EVS27
Barcelona, Spain, November 17-20, 2013

Next generation range extension – 2 glimpses of the future

Høj, Jens Christian Lodberg[1*]; Agerskov, Mai Louise; Jensen, Mads Friis[2]; Lading, Poul[3]
[1]*Insero E-Mobility, Chr. M. Østergaards vej 4a, DK-8700 Horsens, jclh@insero.dk*
[2]*Serenergy, Majsmarken 1, DK-9500 Hobro, mfj@serenergy.com*
[3]*RadiJet, Messingvej 50, DK-8940 Randers SV, poul.lading@radijet.dk*

Abstract

The electric revolution of mobility has left the cradle and is expected to breach the barrier of mass scale commercialisations within the next 3-5 years. To achieve that goal, the issue of range must be resolved. Especially plugin hybrid vehicles address this topic with a combination of batteries and a range extender. Range extender technologies hold a large market potential for the coming years and with the third generation, the possibility of zero emission range extenders exist. These solutions are based on new fuel cell technologies or multi fuel radial jet turbines and will fuel the vehicles of the future.

Comparisons between a High Temperature Polymer Electrolyte Membrane (HT-PEM) Fuel Cell running on methanol and a Radial Jet Turbine with multi-fuel capabilities show that each of them have potential capabilities that make them relevant as solutions for the future EVs. The HT-PEM has a high efficiency and utilizes an existing infrastructure where the Radial Jet Turbine is very compact and extremely flexible when it comes to fuel choice. Both technologies hold interesting potentials but are however currently challenged by the cost of market introduction for new technology and a short track record. With the search still going for a supplement to gasoline, they are however interesting possibilities with their utilization of clean liquid fuels. Furthermore they could together support the introduction of Methanol as an overall fuel for transportation.

Keywords: 3rd generation range extender, Radial Jet turbine, HT-PEM, Fuel Cell,

1 Introduction

The current range of EVs covers in average 80-90 % of most people's needs in most countries. However the most common explanation of not buying an EV is that the range isn't sufficient. [1] That is one of the major reasons why the industry is now turning to range extended vehicles as their main focus – latest with the release of the BMW i3 concept with a range extender [2].

Table 1: Generation types of range extenders

Generation	Description	Producer example
First generation REX	Standard off-the-shelf engines (mainly 3-4 cyl.) being used as REX in order to keep costs down and quickly get solutions out on the road to prove the potential market.	All major manufactures
Second generation REX	Combustion engines designed to work as REX means that they have been optimized to be highly effective and compact. Generally smaller (16-50 kW) than first generation REXs [2].	Polaris, Austro Engine, Lotus, Getrag
Third generation REX	New types of energy production technology, highly different from the existing solutions. Mainly turbines and fuel cells in this segment. Sized at about the same capacity as second generation REXs.	Capstone, Serenergy, RadiJet, Bladon Jets

The development of the range extender (REX) is starting to become an industry since the performance of such an energy source differs from a regular combustion engine. The main source for this is, the REX can be driven constantly at the most energy efficient level since its main purpose is to produce electricity for either propulsion or the battery.
Currently three generations of range extenders are seen in different levels of maturity (see table 1) [3]

In this paper, two technologies for third generation REX will be described and evaluated with the performance and potential to become CO_2 neutral. The future realization of the two technologies will also be described in order to estimate a market entry. The conclusion of the paper will sum up the two technologies and their potentials for bringing forward the automotive industry into a zero emission era.

2 Technology Review

2.1 HT-PEM Methanol Fuel Cell

The system described in this section is a liquid cooled High Temperature Polymer Electrolyte Membrane (HT-PEM) fuel cell, using green methanol as the energy carrier. The system is developed and produced by the company Serenergy. Currently the system is for the first time being integrated in an EV in the MECc project, funded by the Danish Energy Technology Development and Demonstration Program [4].
Besides the electricity production, heat from the liquid cooling loop is utilized for cabin heating and cooling.

A liquid cooled design has a number of advantages compared to an air-cooled design:

- Higher power density is possible due to excellent thermal distribution in cells and stacks.
- Utilization of waste heat is made simple thereby increasing overall efficiency.
- Excellent thermal distribution and lower air-flows allows higher durability.

The HT-PEM fuel cell platform distinguishes itself from competing fuel cell systems through the usage of a higher temperature in the cells and an intelligent design of the reformer system that allows for both cheap and effective reformation of methanol.

To increase the efficiency of the system, the waste heat from the fuel cell is used in two connected systems – the reformation of methanol into hydrogen and for cabin heating/cooling (see figure 1).

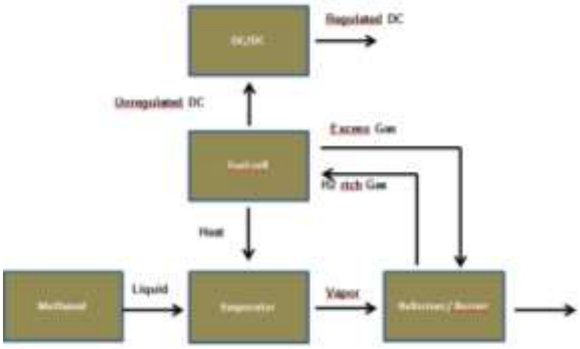

Figure 1 - Reformer/Fuel cell integration

With a working temperature around 150 °C, the excess heat provided by the HT-PEM can be used in a heat pump system to provide both cooling and heating in the cabin [5]. In order to achieve these targets, the Balance of Plants (BOP) is an important aspect to control and is one of the key areas where the technology is now evolving. All parts of the system – evaporator, reformer and fuel cell – must run as well as possible to secure the energy output, life time and efficiency.

Further benefits include [6]:

- Higher CO-tolerance causes for a system with higher durability.
- Higher reaction rate for the cells due to a faster electrochemical kinetics causing a more compact system.
- Less need for very expensive catalysts causing a potential lower price of the fuel cell.

The usage of methanol as the energy carrier is caused by three significant reasons:

- The use of a fluid energy carrier allows for the utilization of the existing infrastructure.
- Reformation of methanol happens at 200-250 °C and is much less energy demanding than reformation of methane (600-800 °C).
- Methanol is potentially produced via green sources as a second generation bio-fuel.

These arguments in combination with the high energy efficiency are central in the reasoning why HT-PEM could bring a new perspective into the fuel cell discussion.

So far the system has been tested and demonstrated in the Danish project EcoMotion [7], where experiences have shown central challenges in the BOP and for life time development of the cells depending on the usage. Both of these are elements of research in the on-going projects.

The concept to be used in the automotive applications is based on a modular system with a 5 kW electric output per full cell stack. A system of this construction can therefore be adapted to needs for both small and larger vehicles and thereby suit a large market span. The small sized systems are mainly planned for vehicles with little or no need for high way driving, which to some extent would demand a REX-system with the same output as the needed energy for the trip.

Conclusions in the MECc project show that 15 kW is needed to continuously support a smaller car with energy for high way driving. These figures are depending of both the design, weight and drivetrain dimensions and should therefore be assessed for each vehicle.

2.1.1 Performance and efficiency

The HT-PEM system is utilizing a methanol-water mix and currently has a Tank to Wheel efficiency between 30 % and 60 % depending on how the calculation is made and how far in the future the projections are made [8]. The system is therefore currently comparable with the regular ICE with a promising potential of reaching far higher efficiency levels in the future.

The fuel cell electrical efficiency is 45-50% net with a further 35-40% thermal output in heat emission for e.g. cabinet heat or to drive an absorption based heat pump for AC. The high efficiency is therefore achieved when the system is completely integrated into the vehicle with both propulsion and climate system, which will then increase the total energy efficiency of the fuel cell to around 80%.

Even when considering these arguments, the main argument for the usage of methanol and HT-PEM is not the energy efficiency. This lies in the distribution of the fuel, as well as the combination of plugin electric drive and fuel cell drive in one vehicle.

The energy density of the current platform is roughly 4 kg/kW power that can be doubled by e.g. pressurising the system, which of course is connected with involvement of a secondary system. The fuel is 0,8 kg/L with an energy content of 3 kWh per L. Methanol is thereby heavier and less energy dense than gasoline but still holds a significant higher amount of energy pr. litre compared to compressed hydrogen [9].

2.1.2 Zero Emission capabilities

Looking at tailpipe emissions there will always be a minor emission as methanol is basically hydrogen bound in carbon. Therefore a vehicle working with such a system cannot locally be considered a zero emission vehicle. However, if the methanol is based on biomass, it will be a second generation fuel which is overall considered zero emission.

There are various manufacturers across the globe working with renewable methanol – especially second generation methanol [10]. Here are three examples:
Carbon Recycling International, Iceland, does production of 2^{nd} generation methanol from geosynthesis where carbon capture combined with renewable hydrogen equals methanol. Currently their production is mainly used as an additive in current fuels. The production site is based on 100 % renewable energy and according to the company, similar production sites are possible all over the world [11].
BioMCN in the Netherlands has the world's largest production site for methanol based on the technology where 2^{nd} generation methanol is produced from the reformation of glycerine. The glycerine used in the process is a residue from the production of biodiesel [12].
Värmlands Metanol in Sweden will use wood biomass to produce methanol through a gasification process. The company is currently working on the build-up of the production facilities and has recently made a stock emission to raise more money for the realization [13].

These three sources depict an extract of the potential renewable production methods and companies working with methanol. In general, methanol as a fuel is flexible – black or green the sources are endless – power to liquids, gas to liquids or biomass to liquids; all is possible with high efficiency and high yield.

2.1.3 Future realization

The HT-PEM methanol fuel cell has proven its worth in segments such as Backup power and Material handling [14]. There is therefore a commercial market for such solutions, however the demands for cars differs significantly from these sectors.

The technology has been demonstrated in smaller vehicles to prove that the concept is sound. The main challenges lie in the cost issue and in building a sustainable ramp though niches towards automotive market. The focus on drivetrains is also important in terms of OEM acceptance and support regimes. In order to ramp up the technology the niches first needed are ones where a shorter life time is accepted and where the combination of clean vehicle combined with the need for a long range is higher than the focus on price.

In order to achieve a lower price the cost of cells needs to be brought down, which demands a shift from hand built systems to actual manufacturing of the systems.

Estimates from Chalmers [15] are that the methanol fuel cell will evolve into the automotive on a 10 year perspective. This process can however be accelerated with the identification of a niche that will allow for the shift from manual production to machined manufacturing.

2.2 Radial Jet Turbine Technology

The technology described in this section is based on a radial jet turbine technology as it is being used by the Danish company RadiJet [16], [17]. Other jet turbine systems are being developed by competing companies and organizations, where the most prominent are Bladon Jetz [18] and DLR [19].

RadiJets gas turbine is comprised by a radial compressor and a radial turbine combined in a single rotating 'monorotor' unit. In addition to a very compact flat design, it obtains a unique thermal barrier between the cold center bearings, as well as the electric generator, and the hot turbine on the outside of the compressor. This way of constructing the system also allows for a very limited number of moving parts and dual functionality of the parts in use. E.g. the generator is in the start of the ignition process used to accelerate the turbine up to its speed of combustion. The low number of moving parts also causes a minimum of wear on the system and therefore low costs associated with this.

The overall major benefit given with the radial jet turbine is its multi-fuel capability. The system is constructed in such a way that the rotation speed of the turbine and the combustion temperature in the chamber makes it indifferent to which type of flammable liquid or even gas that enters the turbine. The system is therefore highly flexible when it comes to the choice of fuel for today and the future, and the same system would work in Europe with gasoline and diesel as well as it would in Brazil with ethanol or anyone of the named Opportunity fuels [20] that could fuel vehicles in the future. The combustion process is also affecting the creation of exhausts and the turbine therefore has a ten time lower exhaust of NO_X and twenty times lower CO-emission compared to a normal generator.

With minor adjustments, the system would be able to run on pressurised liquefied gasses as well, which would open up for usage of fuels such as LPG and LNG in the system. On the far horizon also compressed gasses, such as hydrogen could be used as fuels for the system.

The turbine described in this paper is a 10 kWe REX and is equipped with a heat exchanger in order to be able to re-use the excess heat from the combustion process to heat or cool the cabin in combination with a heat pump system. The potential to energy harvest some of the exhaust heat through thermo-electric elements is also being examined. The compactness of the system makes it possible to fit the solution (tank excluded) in the same place where a spare tire would be stored. This included with the low number of moving parts and constant speed for combustion results in a REX with a low and even noise level of 60 dB(A).

The main benefits with the existing solution are:

- Multi-fuel allows for a flexible and future safe solution
- Compactness of the system combined with a high energy output
- Minimum of maintenance needed.

2.2.1 Performance and efficiency

The Tank to Wheel efficiency of the RadiJet turbine is for pure electricity around 22 %. However, with the construction of the system to exploit the excess heat produced in the combustion, the efficiency can be brought up to more than 80 % shows calculations from RadiJet. This is done via electricity production through thermoelectric generators and with use of the excess heat for the vehicles climate system.

The main benefit of using the radial jet turbine lies in the possibility to use the available fuels without considering mixtures or certain usages.

The system is as described also compact, which also causes a relatively high energy output pr. Kg with 3kg/kW, where the fuel density then differs based on which fuel is used. In comparison with first generation range extenders, this is a factor two level and is therefore a central benefit with the system.

2.2.2 Zero Emission capabilities

Besides the fact that a REX only is used for a minor part of the time a range extended vehicle is running, the radial jet turbine's capability to work with all flammable fuels will allow it to use biofuels of all kinds as well as LNG, which will allow for it to be considered a Zero Emission solution.

Since a turbine is based on combustion, the system will not be able to achieve 100 % local zero emission. However, the relatively clean combustion will result in far less CO and NO_X emissions compared with existing solutions. This will also be influenced by the choice of fuel.

2.2.3 Future realization

Currently RadiJet has a project with the Danish Market Development Fund, where they will develop their solution to be used in three different applications:

- Micro CHP systems
- Range extender for EVs
- Energy source for niche vehicles

The overall purpose of the project is to demonstrate the functionality of the radial jet turbine in these three segments. Currently the system is working on prototype level and by the end of the project in 2015 the system will have been demonstrated for shorter or longer time in each of these application types.

The main challenge for the radial jet turbine in order to achieve mass market is the ramp up of production from single built prototypes to actual mass scale turbines, which of course would demand that sales will follow along with this development. An increase of production volume and standardization of production process would also mean a reduction in price which is also necessary in order to get significant market volume.

On the technical side, the two main focuses are on efficiency increase and size reduction to make the key functionalities even better on the system. A production version is however not to be expected before 2016.

3 Conclusion

When comparing the two technologies it is clear that some of the same benefits and challenges are associated with the new unproven technologies such as large potentials and new functionalities on the one side. On the other they struggle with relatively long time to market and the major hurdles being the transition from small scale production to mass production.
From a technical point of view the differences are larger as depicted in Table 2 that shows the overall technical comparison between the HT-PEM from Serenergy and the Radial Jet Turbine from RadiJet:

Table2: Comparison of the two REX-types

	Serenergy	RadiJet
Type	Fuel cell	Turbine
Output	5 kW	10 kW
Electric eff.	40-50 %	22 %
Total eff.	~85 %	+80 %
Kg/kWe	4 kg/kW	3 kg/kW
Fuel type	Methanol	Multi
Realization horizon (estimated)	5-8 years	3-5 years
Zero Emission	With biofuels	With biofuels

Starting with the difference in output, this is a difference as they will both be targeting to some extent the same market niches; however, the size of the two solutions differs by a factor 2. One of the reasons for this is found in the modularity of the solution by Serenergy, which allows a higher flexibility in their solutions, where RadiJet will have to create a new solution for other energy needs. Also the complexity of the turbine in the RadiJet solution makes it much more expensive to produce a smaller unit, where the HT-PEM is more flexible as it depends on the number of cells in the fuel cell pack.

The combustion of the radial jet turbine causes it to have a relatively low tank to wheel electric efficiency especially compared to the fuel cell which would potentially make the fuel cell more viable as an energy efficient solution. Common for both solutions is the utilization of excess heat to create a cooling/heating system for the EV and such a system will increase the efficiency to approx. 80 % for both. If comparing the two solutions with a regular ICE, only the fuel cell shows electric efficiency significant higher than the 20 % average depicted by the Alternative Propulsions report from the Danish Energy Agency [8].

The major benefit with the radial jet turbine lies in the flexibility when it comes to fuel choice. This flexibility creates a product that is usable over most parts of the world and will adapt to the fuels of the future without any added costs. This functionality could prove especially interesting in countries with a limited overall infrastructure and potential local production of flammable products such as alcohol.

When comparing the two technologies to the other generations of REX it is clear that there is still a way to go before they can enter the market and therefore the next generations of range extended vehicles will be based on standard ICEs. However the functionalities of multi fuel and higher energy efficiency combined with a low local emission and a high density will relatively quickly make way for the first systems in the market in niche areas. The main markets will however be dominated by the cheaper and well known solution until prices are competitive.

Even though the radial jet turbine currently is at a lower development stage than the HT-PEM, which has actual applications running, the potential market launch in the automotive segment for RadiJet lies closer than that of Serenergy, which finds its main reason in the system construction and major challenges in life time associated with fuel cells. The simplicity of the construction from RadiJet will help shorten the verification phase and thereby the entry to market.

An interesting point between the two technologies is that they both will be able to support the creation of an infrastructure for methanol based on the existing available infrastructure due to the multi-fuel capabilities of the radial jet turbine and the

HT-PEM being designed to run on it. A creation of such an infrastructure would therefore be supported by several technical solutions, which could be a central factor in achieving critical mass and thereby a clean fuel and long range vehicles for the future.

References

[1] Green & Energy, http://www.green-and-energy.com/blog/is-range-anxiety-going-to-kill-electric-cars/, accessed 2013-07-15

[2] *BMW*, http://www.bmw-i.co.uk/en_gb/bmw-i3/, accessed 2013-02-11

[3] Harrop, Dr. Peter; *Range Extenders for Electric Vehicles 2012-2022*; IDTechEX,

[4] *MECc project web*, http://www.mecc.dk/, accessed on 2013-01-18

[5] Jensen, Jens Oluf et.al.; *High Temperature PEMFC and the possible utilization of the excess heat for fuel processing;* International Journal of Hydrogen Energy 32 (2007) 1567– 1571

[6] Chandan, Amrit et.al; *High Temperature (HT) polymer electrolyte membrane fuel cell (PEMFC) – A Review;* Journal of Power Sources 231 (2013) 264-278

[7] *Ecomotion*, http://ecomotion.dk/engelsk/ecomotion/ecomotion.aspx, accessed on 2013-02-08

[8] Danish Energy Agency; *Alternative Drivetrains 2.0;* Danish Energy Agency

[9] U.S. Energy Information Administration, http://www.eia.gov/todayinenergy/detail.cfm?id=9991, accessed on 2013-07-08

[10] Danish Technological Institute, *GreenSynFuels*, EDDP project journal number 64010-0011

[11] Carbon Recycling International, http://www.carbonrecycling.is/, accessed on 2013-07-12

[12] BioMCN, www.biomcn.eu, accessed on 2013-07-12

[13] Värmlands Metanol AB, www.varmlandsmetanol.se, accessed on 2013-07-12

[14] Serenergy, http://serenergy.com/applications/, accessed on 2013-07-15

[15] RadiJet, www.radijet.dk, accessed on 2013-07-15

[16] Patent No. WO2009059608

[17] Bladon Jets, http://www.bladonjets.com/, accessed on 2013-07-15

[18] Deutsche Luft und Raumfahrt, http://www.dlr.de/at/en/desktopdefault.aspx/tabid-1523/2160_read-3620/, accessed 2013-07-15

[19] Alternative Energy Solutions International, http://www.aesintl.net/bri/opportunity-fuels, accessed 2013-07-15

[20] Chalmers University, Press release 2011-12-14, http://www.chalmers.se/en/news/Pages/Methanol-replacing-hydrogen-gas-as-the-fuel-of-the-future.aspx, accessed 2013-07-22

Authors

Jens Christian Lodberg Høj is a Business development engineer and has spent half a decade working with innovation projects in several different branches of the industry at the Danish Technological Institute. Jens Christian is the scientific responsible for the Marie Curie funded BUMILLA project and the project manager of the MECc project under the Energy Technology Development and Demonstration Programme (EDDP).

Mai Louise Agerskov is a civil engineer within International Technology Management and works as CEO of Insero E-Mobility. For 7 years she has worked with strategic product development and marketing in Danfoss and since 2007 been working as CEO within the area of clean tech and knowledge transfer. Mai Louise Agerskov works as external lector at the Aarhus University within corporate strategy management.

Mads Friis Jensen is a M.Sc. in Technology Based Business Development and has worked for more than 5 years in the fuel cell business with project and business development. Today Mads Friis Jensen works as Commercial Group Manager for Serenergy.

Poul Lading is the co-founder of RadiJet and the current CEO with many years of managing experience behind him in different technological companies. He is educated as an engineer in Computer Science and has an EBA to supplement it.