |
| Gaskets volume | cm3 | 80 | 60 | 390 | 326 | 2600 | 2400 |
| Gaskets weight | kg | 0,16 | 0,12 | 0,78 | 0,65 | 5,20 | 4,80 |
| Length of stack | mm | 200 | 150 | 308 | 258 | 650 | 600 |
| **Machining and assembling per cell** | **hours** | **0,09** | **0,03** | **0,09** | **0,03** | **0,09** | **0,03** |
| Machining and assembling per stack | hours | 4,5 | 1,5 | 4,5 | 1,5 | 4,5 | 1,5 |
| Price of nickel per kg | kr. | 800 | 800 | 700 | 700 | 500 | 500 |
| Price of gaskets per kg | kr. | 300 | 300 | 300 | 300 | 300 | 300 |
| Price of assembling per hour | kr. | 300 | 300 | 300 | 300 | 300 | 300 |
| **Price of nickel per stack** | **kr.** | **5400** | **1800** | **47250** | **15750** | **337500** | **112500** |
| Price of gaskets per stack | kr. | 48 | 36 | 234 | 196 | 1560 | 1440 |
| Price of assembling per stack | kr. | 1350 | 450 | 1350 | 450 | 1350 | 450 |
| Price of stack | kr. | 6798 | 2286 | 48834 | 16396 | 340410 | 114390 |
| **Price of non zero gab/price of zero gap** | | **0,34** | | **0,34** | | **0,34** | |
| Price per kW | kr. | 3399 | 1143 | 2442 | 820 | 1702 | 572 |

## Power supply

Regarding the power supply, savings and price reductions may also be possible. Most often a transformer is used to match the voltage of the electrolyser to the voltage of the grid. This transformer is costly and gives loss during operation.

Therefore, if the electrolyser is designed to match the voltage of the grid, the transformer can be saved, and so the investment and the power loss in the transformer lead to a cheaper and more efficient system.

Matching the grid voltage means operating the stack at, at least 200 $V_{DC}$. When the stack voltage increases, the so called stray or shunt current also increases. Shunt current is an unwanted current that flows in the electrolyte manifold in the bottom of the stack and in the oxygen and the hydrogen gas manifolds at the top of the stack.

A fraction of the current that flows through the stack will not flow through the cells, but from the electrodes through the ports that connects the cells and the manifolds, into the

manifolds through the manifolds and down through a port in the other end of the stack to an electrode.
The shunt current will produce hydrogen and oxygen, but a part of the oxygen production will take place at the hydrogen side, and part of the hydrogen production caused by the shunt current will take place on the oxygen side in the stack.

Shunt current will flow from the first hydrogen electrode in the stack through the gas manifold and to the last hydrogen electrode in the stack. The shunt current will thus produce hydrogen on one of the hydrogen electrodes and oxygen on the other hydrogen electrode. Therefore at a certain spot of the hydrogen electrode oxygen will evolve.

The opposite will take place on the oxygen side in the stack leading to hydrogen evolution on some spots of the oxygen electrodes.

Under unfortunate circumstances this gas evolution at the wrong electrodes might cause corrosion.

Besides the risk of corrosion and reduction of the gas purity the gas production caused by the shunt currents takes place at an elevated voltage. If the stack is operated at 200 V, the voltage between the first and the last hydrogen electrode is around 198 V. The efficiency of the electrolysis process can be calculated from this formula:

$$\eta = 1.48/V_C$$

$V_C$ stands for the cell voltage. So it is obvious that the shunt current produces gas at a very low efficiency, and thus decreases the overall efficiency of the stack.

When the stack voltage is increased the shunt current increases, not only because the voltage increases, but also because the number of cells that deliver shunt currents increase.

**Tests**

A non zero gap stack with electrodes of 10 cm x 10 cm and 13 cells have been designed and fabricated by Technical Manager Lars Yde at HIRC, Denmark, in order to study stack design for easy and cheap manufacturing concepts and to investigate how to minimize shunt currents.

Fig.5.1.7: Test stack with 13 cells

Fig.5.1.8: Hydrogen and oxygen manifold at the top of the stack.

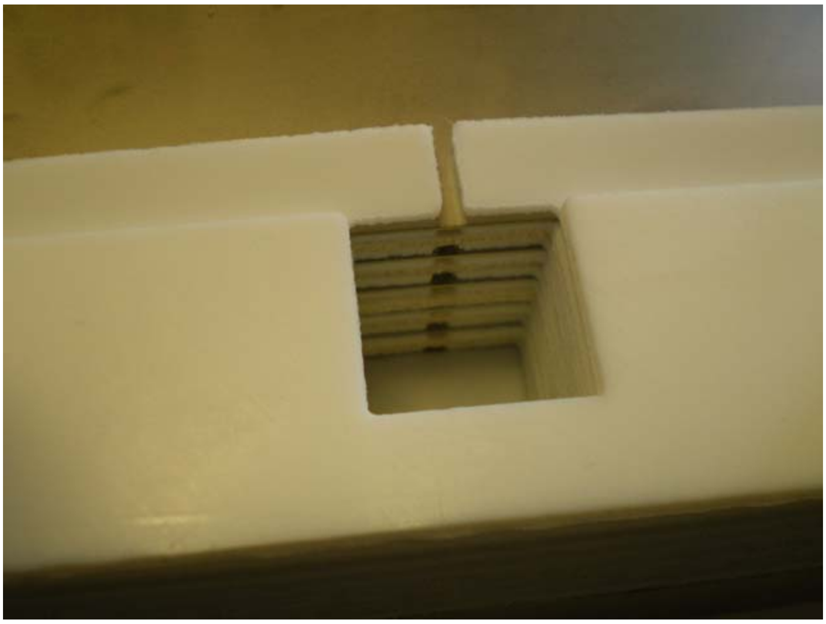


Fig.5.1.9: Electrolyte manifold at the bottom of the stack.

During the testing of the stack it very soon became clear that modifying the stack, testing it and modifying it again and again was too time consuming. Therefore, a model in the form of an electrical equivalent diagram was developed.

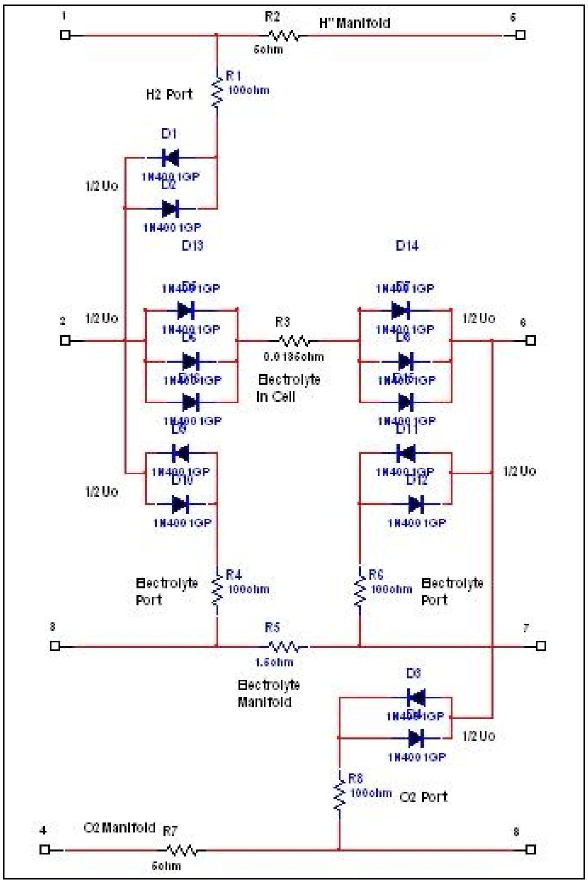


Fig.5.1.10: Equivalent diagram for one cell.

The diodes represent the voltage that has to be overcome, before the electrochemical process can take place and the ion current can start to flow. The resistors represent the ohmic resistance in the electrolyte in the ports; the manifolds and the cell between the electrodes. When the cells are stacked, terminal 2 is connected to plus. Terminal 5,6,7,8 are connected to terminal 1,2,3,4 on the next cell. In all the following cells terminal 5,6,7,8 are connected to terminal 1,2,3,4 on the next cell. At the last cell in the stack terminal 6 is connected to minus at the power supply.

A simulation of a stack with 13 cells was carried out and compared with measurements on the real stack. As it can be seen from the figure below, a reasonable agreement between simulated and measured values was obtained - at least reasonable for the analysis on how to handle shunt currents in the stack design.

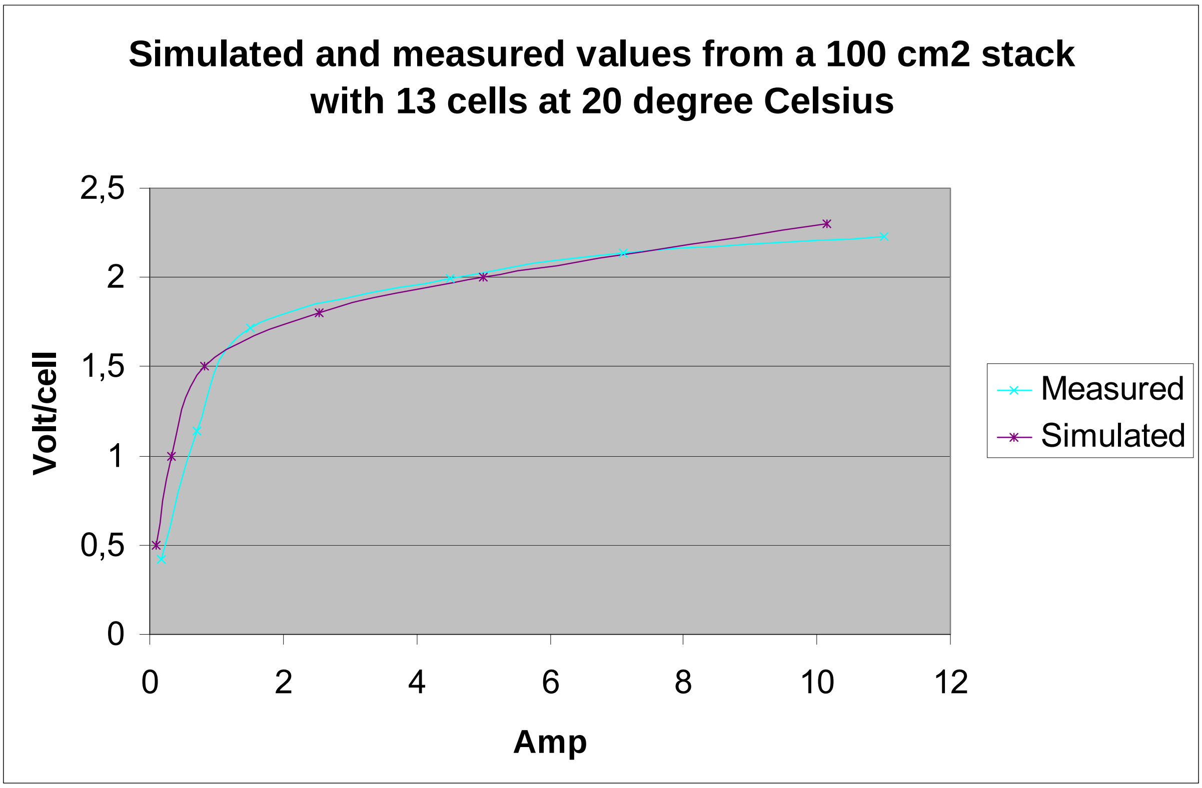


Fig.5.1.11: Simulated and measured values from a 100 cm$^2$ stack with 13 electrodes.

The first steep part of the curve shows the shunt current that runs from the first electrode in the stack, through the port to the electrolyte manifold in the bottom of the stack, as well as the shunt current through the first gas port at the top of the stack to one of the gas manifolds.

Since shunt current is caused by the stacking of cells, the voltage current characteristic for one cell can be used as a target to work for in order to eliminate shunt currents. The photograph and the figure below show such a one cell and its voltage current characteristics.

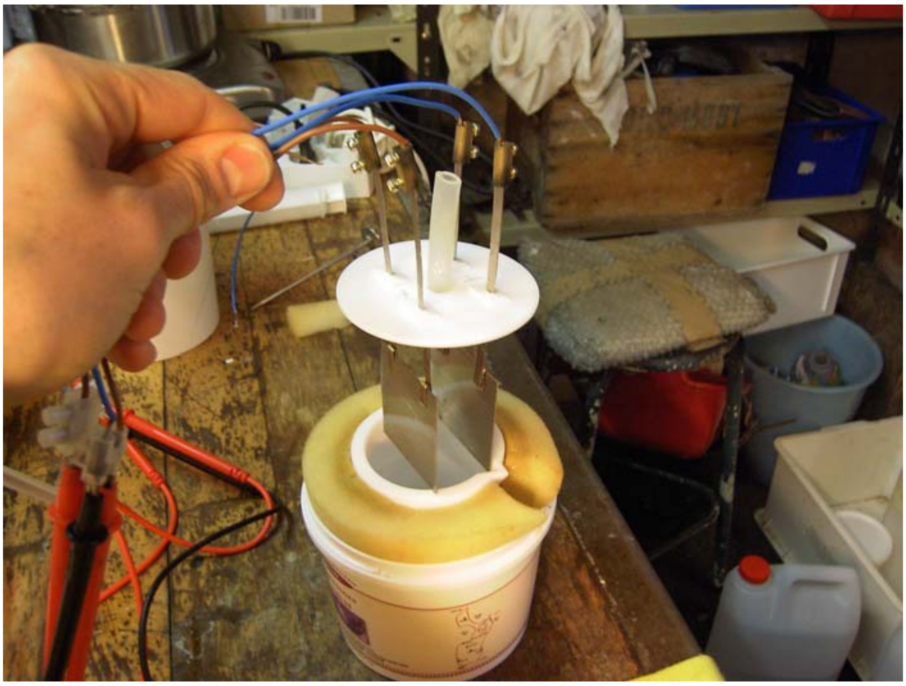


Fig.5.1.12: Single test cell

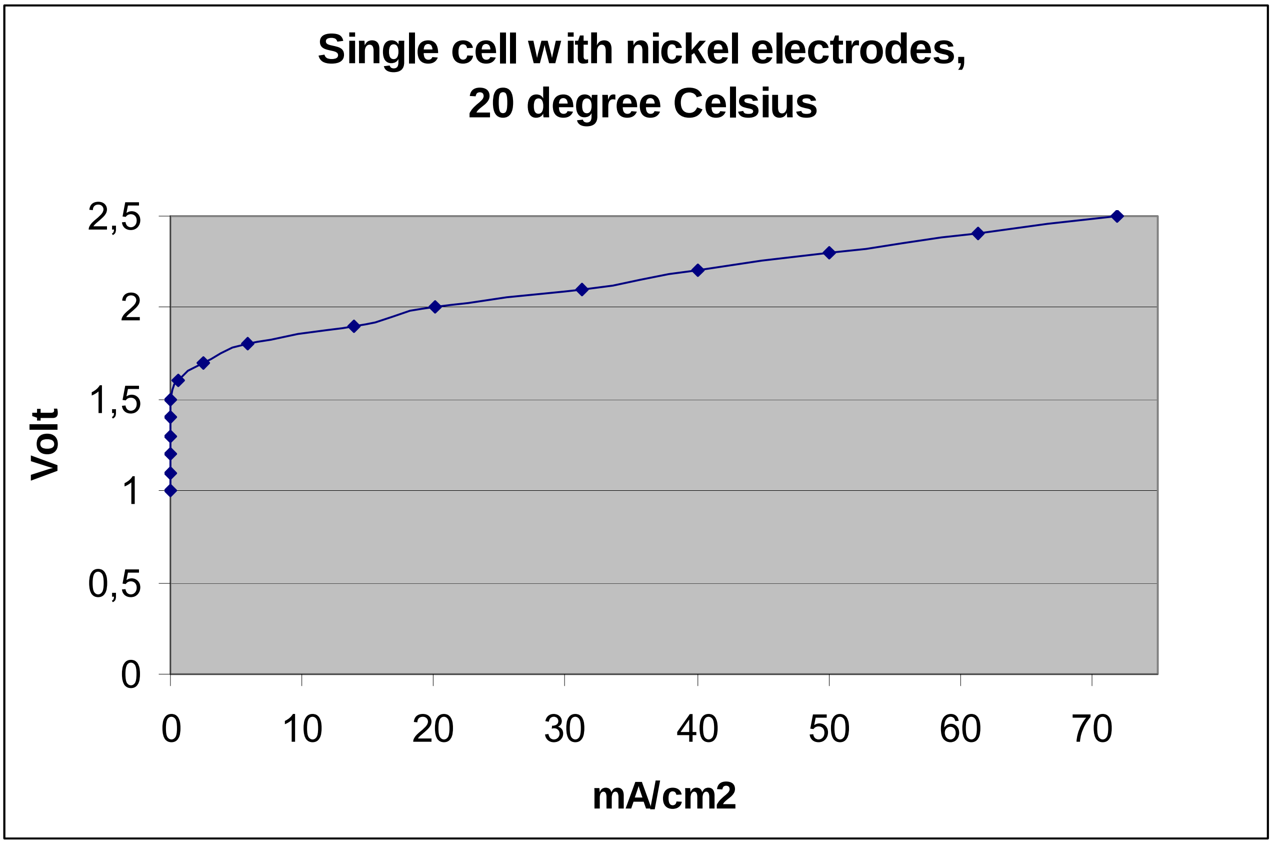


Fig.5.1.13: Singe test cell characteristics

Working with the simulating model the criteria for an improved design with reduced shunt currents was found, which indicated that it is possible to design a stack that can operate without transformer. The figure below shows the simulated characteristics for the improved design compared with the measured characteristics of the original design.

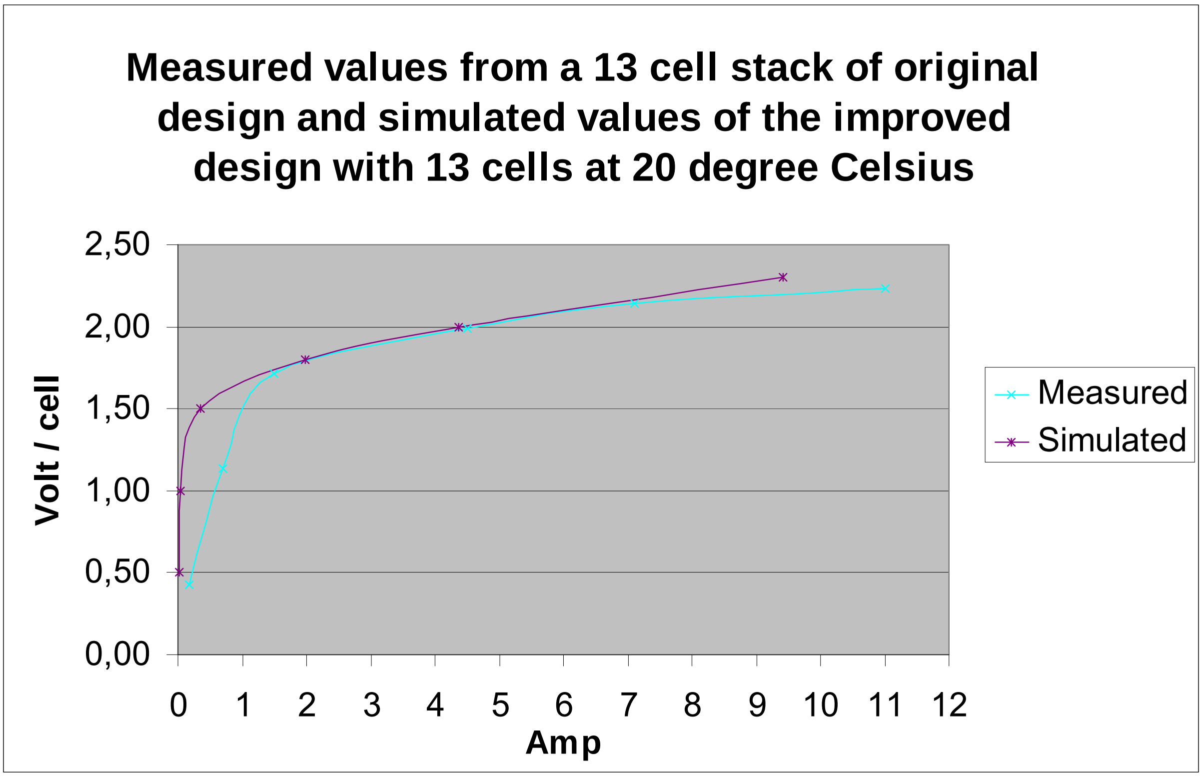


Fig.5.1.14: Simulated characteristics of improved design compared with the measured characteristics of the original design.

**Savings at components and system**

Though savings in the order of 66% is likely if the non zero gap design is applied on small electrolysers the price of the system will not be reduced with the same amount because the stack only makes up 50 % of the total price of the electrolysis system.

The same counts for the power supply, gas handling and compressor. The table and graphic below shows how the savings on the different components influence the total price on the system. Figures obtained from GreenHydrogeen.dk.

| | Price of components % | Possible savings on component % | Price of component after savings % | Possible savings on the plant % |
|---|---|---|---|---|
| Stack | 45 | 66 | 15 | 30 |
| Gas handling | 34 | 0 | 34 | 0 |
| Power Supply | 7 | 50 | 4 | 4 |
| Compressor | 10 | 0 | 10 | 0 |
| Various | 4 | 0 | 4 | 0 |
| Sum | 100 | | 66 | 34 |

Table: Savings at a plant with compressor

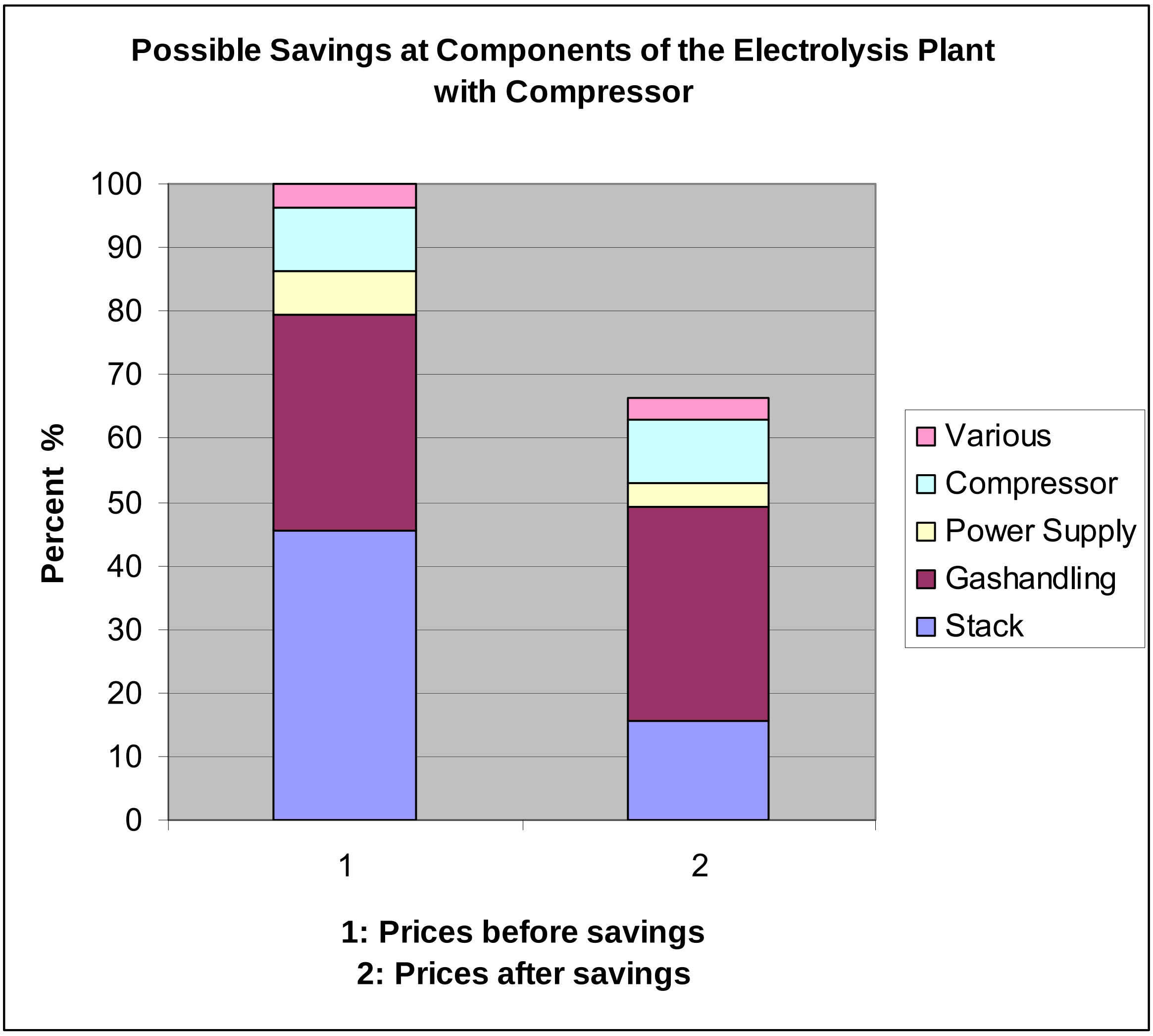


Fig.5.1.15: Savings at a plant with compressor

If the stack can deliver the hydrogen at the pressure necessary for storage the compressor can be avoid. For small systems as we are talking about here there is no doubt a system where the compression takes place in the stack is the cheapest solution. The price of a 10 or 30 bar stack is of cause higher than the atmospheric one but this is the case independent of zero or non zero gap design.

The transformer is the most costly component in the power supply and counts for about 50% of the total price. But since the power supply only makes up 7 % of the system price the savings by using a high voltage stack that does not need a transformer is only 3.5%.

For systems without compressor it becomes even more obvious that the gas handling must be the next target for savings. Se Figs. below.

| | Price of components % | Possible savings on component % | Price of component after savings % | Possible savings on the plant % |
|---|---|---|---|---|
| Stack | 50 | 66 | 17 | 33 |
| Gas handling | 38 | 0 | 38 | 0 |
| Power Supply | 8 | 50 | 4 | 4 |
| Vaious | 4 | 0 | 4 | 0 |
| Sum | 100 | | 63 | 37 |

Fig.5.1.16: Savings assuming a plant without compressor

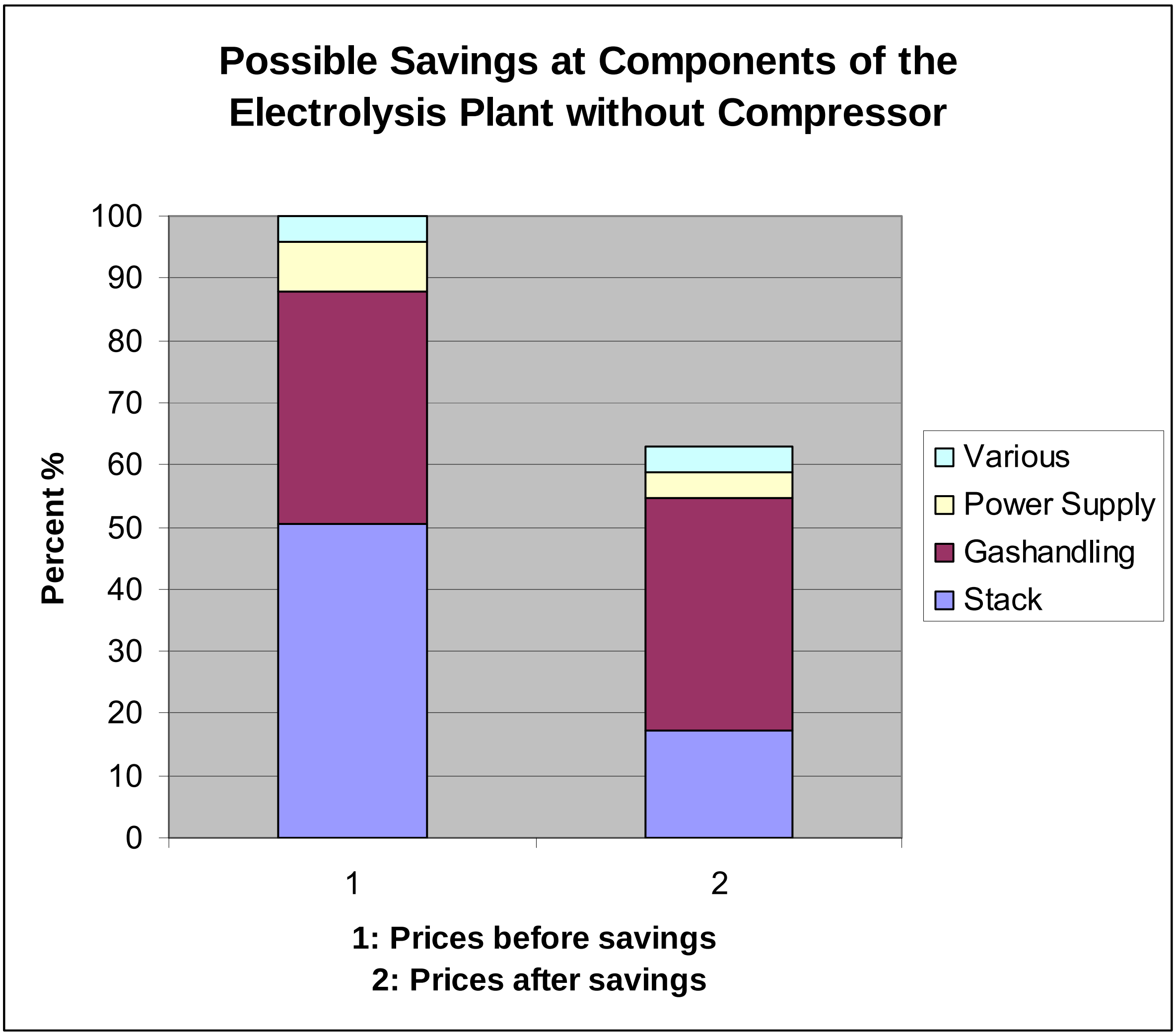
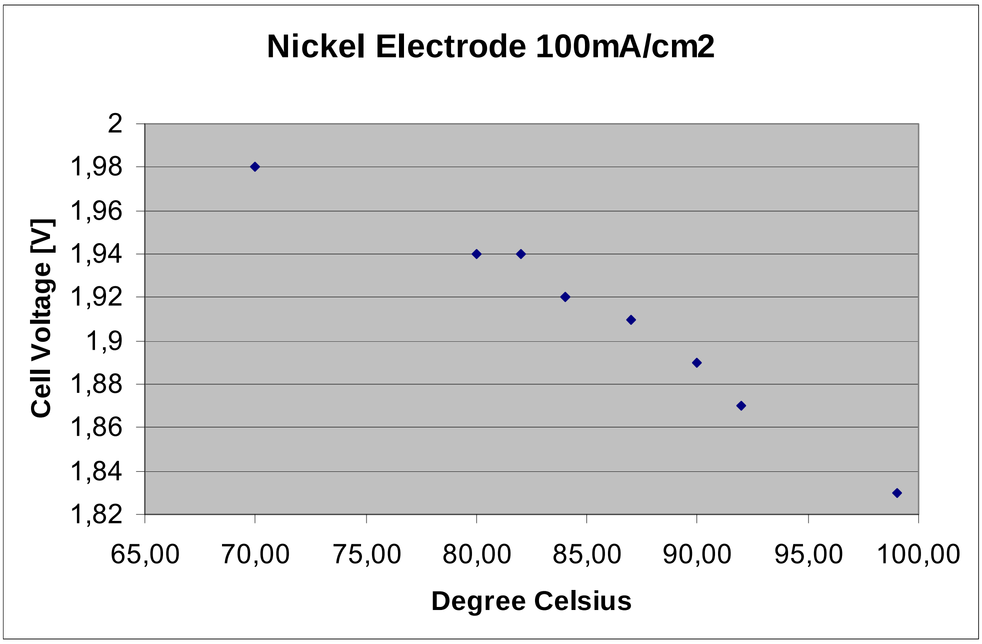


Fig.5.1.17: Savings at a plant without compressor

The operation temperature for commercial alkaline electrolysers is 70-80ºC. If the operation temperature can be increased the efficiency will go up as well.
The fig. below shows measurements on a single cell with pure nickel electrodes. Since the efficiency is proportional to the cell voltage the improvement of the efficiency by raising the temperature from 70-100ºC can be calculated as 1.98 / 1.83 = 1.08

Increasing the efficiency by 8% by raising the temperature 30ºC will cause extra requirements to materials.



**Conclusion**

This new non zero gap design concepts for the electrolyser stack together with batch or mass production may be able to reduce the costs so significantly, that decentralised electrolysers might be a feasible solution.

Besides the price reduction of about 30% the advantaged will be:

- Increased power densities because of the more compact design.
- 50% reduction of the size of the fuel cell in the CHP.
- Op to 10% savings on the electrolysis plant if a pressurised stack is used.
- Op to 8% increase efficiency if the temperature can be raised to 100ºC.

This in a nutshell is one of the main conclusions regarding the task of the team to obtain technical and thereby economical improvements of the system pathway from a renewable energy source through hydrogen produced by electrolysis and more than fulfilling the goal of the RES-FCHS project of a 10% cost reduction.

# 5.2. TECHNICAL IMPROVEMENTS OF TECHNOLOGY FOR EACH FIELD OF RES-FCHS TECHNOLOGY

## 5.2.1. The various pathways to reductions

In the section above we showed how new design aspects could lead to significant reductions in hydrogen production costs by electrolysis.
In the following pages the intention is to go through the various pathways of fuels and processes leading to the use of LT PEM. We start with PEM electrolyser capital costs and thereby continue from the previous discussions of electrolysis.

| **PEM Electrolyzer Capital Cost** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cells | | Material | Unit Cost | | Loading | | | Cost |
| | Anode Cat | Pt | $ 57.690 | /gm | 2.00 | mg/cm$^2$ | | $ 159.94 |
| | Cathode Cat | Pt | $ 57.690 | /gm | 2.00 | mg/cm$^2$ | | $ 159.94 |
| | Matrix | Nafion | $ 0.050 | /cm2 | | | | 69.31 |
| | | | | | | | Material | 389.18 |
| | | | | | | | Processing | 50% |
| | | | | | | | | $ 194.59 |
| | | | | | | | Subtotal | $ 583.77 |
| Stack | | | | | Density | | | |
| | | Ti nitride | $ 45.00 | /kg | 8,360 | kg/m$^3$ | | $ 707.71 |
| | | | | | | | Processing | 50% |
| Electrolyte Regeneration | | | | | | | | $ 353.86 |
| | | 0% | of stack cost | | | | Subtotal | $ 1,061.57 |
| | | $ - | | | | | Stack Total | $ 1,645.34 |
| BOP | | 50% | of stack cost | | | | **System Total** | **$ 2,468** |
| | | $ 823 | | | | | **$/kW** | $ 2,226 |

Table 5.2.2. shows the electrolyzer capital cost based on a number of DoE studies as well as communications with a number of scientists and developers in the US, Canada and Singapore.

When discussing fuels other than molecular hydrogen, we start by looking at biogas.
In the next figure we take a look at anaerobic digestion as a major primary conversion process for the production of biogas.
We study the yield of a fully mixed anaerobic digestion of wood, at mesophilic temperatures. Mass flow of methane, $CO_2$ and solid materials are shown as well as the costs per cubic meter of the gases obtained.

| **Biomass** | **$C_5H_7O_3$** | | | | | | 500 kg/$m^3$ |
|---|---|---|---|---|---|---|---|
| | | C | 5 | 12 | 60 | 52.2% | dry solid |
| | | H | 7 | 1 | 7 | 6.1% | |
| | | O | 3 | 16 | 48 | 41.7% | |
| | | | | | 115 | | |

| **Biogas Yields** | m3/tonne DM |
|---|---|
| Biowaste | 500 |
| Energy crops | 550 |
| Sewage sludge | 400 |
| Manure | 350 |
| Industrial organic waste | 850 |

| **Module Size** | | |
|---|---|---|
| **1 Tonne Stats** | wood | |
| input | 1,000 | kg |
| TDS | 50% | by weight |
| | 500 | kg |
| VS | 80% | |
| | 400 | kg |
| | | |
| conversion | 50% | |
| | 200 | kg |
| | | |
| slurry | 1,000 | kg |
| density | 1,100 | kg/m3 |
| volume | 0.91 | m3 |
| | 240 | g |
| electricity | 7.60 | kWh |
| heat | 300,000 | btu |
| output | 5.45 | MMBTU |
| methane | 4,855 | scf |
| | 138 | m3 |
| | 98.59 | kg |
| w/ | 73.94 | kg of C |
| w/ | 24.65 | kg of H |
| | 55% | by vol |
| carbon dioxide | 3,972 | scf |
| | 113 | m3 |
| | 222.75 | kg |
| w/ | 60.75 | kg of C |
| | 45% | by vol |
| H/C ratio | 1.10 | :1 |
| | | |
| digestate | 800 | kg |
| TDS | 50% | |

| | | |
|---|---|---|
| C | 260.9 | kg |
| H | 30.4 | kg |
| O | 208.7 | kg |

| **Capex** | $ | 100 | tonne/year |
|---|---|---|---|

| **O&M** | | | |
|---|---|---|---|
| electric | $ | 0.02 | /kWh |
| CH4 | $ | 0.50 | /MMBTU |
| | $ | 0.02 | /m3 |
| pellets | $ | 10.00 | /tonne |
| CO2 | $ | 5.00 | /tonne |

| **Feedstock Cost** | | | | |
|---|---|---|---|---|
| $/tonne | | $/m3<br>biogas | | $/m3<br>CH4 |
| $ | 1.00 | $ | 0.004 | $ 0.007 |
| $ | 2.00 | $ | 0.008 | $ 0.015 |
| $ | 3.00 | $ | 0.012 | $ 0.022 |
| $ | 4.00 | $ | 0.016 | $ 0.029 |
| $ | 5.00 | $ | 0.020 | $ 0.036 |
| $ | 10.00 | $ | 0.040 | $ 0.073 |
| $ | 15.00 | $ | 0.060 | $ 0.109 |
| $ | 20.00 | $ | 0.080 | $ 0.145 |
| $ | 25.00 | $ | 0.100 | $ 0.182 |

| **Methane from Biomass Cost Sensitivity** | | | |
|---|---|---|---|
| Feedstock ($/tonne) | $ | 5.00 | $ |
| Feedstock | $ | 0.04 | $ |
| Other Operating Costs | $ | 0.02 | $ |
| Capital Charges | $ | 0.0003 | $ |
| Total ($/m3) | $ | 0.05 | $ |
| Total ($/MMBTU) | $ | 1.52 | $ |

| **Biogas from Biomass Cost Sensitivity** | | | |
|---|---|---|---|
| Feedstock ($/tonne) | $ | 5.00 | $ |
| Feedstock | $ | 0.02 | $ |
| Other Operating Costs | $ | 0.02 | $ |
| Capital Charges | $ | 0.0001 | $ |
| Total ($/m3) | $ | 0.04 | $ |

| **Capital Charge** | | | |
|---|---|---|---|
| Term | | 10.0 | year |
| Interest | | 7% | |
| Principal | $ | 10.00 | /yea |
| | $ | 0.00020 | /m3 |
| Interest | $ | 3.50 | /yea |
| | $ | 0.00007 | /m3 |

Table 5.2.3. Various pathways from anaerobic digestion Sources:, Linde-KCA, RosRoca, Gibbs Energy

The next step taken on the way to analyzing the pathway involves taking methane or biogas to methanol. It is of utmost importance to note that when methanol is produced out of biogas, there is the requirement of one mole of carbon-dioxide and one mole of methane for each mole of methanol produced.

If the carbon dioxide is separated to put the methane from the biogas into a pipeline, there will be the demand for oxygen at the site where the methanol is synthesized, thus adding complexity and cost

Savings would result from synthesizing methanol from biogas.

| **Methanol From Natural Gas** | | |
|---|---|---|
| MT/d | | 2,500 |
| gpd | | 839,886 |
| **Capital Investment** | | 4.2 |
| Battery Limits Investment | | factor |
| ZnO guard beds | $ | 3,200,000 |
| Primary Reforming | $ | 39,400,000 |
| Secondary Reforming | $ | 36,700,000 |
| Steam & Power Generation | $ | 27,800,000 |
| Compression | $ | 11,800,000 |
| Methanol Synthesis | $ | 55,600,000 |
| Methanol Distillation | $ | 15,200,000 |
| Total battery limits investment | $ | 189,700,000 |
| | | |
| Offsited & general facilities | $ | 66,400,000 |
| Contingency | $ | 25,600,000 |
| Total Facilities Investment(TFI) | $ | 281,700,000 |
| | | |
| Other capital costs | $ | 50,700,000 |
| Total capital investment (TCI) | $ | 332,400,000 |
| | | |
| **Operating Costs** | | |
| Natural Gas | | |
| Unit cost($/MMBTU) | $ | 2.50 |
| Annual Cost | $ | 66,519,000 |
| MMBTU | | 26,607,600 |
| Utilities | | |
| oxygen | $ | 10,153,000 |
| cooling water | $ | 1,806,000 |
| process water | $ | 143,000 |
| Catalysts and chemicals | $ | 1,752,000 |
| Labor | $ | 3,746,000 |
| Maintenance (3% of TFI) | $ | 8,451,000 |
| Taxes and insurance (2% of TFI) | $ | 5,634,000 |
| Total Operating Costs | $ | 98,204,000 |
| | | |
| Capital Charges(20% of TCI) | $ | 66,482,000 |
| | | |
| **Total Revenue Required** | $ | 164,686,000 |
| per gallon cost | $ | 0.59 |
| Note: Availability | | 330 |

| **Hydro-Chem Stats** | | | |
|---|---|---|---|
| | | 100 | tpd |
| methanol out | | 33,595 | gpd |
| biogas in | | 90 | scf/g |
| methane | | 55% | |
| | | 50 | scf/gallon |
| capex | $ | 12,000,000 | |
| | $ | 120,000 | /tonne/d |
| | $ | 357 | /gallon/d |
| | $ | 94 | /l/d |

Table 5.2.4. Tables showing methanol synthesis from natural gas and biogas. Notice the no demand for oxygen in the small biogas system.

## 5.2.2
## Fuel cell systems and the potential reduction possibilities in their design, production and operation.

Finally we will  study the PEM fuel cell stack and system. The stack contains or comprises electrode, membrane, seal, bipolar plates, gas diffusion layer, final assembly and the balance of stacks.

The system, however, breaks down into catalyst, MEA minus catalyst, humidity and cooling systems respectively, air system, fuel system and the assembly, testing, conditioning and various other related aspects.
The next figures show the breakdown on a pie chart to illuminate the various aspects. The pie chart presented in figure 5.2.6 is based on the production run of a thousand units.

| **PEM Cost Projections** | **US DOE** | 500,000 units | | **Generic Model** | |
|---|---|---|---|---|---|
| **Stack Breakdown($/kW)** | | **DTI** | **Tiax** | **Fuel** | **Hydrogen** |
| Electrode | 77% | $ 49.87 | $ 42.21 | $ 1,040.72 | $ 1,040.72 |
| Membrane | 6% | $ 3.89 | $ 3.29 | $ 81.10 | $ 81.10 |
| Seal | 2% | $ 1.30 | $ 1.10 | $ 27.03 | $ 27.03 |
| Bipolar Plates | 5% | $ 3.24 | $ 2.74 | $ 67.58 | $ 67.58 |
| Gas Diffusion Layer | 5% | $ 3.24 | $ 2.74 | $ 67.58 | $ 67.58 |
| Final Assembly | 3% | $ 1.94 | $ 1.64 | $ 40.55 | $ 40.55 |
| Balance of Stack | 2% | $ 1.30 | $ 1.10 | $ 27.03 | $ 27.03 |
| | 100% | $ 64.76 | $ 54.81 | $ 1,351.59 | $ 1,351.59 |
| **System Breakdown($/kW)** | | | | | |
| Catalyst | 33% | $ 35.95 | $ 36.95 | $ 824.01 | $ 824.01 |
| MEA minus catalyst | 11% | $ 15.00 | $ 9.88 | $ 281.17 | $ 281.17 |
| Balance of Stack | 10% | $ 13.81 | $ 7.99 | $ 246.41 | $ 246.41 |
| Humidity System | 6% | $ 5.84 | $ 8.00 | $ 156.41 | $ 156.41 |
| Cooling System | 4% | $ 4.79 | $ 4.25 | $ 102.15 | $ 102.15 |
| Air System | 12% | $ 13.19 | $ 13.56 | $ 302.36 | $ 302.36 |
| Fuel System | 4% | $ 5.56 | $ 4.25 | $ 110.91 | $ - |
| Assembly | 5% | $ 5.45 | $ 5.45 | $ 123.21 | $ 123.21 |
| Test & Condition | 6% | $ 6.79 | $ 6.79 | $ 153.44 | $ 153.44 |
| Misc. | 8% | $ 11.10 | $ 6.59 | $ 199.93 | $ 199.93 |
| | 100% | $ 117.48 | $ 103.70 | $ 2,500 | $ 2,389.09 |

Sources: US DOE, Directed Technologies Inc, Tiax Inc,

Table 5.2.5. Showing the cost breakdown of PEM stacks and systems based on a very large scale production capacity.

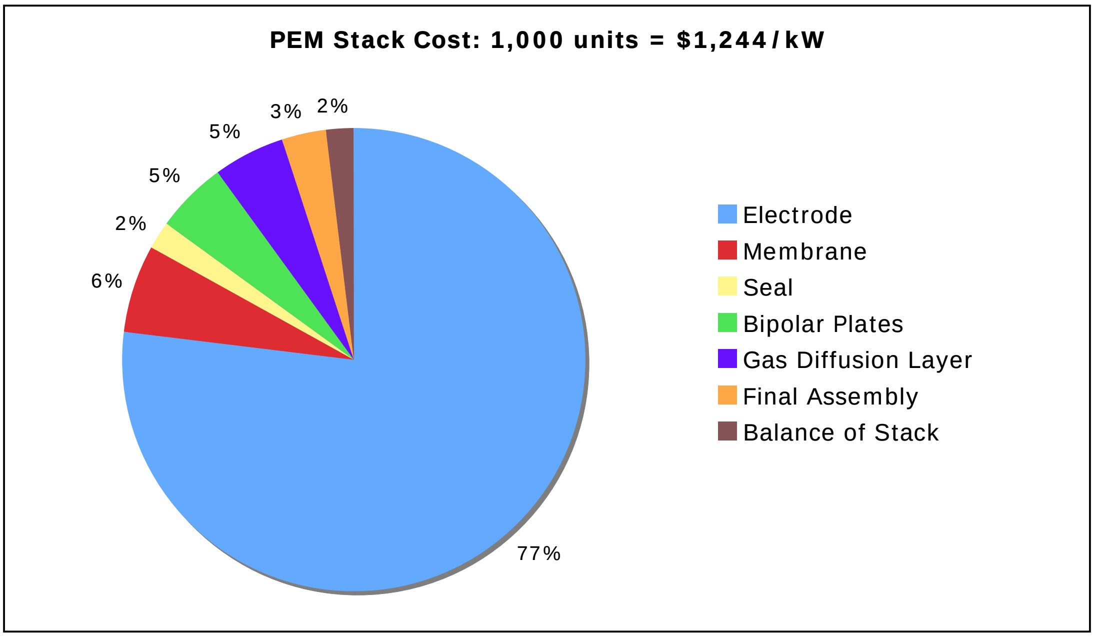


Figure 5.2.6: PEM stack cost calculated from a series of 1,000 units. Based on calculations of DoE .

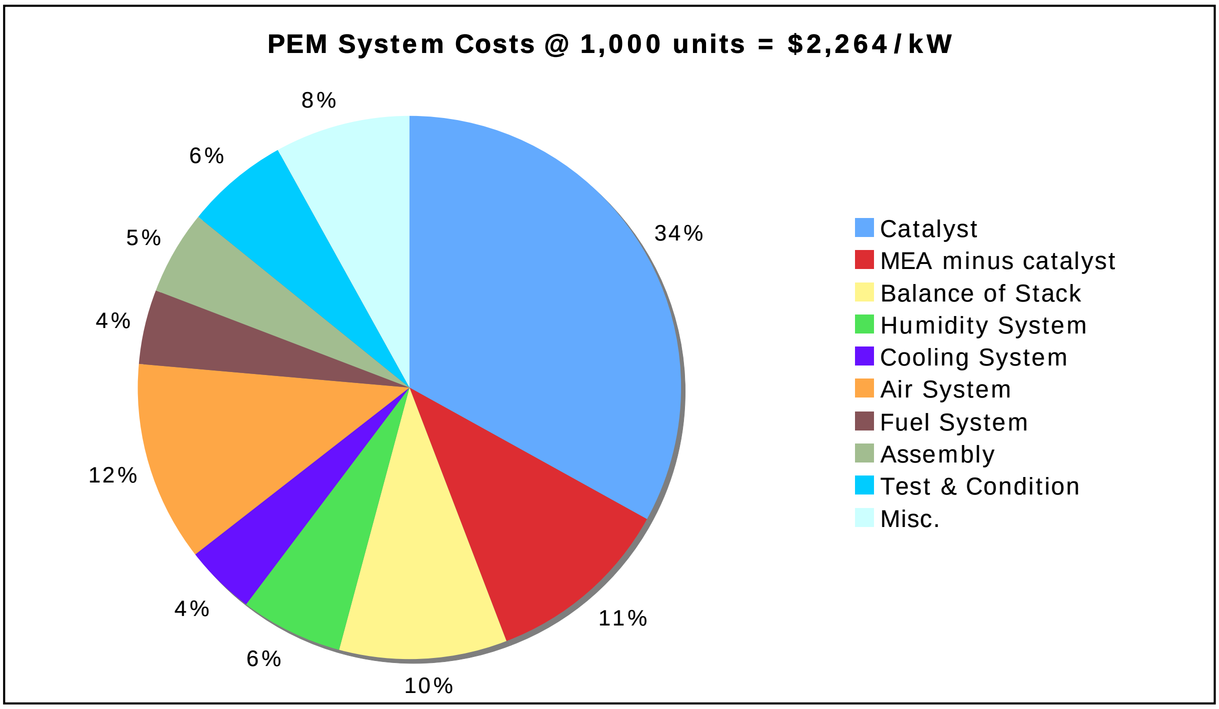


Figure 5.2.7. The PEM system costs for the series of 1,000 units. Numbers derived from DoE.

Possible reduction in the cost of PEM systems would be obtained by going to lower temperatures and thereby eliminating the cost of humidifiers which represent about 6% of the total system cost as shown above. Furthermore, it would be expected that cooling systems costs would be reduced from 4% down to 2%.

| **Performance/Cost Comparison** | | | | | |
|---|---|---|---|---|---|
| **Stack** | **Tokyo Gas** | **Battelle** | **EU FURIM** | **APEMFC** | **AAFC** |
| cell voltage (VDC) | 0.60 | 0.60 | 0.60 | 0.70 | 0.85 |
| cell current density (A/cm2) | 0.66 | 0.50 | 0.70 | 0.80 | 1.00 |
| cell power density (W/cm2) | 0.40 | 0.30 | 0.42 | 0.56 | 0.85 |
| cell efficiency | 49% | 49% | 49% | 57% | 69% |
| **System** | 34% | 34% | 34% | 46% | 55% |
| net output (watts) | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| parasitic losses | 20% | 20% | 20% | 10% | 10% |
| gross output (watts) | 1,200 | 1,200 | 1,200 | 1,100 | 1,100 |
| total active area | 3,030 | 4,000 | 2,857 | 1,964 | 1,294 |
| cost ($/cm2 @ 1,000 units) | $ 0.57 | $ 0.57 | $ 0.57 | $ 0.57 | $ 0.71 |
| total cost | $ 1,715 | $ 2,264 | $ 1,617 | $ 1,112 | $ 914 |

Table 5.2.8.The cost comparison as reported from different international sources. The Tokyo gas and Battelle are humidified and pressurized which lead to 20% parasitic losses.

The fourth one is based on performance, unhumidified at ambient pressure. The parasitic losses are less and a clear improvement of efficiency has been obtained. The fifth column shows an alkaline fuel cell for comparison. The EU target figures were obtained from the FURIM project. The combined result can be seen as very large.
If the details of the data from various producers are examined further, it seems that Tokyo Gas is obtaining much more current density for a similar voltage which is a sign of some superiority of the assumed high temperature perfluorinated or hydrocarbon membrane. We, therefore, have to point out as one of the conclusions of our work that the step from Nafion to hydrocarbon is at least worth much more attention.

The Advanced PEM system, shown in the chart, has higher voltages and current densities but operates at 50ºC and ambient pressure.

In figure 5.2.10 we present our methodology to assess how the reduction in fuel cell costs can be achieved by addressing the various different aspects or components of a cell. Let us initially take a look at the breakdown of costs of various components of a fuel cell in two different scenarios.

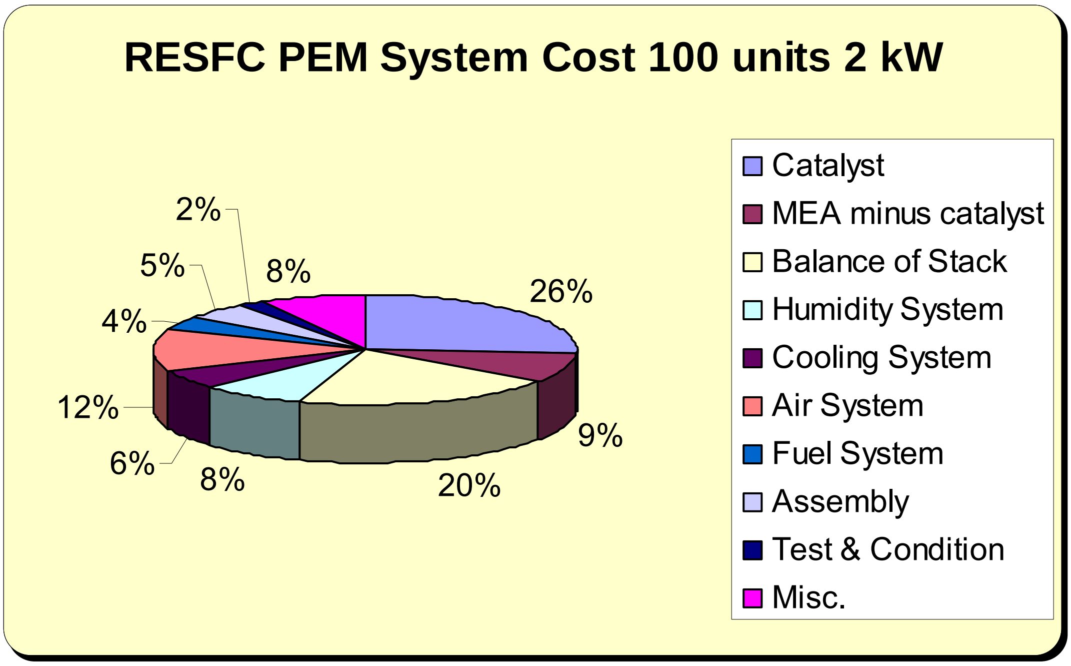


Figure 5.2.8
Following a study of the scope of cost reduction available for the series of 100 residential PEM systems in the 2 kWe range, the RESFC project came to the above result. Notice that catalyst has gone down to 26% compared to the DoE reference below. Balance of Stack is larger now at 20% total and can be divided into 10% from the “suspension” and 10% from system control costs. Humidity is up from 6% to 8%. Cooling is up from 4% to 6%. MEA goes down from 11% to 9%.

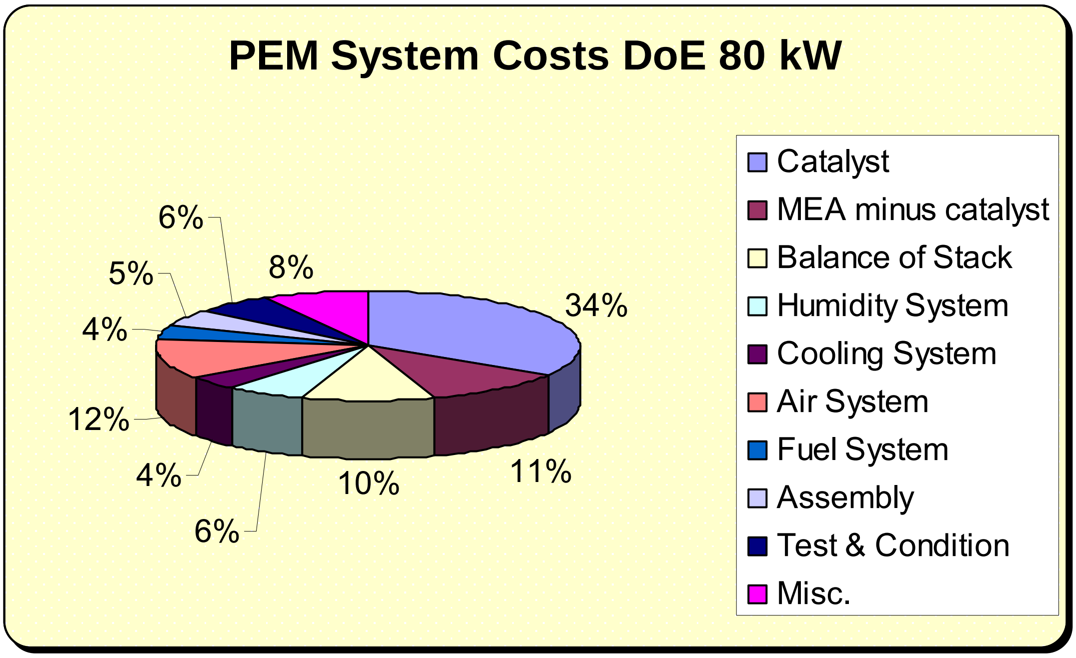


Figure 5.2.9. Data obtained from DoE .

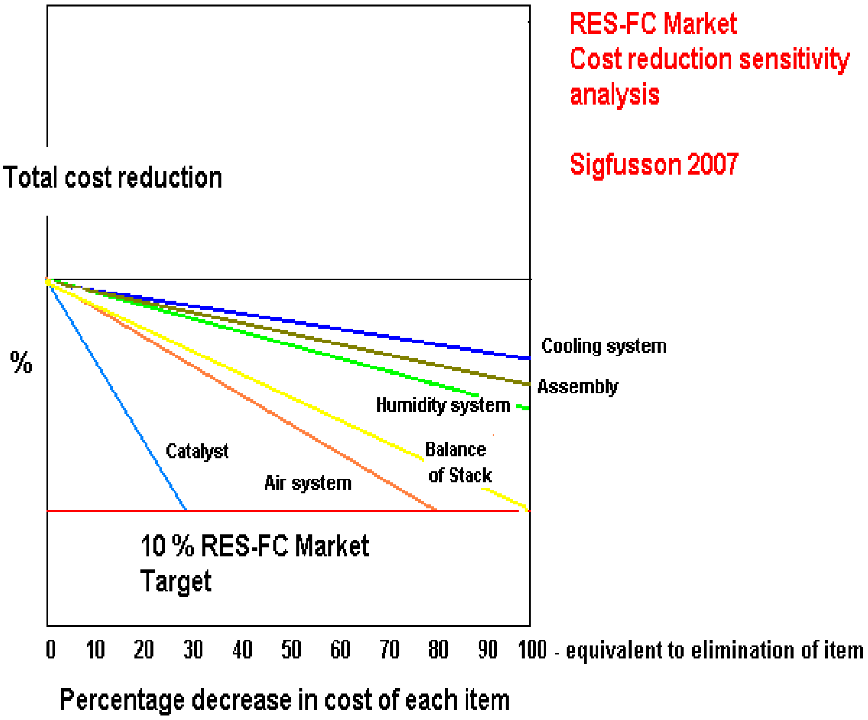
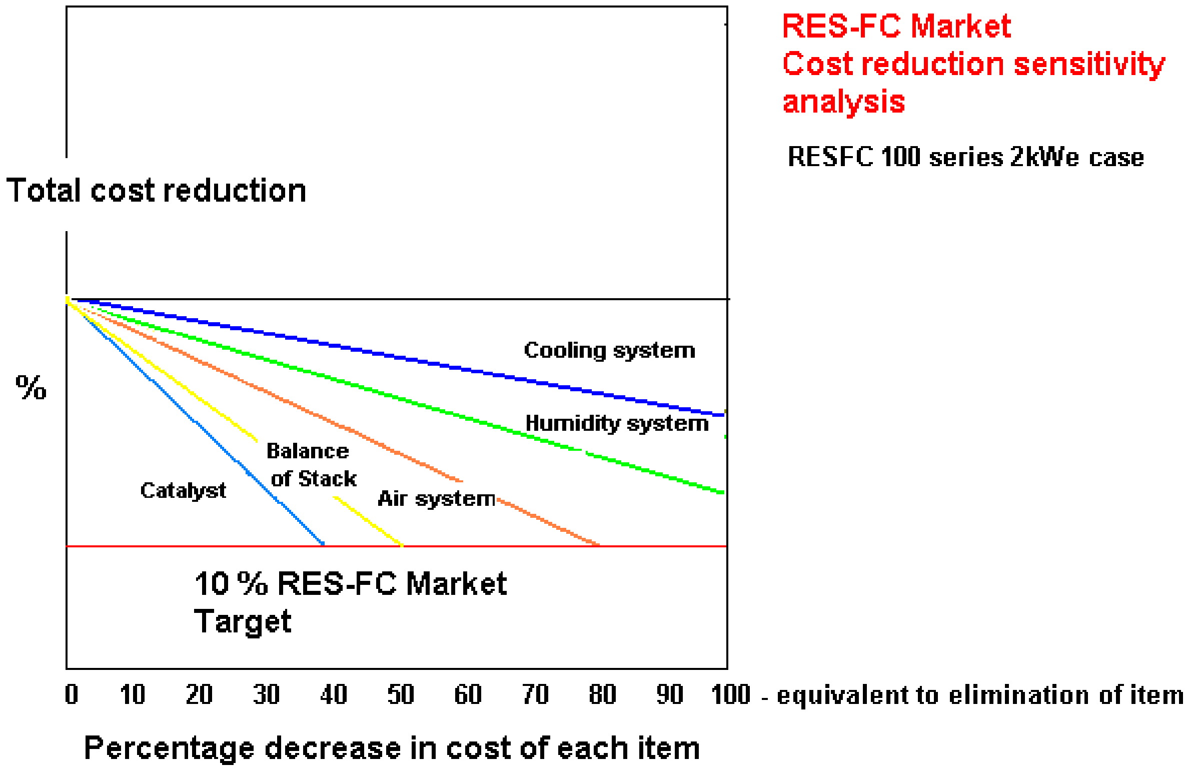


Figure 5.2.10: Cost reduction sensitivity analysis for PEM fuel cells using DoE figures. The different lines show the total cost reduction of the PEM when individual items are reduced in cost.
The items studied are: Cooling system, Assembly, Humidity system, Air system and Catalyst.
Notice that if an item is cost reduced to 100% it equals elimination – which in some cases could be the result of a drastic technical improvement.
The 10% target of RES-FC Market project is indicated by the horizontal red line.
Notice that for example a 60% cost reduction of Cooling system, humidity system and 20% reduction of air system would lead to the desired 10% overall cost reduction.

In the figure above we present a certain methodology to interpret the 10% goal for the RESFC project. The figure shows the effect of cost savings in different parts of the system. We note that for example total elimination of cooling system would never reach a 10% overall cost saving. On the other hand the catalyst dominates the savings and around 30% saving of this important component would immediately lead to the desired 10% savings.
It can be seen from the figure that catalyst, air system or balance of stack all could lead to the desired savings. A mixed solution of savings involving a number of components is the most desirable way to save cost.



RES-FC Market
Cost reduction sensitivity analysis

RESFC 100 series 2kWe case

Figure 5.2.110 : Cost reduction sensitivity analysis for the 100 series RESFC case studied in this project. The different lines show the total cost reduction of the PEM when individual items are reduced in cost. In this case, balance of stack, humidity and cooling weigh considerably more than before.

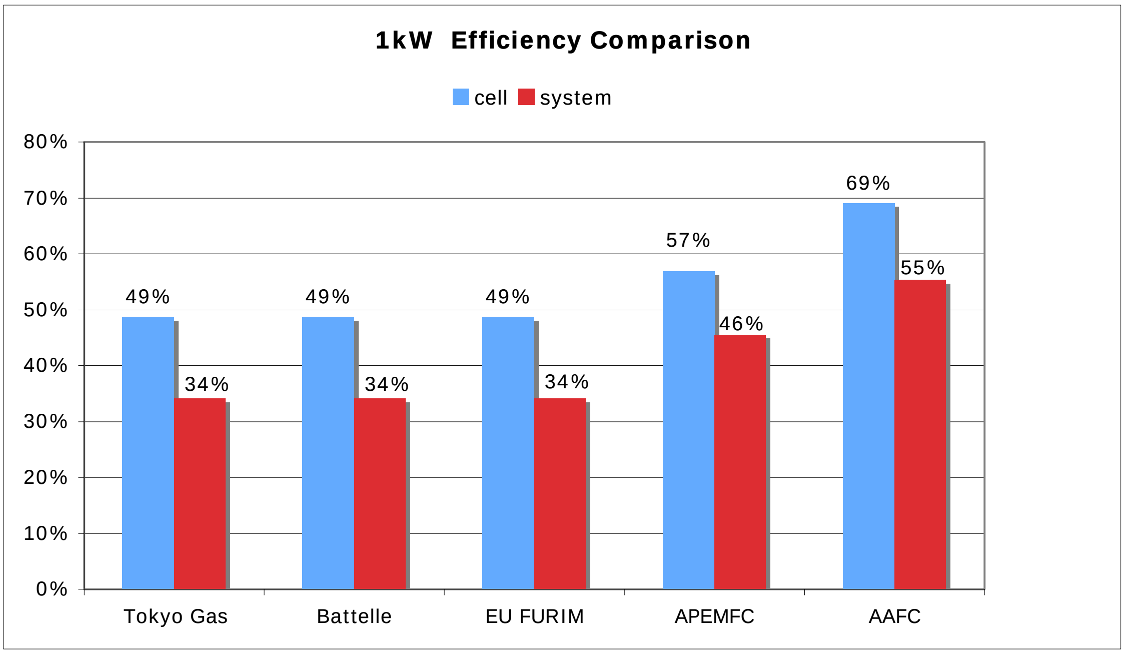


Table 5.2.9. The main results of the previous chart for both cells and systems.

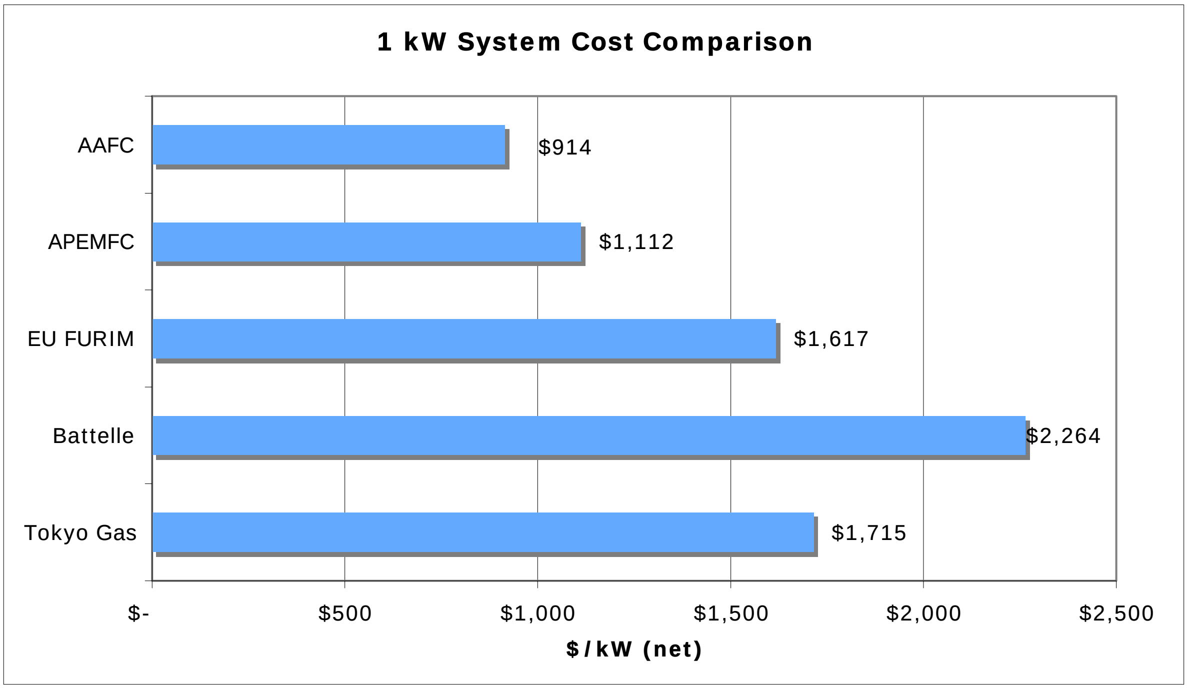
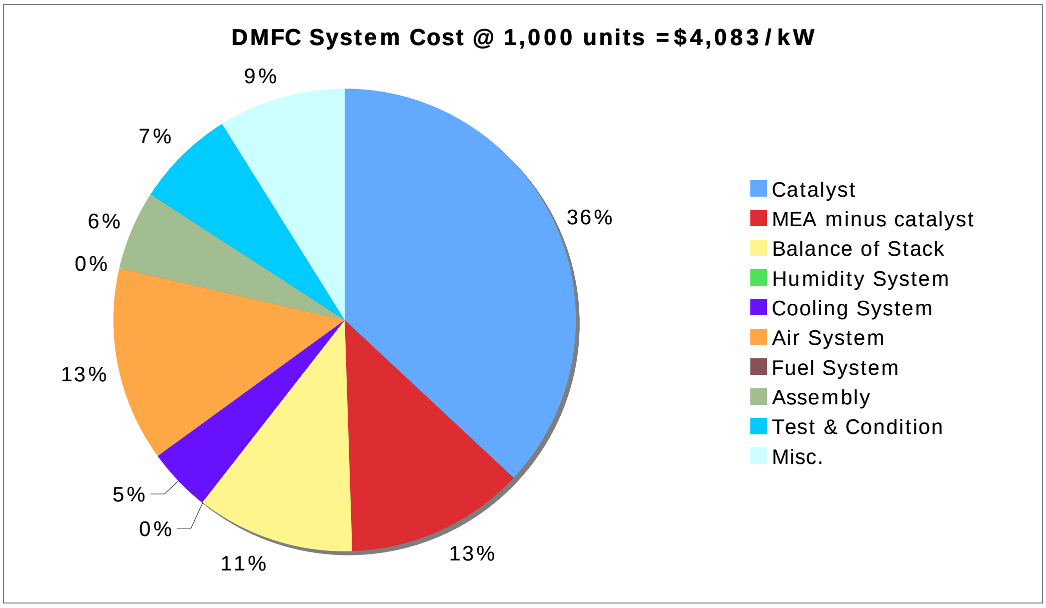


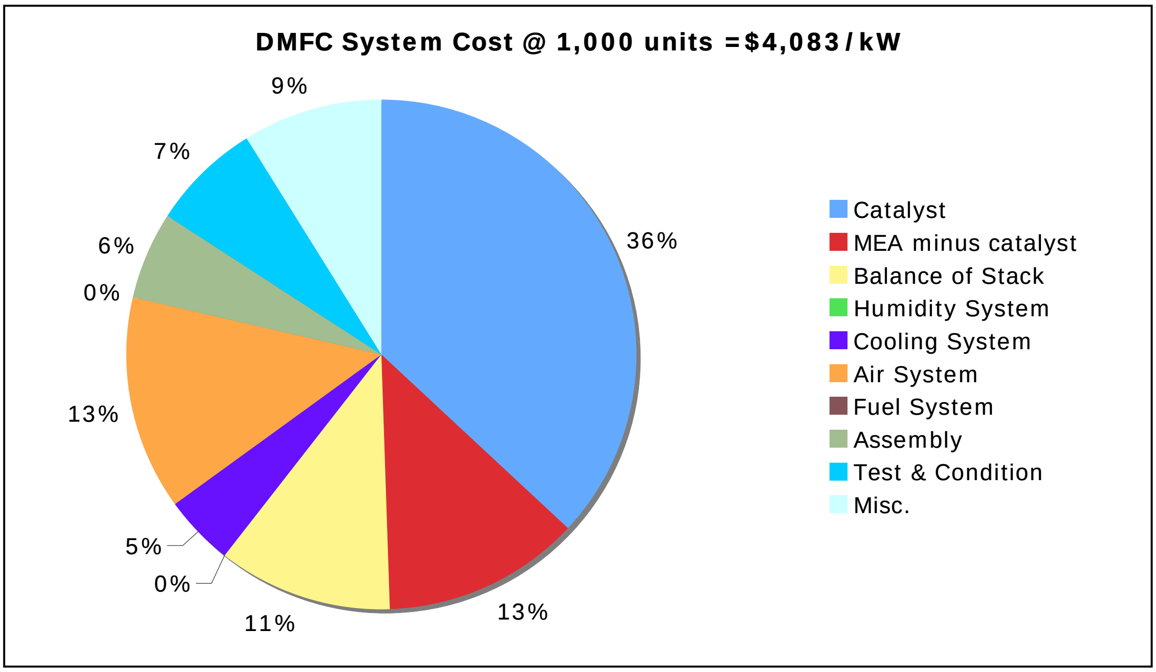
Chart 5.2.10. Showing the 1 kW system cost comparison using the data from the various sources and the prediction of the advanced PEM and AFC models of lower temperature of 50ºC and ambient pressure.

Now, for the sake of completeness, let us look at the situation with DMFC shown on the next table.

| **DMFC Cost Projections** | **US DOE** | 500,000 units | Generic |
|---|---|---|---|
| **Stack Breakdown($/kW)** | | **LANL** | **Model** |
| Electrode | 77% | $ 99.73 | $ 2,081.45 |
| Membrane | 6% | $ 7.77 | $ 162.19 |
| Seal | 2% | $ 2.59 | $ 54.06 |
| Bipolar Plates | 5% | $ 6.48 | $ 135.16 |
| Gas Diffusion Layer | 5% | $ 6.48 | $ 135.16 |
| Final Assembly | 3% | $ 3.89 | $ 81.10 |
| Balance of Stack | 2% | $ 2.59 | $ 54.06 |
| | 100% | $ 129.53 | $ 2,703.18 |
| **System Breakdown($/kW)** | | | |
| Catalyst | 32% | $ 71.90 | $ 1,648.02 |
| MEA minus catalyst | 14% | $ 30.00 | $ 562.34 |
| Balance of Stack | 12% | $ 27.63 | $ 492.82 |
| Humidity System | 0% | $ - | $ - |
| Cooling System | 9% | $ 19.15 | $ 204.31 |
| Air System | 12% | $ 26.38 | $ 604.72 |
| Fuel System | 0% | $ - | $ - |
| Assembly | 5% | $ 10.90 | $ 246.41 |
| Test & Condition | 6% | $ 13.58 | $ 306.88 |
| Misc. | 10% | $ 22.20 | $ 399.85 |
| | 100% | $ 221.73 | $ 4,465.36 |

Table 5.2.11. DMFC cost projections for stack and system.





Figs. 5.2.12 and 5.2.13 DMFC for comparison

## 5.3 Smarter use of materials and other technology growth areas

It is obvious that a substantial cost reduction of PEM FC has to focus on the catalyst as this item presently is the biggest cost driver, which probably is increasing as the Pt-price is rapidly increasing (Fig. 5.3.1). Focus worldwide is to pinpoint a non-PM based catalyst with at least identical catalytic activity. However, the changes of a near future break through within this research are limited, and hence other approaches have to be explored for the short term. Recycling of the PM-catalyst is an obvious approach, that fast can enhance the competitiveness of the technology. Several patents on this issue have recently been granted (e.g. US Patent 7255798 and WO/2006/024507) partly as a result of the on-going DOE program on this issue and partly due to industrial R&D. A successful recycling catalyst technology will full or partly remove the cost barrier for both PEM CHP and the DMFC technology.

Recycling of the polymer (Nafion) membrane is also proven possible, but the energy cost for the developed process makes this option less attractive.

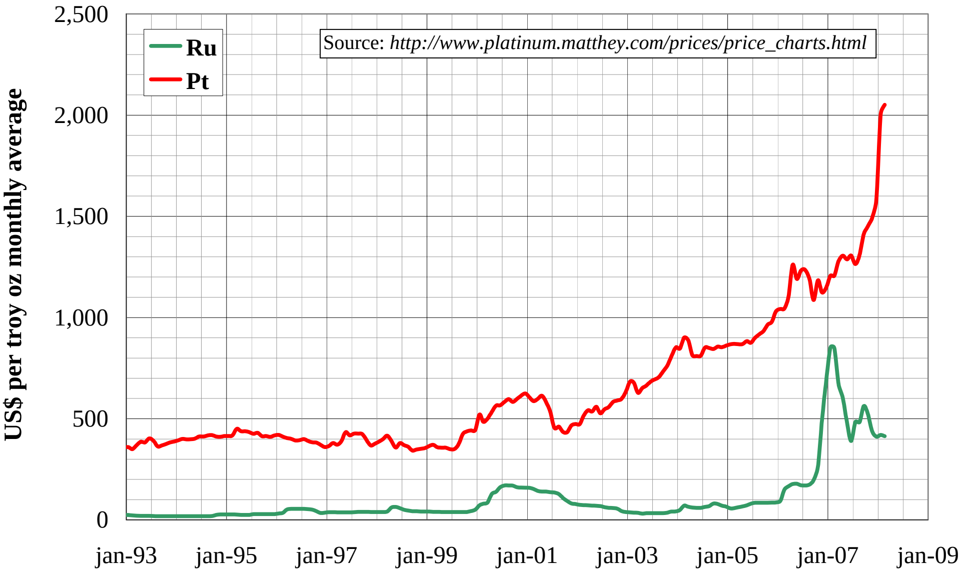


Fig. 5.3.1 PEM catalyst cost development.

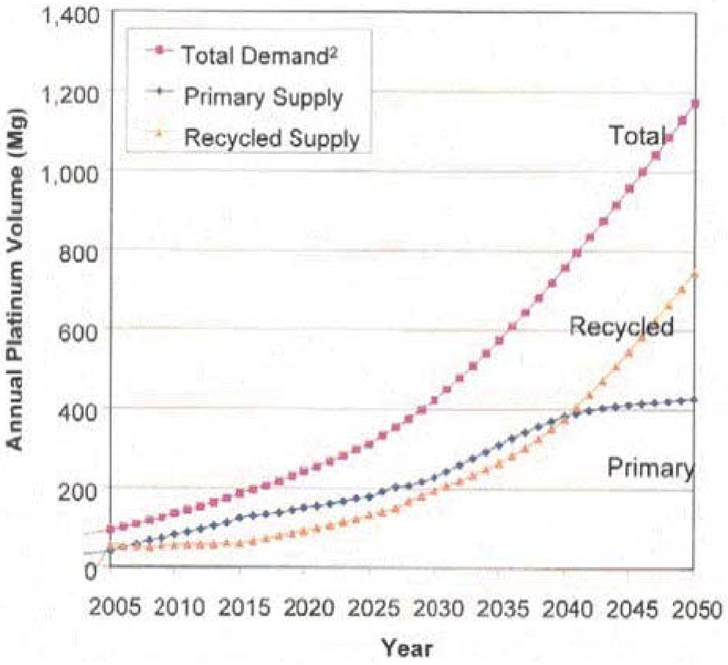


Fig. 5.3.1 Global Pt supply and demand (source: http://www.hydrogen.energy.gov/pdfs/review04/fc_22_shore_04.pdf)

It is to be expected that more standardized testing protocols and test stations will make it possible to compare functionality. Among the growth areas is the development of new methods to facilitate water management and proton conductivity within the catalyst layer, especially the cathode.

By reducing the number of parts in a unit cell assembly by combining the function of the GDL and flow field into a single component is an interesting way to reduce cost. The same applies to the complexity of the multi-layer GDL by design.

When it comes to the production process, the need for assembling all unit cell component interconnects in a single, continuous process, is one of the keys to cost reduction progress.

The water management provides enormous potential for improvements. For example if the product water can be utilized as the sole form of humidification for the stack. On the other hand, heat rejection from the stack is a subject of increased interest which calls for smart materials in the conduction process.

Finally, in order to reduce stack failure incidents, self-healing membranes and seals are among the challenging novelties sought in the fuel cell industry.

In this context the bipolar plates continue to provide a challenge to the cost reduction. Let us take a brief look at the subject:

When addressing the cost of producing a fuel cell stack, the concept of the bipolar plates comes into focus as they are in weight and volume a major part of the PEM fuel stack and therefore a significant contributor to the stack costs. Their functions in the fuel cell stack are to distribute the fuel gas and air uniformly over the active areas; remove heat from the active area; conduct the current from cell to cell; and prevent leakage of gases and coolant. Often this puts constraint on channel dimensions to ensure uniform gas distribution. Then, heat removal requires preferably integrated cooling channels.

Of the available plate materials used for bipolar plates today are: Electrographite, carbon-carbon composites, sheet metals of various sorts, flexible graphite foils or graphite polymer composites.

High purity electrographite is an excellent material for machining prototype plates, but materials costs and production costs are generally considereded to high for mass production.

Sheet metal and graphite foils or graphite polymer composities are potentially low cost materials and in principle suitable for mass production.

Using stainless steel around a 100 micrometer thickness, stamped into plates, is possible but has a drawback in that it can increase contact resistance and introduce ionic contamination of membrane and catalyst and thus limiting the lifetime of a stack.

Composite bipolar plates have shown an intereesting advantage when they are made with compression moulding or injection molding when the starting is done with a powder compound and a thermo-set type of binder is used for the completion of the work.

In an attempt to bring down the power density of a stack the bipolar plate is again a key aspect to be dealt with.

Materials with high electric and thermal conductivities have to be selected and any moulding process has to aim for a short process cycle time and a maximum of integration for example as regards cooling channels.

Thinning down the bipolar plates can easily increase power densiity up to 2 kW/l or 2 kW/kg, while at the same time reducing costs by integrating other functions and saving materials.

In conclusion it can be said that the challenges of bringing down the costs of bipolar plates remains one of the interesting areas for cost reduction in this industry.

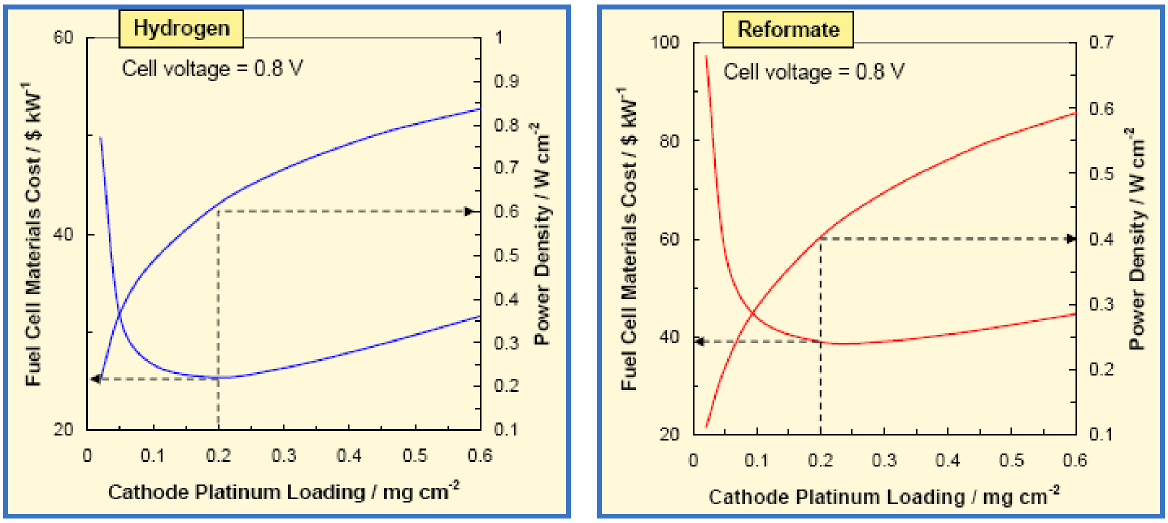


Figure 5.3.2 showing a cost minimum in stack material costs occuring around a platinum loading of 0.2 mg/cm2 when the fuel cell materials costs are shown as a function of cathode platinum loading in mg/cm2. (Source: ANL).

### 5.4. The cost of inverter electronics

The output from a typical fuel cell is measured in high direct current and low voltage. One of the challenges of the RESFC project is to assess the possibilities of converting the dc power of a 1-2kW fuel cell to ac power at 220 V.

The team faces significant technical, cost, and labour challenges. The power system must be able to provide a continual 1-2 kW of and 240 V household power and accommodate a 5 kW peak load. The fuel cell output is not enough for a 5 kW load, so batteries will be one of the options for achieving that goal. Inverters on the world market are still quite expensive or about 700-1.000 USD/kW

One of the potential strategies is to use three or four switches in parallel, to lower the resistance and the losses. This is expected to decrease the cost of the power semiconductors; however, it makes the control and supporting circuitry more complex. This is a tough challenge for the engineering, aspects such as semiconductors cooling and will affect packaging and control. The system must react quickly to changes in the load as residents in the home turn appliances on and off. "We need our system to react dynamically to maintain the power output so that there is always enough available.

For the residential use of fuel cells it is of the utmost importance that the DC to AC inverter system operates smoothly. The cost of this item is well known from for example the solar industry with solar cells.
It is expected in this present work that for a series of 100 units of the 1.6 kW size the cost of each item will be about 1 Euro per watt or 1600 Euros per piece. In the projection to a

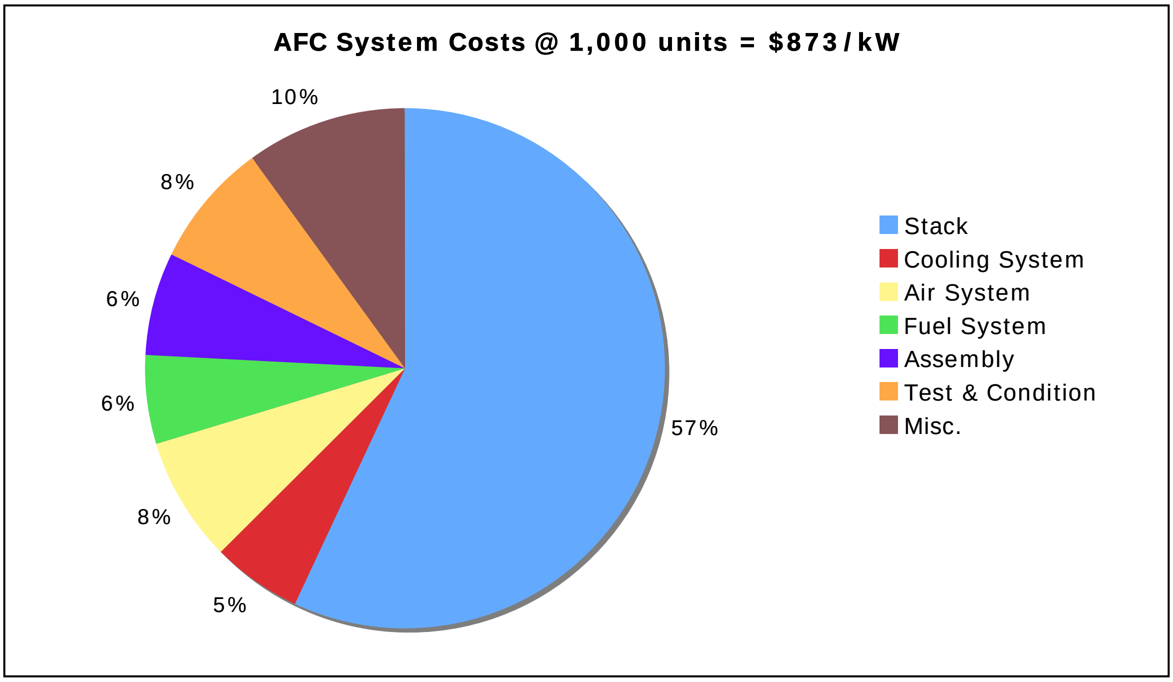
series of 10.000 the project expects costs around 550 Euros per piece in the time frame around 2012.

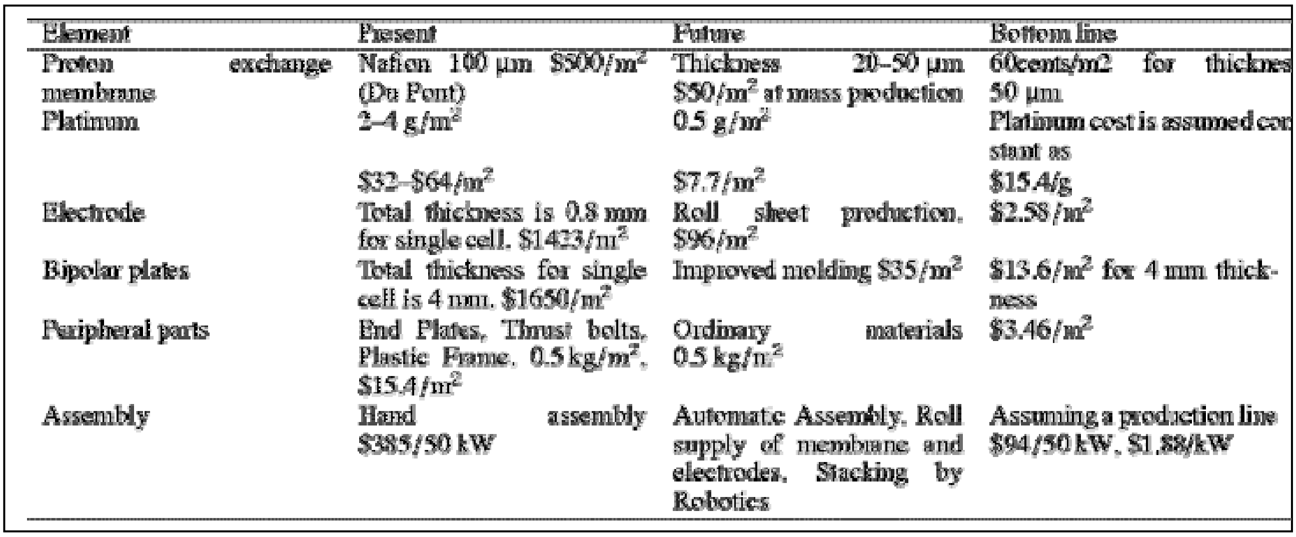
### 5.5.1. A comment on alkaline fuel cells

Aiming for low cost bipolar stack components, we note that in this important area considerable savings can be made. The alkaline chemistry is compatible with far lower cost chemistry than the acid chemistry. Stacks are predominantly plastic, nickel and carbon. Finally the catalyst does not have to be platinum. Silver, nickel and spinels have all been successfully used for this purpose. However, alkaline fuel cells are easily poisoned by carbon dioxide ($CO_2$). In fact, even the small amount of $CO_2$ in the air can affect this cell's operation, making it necessary to purify both the fuel and oxygen used in the cell. This purification process is costly. Susceptibility to poisoning also affects the cell's lifetime (the amount of time before it must be replaced), further adding to cost. This is possibly the most significant obstacle in commercializing this fuel cell technology.
The sensitivity of alkaline fuel cells to fouling caused by the fuel has in the case of the RES-FC market study made the team leave that option.

The next table shows how AFC components can be much cheaper than PEM components.

| **AFC Cost Projections** | | 1,000 units | | **Generic Model** | |
|---|---|---|---|---|---|
| **Stack Breakdown($/kW)** | | **Gibbs** | **Cenergie** | **Fuel** | **Hydrogen** |
| Catalyst | 10% | $ 46.67 | $ 50.00 | $ 11.07 | $ 11.07 |
| Separator | 4% | $ 16.67 | $ 20.00 | $ 4.20 | $ 4.20 |
| Balance of Stack | 51% | $ 277.67 | $ 235.00 | $ 58.73 | $ 58.73 |
| Final Assembly | 35% | $ 170.50 | $ 180.00 | $ 40.15 | $ 40.15 |
| | 100% | $ 511.51 | $ 485.00 | $ 114.16 | $ 114.16 |
| **System Breakdown($/kW)** | | | | | |
| Stack | 57% | $ 511.51 | $ 485.00 | $ 114.16 | $ 114.16 |
| Cooling System | 5% | $ 47.88 | $ 47.88 | $ 10.97 | $ 10.97 |
| Air System | 8% | $ 65.94 | $ 67.81 | $ 15.32 | $ 15.32 |
| Fuel System | 6% | $ 55.63 | $ 42.50 | $ 11.24 | $ - |
| Assembly | 6% | $ 54.50 | $ 54.50 | $ 12.49 | $ 12.49 |
| Test & Condition | 8% | $ 67.88 | $ 67.88 | $ 15.55 | $ 15.55 |
| Misc. | 10% | $ 111.00 | $ 65.88 | $ 20.26 | $ 20.26 |
| | 100% | $ 914.32 | $ 831.44 | $ 200.00 | $ 188.76 |





| Element | Present | Future | Bottom line |
|---|---|---|---|
| Proton exchange membrane | Nafion 100 μm $500/m$^2$ (Du Pont) | Thickness 20–50 μm $50/m$^2$ at mass production | 60cents/m2 for thicknes 50 μm |
| Platinum | 2–4 g/m$^2$<br>$32–$64/m$^2$ | 0.5 g/m$^2$<br>$7.7/m$^2$ | Platinum cost is assumed co stant as<br>$15.4/g |
| Electrode | Total thickness is 0.8 mm for single cell. $1423/m$^2$ | Roll sheet production. $96/m$^2$ | $2.58/m$^2$ |
| Bipolar plates | Total thickness for single cell is 4 mm. $1650/m$^2$ | Improved molding $35/m$^2$ | $13.6/m$^2$ for 4 mm thickness |
| Peripheral parts | End Plates, Thrust bolts, Plastic Frame, 0.5 kg/m$^2$, $15.4/m$^2$ | Ordinary materials 0.5 kg/m$^2$ | $3.46/m$^2$ |
| Assembly | Hand assembly $385/50 kW | Automatic Assembly. Roll supply of membrane and electrodes. Stacking by Robotics | Assuming a production line $94/50 kW, $1.88/kW |

Table: Estimates for a “Mass production cost of PEM fuel cell by learning curve”, the paper by Haruki Tsuchiya and Osamu Kobayashi, in Science Direct by Elsevier 2003.

### 5.5.2. Comments on DMFC technology:

In regions with no district heating and natural gas networks the main heat supply is oil fired boilers or electric resistant heating. These regions will also need to integrate a higher share of renewable energy in the future. The number of households in the regions with no district heating is in Denmark even larger than the regions which are supplied with natural gas, making the market for cogeneration of heat and electricity even larger than the market for natural gas fired boilers. In Denmark about 680.000 households are outside regions with district heating or natural gas supply, giving a replacement driven market potential for µCHP of 34,000 units per year. Grid investment cost will be minimized in these regions, if a liquid fluid is used as hydrogen carrier. Methanol is easy to process to hydrogen and methanol is a widely used fluid today with a well established distribution network. Methanol is therefore an obvious choice as hydrogen carrier. Today methanol is produced from natural gas and methanol is a relatively inexpensive fuel on the world marked. On the long term methanol shall be produced from sustainable resources.

The direct methanol fuel cell (DMFC) is very attractive for small-scale stationary as well as mobile power generators. Direct catalytic conversion at a lower temperature facilitates extremely low emissions. DMFCs produce less than half the $CO_2$ emissions of today's conventional power plants. DMFC technology, using methanol derived from biomass or other renewable energy sources, gives the same advantages as the PEM FC technology, e.g., high energy efficiency, low, neutral or zero emissions. This will dramatically reduce contributions to the global greenhouse effect (and hence green-house gases: GHGs). From today's perspective, due to system simplicity and easy fuel handling, the DMFC has the potential to act as a market driver. The DMFC technology has improved significantly in the last 5-10 years, and has now reached a stage in its development where commercial exploitation is a reality. I the period 2000-2007 IRD Fuel Cells have developed a range of DMFC stacks and systems in the power range of 0.1-2 kW e.g. the IRD 2 kW DMFC generator with the below listed specification:

| | |
|---|---|
| DMFC Electrical power @ 0.3 A/cm$^2$ | 2.5 kW$_{DC}$ |
| Fuel | $CH_3OH$/air |
| $\eta_{el}$ FC-stack (incl. fuel loss) | 24% |
| Output voltage, inverter (One phase /50 Hz) | 230 V$_{AC}$ |
| AC-power | 2 kW$_{AC}$ |
| Electrical efficiency, system | 18% |
| Heat from FC (calculated based on HHV) | 8.0 kW$_{TH}$ |
| Total system efficiency (calculated based on HHV) | 83% |
| Total system volume | 130 L |
| Total system weight | 75 kg |
| System temperature | 75ºC |
| Start up time (Full FC Power) | <5 min |
| | |
| Emissions: | |
| $CO_2$ | 1.4 kg/h |
| Water | 1.7 l/h |
| Environment temperature | 25±15°C |

The DMFC stack principally consists of the materials identical to the materials used for LT PEM stacks. The major important differences between the LT PEM and the DMFC stack is the higher cost of the DMFC stack mainly due to higher catalyst loading of the DMFC electrodes (5-10X the catalyst loading of the PEM electrodes) and the lower electrical efficiency. However, the platinum based catalyst is still present after FC stack End-of-Life although probably sintered and not available for direct reuse in other fuel cells without rework. The DMFC system can on the other hand be simpler than even hydrogen fuelled PEM systems, as the cooling and fuel circuit can be totally integrated e.g. as proven in the IRD 2 kW DMFC generator. It is however, important to note that while there worldwide are many actors on the development of PEM based µCHPs the numbers are limited for DMFC-based µCHPs, IRD Fuel Cells is one of the few industries that have made DMFC-prototype systems in the kW-range.

### 5.6 The effect of mass production

In our estimates of cost reductions of fuel cell production we have not included the influence of mass production which of course would be expected to affect prices to a very large extent. To shed light upon this principle, we point to an interesting article by Tsuchiya and Kobayashi from WENET Japan the authors attempt to develop a learning curve model to analyze the mass production cost structure of proton exchange membrane fuel cells for automobiles. The fuel cell stack cost is aggregated by the cost of membranes, platinum, electrodes, bipolar plates, peripherals and assembly process. The mass production effects on these components are estimated. Nine scenarios with different progress ratios and future power densities are calculated by the learning curve for cumulative production of 50 000 and 5 million units. The results showed that the fuel cell stack cost could be reduced to the same level as that of an internal combustion engine today, and that the key factors are power density improvement and mass production process of bipolar plates and electrodes for reducing total cost of fuel cell stack. The effect can be seen clearly in the future predictions indicated in the table above.

## 5.7 Improving the fuel cell systems

On a fuel cell system level it has been concluded in WP 3 that there are a number of differences between the requirements for the different European Regions that affect the system design. The trend was pointing towards central reforming/electrolysis and the proven LT-PEM technology for the fuel cell system in the households. In WP 4.2 a number of trade off’s were investigated leading to the recommendation that a modular system design running on hydrogen from central hydrogen generation (reforming or electrolysis) should be investigated further. Also it was recommended to focus on longer lifetime

(40.000 hours) as the technological improvements allowed for this new focus. When looking for European manufacturers of this kind of systems, In WP 4.4, it revealed that none of the existing companies had any ongoing developments focussing directly in this direction. As it was discovered that the upcoming HT-PEM fuel cell technology may lead to a solution capable of solving the needs for one system fulfilling all regional requirements and even leading to a higher overall energy efficiency, Dantherm Power undertook the task of developing on its own a HT-PEM system fulfilling the defined requirements. This system seems to have a great potential for developing the aggregated market of 3000 fuel cell systems of “one kind” in order to get the requested cost reductions set up as a target for this project.

### HT-PEM technology

Based on the requirements set up for a modular system with very high system efficiency and the capability of coping with different fuels it was clear that simple system design with a few components, low parasitic losses and easy adaption of a reformer was required. Looking at the same time at the HT-PEM technology needing no humidification whereby the need for a humidification system is avoided and also the need for air pressure for handling the water in the stack is avoided it seemed very suitable from a simplicity point of view. Also the ability of coping with more impurities in the reformate stream leading to a simpler reforming of any fuel to hydrogen rich gas for the fuel cell seems to be very attractive. Operating at a temperature of 180°C has the advantage of higher thermal efficiency and more easily heat integration of both reformer and hot water storage.

Description of the HT-PEM technology

Alongside this project a HT-PEM fuel cell module has been developed by Dantherm Power in order to verify the advantages of such a system. A ~250 W module is shown in figure 5.7.1.

*Figure 5.7.1 HT-PEM Fuel Cell Module, 250 $W_e$.*

This consists of a fuel cell stack, an insulating enclosure for maintaining an adequate temperature, a hydrogen (or reformate from reformer) connection, a small blower for air, a small air exhaust tube and electrical connections. It has been chosen to build an air cooled system for simplicity and for ease of integration with a reformer. The module in its existing enclosure measures about 50x20x16 cm and has a weight of approximately 5 kg. The electrical efficiency of the module has been measured to 51% (HHV) which equals 44% (HHV) after adding an inverter for electrical grid connection. The lifetime is proven for 10.000 hours with a degradation of <2% and is therefore expected to be close to 40.000 hours.
The HT-PEM module seems to fulfil all the technical requirements for the fuel cell systems for all regional markets.

The cost curves for this module are shown in figure 5.7.2

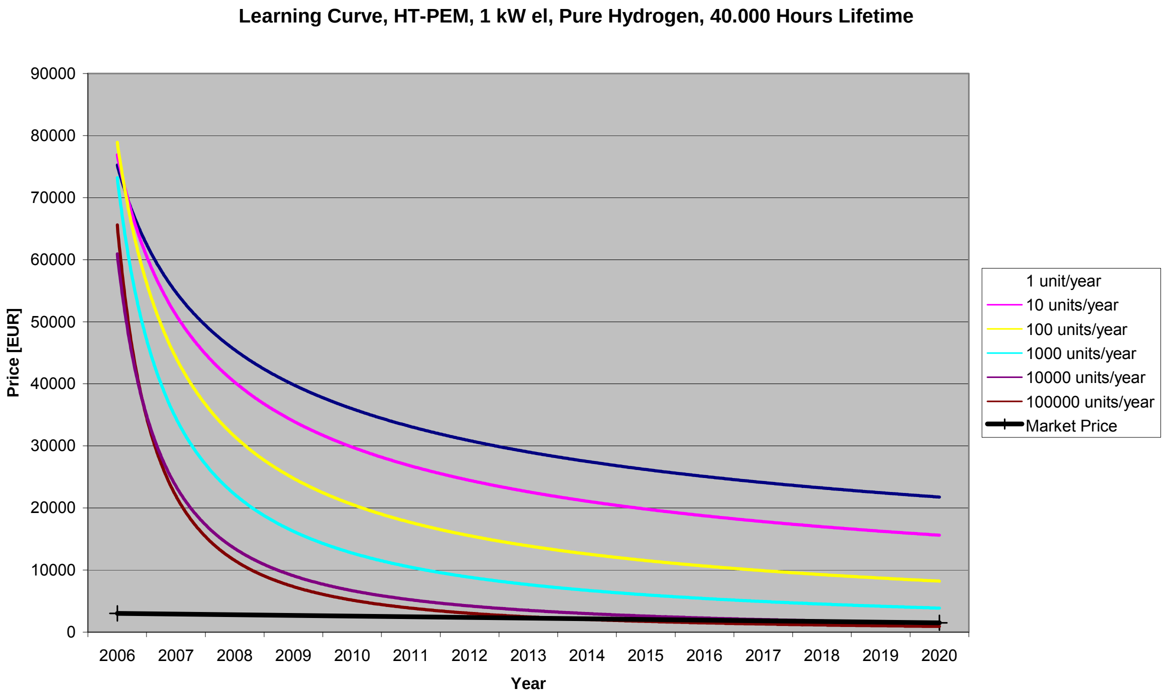


*Figure 5.7.2 Learning curve for HT-PEM fuel cell unit (1 kW equals 4 pcs 250 W modules)*

As this module can be used for a large number of other applications such as power backup units, power modules for fork lift trucks and other early markets for fuel cells without and modifications the numbers of units produced will increase dramatically over the coming year whereby the cost is expected to decrease much faster than the quantity of 3000 systems can justify.

## Simple de-central methanol cracking

As different regions have different requirements for the fuel cell system it has been considered important to be able to add a methanol cracker to enable de-central (on-site) cracking of methanol in order to obtain high energy efficiency. It should be possible to add the methanol cracker directly to the fuel cell module above in order to get an aggregated market on the same fuel cell system.

A well known methanol cracking method has been developed by Mitsubishi Gas Chemical (MGC) of Japan for the production of high purity hydrogen gas from liquid methanol. In fact MGC has produced more than 80 methanol-to-hydrogen stations ranging in size from 0 normal cubic metres per hour to 4.000 normal cubic metres per hour. The process is a two step process using a steam reformer containing a catalyst specially designed for methanol cracking. MGC quotes relatively low temperatures for their catalyst or between 240 and 290 Centigrades. In turn, this low temperature allows rapid start-up and stop, efficient idling and flexible operation on loads ranging from 40-100%. The leader of work package 5 has visited the MGC facility in Japan for information gathering.

Alongside this project Dantherm Power has undertaken the development of a methanol cracker for the HT-PEM module described above. This methanol cracker is extremely simple and cost efficient. It fits into same dimensions as the fuel cell module and can thereby be integrated in an expanded enclosure. On figure 5.7.3 the fuel cell module and the fuel cell module integrated with a methanol cracker are shown.

*Figure 5.7.3 HT-PEM fuel cell module (left) and HT-PEM fuel cell module with methanol cracker module (right).*

The HT-PEM methanol module will have approximately the same characteristics as the HT-PEM module for hydrogen described above except for a few parameters. The weight and the width of the module will be around the double. The electrical efficiency will be decreased to about 45% (HHV) on the module and 41% (HHV) including inverter.

This product is still in the development phase and thus the price level is not known yet. Still the cost of adding a methanol cracker is estimated to be less than the cost of the fuel cell module in quantities. Again the introduction on this module into early markets for fuel cells will bring down the cost rapidly.

**Upgraded biogas/natural gas reforming**

As different regions have different requirements for the fuel cell system it has been considered important to be able to also add a biogas or natural gas reformer to enable de-central (on-site) reforming of biogas or natural gas in order to obtain high energy efficiency. It should be possible to add the reformer directly to the fuel cell module above in order to get an aggregated market on the same fuel cell system.

Biogas or natural gas reforming is…… Technical description will appear later…..

Alongside this project Dantherm Power has undertaken the development of a biogas and natural gas reformer for the HT-PEM module described above. This reformer is quite simple and cost efficient. It fits onto fuel cell module and can thereby be integrated in an expanded enclosure.

The HT-PEM reformer module will have approximately the same characteristics as the HT-PEM module for hydrogen described above except for a few parameters. The weight and the volume of the module will be around the tripled. The electrical efficiency will be decreased to about 41% (HHV) on the module and 36% (HHV) including inverter.

This product is still in the concept development phase and thus the price level is not known yet. Still the cost of adding a reformer is estimated to be slightly more than the cost of the fuel cell module in quantities.

### Conclusion on fuel cell systems from WP5

A completely new concept for a competitive modular approach to residential CHP systems has been established.

- It has been concluded that it is possible to use one fuel cell module for all regional markets using the modular approach, adding reforming/cracking where needed and adding up modules to reach the needed system output.
- It has been shown that the modular approach has financial benefits by getting high numbers of the same module instead of developing specific solutions for each specific regional requirement. Here the simplicity of the module is the key driver cost reductions and economics of scale.
- Alongside this project the modules have been developed and tested in order to verify that these meet the requirements. Also a methanol cracker has been developed and verified and a biogas / natural gas reformer is under development (not verified yet).

In conclusion a feasible cost-efficient RES-FCHS system has been identified and in addition the system has been verified practically.

## 5.8 The lessons learned from the Danish wind - generator industry

When preparing the present project on RES-FC Market analysis, the European team behind its execution was engaged in discussions about lessons learned in similar transitions within European industry.

One of the striking success stories is about the development of the Danish wind-generator industry. Traditionally this industry has for about two decades had a market share of 40-50% - but is witnessing some reduction in this dominant position as other nations become aware of the potential of this sector of energy harnessing.

In fact about 40% of installed wind-generator capacity of the world at the beginning of 2007 originated from Danish producers.

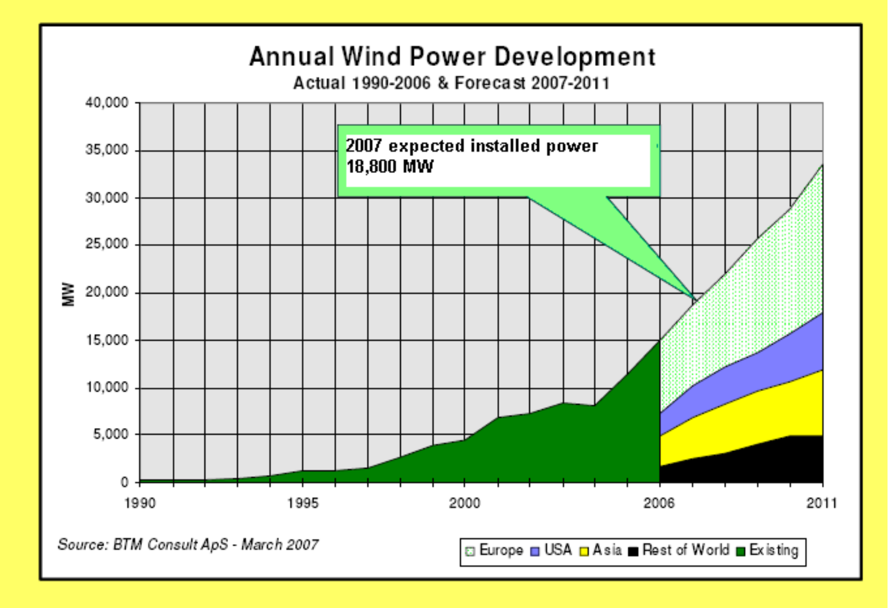
There are of course a number of reasons for this unusual development. One of the first important points to mention is the relatively early start by authorities, realised with a dedicated development funding and assistance in 1979-89. Danish producers were early enough to be able to grab hold in the “First mover” opening of the US market in 1982. The legislative assembly in Copenhagen supported these moves very strongly.

An important decision by Denmark was made when the Risoe Energy Research Institute was given the leading position in benchmarking and a subsequent quality control over the products that were created. The industry followed closely and a Federation of Danish wind generator producers was established.

On the other hand the extremely favourable conditions within the US market came to end in 1986. The Energy Ministry ordered some 100 MW installation in the following year and the producers started planning an upscaling of wind-generator sizes.

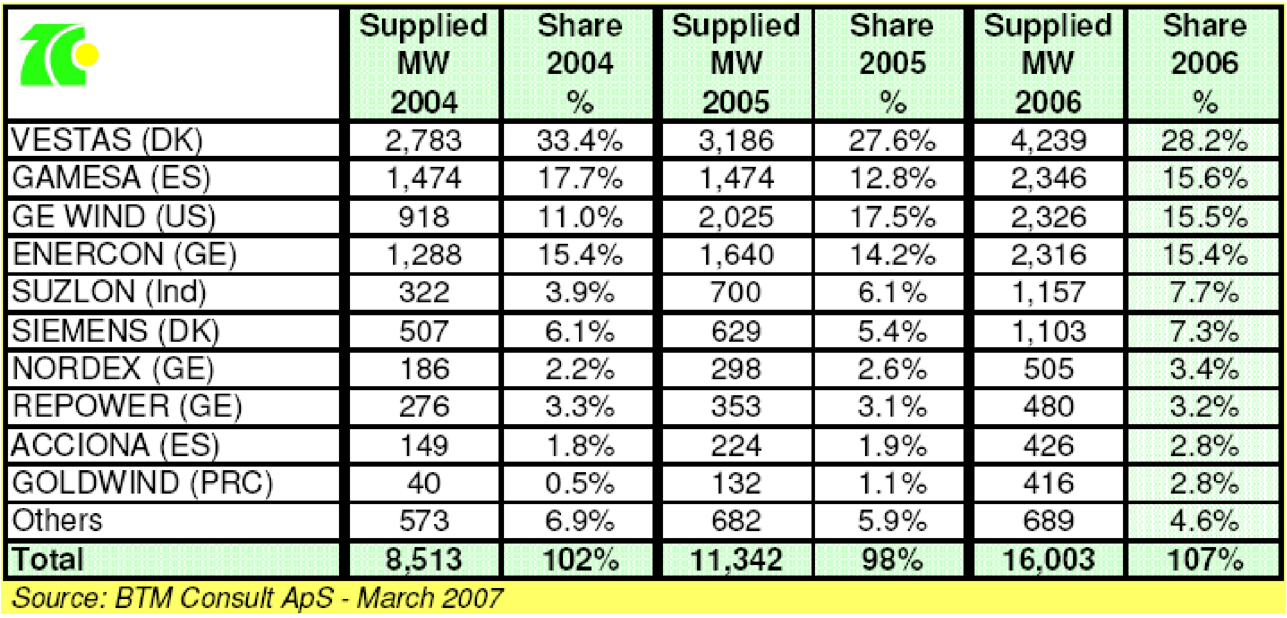
In a very thorough analysis by BTM Consulting Company last year it is concluded that the pathway the Danish authorities, in close cooperation with the industry, took already at the beginning of the development of wind – energy was crucial to the successes. The combination of research and development with the market developement is another key success factor as seen from BTM.

It has been very much in the spirit of this experience that the RES-FC Market project reported here has been striving to work. One of the conclusion of the BTM analysis of Danish wind-generator development has been that one of the main barriers or hindrances for success has always been a relatively low degree and shortage of opportunities for setting up demonstration experiments. This is exactly one of the challenging aspects of the present RES-FC Market project.



Source: BTM Consult ApS - March 2007

Fig 5.8.1. The diagram shows the development of annual wind power in the world including a forecast until 2011.



| | Supplied MW 2004 | Share 2004 % | Supplied MW 2005 | Share 2005 % | Supplied MW 2006 | Share 2006 % |
|---|---|---|---|---|---|---|
| VESTAS (DK) | 2,783 | 33.4% | 3,186 | 27.6% | 4,239 | 28.2% |
| GAMESA (ES) | 1,474 | 17.7% | 1,474 | 12.8% | 2,346 | 15.6% |
| GE WIND (US) | 918 | 11.0% | 2,025 | 17.5% | 2,326 | 15.5% |
| ENERCON (GE) | 1,288 | 15.4% | 1,640 | 14.2% | 2,316 | 15.4% |
| SUZLON (Ind) | 322 | 3.9% | 700 | 6.1% | 1,157 | 7.7% |
| SIEMENS (DK) | 507 | 6.1% | 629 | 5.4% | 1,103 | 7.3% |
| NORDEX (GE) | 186 | 2.2% | 298 | 2.6% | 505 | 3.4% |
| REPOWER (GE) | 276 | 3.3% | 353 | 3.1% | 480 | 3.2% |
| ACCIONA (ES) | 149 | 1.8% | 224 | 1.9% | 426 | 2.8% |
| GOLDWIND (PRC) | 40 | 0.5% | 132 | 1.1% | 416 | 2.8% |
| Others | 573 | 6.9% | 682 | 5.9% | 689 | 4.6% |
| **Total** | **8,513** | **102%** | **11,342** | **98%** | **16,003** | **107%** |

*Source: BTM Consult ApS - March 2007*

The table shows the market shares in 2004, 2005 and 2006. Notice that the summed up ratio of Danish companies is between 35 and 39%.

What is particularly important when looking at the development of the industry in Denmark, is that even when assuming certain market saturation tendencies in 2025 the industry is beginning to plan replacing obsolete systems of about 55.000 MW annually.

We now turn to a crucial question that has been a central one throughout our whole work in the project:

## 5.9 WHAT CAN BE LEARNED FOR RES-FCSH SYSTEMS TECHNOLOGY AND MARKET DEVELOPMENT FROM THE TECHNOLOGY AND MARKET DEVELOPMENT OF WIND ENERGY?

### 5.9.1. Introduction

### 1.1 Fuel cell technology development

Concerning the description on what shall be the focus in RES-FCHS system technology development seen from a fuel shell point of view is referred to the parts of this report specifically dealing with these issues. So these elements are not included in this part.

### 1.2 comparing wind energy and RES-FCHS systems

Wind energy has been chosen as a reference of successful technology and market development of a new energy technology. The reasons for choosing wind energy as an inspiration source are several:

- Very strong success on technology development with reduced costs and increased scale of the technology.
- Very strong success on market development with big growth rates and prospects of very big markets.
- A start position where profitability of end-user investment in the technology was not profitable, similar to the case for RES-FCHS systems.
- Both energy technologies are sustainable energy.

There are also differences between wind energy and RES-FCHS systems, which have to be taken into consideration, when evaluating the experiences from the wind energy technology and market development:

- Wind energy is an energy production technology - RES-FCHS systems are an end-user technology, which as an example can be compared to gas boilers.
- Wind energy technology development had a strong basis in small and medium sized companies, where there is a tendency of bigger companies behind parts of RES-FCHS systems technology development.

### 1.3 Methodology of analyzing what can be learned from the technology and market development of wind energy

The methodology of analyzing what can be learned from the technology and market development of wind energy is based on the inputs from persons playing a leading role in the technology and market development of wind energy in Denmark and internationally. Denmark is chosen, because Denmark was the place for the successful development of the modern wind energy technology and also the first place for a parallel successful market development.

The experts used as references are:

- Birger T. Madsen, now the owner of the leading market evaluation companies for wind energy, BTM Consult, was the former managing director of Vestas, the World´s leading wind turbine manufacturer, in the upstart of the company, and he was the chairman of the Danish wind manufacturers association for several years. Birger T. Madsens presentation: "What can be learnt from the wind energy development?", Vækstforum Midtjylland, Conference 14.11.2007, has been used as a main source of information.
- Lars Yde, B.Sc.E.E, participating in the technology development of wind turbines in the pioneer phase and later director of the HIH Wind Energy Academy for educating wind service staff. Lars Yde is now the leading technical expert of HIRC, and he thereby represents expertise in technology development in both wind energy and RES-FCHS systems.
- Professor T. I. Sigfusson, University of Iceland, playing a leading role in Iceland’s change to hydrogen, and he is the co-chair of the International Partnership for the Hydrogen Economy Implementation and Liaison Committee. Professor Sigfusson represents expertise on RES-FCHS systems technology and market development. His recent book, Planet Hydrogen – The Taming of the Proton, published in Oxford by Coxmoor Publishing  describes a number of the challenges faced by the transition to a hydrogen economy.

## 5.9.2. Framework conditions for technology development

### 2.0 Introduction

Denmark was the place, where the modern wind technology was developed. This happened even if the financial support given in countries as USA and Germany was higher than in Denmark. In USA and Germany big companies with big capacities in technology development were involved in developing wind energy technology. In Denmark it was private persons, smaller scientific institutions and small and medium sized companies, which were involved. But, anyway, they were the "technology winners". What can be learned from this experience, and can the experience be transferred to the technology development of RES-FCSH systems? This question has been a leading one in the work of the present team.

#### 5.9.2.1 Don't make technology development too difficult

Wind experience

Probably due to limited financial resources the Danish wind energy technology development was focused on not making the job more difficult than necessary. This meant that for several components to be used in a modern wind turbine standard well proven components were used, e.g. the gear box and generator. This meant that the development activities could focus on the important innovative components, e.g. the blades, the security systems connected to the blades, and the system performance. This again meant that parties from the existing metal and electric industry could take part in the technology development. When something went wrong (and it does) then it is also easier to identify, where it went wrong. Typically for the Danish development it was actually a carpenter, who developed the modern (Danish) wind technology concept.

In other countries technology development was dominated and took its out-spring from universities and R&D-departments in big companies, typically developing very innovative technology concepts, which it turned out could not deliver products to the market. Either the concepts did not work, or the machines were much too expensive. Another problem could be that the wind turbines were too big in the pilot phase making them expensive to develop, whereas in Denmark the turbines were small in the pilot phase.

Lessons to be learned:
KISS (keep it simple s.....), use standard components, where it is possible and keep focus on key elements of technology development.

Recommendations for RES-FCHS systems

RES-FCSH systems are different from a wind turbine, being an electro-chemical and not a mechanical process. RES-FCSH systems are based on innovative solutions for developing reliable and cost efficient fuel cells with a long lifetime. In developing RES-FCSH systems it is important to keep focus on key elements.

Developing the fuel cells is not limited to the use in RES-FCSH systems but in all applications, so this part must be seen in that context. As an example this can mean that this part of technology development is "out-sourced".

Another focus of technology development could be developing the total system of RES-FCSH systems and how to optimize the function, cost efficiency etc. of the total system, parallel to developing a wind turbine buying all components from (efficient) sub-suppliers, which is a strategy that has been applied by wind turbine manufacturers.

### 5.9.2.2 You don't know who will develop the winner technologies

Wind experience
In the pioneer phase of the Danish wind energy technology development there were several different technology concepts competing. Among those can be mentioned the Darieus Rotor (single blade around a vertical axis), "wind tunnel" concepts leading the wind to the blades, blades turning around a vertical axis, one-bladed, 2 bladed and the 3-bladed versions turning around a horizontal axis.

The (well known) winning concept with an asyncronus generator, gearbox and with 3 blades around a horizontal axis was developed by a Danish carpenter. Many of the other competing concepts were backed up by universities and big companies. The lesson is, no-one could foresee, what would be the winning concept. So it is very dangerous on beforehand to select the winner, typically based on the well known and big institutions/companies.

Also in an international context this lesson seems to be valid, with very big German and American companies and institutions being involved in wind technology development without much success.

The selection of the winner technologies took place through the market, the investors/end-users choosing the technologies, which had a reasonable price and was working in practise.

The lessons to be learned:
The development of the winner technologies is unpredictable, so keep the technology development open and let the market choose the winners.

Recommendations for RES-FCHS systems
The small scale of the RES-FCSH systems is an advantage in the sense that also small players potentially can take part in technology development. It is important in the technology development, support mechanisms etc. to keep them open also to small and medium sized companies (Vestas was once a small company), individuals and other small parties.

### 5.9.2.3 Open exchange of know how

Wind experience
In the pioneer phase of wind energy technology development there was a relatively open exchange of know how on technology development through network cooperation, open workshops etc. A reason to this was the limited capacity of the individual party making it important to cooperate. Another element was the attitude that the sector had to work together to have a future for the sector at all - in competition with other competing energy sectors.

This "solidarity attitude" was manifested in going together about common security standards in order to avoid the collapse of the whole wind energy sector due to security problems resulting in serious accidents. This strategy was followed in stead of keeping security system, e.g. brake systems integrated into the blades, as a secret/patent of each company. Other common standards were also developed, which made it easier to develop key components.

In the later stages of the wind technology development the open exchange of information has decreased in importance, due to stronger competition between the suppliers of wind turbines and due stronger capacity of each supplier to carry out technology development.

The lessons to be learned:
Keep exchange of know how on technology development as open as possible in the pioneer phase of development.

Recommendations for RES-FCHS systems
The RES-FCSH system sector has some way to go before the systems are competitive in the market compared to other energy systems, meaning that there is also an element of the theme of the survival of this sector. So there can be good reason for keeping an open exchange of know how to promote the sector as such in order to have a future.

Especially for small parties taking part in the technology development it can be a good idea to work together, including exchange of know how. In this aspect the EU Commission can potentially play an important role in promoting exchange of knowhow by arranging workshops, support networks and support trans-national R&D-projects, as it is already taking place in the Framework Programs, but this aspects might even be in-forced in future activities.

#### 5.9.2.4 Common technical standards - common test facilities

Wind experience
Above is mentioned the example of developing common standards on security systems for wind turbines. Another example is common standards for different kinds of calculations, e.g. for load calculations for blades.

When developing such common standards there is a need for a "neutral technical centre", which can facilitate the development of such standards, not being linked to any special interests. Such a "test facility centre" was established early in the technology development of wind energy in Denmark, and this centre has played an important role in the Danish technology development. EU already has established a fuel cell test centre at Petten in Holland (http://www.jrc.nl/publications/info_sheets_docs/Info%20Sheet%20Fuel%20Cell%20test%20Facility.pdf)

When developing common standards there are big potential risks that it can lead to bureaucracy linked to a slow standardization process and a danger of some people/interests are trying to monopolize the standards in favour of their own products.

Developing common standards can be an important way of communicating with other sectors, e.g. as the utility sector concerning what standards shall be used for delivering electricity from RES-FCSH systems to the grid.

The lessons to be learned:
Common technical standards and common test facilities are important for technology development.

Recommendations for RES-FCHS systems
The security issue is crucial to the development of RES-FCSH systems, so it is important to develop common standards in this field. The EU-Commission has also given this field of development substantial support through the FP-programs. This focus shall be maintained in the coming demonstration activities operating close to the end-users.

Test facilities using common standards shall also be used, either being European/national, and public/private.

#### 5.9.2.5 Financial support systems aimed at the investors/end-users - "SUPER $CO_2$-quotas"

Wind experience
Financial support systems aimed at the investors/end-users played a crucial role in technology development for wind energy. First the Danish 30%-grant to the investors in wind turbines helped to create a market. Later this grant was replaced by a favourable feed-in tariff, which in principle is preferable, because the grant element is linked to actual production. This Danish grant system facilitated the development of a reliable Danish wind energy technology operating on the market, but still small in scale.

As a parallel to a "decentralized" support systems as the 30%-grant to small individual investors, being a great success able to deliver a market very fast, can be mentioned the decision that the Danish utilities should establish 100 MW wind energy capacity. This was a very slow and in-efficient way of market development, even leading to much opposition against wind power in local communities.

In California was an implemented tax regulations systems and feed-in tariffs, which made renewable energy investments favourable and established a large scale market for wind turbines, which the Danish manufacturers were able to supply due to their track record on the Danish market. Wind turbine production by this changed from hand craft production to a more industrial production, reducing costs. It also lead to an up-scaling of the industry giving the wind industry more capacity to carry out technology developing activities, an important part being the up-scaling of the wind turbines, reducing costs of wind electricity production and increasing the energy production. So the flourishing European wind energy sector can thank the Californian energy policy of their success.

The lessons to be learned:
Financial support systems aimed at the investors/end-users plays an important role in creating a market, which can foster technology development.

Recommendations for RES-FCHS systems - "SUPER $CO_2$-quotas"
RES-FCSH systems are under normal market conditions not profitable for the end-user and thereby not profitable for the investors in the systems. To make it attractive for investors/end-users to invest in RES-FCSH systems there must be a substantial grant element.

It is proposed that such a grant element is established through "SUPER $CO_2$-quotas" devoted to RES-FCSH systems. The principle behind "SUPER $CO_2$-quotas" is to promote new $CO_2$-reducing technologies by giving an extra financial support in the initial technology phase, e.g. 10 x the normal $CO_2$-quota price. The rational behind the "SUPER $CO_2$-quotas" is that there is a multiplication $CO_2$-reducing effect linked to the technology development.

The multiplication effect is linked to emerging technologies, where the effect of the specific energy equipment is not only the concrete reduction of $CO_2$-emissions, but especially is the derived effect in terms of market developing of the technology leading to substantial $CO_2$-reductions, when the technology will be on the market. The "SUPER $CO_2$-quotas" can also be used for other new emerging $CO_2$-reducing technologies.

The "SUPER $CO_2$-quotas" shall be certified and tradable like other $CO_2$-quotas.

Lessons to be learned:
The "SUPER $CO_2$-quotas" can be used as an efficient and flexible strategy for technology development of RES-FCSH systems.

## 5.9.3. Framework conditions for market development

### 5.9.3.0 Introduction

3.0.1 Market development is regulated
Markets are not "free". Especially in the energy sector the markets are very much regulated, because energy is such an important factor in each society's development. Therefore the framework conditions for market development of wind energy and RES-FCHS systems are politically defined. This gives the potential to tailor the framework conditions, e.g. in order efficiently to promote technology development.

Technology and market developments are linked, or as the lessons from the wind energy technology and market development tells, they should be. It is important that the technology development has a market focus, in order to develop technology which relatively quickly can be introduced into the market place. It is also important that the market development is facilitating technology development, e.g. in a competitive market, where market players are forced to technology development to stay in the market.

3.0.2 Initial market development for wind energy

Denmark was the first country to establish a market (small!) for wind turbines from 1979 by giving the investors a 30% grant for investing in wind turbines. This market, together with other measures, established the basis for a Danish wind energy sector with a number of manufacturers.

California established in 1982-86 a big market for wind energy, which created the commercial basis for the global wind industry, not least the Danish wind industry being able to be "first mover", because of the experiences and references of the Danish market. After the Californian market collapsed the Danish wind market grew and other European countries as Germany and Spain established new and growing markets for wind energy.

The main markets in Germany and Spain copied the Danish system of fixed feed-in tariffs for electricity produced from wind turbines and delivered to the electricity grid.

### 5.9.3.1 Let the market select the technology winners

Wind experience

Major parts of financial support for Danish wind development was given through a 30% support to the investors of the wind turbines, all being private investors, typically people establishing local wind cooperatives or farmers.

With this support scheme it is the market, which chooses the best technology, and not a committee or similar, with lobbying interest, typically of existing larger companies. This "bottom-up" approach has shown to be most efficient in selecting the best technologies.

In the early stage of the market phase there were different technology concepts for wind turbines, e.g. the Darrieus-rotor, and only in Denmark 19 wind turbine manufacturers were competing in a small market. But the market selected the technology winner, being the well known modern wind technology concept of an asyncronous generator, 3 vertical blades and a gearbox. If committees had to choose the technology winners, this could have slowed down and likely mis-directed the technology development.

The lessons to be learned:
Let the market in an early stage of technology and market development chooses the winner technologies.

Recommendations for RES-FCHS systems

With the decentralized and limited scale of investor-investment RES-FCHS systems seems to be very well fit using the market for selecting the winner technologies. But the level of support has to be substantial, either through the feed-in tariffs for electricity produced, as being used for PV-systems in Germany, Spain Italy and other countries, or as direct financial support to the investor.

### 5.9.3.2 Subsidies for promoting the market development

Wind experience
In the beginning of the wind development in Denmark (and other countries) subsidies were given as public 30% financial support to the investor of the wind turbine - in order to establish a market. Later this was changed to legally regulated "over-prized" feed-in tariffs, where all electricity consumers pay the subsidy to the wind turbine investors. This has been supplemented with subsidies connected to renewable energy certificates or similar. You can also see the subsidies as a way of compensating the lacking payment of environmental costs etc. related to fossil fuel (and nuclear) electricity production.

The lessons to be learned:
Subsidies, e.g. "over-prized" feed-in tariffs, for promoting market development is necessary to establish a market for new energy technologies.

Recommendations for RES-FCHS systems
There is clearly a need for subsidies for establishing a market for RES-FCSH systems. It is recommended to give an "over-price" for electricity produced by RES-FCSH systems, similar to what is seen for PV and other renewable energy technologies.

As a new idea is proposed to give a "super $CO_2$-quota price", e.g. 10 times the normal $CO_2$-quota price due to the character of long term positive $CO_2$-reduction effect related to the development of new $CO_2$-reducing technologies. See also in part 2 of this chapter about this.

### 5.9.3.3 Strong public regulation of grid connection

Wind experience
A major barrier for establishing a market for wind turbines was difficulties for grid connection, and it is still a major barrier in many markets. Utilities often use their control and monopoly ownership to the electricity grid as a way to stop or slow down grid connection of wind turbines, referring to a limited capacity of grid for connection of wind turbines.

In Denmark this problem was solved wit strong public regulations demanding that the utilities have to reinforce the grid in order to make it possible to establish wind turbines.

Lessons to be learned:

Strong public regulation of grid connection prevents utilities from creating "technical barriers" for grid connection.

Recommendations for RES-FCHS systems
Grid connection of RES-FCHS systems can be expected to have problems in getting the right to grid connection and to electricity deliverance to the grid, most expectedly utilities referring to "technical problems" etc.

Public regulations of this field is recommended defining quality standards for electricity supplied to the grid from RES-FCSH systems and stating that RES-FCSH systems have the right to grid connection.

#### 5.9.3.4 Involve the "enthusiastic investors" in the market development

Wind experience
In Denmark but also in Germany civil people and the private sector were the dominant investors in wind turbines, also in the situation, where there was some technology and thereby financial risk connected to the investment, and the investment was not really profitable. But these private "enthusiastic investors" invested anyway, because they wanted to own a wind turbine (as many people will like to own a Mercedes, although it is an expensive way of car transportation). Investment in a wind turbine was a way to show your interest and concern for the environment.

Now the "enthusiastic investors" don't play an important role, although investment funds involving smaller investors play an important role in Germany

The lessons to be learned:
"Enthusiastic investors" can be used as a way to establish a market, even if the market situation is not that favourable.

Recommendations for RES-FCHS systems
With the positive "aura" connected to hydrogen and fuel cell technology, especially in combination with renewable energy, "enthusiastic investors", e.g. as private house owners, shall be used as a strategy for promoting the market of RES-FCHS systems.

This market segment is probably not very big for RES-FCHS systems (as it is for Mercedes), but it can potentially play an important role in the initial development of the market.

#### 5.9.3.5 Testing centres controlling minimum quality standards, e.g. of security

Wind experience

Independent testing centres with a special focus on security of wind turbines, e.g. with demands of brake systems to prevent wind turbines in over-speed of the wings, played an important role in raising the investors and the authorities trust in wind energy technology.

Another important issue is quality control of the electricity output. So in order to obtain public financial support the wind turbines had to be approved by the testing centre. When an accident happens with a wind turbine, it is also important to have an institution to evaluate the accident and to make proposals for regulations to prevent more accidents.

But it is most important that such testing centres are flexible, non-bureaucratic and don't see their role in regulating technology development as such, but in stead let the market select the best technologies, and the test centres serving the market development.

The lessons to be learned:
Testing centres play an important role for market development in controlling minimum quality standards, e.g. on security issues.

Recommendations for RES-FCHS systems
For RES-FCSH systems trust to the security of the systems is playing a very important role for the end-users, investors, utilities and authorities. So their must be independent testing centres or similar for such systems giving very clear and convincing guidelines for installation, maintenance etc. of RES-FCSH systems. Such a system/institution already exists in connection to gas heating installations, so it is recommended to involve these institutions in developing guidelines for installation, maintenance etc. of RES-FCSH systems. In Denmark The Gas Technical Centre is working with preparing security standards etc. for hydrogen gas installations.

EU has put an effort in developing guidelines on security etc. in its R&D-activities, including programs as: HYSAFE, HYSAFETEST, HyCourse, Marmony, HYFIRE, FCTES, FCTEDI, FCTEST and HYPER. This means that there is a strong fundament for developing and implementing security, quality standards etc.

### 5.9.3.6 Investor trust and "consumer labelling"

Wind experience
The independent testing facility described above has had an important task in "consumer labelling" of wind turbines, e.g. with respect to the wind turbines power curve, describing the relation between wind speeds and power output. This information is crucial for investors in wind turbines. By making these calculations according to recognized standards there is not a insecurity among investors and other about the actual energy production from wind turbines, and this is crucial, when developing a market.

Lessons to be learned:
"Consumer labelling" plays an important role in promoting the market development.

Recommendations for RES-FCHS systems
It is recommended that standardised "consumer labels" are made for RES-FCSH systems, the "consumer labels" being made by independent testing facilities. Among the key elements to label are: Energy efficiency of the fuel cell systems, the demands to the cleanness of the fuel and the life time of fuel cell membranes.

### 5.9.3.7 Developing ownership models to RES-FCSH systems

Wind experience
The early markets for wind turbines in Denmark (and also in Germany) were totally dominated by private small investors, who were willing to take the risk of investing in a new innovative technology as wind energy. Typically the utilities and professional investors were absent. The private investors were involved in several ways:

- "Ethical investors" with a main motivation of supporting the environmental aspects, broader society perspectives of creating employment etc., typically establishing cooperatives with other local private persons with the same motivation.
- Independence of oil and fossil fuels as the main motivation of investment.
- Enthusiasm for new technology
- Making business, in creating investment funds investing in wind turbines in USA and other places, using tax regulation as a way to improve the profitability of the investment.

In a later stage of the market development of wind energy the European market is increasingly being dominated by especially large utilities and energy companies and also big private investors and banks, and the smaller private investors are playing an insignificant role.

Lessons to be learned:
Developing different ownership models play an important role in the market development.

Recommendations for RES-FCHS systems
RES-FCSH systems have a different character than wind energy, RES-FCSH systems being more an end-user technology covering the energy needs of the house owner, while a wind turbine is an energy producing technology as such.

But anyway the experience from the pioneer development of wind energy with smaller private investors playing a key role can be taken into consideration, when preparing how to facilitate the development of the market of RES-FCSH systems.

It is proposed to follow a diversified strategy for ownership and investment in RES-FCSH systems with testing in parallel of different models:

- End-user investment similar to investment in a gas boiler for a house. The difficulty in such a strategy for systems based on electrolysis and a hydrogen grid systems to each individual building/consumer; you need that all/most end-users want to invest in RES-FCHS systems. A way to promote this investor concept could be a municipality deciding to establish a new housing area, where the energy supply shall be based on RES-FCSH systems. The municipality of Herning, Denmark, has decided to establish such a "H2PIA-town area", because the municipality wants to brand itself as a hydrogen town.

- The "enthusiastic investors" can play a role in the early pioneer phase of the market development, also in a phase where not all conditions for creating a well functioning market is in place.
- Energy service companies (ESCO) investing and owning the RES-FCSH systems delivering heat to the house owner and electricity to the grid. ESCO's could, as an example, be established in cooperation between suppliers of RES-FCSH systems and investment companies. Suppliers of (hydrogen) gas could also potentially have an interest of being in the role of being ESCO for RES-FCSH systems securing the need for their gas supply.
- A similar approach could be the utility owning the RES-FCSH systems delivering heat to the house owner and electricity to the grid, seeing the systems as "normal" energy producing units similar to large electricity producing plants, but just with a decentralized technology. The utilities can have motivation for involvement in order to maintain their strong position of energy production also in a market with decentralized energy producing technologies.

With the experience from the wind development of the conservatism of big investors and utilities in investing in new energy technologies, it is important to work actively for involving smaller private investors in the development of the market for RES-FCSH systems, maybe with a perspective that the bigger (and conservative) players later can play a leading role in market development.

It is recommended to include the ownership/investor aspects in future demonstration projects, because this aspect is a main element in developing a market for RES-FCSH systems.

### 5.9.3.8 Developing ownership models for hydrogen production and distribution systems

Wind experience

RES-FCSH systems based on hydrogen gas have a supplementary challenge compared to wind energy in the sense that there has to be identified parties with an interest in owning, investing and operating the hydrogen production (electrolysis) and distribution systems. In this respect there are no direct experiences from the wind energy sector that can be used, but the general experience of the importance of developing ownership models is also valid in this context.

As a parallel can be seen the importance of developing clear roles and regulations of the outbuilding of the electricity grid connection for wind energy. As positive examples can be mentioned the regulation for offshore wind energy development in Denmark, where the public transmission company is obliged to out-build the transmission system for receiving the electricity produced from the new offshore wind parks.

Recommendations for RES-FCHS systems
There are several potential parties taking the role of owning, investing and operating the hydrogen production and distribution systems. For the Danish demonstration project, "H2PIA" with planned 200 dwellings supplied with hydrogen gas from an electrolysis plant, a private producer and supplier of industrial gasses want to establish and operate the electrolysis plant. The regional public (natural) gas distribution company wants to own and operate the hydrogen gas distribution system.

So there are already existing parties, who potentially could take the role of owning, investing and operating the hydrogen production and distribution systems. But it is important to test different models in different contexts and countries.

Lessons to be learned:
Potential parties, e.g. producers of industrial gasses and gas distribution companies, shall be involved in developing models of ownership and operation.

#### 5.9.3.9 Public planning - global scenario

Wind experience
The Danish government included relatively early (in 1988) ambitious goals for wind energy development with 10% of all electricity consumption being covered by wind in year 2000. This was considered unrealistic by many parties, especially among utilities. But this goal, in the beginning only being a scenario, has played an important role for the ambitions for the Danish wind energy sector and also in relation to other countries governments, seeing that Denmark officially had ambitious goals.

Later this Danish strategy was directly copied for "Wind Force 10", which was a global scenario for wind covering 10% of electricity consumption in year 2017, developed and promoted by EWEA (European Wind Energy Association), Greenpeace International and Danish Forum for Energy and Development, the latter being the initiator. The scenario was communicated on the UN Climate Top Meeting in 1998 in Buenos Aires and globally with great success, for the first time creating a global scenario for wind energy development. It has later shown that the scenario is realistic, even being too pessimistic.

Lessons to be learned:
Public planning with clear and ambitious goals is important for developing markets.

Recommendations for RES-FCHS systems
Binding regional/national targets for RES-FCSH systems can play a crucial role in the development of RES-FCSH systems markets. This will give a framework for policy development and will also make it possible for manufacturers of RES-FCSH systems to allocate resources to technology and market development.

It could also be relevant to describe a European market scenario for RES-FCSH systems, divided into the different potential technologies and describing relevant measures to be implemented to create the market.

### 5.9.3.10 Financing arrangements

Wind experience
To establish an efficient market it is important with well functioning financing arrangement and a good cooperation with financial institutions. The financing sector shall have a good in-sight into the technology and the arrangements around the technology as independent testing, technical guarantees from the suppliers of the wind turbines, service arrangements etc. By nature the financing sector is conservative, when it comes to financing new technologies, and it takes time to overcome this conservatism. Therefore it is the experience from the wind sector that it is important in an early stage of development to establish a close cooperation with the financing sector.

On the other hand when the financing sector gets well acquainted with the wind energy sector, then it can play a leading facilitating role in promoting the market development, as it can be seen in Spain, where banks are active investors and owners of large scale wind energy development.

Lessons to be learned:
Financing arrangement and cooperation with financing institutions is important for market development.

Recommendations for RES-FCHS systems
For investors in a new house it is crucial that the investment of the RES-FCSH system can be integrated into the financing packet of buying the house, e.g. low cost real estate loans. The financing aspects of RES-FCSH systems must be taken into consideration in an early stage of market development.

## 5.9.4. Resume  of recommendations for RES-FCSH systems technology and market development

Although the technologies and markets of wind energy and RES-FCSH systems have differences, it is the estimation in this report that the lessons learnt from wind energy technology and markets develop also can be used for RES-FCSH systems.

It is important that the "infra-structure" of technology and market development, which is closely inter-linked, is covering all main themes and the different themes are mutually supporting. One element, e.g. public regulation of grid connection, missing would mean that the market will not function.

It is important that there is a "body", which takes responsibility of securing technology and market development, typically being an authority. Under the actual terms this "body" will typically be a national or regional authority. Actively using the European angle could also play an important role in the technology and market development of RES-FCSH systems. The advantage of the European angle could be a "pooling effect" with respect to:

- Technology development, involving a broader "innovative pool".
- A larger aggregated market. Making it easier to reach an effect of scale.
- Involving economic sources from more countries, making it possible to create a larger market.

Below the resume of recommendations for RES-FCSH systems technology and market development.

| No. | Measure | Recommendations |
|---|---|---|
| **Framework conditions for technology development** | | |
| 2.1 | Technology development | KISS - use standard components, where it is possible and keep focus on key elements of technology development. |
| 2.2 | Selection of winner technologies | The development of the winner technologies is unpredictable, so keep the technology development open and let the market choose the winners. |
| 2.3 | Exchange of know how | Keep exchange of know how on technology development as open as possible in the pioneer phase of development |
| 2.4 | Common technical standards | Common technical standards and common test facilities are important for technology development. |
| 2.5 | Financial support systems | Financial support systems aimed at the investors/end-users play an important role in creating a market, which can foster technology development. |
| | "SUPER $CO_2$-quotas" | The "SUPER $CO_2$-quotas" can be used an efficient and flexible strategy for technology development of RES-FCSH systems. |
| | | |
| **Framework conditions for market development** | | |
| 3.1 | Selection of the technology winners | Let the market in an early stage of technology and market developments choose the winner technologies. |
| 3.2 | Subsidies and the market development | Subsidies, e.g. "over-prized" feed-in tariffs, for promoting market development is necessary to establish a market for new energy technologies. |
| 3.3 | Strong public regulation of grid connection | Strong public regulation of grid connection prevents utilities from creating "technical barriers" for grid connection. |
| 3.4 | Investors | "Enthusiastic investors" can be used as a way to establish a market, even if the market situation is not that favourable. |
| 3.5 | Quality standards | Testing centres play an important role for market development in controlling minimum quality standards, e.g. on security issues. |
| 3.6 | Investor trust | "Consumer labelling" plays an important role in promoting the market development. |
| 3.7 | Ownership models - RES-FCSH systems | Developing different ownership models play an important role in the market development. |
| 3.8 | Ownership models - $H_2$ production and distribution | Potential parties, e.g. producers of industrial gasses and gas distribution companies, shall be involved in developing models of ownership and operation. |
| 3.9 | Planning | Public planning with clear and ambitious goals is important for developing markets. |

|  |  |  |
|---|---|---|
| 3.10 | Financing | Financing arrangement and cooperation with financing institutions is important for market development. |

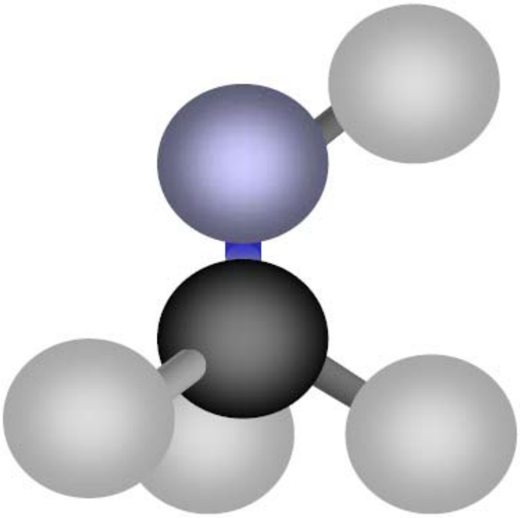
## 5.10 Cost reductions in the Methanol Pathway by changing focus

As we approach the end of this present work-package and having reported the various important lessons to be learned from the Danish wind generator industry we will for a while turn to an alternative pathway for the sake of completeness.

Previously the project was focused on using LT-PEM cells operating on pure hydrogen, in order to obtain a critical mass of fuel cells. The hydrogen could be produced through reformation of biogas, Methanol/ethanol or by electrolysis of water. Recent studies in the project have however realized that fuel cells with onboard methanol reformers could potentially be a feasible solution, and hence it makes sense, for the sake of completeness, to study the methanol pathway from producer to end user. In this case the end user also has to be familiar with local methanol storage, as the consumption for 0,5 KWe Fuel Cell will utilize around 1,5 ton of methanol per year, if the fuel cell run 100% load. Methanol is already heavily traded on the world market, but the distribution to the end user is non-existing.

### *What is Methanol*

Methanol is a hydrocarbon, comprised of carbon, hydrogen and oxygen. Its chemical formula is $CH_3OH$. Methanol is an alcohol and is a colourless, neutral, polar and flammable liquid. It is miscible with water, alcohols, esters and most other organic solvents. It is only slightly soluble in fats and oils

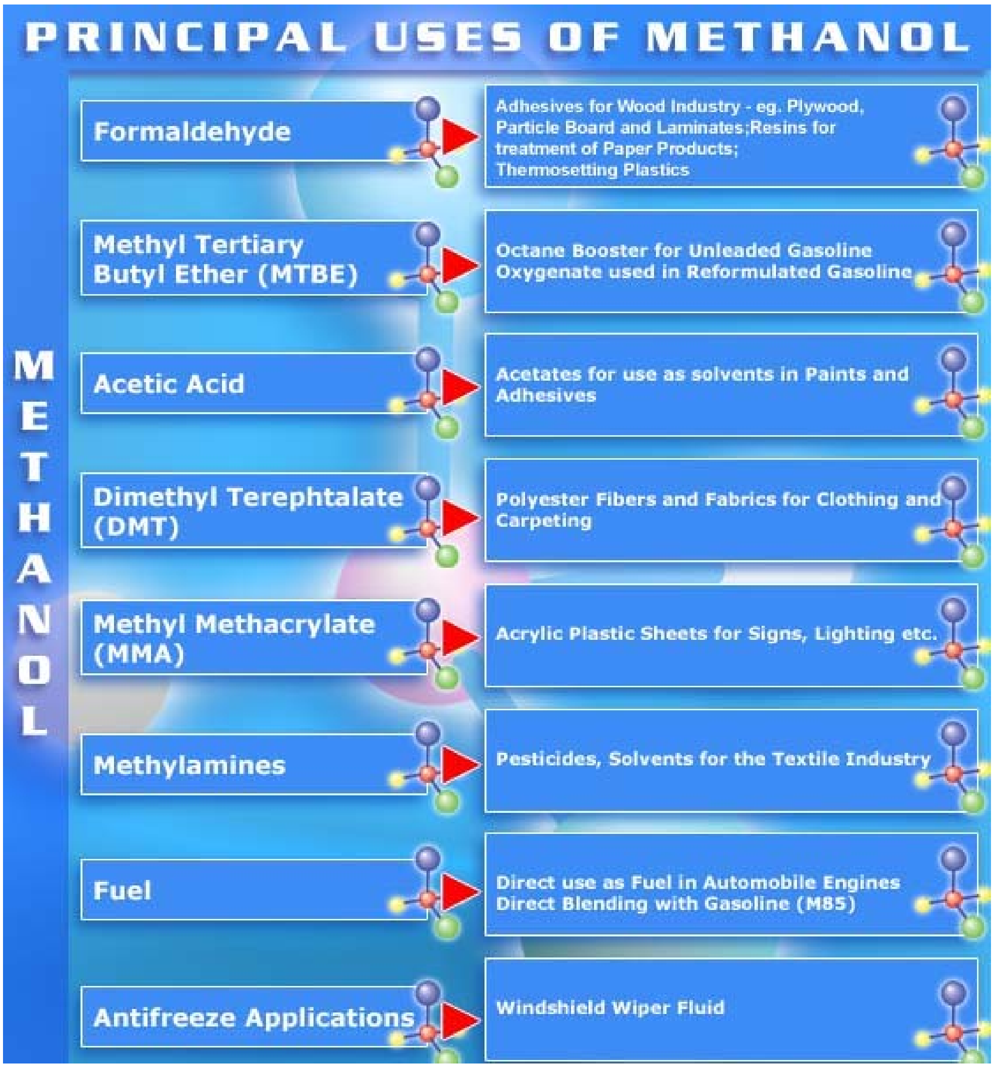


| | |
|---|---|
| Boiling Point: | 64.6 $^{o}$C |
| Freezing Point: | -97.6 $^{o}$C |
| Molecular Weight: | 32.04 g/mol |
| Higher Heating Value: | 22.7 MJ/kg |
| Lower Heating Value: | 19.9 MJ/kg |

**Applications for methanol**

The primary uses for methanol are the production of chemical products and use as a fuel. It is also being used increasingly for waste water treatment and for producing biodiesel. Methanol is used in the production of formaldehyde, acetic acid and a variety of other chemical intermediates which form the foundation of a large number of secondary derivatives. These secondary derivatives are used in the manufacture of a wide range of products including plywood, particleboard, foams, resins and plastics.

Much of the remaining methanol demand is in the fuel sector, principally in the production of MTBE, which is blended with gasoline to reduce the amount of harmful exhaust emissions from motor vehicles. Methanol is also being used on a small scale as a direct fuel and it is fuel for fuel cells. Methanol can also be used as a fuel in ICE engines, and in 1980's almost 100 methanol refuelling stations were delivering methanol to around 15000 cars in California running on almost pure methanol.



PRINCIPAL USES OF METHANOL

METHANOL

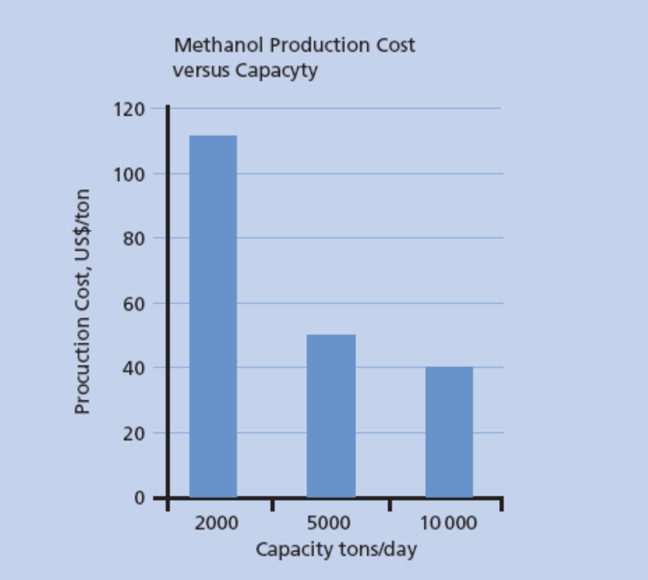
| | |
|---|---|
| Formaldehyde | Adhesives for Wood Industry - eg. Plywood, Particle Board and Laminates;Resins for treatment of Paper Products;<br>Thermosetting Plastics |
| Methyl Tertiary Butyl Ether (MTBE) | Octane Booster for Unleaded Gasoline<br>Oxygenate used in Reformulated Gasoline |
| Acetic Acid | Acetates for use as solvents in Paints and Adhesives |
| Dimethyl Terephtalate (DMT) | Polyester Fibers and Fabrics for Clothing and Carpeting |
| Methyl Methacrylate (MMA) | Acrylic Plastic Sheets for Signs, Lighting etc. |
| Methylamines | Pesticides, Solvents for the Textile Industry |
| Fuel | Direct use as Fuel in Automobile Engines<br>Direct Blending with Gasoline (M85) |
| Antifreeze Applications | Windshield Wiper Fluid |

http://www.ttmethanol.com/web/enduses.html

**Methanol Production**

In 2004, the worldwide demand for methanol stood at 32 million tones. Although virtually any hydrocarbon source (coal, petroleum, naphtha, coke, natural gas, biomass etc.) can be converted into methanol via derived syngas, natural gas accounted for some 90% of the feedstock used for methanol production. Most existing plants have capacities from 100,000 to 800,000 tons per year. In the past the plants were generally located close to large methanol consuming units in United States or Europe. However, with increasing prices of natural gas in these regions, the methanol plants have closed down, and moved to regions with plenty of cheap natural gas as Chile, Trinidad, Qatar, Saudi Arabia and Indonesia. The new plants that are under construction are really mega plants in the sizes of up to 3,500,000 tons per year, and such plants located in regions with cheap natural gas, can produce methanol at a very low price, due to economy of scale.

Since 1995 the capacities of methanol plants have been increased from 2,000 t/d to 5,000 t/d in 2003 and will rise further to 10,000 t/d in the near future. The companies operating "Mega" plants are experiencing a tremendous reduction in production cost ex gate from about US$ 110/t to 50/t and ultimately less than 40/t. The conversion of natural gas to methanol and downstream petrochemicals is highly economic on a natural gas price level below US$ 1/million BTU. Some regions such as the Middle East, locations in South America or Africa allow for natural gas prices of between US$ 0.2 and 0.7/million BTU, compared to an oil price of between US$ 12 and 14/barrel. (http://www.lurgi.com)



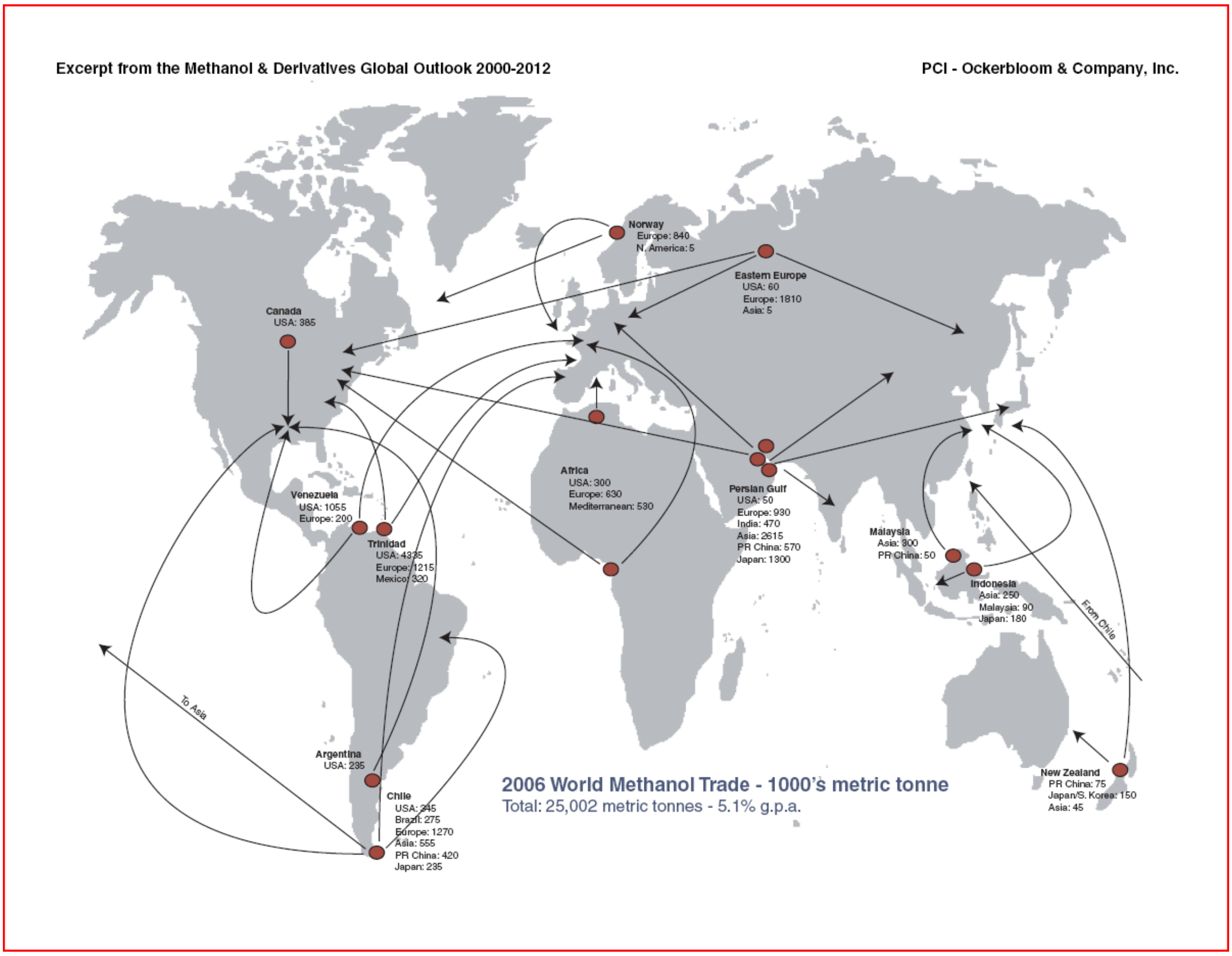
### Methanol Storage and Distribution

As methanol is a liquid like gasoline, refueling stations dispensing methanol will be almost identical to today's gasoline fueling stations, reflecting very little change to consumer's habits. In general methanol has to be distributed as diesel, gasoline and fuel oil is distributed today. Today already, methanol is a widely available commodity with extensive distribution and storage capacity in place. More than 500,000 tons of Methanol are presently transported each month to diverse and scattered users in the United States alone; either by rail, boat or truck. Another means of transporting large quantities of liquids, and one which is also extensively used for oil and natural gas is via pipelines. At present, methanol pipelines are only viable in regions where major methanol producers and users are concentrated in close proximity, such as on the Texas Gulf Coast between Houston and Beaumont. For long-distance transportation the, the volumes of Methanol to be transported are generally too small to justify the investment in a pipeline. In the future, if methanol has a real breakthrough as a fuel, it will be transported and distributed by pipelines. Technically, transporting methanol through pipelines does not pose any problems. When methanol is produced in remote locations where cheap natural gas is available, it is shipped throughout the world by dedicated methanol ocean tankers which ranges in sizes from 15,000 to almost 100,000 DWT. When transported in such large vessels, the cost of shipping methanol is very little. Once delivered, methanol can easily be stored in large quantities like petroleum in tanks with capacities exceeding 12,000 tons. Such tanks can be constructed in a variety of materials, including carbon steel and stainless steel. In areas for new housing, a cluster of houses with methanol fuel cells, can either have their own storage tank in a size of 1 ton, or share a common storage, and distribute the methanol to the individual house by small pipelines.

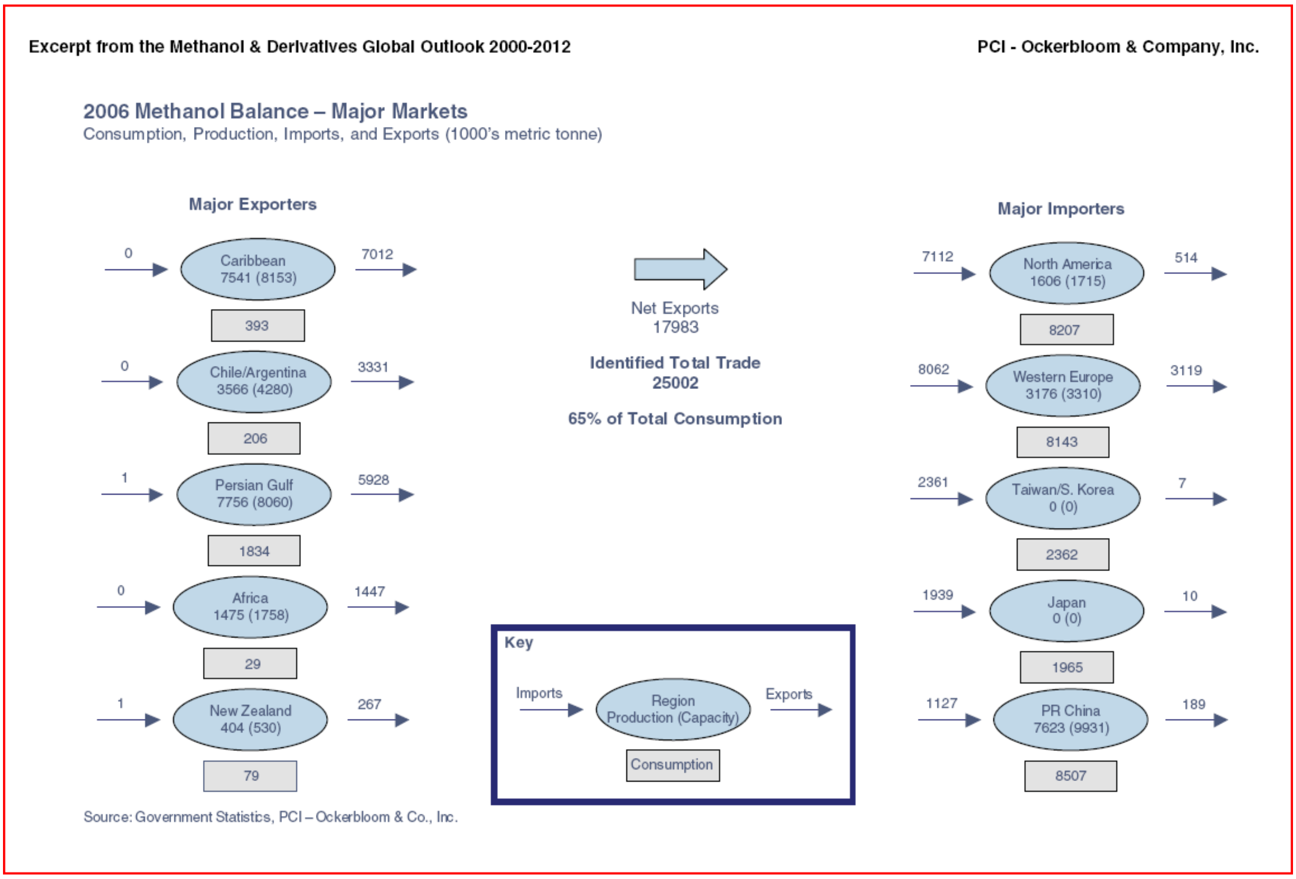
Methanol Tanker

## Trading and pricing of Methanol

Methanol is traded all over the world in large quantities, and hence methanol can easily be delivered all over the world. When the production capacity is balanced with the demand for methanol, the world methanol price will reflect the production cost from the most expensive plants. This will typically be old plants located in regions with moderate prices of natural gas, as many plants in regions with high natural gas prices already have closed down. The methanol production is however controlled by large companies as Methanex, who has a market share in the range of 20% of the world production of Methanol, and hence the price can be somewhat controlled.



Methanol Trading Chart



Source: Government Statistics, PCI – Ockerbloom & Co., Inc.

The Methanol Balance

From the above chart one can conclude that the majority of the produced methanol (>65%) is being traded, and hence it's is accessible for potential end users.

Chemical Market Associates has just completed the 2008 World Methanol Analysis, and the following is stated with respect to Supply and Demand:

SUPPLY:

For the five-year period beginning in 2008, nearly 26 million metric tons of new capacity has been announced in an industry with an average demand of about 47 million metric tons per year across the same timeline—over 50 percent of current methanol capacity is under threat from new, low-cost capacity. Other units are under study in Azerbaijan, Algeria, Russia, China and Iran. Much of this newly planned capacity is not methanol demand driven and is set to flood the industry with overcapacity by the 2009/2010 timeframe.

DEMAND:

CMAI predicts for the next five years overall methanol demand will increase significantly. However, it is witnessing growth in some regions/segments and decline in others. The largest absolute growth for methanol in the future will be fuelled by the Middle East and

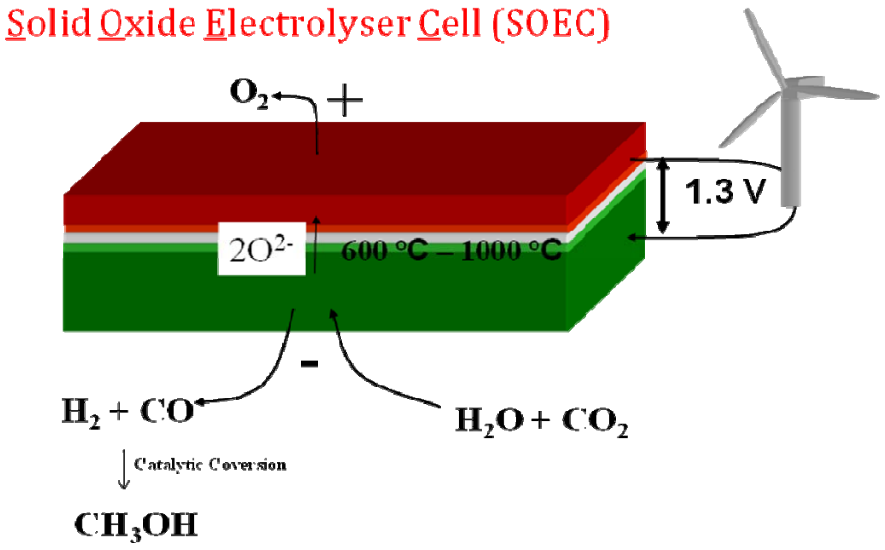
Northeast Asia, most notably China, as this country continues to build infrastructure to support its very strong economic development. The Middle East will witness extensive growth as well, but in most all cases, new methanol and derivative demands will be for export to the major consuming centres of North America, Europe and Asia.
http://www.cmaiglobal.com

### The production of Renewable Methanol

Properly the most viable way of producing renewable methanol is through biomass gasification, and several projects on this topic are announced. In Germany the company Choren has just finalized the construction of a demonstration plant that will convert biomass through gasification into Diesel. Actually the plant could have been simpler if the output had been methanol instead of diesel, but the company is targeting diesel engines. Methanol production compared to diesel from a gasification process, is both on capital and technology an easier task. There is however no market for bio methanol yet. The production cost of biomethanol compared to methanol from stranded natural gas in rural areas, will however be much more expensive for many years. The production of methanol through a gasification process, really benefit from economy of scale, and hence it's doubtful if smaller decentralized production unit ever will be able to compete.

### Future small-scale de-central methanol production technology

In theory a fuel cell (SOFC) can be operated in reverse, and feed with water, carbondioxide and electricity. This mode will be used when the electricity price is low, and when the price is high, it will convert the produced methanol back into electricity.



This concept is however in it's very early states, and requires many years of further development, before demonstration at end users can take place. The Danish Company

Risø is among the frontrunners in this technology, and has already demonstrated in the lab that a SOFC can be used for hydrogen production from steam and electricity. From a thermodynamic point of view this process is superior compared to traditional alkaline electrolysers.

We have previously studied the possible methanol pathway in Iceland where a combination of renewable hydrogen and the use of $CO_2$ from the metals industry are being planned to form the basis for a methanol fuel.

**Conclusion**

Methanol is an excellent fuel that is easily available all over the world and easy to store. Hence it will be no problem to use methanol as a fuel in various applications of fuel cells, from an availability point of view. There is however not a market for renewable methanol, and the price of renewable methanol is expected to be higher than fossil methanol, even when accounted for $CO_2$ credits. It is however suggested that the fuel cell market shall be kick started using fossil methanol, as this is easily available and easy to reform into hydrogen. As the methanol pathway is based on very mature technology, cost reduction from a technological point of view will be through economy of scale, by construction larger and larger plants. Furthermore cost reductions will be obtained by locating new plants in areas with cheap natural gas. The above mentioned reductions are reduction in production cost, but the cost for the end user will be set by the balance between demand and methanol availability.

## 5.11. Concluding remarks by work package leader.

The work package just concluded bears witness to the cooperation of the RES-FC Market team across Europe. Contributions are from 7 teams, evenly spread over subject areas that were intended for analysis.

The dialogue that had to be undertaken to unify the views of the different regions involved proved very important to the project as a whole.

Most importantly the team has managed to identify areas and technical issues all down to component level, where cost savings can be achieved with a resulting lowering of the market prices.

One of the unique features of our cooperation has been the opportunity to gather valuable information from the energy transition that took place in Denmark with the introduction of wind-generators into the energy industry. This work package contains recommendations resulting from a careful examination of lessons to be learned from the Danish experience.

These findings contain valuable information which the team originally set out to gather and can form the foundation of much more detailed work for paving the way for residential fuel cells in the area covered and for that matter world-wide.