

Investigation of fuel cell technology for long-haul trucks

Cezary Misiowecki

The Master Thesis was supported by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism - Project PL0460.



UNIVERSITY OF ICELAND



University
of Akureyri



Investigation of fuel cell technology for long-haul trucks

Cezary Misiopiecki

A 30 ECTS credit units Master's thesis

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A Master's thesis done at
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ABSTRACT

Almost 95% of transportation sector uses liquid hydrocarbons made from fossils as primary fuel. That sector is responsible for 21% of CO₂ in European Union (Eurostat 2004) and 21% of Australian's greenhouse gas emissions (Tasman 2004). Many improvements to conventional truck technology proofed that it possible to reduce emissions of SO_x, NO_x and particles by special systems assembled in vehicles but it is impossible to implicate sophisticated systems which can reduce to zero CO₂ emissions because of huge dimensions and complexity.

Usage of hydrogen as energy carrier is considered as one of the most feasible and suitable for transportation. Instead of using hydrogen as a fuel for internal combustion engines where efficiency is constrained by the Carnot law, this energy carrier can be converted to electricity directly by electrochemical reaction in the device called fuel cell with high efficiency while not generating tailpipe CO₂ emissions or other pollutants.

In this mater thesis study of feasibility of fully operational heavy duty truck powered by hydrogen is done. The most suitable technologies of powertrain components are investigated in order to create preliminary design of full-scale hydrogen fuel cell truck. Conducted research pointed that the most suitable technology for electrochemical conversion of hydrogen is high temperature PEM fuel cell. The most energy and cost effective technology for hydrogen storage seems to be compressed hydrogen at pressure of 35 MPa. Further investigation indicated supercapacitors as probably the most suitable technology for energy buffer. It seems to be effective to use hub motors instead of conventional driveline mechanism.

Calculation and comparison of gravimetric power and energy density for drivelines of hydrogen fuel cell and conventional diesel trucks is the next focus of this paper. Investigation showed that the hydrogen fuel cell powertrain can be comparable with conventional diesel powertrain in terms of gravimetric energy density. Advantages and disadvantages of innovative hydrogen drivetrain are presented. Additionally, the investigation of the best technology for refrigeration unit for semi-trailer which can cooperate with fuel cell is conducted.

This master thesis also includes comprehensive design of small-scale model of fuel cell hydrogen truck. Small-scale model was designed and partially constructed in order to demonstrate feasibility of hydrogen fuel cell innovative application and to deliver important information about performance and behavior of particular system elements of the hydrogen fuel cell powertrain.

The final section focuses on refueling infrastructure and possibility of direct introduction of hydrogen fuel cell truck technology in Poland. Modified powertrains which includes on-board reformer are analyzed.

PREFACE

The following master thesis is part of master course at RES (The School for Renewable Energy Science in Iceland). It was completed with cooperation with SAMME (School of Aerospace, Mechanical and Manufacturing Engineering) of RMIT (The Royal Melbourne Institute of Technology). The Master Thesis was supported by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism - Project PL0460.

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1 INTRODUCTION

1.1 Background

Air pollution is currently considered as one of the most important problem of XX and XXI century. Major pollutants produced by human activities are: carbon dioxide, carbon monoxide, nitrogen oxides, sulphur oxides and particles. All of those pollutants are attributed to usage of fossil fuels. According to surveys (CDIAC 2008) carbon dioxide concentration increased from 325 ppm to 380 ppm in period 1958 – 2008 and concentration is likely increase in the future. This could implicate rapid global climate changes with drastic consequences for humanity.

Moreover, reserves of fossil fuels are limited and future shortage of oil is unavoidable. Because of depleted resources and still growing consumption of fossils we can expect raising prices of oil. Next disadvantage of wide usage of convectional liquid hydrocarbons is that World is dependent on countries which have oil deposits. All those matters caused interest and development of alternative energy sources and carriers.

Almost 95% of transportation sector uses liquid hydrocarbons made from fossils as primary fuel. That sector is responsible for 21% of CO₂ in European Union (Eurostat 2004) and 21% of Australian's greenhouse gas emissions (Tasman 2004). It is possible to reduce emissions of SO_x, NO_x and particles by special systems assembled in vehicles but it is impossible because of scale and complexity to implicate sophisticated systems to reduce to zero CO₂ emissions.

Many solutions for improving quality of exhaust have been invented and tested, however most of them lower overall system efficiency of powertrain (IEA 2009). Because of unavoidable oil shortage, lack of perspective for improving remarkably efficiency and emission of vehicles engineers started research for new concepts.

Usage of hydrogen as energy carrier is considered as one of the most feasible and suitable for transportation. Instead of using hydrogen as a fuel for internal combustion engines where efficiency is still constrained by the Carnot law this energy carrier can be converted to electricity directly by electrochemical reaction in the device called fuel cell (FC) with high efficiency while not generating tailpipe CO₂ emissions or other pollutants.

That technology has been implicated in passenger cars and city busses. There were many demonstration projects which proof operation of this technology in those means of transport (E-traction 2010).

There are also projects and researches focussing on implication of fuel cell technology into trucks. Firstly, conventional diesel generators were being replaced with small fuel cell unit provides electricity for auxiliaries of truck during stops.

In early 2010, Vision in the US released the “Tyrano” which is claimed to be the world's first short and medium range haul fuel cell truck with zero tailpipe emissions (Vision Corporation, 2010). The truck is powered by a combination of a hydrogen fuel cells and lithium-ion batteries. Its range is 400 miles thanks to 33 kg of stored hydrogen. According to the manufacturer the Tyrano truck is 35% cheaper in operation than current trucks powered by diesel and 50% cheaper than trucks running on liquefied natural gas. The

torque and peak power output of the Tyrano equals respectively 4500 Nm (approximately two times more than average diesel-powered truck) and 400 kW.

1.2 Research aim and objectives

The main aim of this research is to gain a more complete understanding of the application of hydrogen fuel cell systems in heavy duty vehicles.

The specific objectives of the project are to:

- Review of technical options for replacing conventional diesel powertrain of heavy duty vehicle with hydrogen fuel cell technology
- Assess the feasibility of replacing the standard diesel engine drive-train of long-haul trucks with an equivalent hydrogen fuel cell and buffer system. The aim of the replacement system will be to supply sufficient energy for 500 km range under typical conditions and truck auxiliaries systems
- Obtain preliminary design of fuel cell power system for full-scale heavy duty truck from hydrogen storage to wheel output aimed at maximizing the overall energy efficiency
- Investigate the best technology for semi-trailer refrigeration unit which would cooperate with hydrogen fuel cell powertrain system
- Assess the possibility of introduction fuel cell technology for heavy duty trucks in Poland
- Conduct a comparative technical and environmental comparative evaluation of hydrogen fuel cell truck design and conventional diesel truck

The following research questions are addressed:

- Is it feasible to develop a hydrogen fuel cell heavy duty truck that is fully operational?
- Which available technologies are the most suitable for hydrogen fuel cell drivetrain?
- Are the gravimetric power and energy densities of powertrain of the fuel cell truck competitive with these factors for conventional diesel truck?
- What kinds of advantages would fuel cell trucks over conventional diesel trucks?
- Is it possible to use different kinds of refrigeration units for semi-trailers than conventional ones which can achieve better performance and better suit for hydrogen fuel cell drive train?
- Is it possible to implement fuel cell technology for heavy freight transportation in Poland in near future?

1.3 Scope

In order to establish requirements for hydrogen fuel cell truck design review of current technology for heavy duty conventional vehicles is conducted. Moreover, predictions of potential improvements for current conventional heavy duty vehicles technology are presented.

The most suitable technology of full-scale fuel cell heavy duty truck is investigated. Components of driveline are analysed in details (in terms of performance, complexity and unit size, price, durability, sustainability of production, availability of raw materials for production components) then the preliminary design of full-scale hydrogen truck is done. In addition, the incorporation of a small energy capacity buffer will be investigated to provide storage for energy derived from regenerative braking and for better system balance. Thanks to electrification of drivetrain direct use of electricity or heat from fuel cell for refrigeration needs is feasible. This approach eliminates necessity of additional generator required for conventional truck for chilled semi-trailer. Two options for the semi-trailer refrigeration system will be considered including an electric chiller supplied directly by the fuel cell or an absorption chiller using heat from the fuel cell.

In order to get familiar with fuel cell technology, gain more experience in system controlling and optimizing, expose the biggest challenges of proposed design and get experimental data which can be further used for scaling up the comprehensive design of small-scale truck model is completed. System components have been ordered. Unfortunately, some of them had not arrived before this thesis was completed. Model has not been assembled however some of the components have been tested.

One of the most important aims of this thesis is comparative evaluation of hydrogen fuel cell truck with internal combustion engine conventional truck powered by diesel fuel.

Comparison with other type of trucks like bio-diesel and hybrid battery hasn't been done in this master thesis. Diesel trucks are currently the most popular around the world. Bio-diesel trucks are very similar in terms of design, but virtually cause no CO₂ pollution because organic fuel derives mainly from plants. However global usage of bio-fuels can cause some negative phenomenon like growth in food prices or too intensive exploitation of soil.

Hybrid battery trucks are currently unavailable on the market so lack of the data makes the comparison not possible.

Moreover, assessment of implication of this solution in Poland is done. Analysis will take into account some issues like polish regulations about hydrogen and refuelling infrastructure in the country. Some modified systems which could be suitable for Poland conditions will be presented (e.g. including on board gasoline reformer).

1.4 Dissertation organization

The dissertation is divided into six chapters. Chapter two provides a review of current heavy duty vehicles technology. In this chapter also the requirements and scopes for fully operative truck are established. One section is devoted to refrigerated semi-trailer in which overall design and energy requirements are presented. Moreover this part of thesis contains information of potential improvements for current conventional heavy duty vehicles technology.

Chapter 3 is devoted to investigation of the best technology of full-scale fuel-cell heavy duty truck. All components of driveline are analysed in details then most suitable technology is chosen for each unit (in terms of performance, complexity and unit size, price, durability, sustainability of production, availability of raw materials for production components).

Chapter 4 is devoted to designing and partially assembling of small-scale model of hydrogen fuel cell truck. Firstly, the technical parameters of model are measured and presented. The comprehensive design and components of fuel cell driveline are presented. Further, measurement of fuel cell stack performance is done in order to confirm its performance with manufacturer data.

Focus of the chapter 5 is hydrogen refuelling infrastructure in Poland and different design which will be suitable for polish conditions.

The last chapter focuses on refuelling infrastructure and possibility of direct introduction of hydrogen fuel cell truck technology in Poland. Modified powertrains which includes on-board reformer are analyzed.

2 FUNCTIONAL AND SERVICE REQUIREMENTS OF A CONVENTIONAL TRUCKS

2.1 Introduction to conventional truck technology

This chapter is devoted to the introduction into truck technology. Firstly, some general information about importance of trucks in current world is presented. Further, using data of one of the market available truck, detailed requirements and scopes for propulsion system are provided. Also the overall design and parameters of refrigerated semi-trailer are described. The final section contains data related to potential of improvements in terms of efficiency and emissions for conventional heavy vehicle technology.

2.2 General information about trucks

In 2006 truck transport accounted for 540 MTOE of energy which is more than 24% of global transport energy use (IEA 2009). According to Australian Bureau of Statistics (2009) data there are 421 702 rigid trucks in Australia. In European Union according to European Commission (2010) number of heavy vehicles in 2008 was 33 490 000.

Those numbers are still growing. There are four major scenarios (Baseline scenario, High Baseline, BLUE map, BLUE Shifts scenario) that predict level of truck freight and emission from this sector in the future. According to Baseline scenario number of goods tracking will double before 2050, High Baseline predictions are higher about 20%. BLUE Shifts scenario shows possibility of 35% increase in number of truck by 2050.

As it can be seen from above presented data that truck freight is nowadays and likely to be in the future substantial part of transportation sector. Designing and popularization of zero emission technologies within trucks is as very important for sustainable development of the world.

2.3 Classification of trucks

Every country has its own vehicle classification. Classifications differ between countries but usually they are based on total mass of vehicle. The most representative classification for European Union countries is given below in Table 1.

Table 1- Vehicle classifications for EU according to Directive 2004/52/EC

Group	Description	Characteristics
0	Motorcycles	2 or 3 wheels
1	Small passenger vehicles	Seats < 8 + driver
2	Light good vehicles	Mass < 3.5 t
3	Large passenger vehicles	Seats > 8 + driver
4	Heavy goods vehicles (up to 12 t)	Mass between 3.5 t and 12 t

5	Heavy goods vehicles (over 12 t)	Mass > 12 t
6	Other vehicles	

According to Table 1- Vehicle classifications for EU according to Directive 2004/52/EC heavy vehicles are those with a total mass above 3,500 kg (total mass stands for total vehicle mass + maximum load). Group number 5 five concerns group of trucks heavier than 12 tonnes.

Due to research of International Energy Agency (2009) it is more effectively to load the truck up to its maximum limit. The chart below presents the relationship between load and energy consumption.

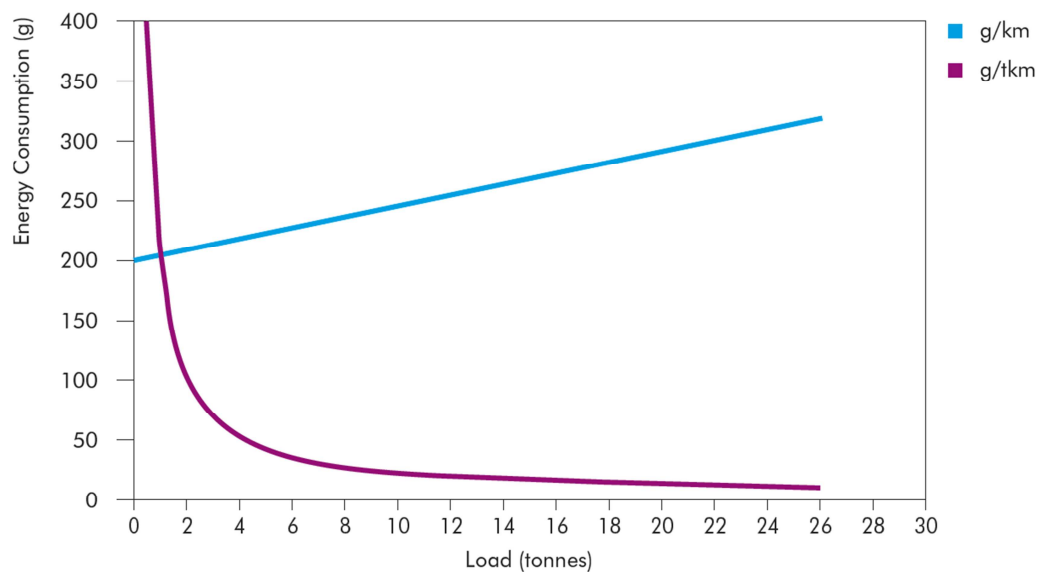


Figure 1- Relationship between fuel efficiency/energy intensity and payload mass in a 40T, 5-axle truck (IEA 2009)

Typically within the European Union allowed total mass of heavy vehicle is 40 T. In United Kingdom and Denmark the maximum truck mass has been changed from 41 to 44T because of potential energy savings. (IEA 2009)

In Australia allowed total mass of heavy vehicle with trailer is 42.5 tonnes. Exceptions of this role are so-called Road Trains and B-doubles. Those vehicles are restricted to operation on approved routes because of their size and mass. B- Doubles and Road Trains may operate under the special provision on special allowed routes. Mass of B-Doubles and Road Trains must not exceed 50 tonnes. (RTA 2008)

The conclusion on the basis of presented above statements is that the most efficient is big scale freight. That is the reason why further in this thesis 40T heavy duty truck is considered.

Moreover, methods of hydrogen storage are still not so efficient in terms or gravimetric and volumetric energy density as liquid hydrocarbons. Demonstration of feasibility for

biggest freight trucks will prove that it hydrogen technology all storage weaknesses can be solved somehow.

2.4 Freight task to be performed heavy duty trucks

Main task for heavy duty vehicles is moving goods between locations. According to (IEA 2009) most goods freight by road transportation takes place within country rather than between countries. Most intercontinental transportation is carried by ships.

Transportation sector is in relation with GPD (Gross Domestic Product) and depends of availability of transportation infrastructure that's why it differs for every country.

According to International Energy Agency (2009) average payload mass on European Union is about 10 tonnes. In the Figure 2 can find differences in payload in European countries.

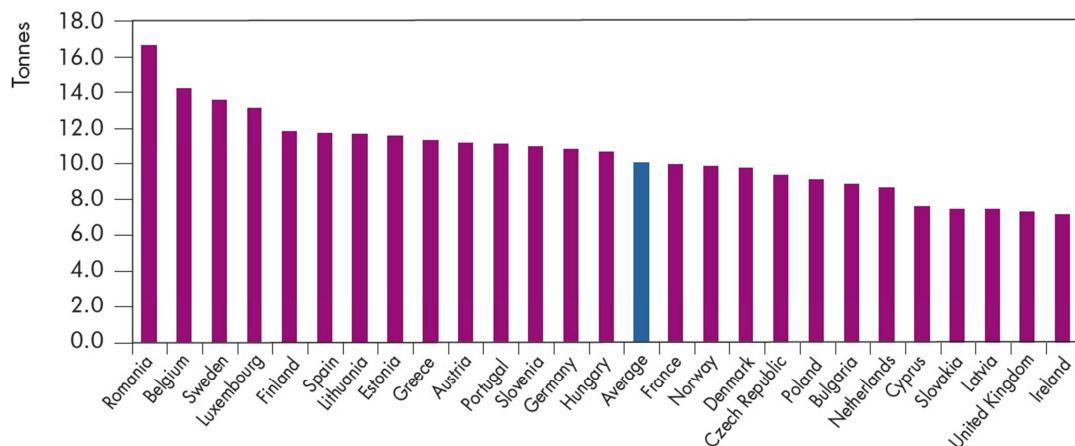


Figure 2 - Average payload weight on laden trips in Europe (International Energy Agency 2009)

Note that statistics apply for all kinds of truck, not only for heavy duty trucks.

Many institutions and organizations working on the universal heavy vehicle driving cycles, which would imitate the best real trucks routes. It is very important to establish driving cycle because then it is possible to measure and compare performance of trucks in terms of efficiency, energy use and emissions.

Moreover, every new produced model of vehicle must be subjected under proper driving cycle before being authorized for sale. The emissions from vehicle must be lower than limits for particular pollution. This rule accounts also for heavy duty vehicles.

The most common of the cycles are those used by the United State Environmental Protection Agency and the European ECE (established by: European Parliament, European Council and Commission).

The most universal driving cycles, which include features of many drive cycles and have worldwide approval are describe below.

“The WHSC test is a steady-state engine dynamometer schedule defined by the proposed global technical regulation (GTR) developed by the UN ECE GRPE group. The GTR is covering a world-wide harmonized heavy-duty certification (WHDC) procedure for engine exhaust emissions. Two test cycles, a hot start steady state test cycle (WHSC) and a transient test cycle (WHTC) with both cold and hot start requirements, have been created covering typical driving conditions in the EU, USA, Japan and Australia

The WHSC is a ramped steady-state test cycle, with a sequence of steady-state engine test modes with defined speed and torque criteria at each mode and defined ramps between these modes (WHSC). The parameters of the WHSC are listed in

Table 2” (DieselNet 2010)

Table 2- World harmonized Stationary Cycle (WHSC) (DieselNet 2010)

Mode	Speed	Load	Weighting Factor	Mode Length†
-	%	%	-	s
0	Motoring	-	0.24	-
1	0	0	0.17/2	210
2	55	100	0.02	50
3	55	25	0.10	250
4	55	70	0.03	75
5	35	100	0.02	50
6	25	25	0.08	200
7	45	70	0.03	75
8	45	25	0.06	150
9	55	50	0.05	125
10	75	100	0.02	50
11	35	50	0.08	200
12	35	25	0.10	250
13	0	0	0.17/2	210
Sum			1	1895
† Including 20 s ramp				

“The WHTC test is a transient engine dynamometer schedule defined by the proposed global technical regulation (GTR) developed by the UN ECE GRPE group. The GTR is covering a world-wide harmonized heavy-duty certification (WHDC) procedure for engine exhaust emissions. The proposed regulation is based on the world-wide pattern of real heavy commercial vehicle use. Two representative test cycles, a transient test cycle (WHTC) with both cold and hot start requirements and a hot start steady-state test cycle (WHSC), have been created covering typical driving conditions in the EU, USA, Japan and Australia.

The WHTC is a transient test of 1800 s duration, with several motoring segments. Normalized engine speed and torque values over the WHTC cycle are schematically shown in Figure 3” (DieselNet 2010).

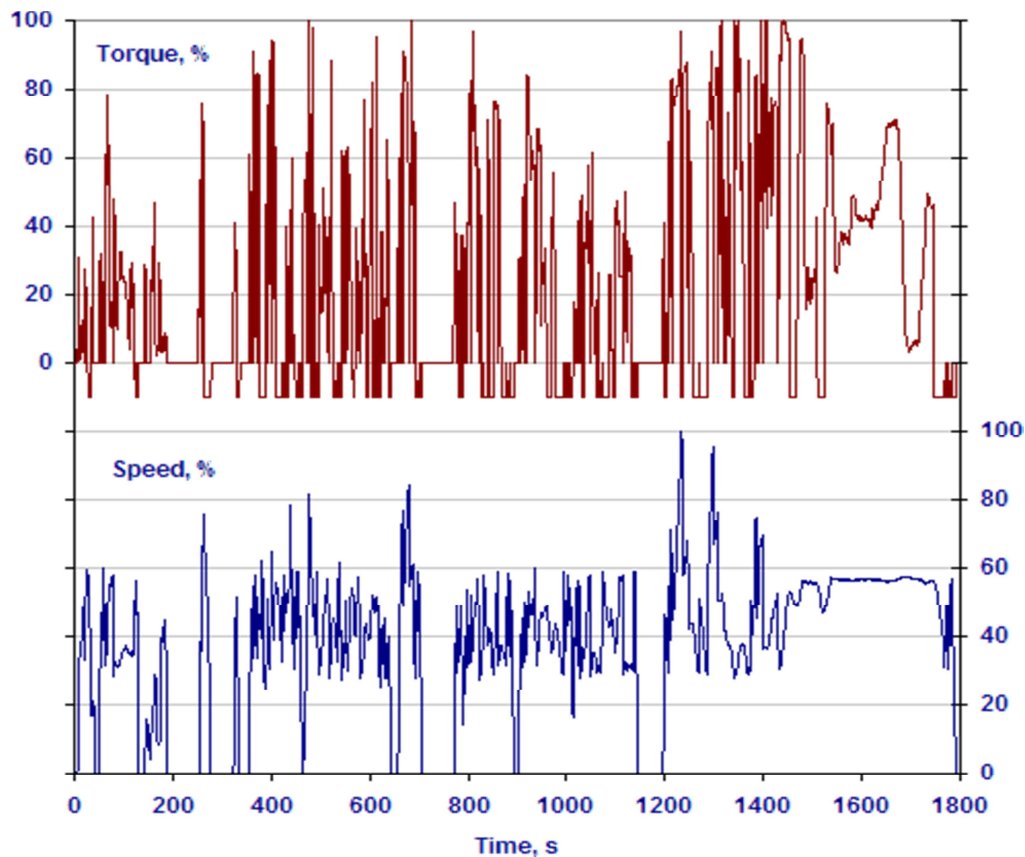


Figure 3- World Harmonized Transient Cycle (WHTC), (DieselNet 2010)

Note: Negative torque values are arbitrary representation of closed rack motoring

2.5 Energy requirements for heavy duty trucks

2.5.1 State of the art of current diesel truck technology

This section is devoted to energy requirements for full-scale heavy duty truck. As a representative example of conventional diesel powered truck series TGX manufactured by MAN have been chosen. That truck is state of art in terms of performance and emissions of current heavy vehicle technology. TGX was tilted as “Truck of the Year 2008”. (MAN Australia 2010)

Because of innovative engine design and many technical improvements (like: drag coefficient lower by 4%, electronic control system saving energy from auxiliaries) the TGX trucks are the current leaders in terms of energy use and lowest CO₂ emissions.

According to producer data the gross vehicle mass is max 18 tonnes.

The current trucks are equipped with following active and passive safety systems:

- Electronic stability program (ESP),
- Adaptive Cruise Control (ACC),
- Anti-lock braking system (ABS),
- The lane guard system (LGS),
- Brake assistant and Continuous Damping Control (CDC)

2.5.2 Propulsion system

Truck propulsion must ensure enough torque and power for normal truck operation. General design of propulsion system for truck is very similar as for passenger vehicles. Engine gives required torque which is passed to wheels by clutch, gear box and transmission to wheels.

Usually heavy tractors are produce in two configurations: 4x2 and 6x4. First number indicates the number of wheels of truck and following number indicates powered wheels. Trucks with propulsion 6x4 are more powerful and guarantee better performance.

Gear box mounted in TGX series is 14 speeds (12 forward, 2 reserves). The ration of gear box is 15.86-1. (MAN Australia 2010)

Below we can see the general chart of conventional flat nose truck 4x2.

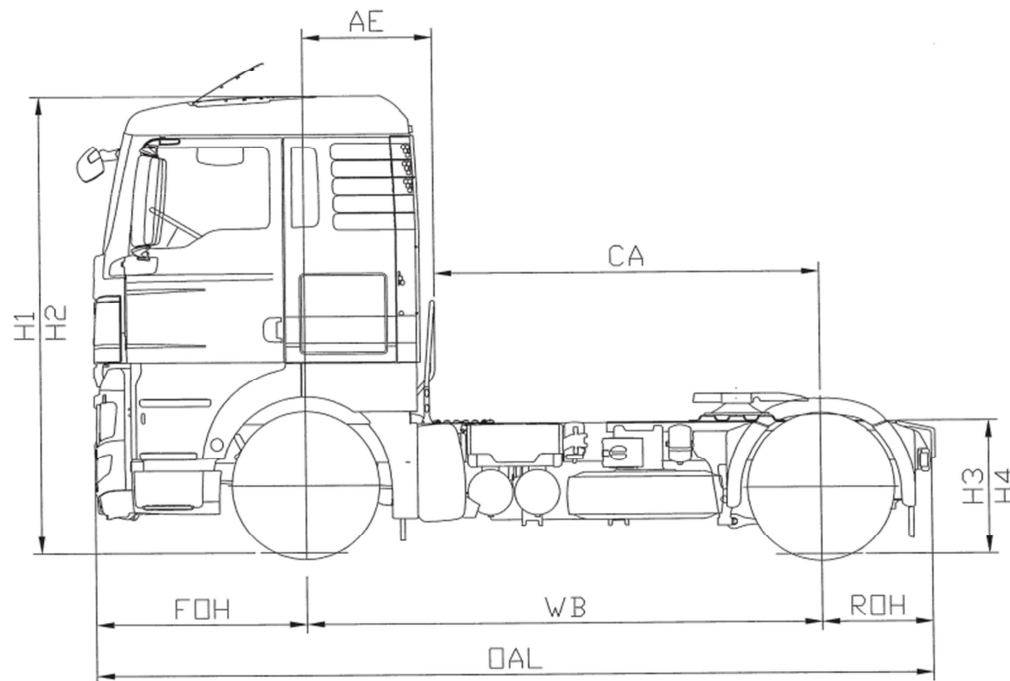


Figure 4- General truck design, flat nose type, 4x2 (MAN Australia 2010)

2.5.3 Engine

Trucks series TGX are powered by MAN 6-cylinder 4-valve in-line engine mostly with Common Rail injection, turbo-charging and intercooling and Electronic Diesel Control (EDC) engine regulation. Modern diesel engines can fulfill EURO 5 and EURO 4 emission

standard thanks to very good efficiency, NOX-control, external controlled exhaust gas recirculation (EGR) and Particle Matter Catalytic Converter. (MAN Australia 2010)

In order to present parameters of modern engines the D2676 MAN diesel line engine has been chosen. This engine fulfills the Euro 5 emission standard. The D26 series engines are very often use for as a main source of power in TGX MAN trucks.

Engine D2576 is produce in two versions: LF09, LF08 output power is respectively 353 kW and 397 kW. Below the performances of two versions of D2676 engine are presented.

Table 3- Technical Data for D2676 Engines (MAN engines 2010)

Technical data D2676						
Bore	mm	126				
Stroke	mm	166				
Displacement	litre	12.4				
Exhaust-gas standard		EEV		Euro 5		Euro 4
Engine model		LF18	LF17	LF09/07 ³	LF08/06 ³	LF05
Rated output ¹	kW	353	397	353	397	353
Rated output ¹	hp	480	540	480	540	480
At speed	rpm	1900	1900	1900	1900	1900
Max. torque	Nm	2300	2500	2300	2500	2300
At speed	rpm	1050	1050	1050	1050	1050
Fuel consumption ²	g/kWh	188	188	188	188	193
Exhaust aftertreatment		SCR	SCR	SCR	SCR	PM-Kat
OBD-Step		2	2	2	2	1 ⁴

¹ According to ISO 1585 89/491 EEC. ² Bottom specific fuel consumption. ³ LF07 and LF06 with torque reduction if OBD is installed, LF09 and LF08 without torque reduction if OBD is installed (for special-purpose vehicles). ⁴ OBD-Step 1 with NOx check.

Table 4 - Dimensions D2676 engine, (MAN engines 2010)

Dimensions D2676		
A-Overall length	mm	1 510
B-Overall width	mm	849
C-Overall height	mm	1 119
D-Bottom edge of oil pan to crankshaft centre	mm	419
Weight (dry)	kg	1 050
For detailed examinations of installation dimensions, please order drawings from our factory.		

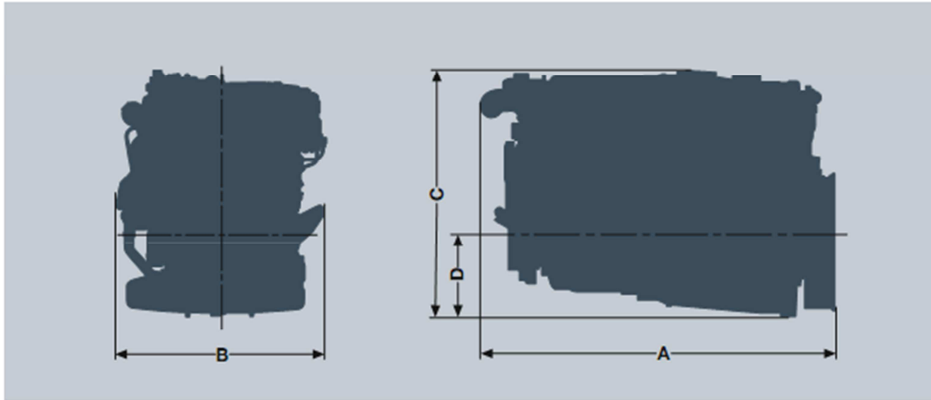


Figure 5 - Dimensions D2676 engine, (MAN engines 2010)

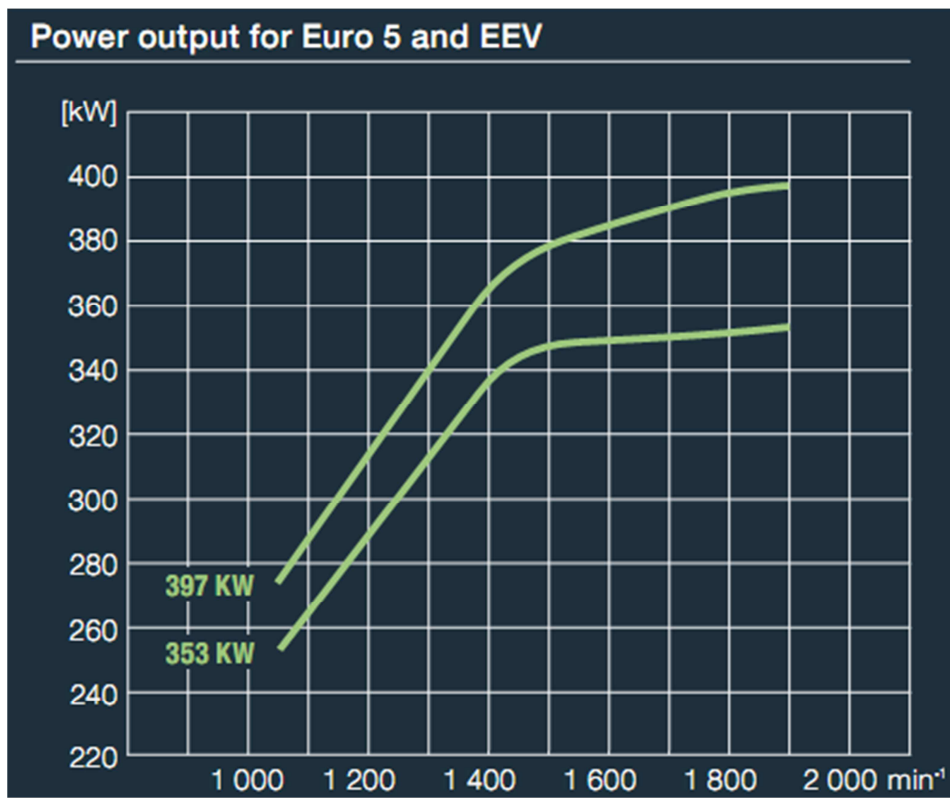


Figure 6-Performance chart D2676, Power Output vs. RPM (MAN engines 2010)

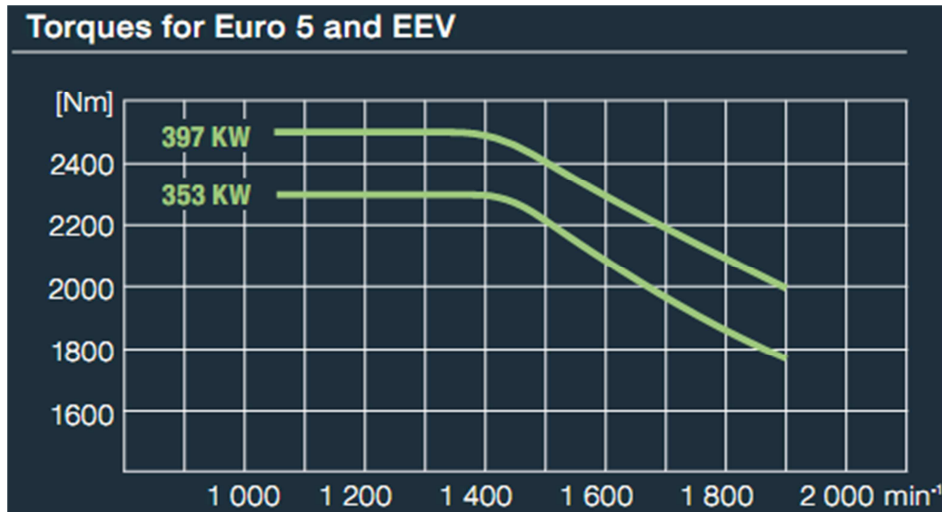


Figure 7- Performance chart D2676, Torques vs. RPM (MAN engines 2010)

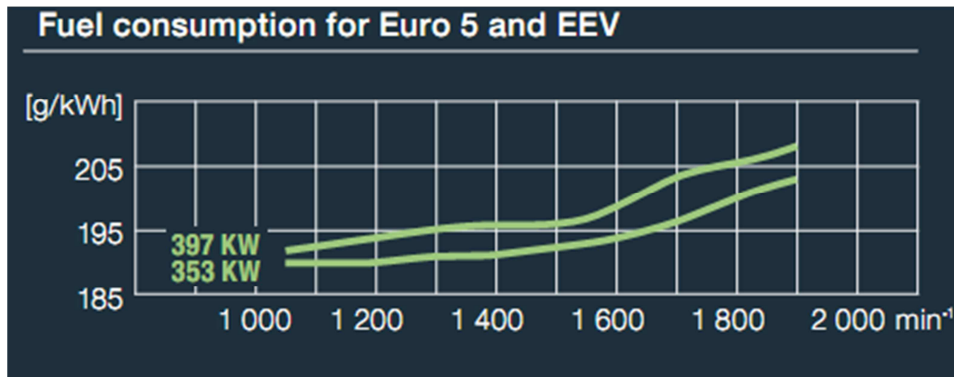


Figure 8- Performance chart D2676, Fuel Consumption vs. RPM (MAN engines 2010)

2.6 Fuel tanks

The heavy duty trucks series TGX are equipped with aluminum fuel tanks fitted with lockable fuel caps. Standard capacity is 400litres. There are also available options which capacities are 600 and 780 L.

With this standard capacity truck is able to drive about 1100-1300 km between refueling (on the basis of users feedbacks assumption was made that TGX truck uses between 30-35 liters per 100 km with full load).

2.7 Refrigerated semitrailers

2.7.1 Overall design of refrigerated semi-trailers

Some goods require special transportation conditions one of the biggest group with special transportation requirements are frozen products. Frozen goods must be transported in the temperature from 7°C to – 20°C. The temperature depends on kind of the products. To

satisfy those specifications special refrigerated semitrailers are in use. The main components of refrigerated semitrailer are presented on Figure 9.

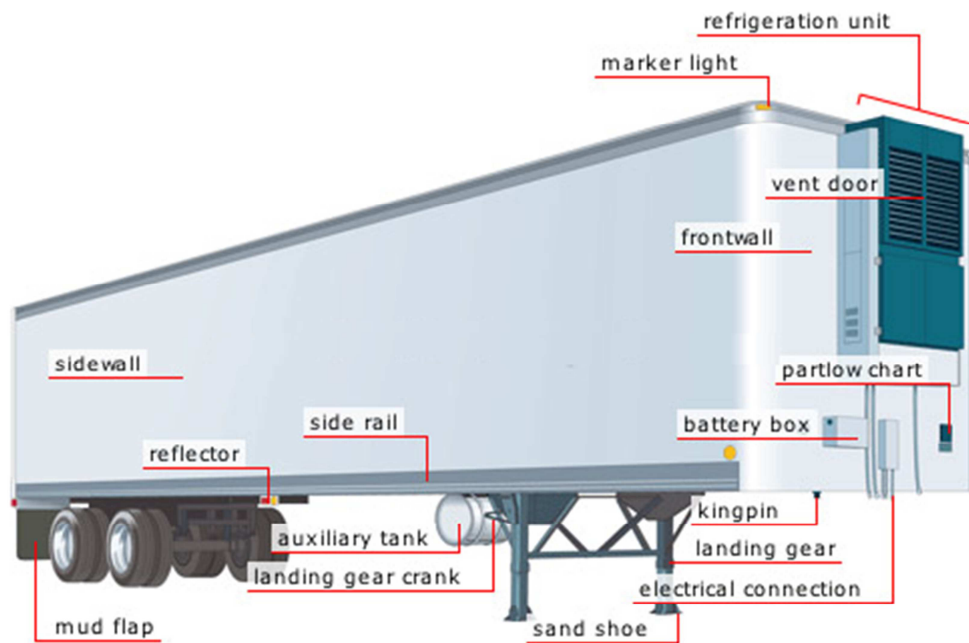


Figure 9- Overall design of refrigerated semitrailer (Merriam-Webster 2010).

Main differences between multipurpose standard semitrailers and refrigerated semitrailers are listed below:

- Different construction of walls, refrigerated units walls are well isolated
- Refrigeration unit is mounted on the sidewall
- Auxiliary tank for fuel for refrigeration unit is typical for chilled semi-trailers
- Battery box – for start-up of auxiliary unit
- Refrigerated units have smaller volumetric capacity, because of ventilation system which distributes chilled air equally within trailer

2.7.2 Refrigeration units for semitrailers

The most typical current design of refrigeration units for chilled semi-trailers is following: separated diesel internal combustion engine provides torque for compressor which increases pressure of working fluid. Some of units includes also electrical motor which provides torque to compressor when electrical power is available for example during long stops. Cooling capacity which can maintain required temperature for standard size semi-trailer is in the range 10 to 20 kW.

One of the leading international companies which offers refrigeration units for semi-trailer is Carrier. The newest series of refrigeration unit Vector is one of the most efficient

available on the market. General technical data of Carrier refrigeration unit is presented in Table 5.

Table 5- Technical parameters of Vector refrigeration units for semi-trailer units (Carrier 2010)

		Vector 1550	Vector 1850	Vector 1850 MT
Cooling Capacity Road (Watts)	0°C/+30°C	14 800	18 000	18 000
	-20°C/+30°C	8 100	9 600	9 600
Cooling Capacity Stand by (Watts)	0°C/+30°C	12 400	14 900	14 900
	-20°C/+30°C	7 000	9 000	9 000
Heating Capacity (Watts)		8 800	9 000	9 000
Airflow (m³/h)		5 600	5 600	5 600
Weight (Kg)		739	923	955
Dimensions (mm)		2050 x 430 x 2227	2050 x 430 x 2227	2050 x 430 x 2227
Sound Pressure (dB(A))	Standard	73	78	78
	Low Noise	71	76	76

2.8 Efficiency and potential of improvements for modern trucks

During last 40 years, fuel efficiency for new designed trucks has been improving with average rate of 0.8%/year (IEA 2009). Most of those improvements have been made in the 1970s and 1980s. During 1990s rate of efficiency improvements was lower because manufactures had to meet tightening emission limits especially related to NO_x. According to estimations (IEA 2009) without concern of NO_x emission today's truck engines could have higher efficiency roughly from 7 to 10%.

Many efforts have been done in the field of improving efficiency of conventional trucks in recent years. As it can be seen from Figure 10 changes in energy intensity are almost inconspicuous.

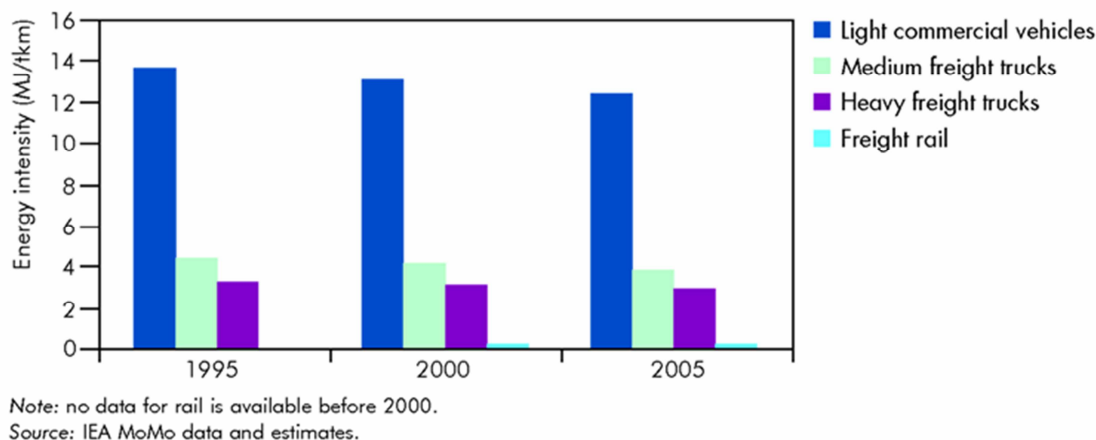


Figure 10- Global Average intensity trends by surface freight category (IEA 2009)

There are many scenarios which try to predict efficiency improvements for truck technology. In the chart below it can be seen predictions for different scenarios of reduction in GHG emission.

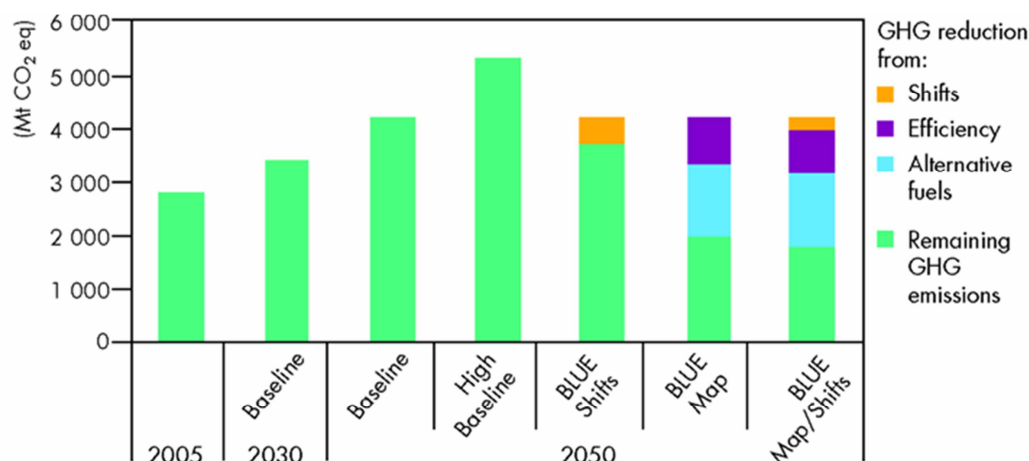


Figure 11- Well-to-Wheel GHG emissions and source of reduction from truck and rail freight by scenario

Improvements of diesel engines efficiency will never lead to zero CO₂ tailpipe emission until technology will be changed for fuels with no carbon content. The most feasible alternatives for diesel oil are bio-fuels and hydrogen. Bio-fuels seem to be very suitable as fuel for transportation because of high energy density, similar engines technology, moreover it is possible to convert existing refuelling infrastructure for bio-fuels. However, the potential of production bio-fuels is not sufficient and popularization of them can cause increase in food prices. Furthermore, problem with particles emissions will still remain.

Hydrogen and fuel cell technology is the most considered as a future technology for transportation sector. Advantages of this technology are no tail pipe emissions, high efficiency and potential of production hydrogen from any renewable sources. One of the biggest barriers is lack of expensive refuelling infrastructure without which popularization

of hydrogen vehicles is not possible. It is possible to overcome this obstacle by locating refuelling stations firstly in strategic points (Andrews 2010). Other disadvantages like high price of technology might be partially solve by massive production.

2.9 Summary of conventional truck technology

The majority of heavy transportation sector uses diesel as primary fuel. This sector is responsible approximately for 20% of worldwide CO₂ emissions. Transportation sector is likely to grow in the future due to worldwide development. Moreover, unavoidable oil shortage and lack of perspective for improving remarkably efficiency of vehicles internal combustion engine made engineers to start researching for new concepts.

Usage of hydrogen as energy carrier is considered as one of the most feasible and suitable for transportation. Instead of using hydrogen as a fuel for internal combustion engines that energy carrier can be converted to electricity directly by fuel cell without generating tailpipe CO₂ emissions or other pollutants.

Still the main challenge seems to be cost of hydrogen fuel cell technology which is cause mostly because of platinum usage for membranes. Other challenges like lower system power and energy density could be overcome by designing completely different drivetrains.

In order to completely eliminate diesel oil usage for freight transportation new refrigerated semi-trailer designs must be considered.

All of those concerns are described in the next chapter.

3 ANALYSIS OF DIFFERENT TECHNOLOGIES FOR FUEL CELL TRUCK

3.1 Introduction to hydrogen fuel cell truck technology

Chapter 3 is devoted to investigation of technology of full-scale fuel cell heavy duty truck. Firstly, all requirements which must be fulfilled for freight heavy vehicle are gathered and presented. Furthermore, all components of driveline are analysed in details. The most suitable technology is chosen for each unit. Components are preliminary analysed using the following criteria:

- Performance
- Complexity of unit
- Size
- Price
- Durability
- Sustainability of their production
- Availability of raw materials for production components

The most suitable solutions are chosen to create truck design which is feasible and have potential of replacing conventional diesel powered heavy duty trucks.

3.2 Overall design of hydrogen truck

To convert hydrogen for useful mechanical power in automotive application there are two main approaches: adaption of internal combustion engine for hydrogen or application of fuel cell technology.

Internal combustion engine powered by hydrogen is feasible (Subic 2009). Many demonstration projects proved it. This approach has following advantages: no tailpipe emission and bases on internal combustion engine technology which is well known and relatively cheap. The biggest drawbacks of this solution are efficiency which is constrained by the Carnot law, additionally high NO_x emission is still unsolved issue.

Second approach is application of fuel cell as a main source of power. This solution gives following advantages:

- Electrification of vehicle propulsion
- No tailpipe emissions
- Theoretically unconstrained efficiency of converting chemical energy to electricity
- Possibility of implementation regenerative braking

The fuel cell technology has been chosen as a leading technology of future for hydrogen power vehicles by automotive industry. Many companies conduct researches in this field. Honda last year introduced fully fuel cell powered first passengers vehicle in the world in series production: Honda FCX Clarity (Honda 2010).

For these reasons hydrogen fuel cell technology has been chosen for hydrogen truck design. Schematic drivetrain of the fuel cell truck is shown on the Figure 12. In the next sections all components are described and analyzed.

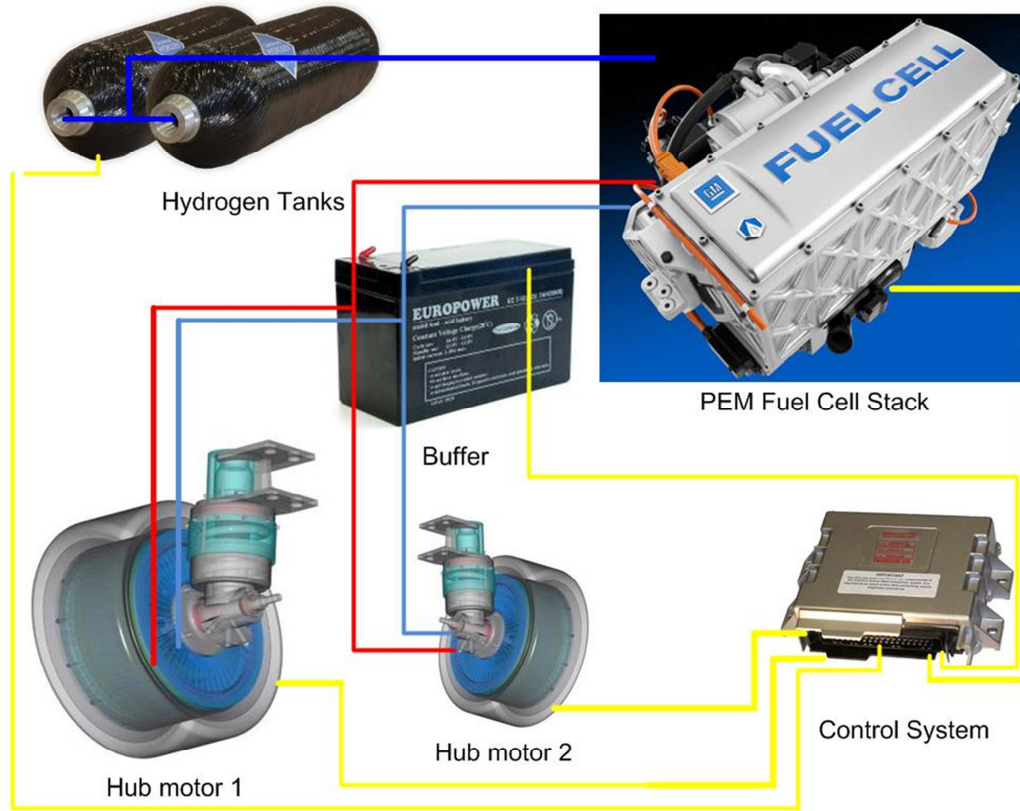


Figure 12- Overall design of hydrogen fuel cell truck drivetrain

3.3 Requirements which must be fulfilled by hydrogen fuel cell truck

In the second chapter of this thesis the requirements that must be fulfilled by conventional heavy duty semi-trailer truck are presented. To obtain fully serviceable vehicle based on the fuel cell technology those requirements must be fulfilled. Table 6 presents specific technical requirements that need to be fulfilled by hydrogen fuel cell truck.

Table 6- Requirements which must be fulfilled by hydrogen truck design

Requirement/Target	Value	Unit	Comments
Engine torque	2400	Nm	Torque of internal combustion engine which is required by drivetrain
Max torque on wheels	38 064	Nm	Gear box ratio is 15.86 – 1. It means that 1 st gear increases the torque by 15.86 times.
Power	350	kW	For electrical motor the power may be lower, it depends of torque, electrical engines performance differs from internal

			combustion engines
Mass	18 000	Kg	Mass of conventional ICE truck
Power for semitrailer	15	kW	Refrigeration Unit Power

3.4 Electrical drivetrain

3.4.1 Advantages of electrical drivetrains

In contrast to internal combustion engine fuel cell converts chemical energy for electricity instead for mechanical power. This reason causes necessity of different drivetrain system than for conventional vehicle. To convert electricity for mechanical power electrical motor is essential. Electrical motor differs from internal combustion engines in terms of design and performance.

Electrical motors are more efficient than piston engines. There are some designs for which efficiency is higher than 90%. The relationship between torque and engine cycles looks different – electrical engine attains the higher torque at the wide spectrum of rotation speed, moreover is capable to generate reasonable torque at very low rotation speeds.

Those reasons lead to new conception of electrical wheel motors (also known as hub motors) which give the power to each wheel. Below two different approaches are presented: central electrical motor and electrical wheel motors.

3.4.2 Central electrical motor

Application of a central electrical motor leads to very similar to current trucks drivetrain design. Instead of internal combustion engine main device which gives power is electrical motor.

Because of the different relationship between torque and rotation speed the gearbox ratio must be changed. The other components of drivetrain can stay almost unchanged. This fact is a great advantage of central electric motor technology because of well-known technology, what is more, current production on big scale would assure low cost of production. Furthermore, techniques of maintaining are already developed and technical staff is already trained. Construction of one bigger electrical motor instead of two or four wheel motors with the same summary power would absorb fewer raw materials like copper and steel.

However, this solution is less efficient because of losses in transmission. Losses occurring in transmission mechanism can be relatively high especially on lower speeds. Other propulsion devices like gear box and differential system also generates losses. Because of transmission of Very high torques drivetrain requires heavy, resistant components. Usually all components are made of steel and accounts for substantial part of mass of vehicle. Conventional drivetrain is very complex and relatively expensive because some parts need to be maintained or replaced periodically (e.g. clutch).

3.4.3 Wheel electrical motors

Wheel motors solution is a new opportunity which can be implicated thanks to electrification of drive train. Instead of central motor, clutch, gearbox, differential system

the drivetrain consist of wheel motors contained in wheel rim, electric wires and control unit.

In the past wheel motors were not considered as a suitable for transportation application, because there was no solution which allows coordinating precisely motors speed without mechanical connection. The company e-Traction® Worldwide S.C.A. in 2000 solved this problem by introducing proprietary electronic control system. (Bullis 2009)

Big Companies like Michelin, Volvo and Ford are working on this technology mainly for passenger cars. The feasibility of application of this solution for heavier vehicles has been presented by company e-Traction® Worldwide S.C.A. revealing “Whisper” the first electric bus propel by wheel motors. After modification Whisper reached speed of 120 km/h in 2006 (e-Traction 2010). Couples of this type busses are under still under operation and the company is going to deliver more vehicles with wheel motor technology.

Design of wheel motor is quite simple. Wheel motor is electric motor mounted in the wheel rim, which is simultaneously the rotor of electric motor. Rotor contains the permanent magnets while the stator is electromagnet. Mounting units in the wheel rim allows designing electric motors with greater diameter which takes effect on greater torques. Assembly of example wheel in motor is presented on figures below.

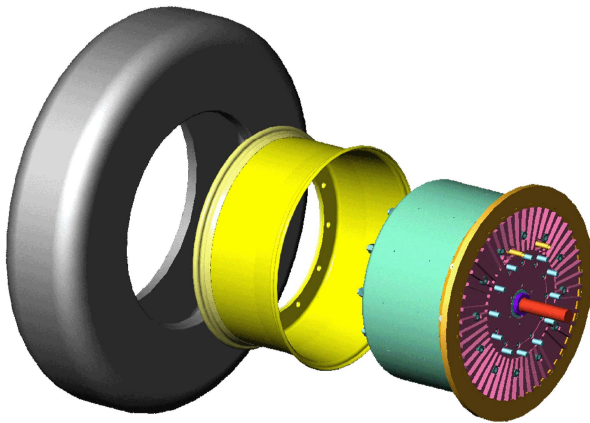


Figure 13- Wheel motor design - main components (from left: tire, rim, wheel motor) (e-Traction 2010)

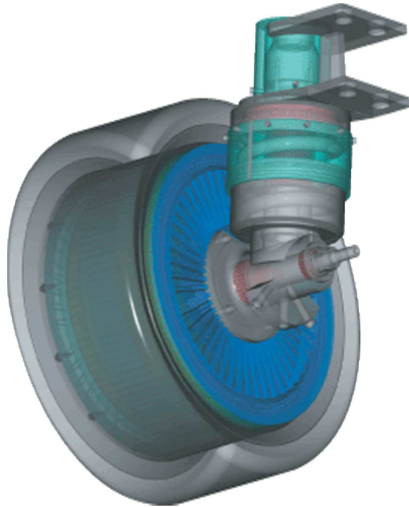


Figure 14- Wheel motor design - assembled unit, (e-Traction 2010)

E-Traction ® Worldwide S.C.A. is one of the leading world's companies in wheel motors. Their solutions have been used in many projects all over the world.

There are two product lines which are suitable for implication for heavy duty truck which are detailed in Table 7.

Table 7 - Technical Parameters of wheel motor (E-Traction 2010)

	TheWheel SM500/3*					TheWheel SM700/2*				TheWheel SM700/3			
Voltage	96	144	192	384	768	96	192	384	768	96	192	384	768
RPM Y	67	100	133	267	533	55	90	165	330	40	65	125	250
RPM Δ	115	172	229	459	917	95	155	284	568	69	112	215	430
Field Weakening Y	133	200	267	533	NA	120	235	465	NA	90	175	350	NA
Field Weakening Δ	229	333	417	833	NA	206	404	800	NA	155	301	602	NA
KW	15	22.5	30	60	120	30.0	65.0	95.0	190	40.0	80.0	120.0	240
AMP - nominal	300A					300A				300A			
AMP - peak	1,000A					1,000A				1,000A			
Torque - nominal range	3,000 to 3,750 Nm					3,900 to 5,400 Nm				5,200 to 7,200 Nm			
Torque - peak	7,500 Nm					10,000 Nm				15,000 Nm			
Weight	Steel 600 kg					FE: 750 kg		AL: 625 kg		FE: 850 kg		AL: 725 kg	
Max. Load	9 TON					30 TON		7.5 TON		30 TON		7.5 TON	
Nominal Load	6 TON					15 TON		5 TON		15 TON		5 TON	
Diameter	539 mm, tire 455/45 R22,5"					715 mm, tire 455/45 R30"				715 mm, tire 455/45 R30"			
Length	555 mm					525 mm				625 mm			
Max. Revolutions	1,000 RPM					665 RPM				500 RPM			
Cooling	Air, contact and water												
Protection	IP54 - or higher												
Isolation Class	H												

The motor SM500/3 has been applied for WHISPER bus. Bus is able to drive from 0 to 120 km/h without any transmission. To provide required torque 4 units of SM500/3 motor or 2 units of SM700/3 must be applied for designed truck.

The application of wheel motors in driveline truck technology has many advantages. Firstly, reduction of maximum power in comparison to central electric motor solution can be expected because of lack of losses from mechanical transmission.

Less complex system would lead to easier and faster maintenance. There is no need of using separated units like clutch, gear box, transmission and differential system. As it is known all of those components need often maintenance, furthermore it is hard to get to some of the parts like clutch, gear box what make maintain cost and time consuming. In contrast to classic drivetrain service of wheel motors is relatively easy and would take less time. To get to the motor interior it requires only removal of twelve bolts and a wires connection. Moreover it is possible easily remove/replace motor unit and then servicing it on the special stand (E-traction 2010). Absence of typical heavy elements of drive train would lead to less mass of truck. Simple implication of safety systems is next advantage of this solution. All safety systems are easier to implement since wheels are controlled by software instead of mechanical coupling. The braking can be done magnetically by simple powering the engine pole in opposite direction. During this action the power is produced and stored in battery or super capacitors, so called regenerative braking.

Consumption of more raw materials (especially copper) for production of two electrical motors than for one motor which power will be equal is one of disadvantages. Due to safety reasons doubling of braking system might be essential. Next problem to overcome is greater demands on suspension – assembling motors in the wheels increase the mass of wheels causing more resistant suspension to hold rotating wheels. Electronic control of differential is not such reliable as mechanical one that's why risk of accident caused by software errors seems to be high. Constructing big wheel motors is currently very expensive. According to E-traction Company larger-scale production could solve the problem (Bullis 2009).

3.4.4 Preferable technology

On the basis of this preliminary analysis the most suitable technology for drivetrain for full-scale hydrogen truck appears to be wheel motors. Truck power by this kind of motor doesn't require conventional heavy and complex drivetrain. In addition having electrical control on separate wheels it makes much easier to apply sophisticated safety systems like: Electronic stability program, Adaptive Cruise Control, Anti-lock braking system, the lane guard system, Brake assistant and Continuous Damping Control.

On the market there are available wheel motors that can fulfill torque requirements. In truck 6x4 it is possible to use motors with different power in this case two motors would perform as master motor and two smaller as slave motors. Master motors should have continuous contact with road and slave motors can be attached to lift axle and use only when high torque is required (start or slope). Thanks to this solution motors can be operate with higher efficiency most of driving time.

3.5 Fuel Cell

3.5.1 Introduction to fuel cell technology

Fuel cell is the main component of drivetrain. It converts chemical energy contained in hydrogen to electricity which is used by electric motors to drive the wheels.

Fuel cell technology has been developed by several years. During this time many types of fuel cell have been developed. There is still strong interest in fuel cell technology, researchers working on improvements and on the new technologies. Further in this section, the different types of suitable fuel cell for automotive application are analyzed.

3.5.2 Polymer Membrane Fuel Cell

Polymer Membrane Fuel Cell (PEMFC) is the most considered for automotive application. Many projects all over the world prove that this technology is suitable for vehicles. First series production car Honda Clarity FCX is powered by low temperature PEM.

Low temperature fuel cell consists of membrane made of Nafion which conducts the ions only when it is humidified enough. Essential water content is the reason why this type of fuel cell operates under 100° C. Because of low temperature catalyst is needed to start reaction. The only catalyst which is efficient enough is platinum which is very expensive.

Low temperature fast start-up has been presented by many demonstration projects. This type of fuel cell is even capable of start under very low temperatures. Moreover, efficiency of producing electricity from hydrogen can exceed even 50% (based on HHV).

Low durability is one of the biggest disadvantage of low temperature PEMs. Usually first observed degradation will occur between 1 000h and 3 000h of operation. The expected minimum limits of durability for passenger and for heavier vehicles (like trucks and busses) is respectively 5 000h and 20 000h. Currently the longest lifespan of fuel cell has achieved 7 300h under cyclic conditions (DOE 2008).

Necessity of using humidification system increases complexity and cost of units. The water management system is essential to prevent drying of Nafion membrane both hydrogen and air must be humidified before reaction in fuel cell. What's more, humidification system causes losses of energy and makes system very complex. Usually balance of plant system is as big as a fuel cell stack itself. In order to assure good kinetics of reaction platinum is required as a catalyst. This raw material is very expensive and limited in deposits. Currently many companies working on substitute catalyst for fuel cell. Standard content of platinum is estimated at 1 mg/cm² of cell, the lowest platinum content has been achieved by Ballard Company (approximately 0.7mg/cm² thanks to usage of carbon silk) without losing efficiency.

Recently, Monash University (Melbourne, Australia) started research of novel conducting polymers for fuel cell membranes. Idea is to replace the conventional electrode and catalyst materials in fuel cells by new materials with similar performance (or better) in much cheaper price. In this solution researchers want to build PEDOT based electrodes and use ionic liquids as a new catalyst. First tests give very promising results. (Winther-Jensen et al. 2008)

The operating temperature of PEM FCs is about 60-80°C. To not exceed those limits stack must be cooled during operation, lower temperature of coolant causes less intense rate of heat exchange and bigger heat exchangers are required in comparison to conventional systems. For truck consideration low waste heat temperatures make impossible to use adsorption pump for refrigeration needs.

In order to assure stable working parameters of fuel cell very pure hydrogen must be delivered. Low temperature fuel cells are very sensitive for impurities of hydrogen

especially for carbon monoxide. This feature almost rules out implementation of fuel reforming on board vehicle because of cost and size of purification system.

The new technology of high temperature fuel cell is still under development. The biggest differences between low and high temperature fuel cell is material of membrane. For high temperature PEM it is based on polybenzimidazole fiber (PBI). Operating temperature of this type of membrane is 100-200 degrees C. Some researches proved that this technology is suitable for automotive application (Andreasen & Ashworth 2008)

In comparison to low temperature PEM fuel cells those operating on higher temperature leads to less complex system. Humidification system which is necessary for low temperature fuel cells water management takes relatively lot of space, moreover is costly and complex.

In general the efficiency is almost equals for low and high temperature PEM fuel cells. However, high temperature waste heat is advantage of this type of electrochemist devices. Waste heat temperature is in rage of 140-160 °C such a high temp results in higher intensity of heat exchange – smaller heat exchangers are required. Moreover, this level of temperature might ensure good COP of absorption chiller for refrigeration needs. Utilization of waste heat may substantially improve overall efficiency of system.

Furthermore, high CO tolerance allow introduce less complex reformer designs without expensive carbon monoxide cleaning system. Moreover it also gives opportunity to power this type of fuel cell by other types of fuels (e.g. natural gas).

Start-up of high temperature fuel cell is possible if the average temperature of this device will be above 100C. Warming from cold state is only possible with pre-heating of stack. There are two developed methods of adding heat to cold stack. First method uses special heating foils attached to the sides of stack. Energy is derived to heating element from batteries and by conductive heat transfer warming up the stack. Second method which is faster and more efficient combust hydrogen in order to produce heat which is deliver by air flow to cathode exhaust. Second method can shorten start up time up to few min. (Andreasen & Kær 2008). For truck application fast start up is not as important as for passenger cars because usually freight routes are planned in advance and longer stop results from law regulation. In order to improve convenience of using truck with this type of fuel cell is possible to implement inexpensive system which can start heating up the stack before driving.

3.5.3 Solid Oxide Fuel Cell

Solid oxide fuel cell (SOFC) technology was developed for automotive application mainly as an auxiliary power unit for trucks. Two companies Delhi and BMW in 2000 developed fully working auxiliary unit which provides electricity for electrical appliance during long stops while waste heat is using for thermal needs. This technology differs completely in general design from PEM FC. The single cell consists of a porous air cathode made of MnO₃, membrane is a gas tight oxygen ion conductive yttria- or scandia-stabilised ZrO₂, and porous anode made of ZrO₂/Ni.

The main advantage is that SOFC doesn't require expensive catalyst because operating temperature is high enough (usually above 700° C) to assure good reaction kinetics. However, some raw materials are still required, mainly for auxiliary system of fuel cell. Thermal efficiency may exceed 50% (Lin & Hong 2008) which is excellent result.

In comparison to low temperature fuel cells lifespan of SOFC is much longer. Siemens Westinghouse state of the art design (tubular fuel cell) has been tested by continuous electrical operation over 69 000 hours. Survey shows that degradation was about 0.5% drop in voltage per 1 000 hours of operation. Because expected durability for buses and heavy duty truck is 20 000 h durability of SOFC is not an issue (DOE 2004).

This kind of fuel cell is resistant for CO and CO₂ impurities in hydrogen. However other impurities like hydrogen sulfide (H₂S) hydrogen chloride (HCl) and ammonia (NH₃), which can be finding in coal gas may cause degradation of stack. The most important feature of SOFC regarding to automotive application is that they can cooperate with portable reformer without any sophisticated purification system what gives flexibility of fuel (DOE 2004). Alternative fuel like methane or natural gas can be used.

However, long start-up for this type of fuel cell is still a barrier for automotive application. To start electrochemical reaction of oxidation stack must be heated up to temperature which allows produce meaningful amount of energy by stack. One of the fastest methods is to feed the air channels by hot air (Colpan, Hamdullahpur & Dincer 2009). Trucks routes are usually planned in advance so slow star-up is not big issue for heavy duty vehicle application. Some simple programmable systems can be applied in order to start fuel cell preparation before a travel.

To operate fuel cell at such high temperature the sophisticated power management is required. Power management is one of the functions of balance of plant unit which consist of heat exchangers, recuperators and afterburner. All of those elements are costly, relatively big in dimensions and require careful management.

3.5.4 Preferable technology for fuel cell

The most suitable solution for full-scale heavy duty vehicles seems to be high temperature PEM fuel cell. The most important challenge for designers is still seeking for solution which reduces usage of platinum which is the main reason of high prices of those devices.

3.6 Buffer

3.6.1 Main tasks for energy buffer

Buffer is very important part of the system. The main task for buffer is to stores energy for short time and delivers power during peak demands. It is also necessary component of regenerative braking system. The capacity of the buffer should be derived from modeling of the system. Too big buffer will be too heavy but too small capacity of buffer would not deliver enough power. Energy stored in buffer can be provided by the regenerative braking system or from the fuel cell during low energy demands for driveline. By good designed buffer it is possible to reduce maximum power of fuel cell.

Buffer task can be carry out by two devices which are described below.

3.6.2 Battery

Battery is electrochemical device which is can convert stored chemical energy into electricity. Batteries were invented at the beginning XIX by Alessandro Volta. From this time many technologies have been developed.

Batteries have been applied for conventional vehicles for many years. Their main task is to provide energy to start internal combustion engine and power auxiliary systems.

From the beginning of 90's batteries have been used also as main source of energy for battery electric vehicles prototypes (Pistoia 2010). Inseparable component of battery pack is balance of plant unit. This is electronic system perform as a thermal management system and voltage monitoring system, prevents from overheating and controls degradation of cells.

Batteries are characterized by several factors, like: power-to-mass ratio, energy to mass ratio and energy density. In comparison to diesel capability of storage energy battery technologies have still much lower specific energy.

Below descriptions of the most considered types batteries for automotive application can be found.

Lead-Acid batteries are one of the oldest technologies. Fabrication of them is relatively cheap and well-known. Those batteries are used as energy source for start internal combustion engine in conventional vehicles.

Describing batteries contain toxic materials but most of the can be recycled. Low durability especially if deep discharges occur is one of the disadvantages. Furthermore, low storage efficiency (estimated to be around 70-80%) and low gravimetric energy density (usually about 30-45 Wh/kg) make them not ideal solution for energy buffer.

Nickel-metal hydride (NiMH) batteries are example of more advanced technology. This type of storage was implicated to GM electric vehicle I and for Toyota RAV4EV. Additionally, they have been installed to Toyota Prius Hybrid thanks to usage on big scale caused in many improvements for that type of battery.

In comparison to Lead-Acid Batteries, NiMH has better gravimetric energy density (from 30 up to 80 Wh/kg). Relatively long durability - under repeatedly deep cycles with high load currents first degradation of operation is perceived after 200 - 300 cycles. The shallow discharge cycles are preferable what cause reduce of useable capacity of the battery. Made of mild toxins which can be recycled make them environmentally friendly.

Nickel-metal hydride batteries are less efficient than lead-acid batteries (max efficiency 60-70%). What's more in the minus temperatures batteries have poor performance. The next drawback is limited discharge current. In contrast to Lead-Acid batteries the NiMH batteries are not suitable for delivering high discharge currents. Best results in terms of durability are achieved for one-fifth to one-half of the unit capacity (Energizer 2010).

Because of high quantities of waste heat generating during charge batteries requires a longer charge time than the other types of batteries. The careful management is required to prevent overheating of batteries. In comparison to Lead Acid the NiMH has about 50% higher self-discharge. This type of batteries requires regular full discharge to prevent crystalline formation. The last significant disadvantage is high cost of production as for all batteries technology. Currently the batteries cost about \$300-\$320 per kWh. According to researches (Anderman, Kalhammer & MacArthur 2000) estimated cost of NiMH batteries produced at 100,000 or more units per year would be \$250/kWh.

Lithium-ion (Li-ion) batteries technology is well known, due to their widely application in consumer electronic. This solution is the most considered for new designs of battery vehicles. High energy densities can be achieved (some of units have power density up to 250Wh/kg) by those batteries. Very high efficiency range up to 90% (Pistoia 2010), the best durability among other batteries (Pistoia 2010) and slowest self-discharge make them the most suitable of all types of batteries.

High cost is the most significant drawback. According to (Kromer and Heywood 2007) prices varied from 420 to 300 \$/kWh (it depends of capacity, for bigger capacities unit price is lower). Kromer and Hywood (2007) in their report estimated that cost of materials is about 50% of price of the battery, and with a big volume production it is possible to reduce cost of materials with ratio 2,5%/year.

3.6.3 Electric double-layer capacitor

Electric double-layer capacitors are also known as: supercapacitor, ultracapacitor or pseudocapacitor.

This device works on the same principles as usual capacitor. Main differences in design are following: instead of dielectric plate with two layers which are able to separate of charge the porous material is used. Thanks to porous material supercapacitors can achieve thousand times higher energy densities than conventional capacitors.

In comparison to batteries ultracapacitors lifespan is substantial longer. Pseudocapacitors can operate over 1 million of duty cycles with little degradation according to Maxwell (2010). Lack of toxic substances and long durability make the supercapacitor environmental friendly solution.

High range of discharges (capacitors are able to fast charge and discharge without overheating) and resistance for deep discharges make this kind of energy storage ideal for automotive application. Moreover, pseudocapacitors can achieve high storage efficiency up to 95%. Research conducted at Institute of Transportation Studies, Davis, California showed that the specific possible power is approximately 6 kW/kg.

Low energy density is one of the drawbacks of supercapacitors. The highest energy density available on the market is about 30Wh/kg while Li-ion batteries can achieve densities up to 250 Wh/kg. Moreover, for this type of capacitors the voltage varies with the level of charge. In order to effective discharges complex electronic control is required what makes system more expensive. Supercapacitors faster loose energy by self-discharge than batteries which is not big issue since energy is store in trucks for short periods.

Below it can be seen the comparison between batteries and supercapacitors in terms of energy density, power density and discharge time presented as diagonals.

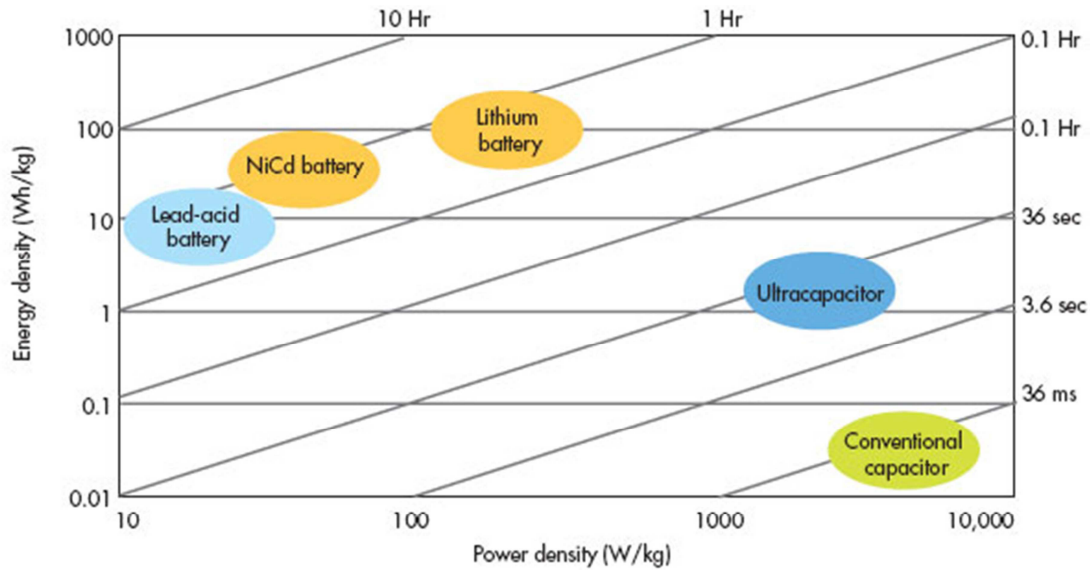


Figure 15- Comparison of parameters for batteries and ultracapacitors (Tuite 2007)

3.6.4 Preferable technology for buffer

The best technology for providing the buffer storage in full-scale hydrogen trucks seems to be ultracapacitors. The biggest advantage of ultracapacitors is their durability probably which would last longer than truck lifespan. Moreover many times higher recharging ratio allow to storage big quantities of energy during regenerative breaking without necessity of sophisticated thermal management. Ultracapacitors is heavier solution but it is not as important as for passenger vehicles. Taking into account costs associated with maintenance and replacing this solution will be much cheaper than batteries.

3.7 Hydrogen storage

Hydrogen can be stored under three forms: compressed, liquefied and reacted or contained in other materials, usually with metal hydrides. All of those techniques are described further in this section.

3.7.1 Compressed hydrogen

This is the leading method of hydrogen storage for vehicle application. The hydrogen is stored usually at pressures 35 MPa or 75 MPa. In order to store compress hydrogen special designed high pressure vessel are required. 4th generation pressure vessels are currently the state of the art of this technology.

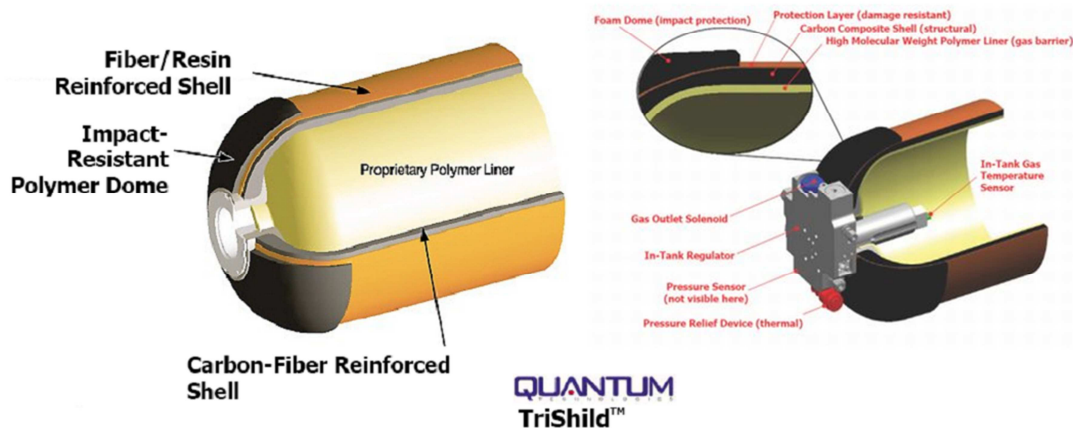
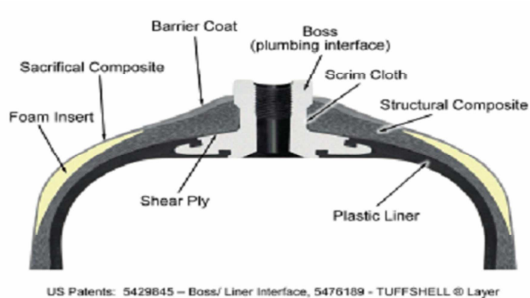


Figure 16- Design of compressed hydrogen storage generation IV
(Future Transportation 2010)

Hydrogen tanks generation IV consist of high molecular mass polymer liner which is wrapped with resin impregnated carbon composite. The most outer 3rd layer prevents container from environment factors.

According to calculations (Eliasson&Bossel 2003) to compress hydrogen from 0.1 MPa to 80 Mpa at least 15% of energy content related to HHV must be spend.

3.7.2 Liquefied hydrogen

Technique of storage hydrogen as a liquid is very complicated. Hydrogen needs to be stored under very low temperature to stay in liquid state. Containers require very good insulation to prevent heat losses. Figure below presents example design of liquid hydrogen storage for automotive application.

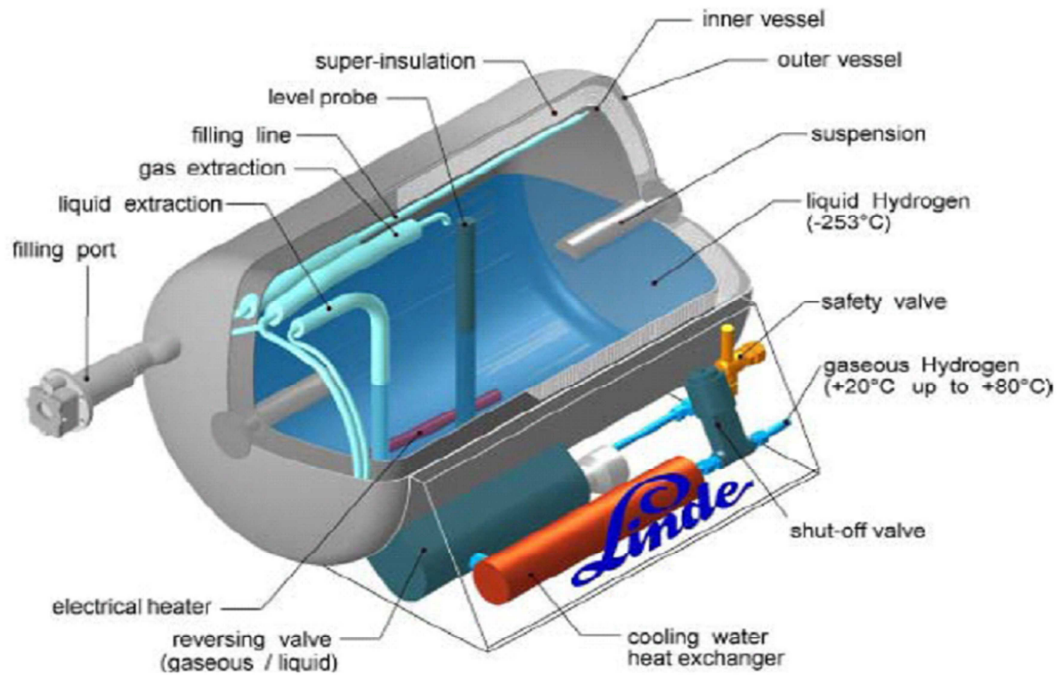


Figure 17- Overall design of liquid hydrogen storage unit (Linde 2006)

It is not possible to prevent completely from heat losses. After some time temperature in the tank will increase and liquid hydrogen starts to boil-off. If the pressure inside will be too high safety valve will release some hydrogen. According to (Burns 2002) rate of losing hydrogen from medium size tank is 3-4% of volume per day.

However, production of liquefied hydrogen is very inefficient. Temperature required to liquefy hydrogen is -253°C . Theoretically to achieve this temperature only about 4MJ from 1 kg of hydrogen must be removed to condense gas hydrogen. In practical to carry out that process it is needed to put to 10 times more energy than in theory (efficiency of process is about 10%).

Relation between HHV and energy needed for liquefy H_2 in terms of size of unit is shown in Figure 18.

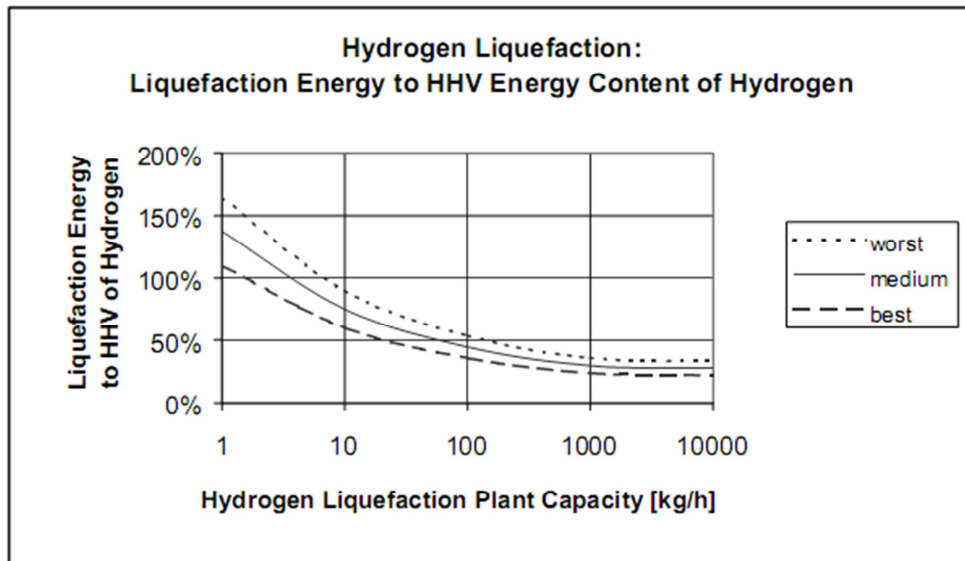


Figure 18- Typical energy requirements for the liquefaction of 1 kg hydrogen (Eliasson&Bossel 2003)

As can be obtained from Figure 18 at least 35% of energy content must be spent in the process of liquefaction. This process is very inefficient in terms of primary energy use (Eliasson & Bossel 2003).

3.7.3 Storage in metal hydrides

There are two method of storing hydrogen using metal hydrides – physical and chemical.

Physical method relies on adsorption hydrogen in spongy matrices of special alloys as physical hydrides. Hydrogen bonds with alloys like LaNi_5 thanks to this process hydrogen forms are very close.

To storage hydrogen using this method first hydrogen must be compressed to low pressure. Additional energy is needed to create metal hydrides. During filling the container it heats ups and usually generated energy is waste. To release the hydrogen additional energy must be added. For small containers it is possible to exchange heat with environment but for bigger containers with higher hydrogen flow rate heat form environment is not sufficient. Nevertheless, less energy is needed for storage hydrogen in physical metal hydride then for 75 MPa compressed hydrogen.

The most important disadvantage of this method in terms of automotive application is mass of metal hydrides needed for storage hydrogen. Because of complicated thermal management and heavy mass this type of hydrogen storage is impractical for automotive application.

Chemical method stores hydrogen chemically in alkali metal hydrides. None of suitable compounds (LiBH_4 , NaBH_4 , KBH_4 , LiAlH_4 , NaAlH_4) can be found in nature all they are artificial synthesized.

According to (Eliasson&Bossel 2003) to store 1 kg of hydrogen 1.6 times more energy than 1kg of H_2 (based on HHV) energy must be added. This type of storage is the most inefficient in terms of energy use.

Mass ratio of storage in chemical metal hydrides is on good level the best technologies are capable of achieving the 9 wt. %. In order to store 1 kg of hydrogen mass of container is about 10 kg.

3.7.4 Comparison of storage method

Figure 19 and Figure 20 show comparison of storage the most suitable methods for hydrogen storage for automotive application in terms of volume, mass and cost. Truck requirement of stored hydrogen mass is at least 50kg to assure satisfactory range. Note that graphs have been updated due to development of new metal hydride technologies (Hydrogen Program Report 2009).

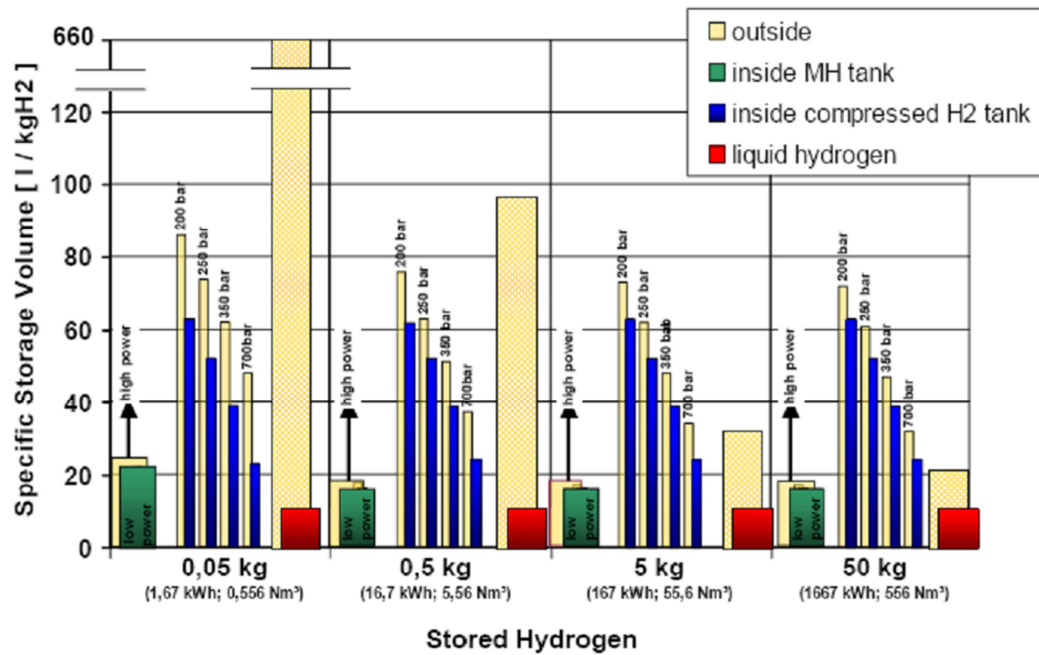


Figure 19- Specific Storage Volume of Different Technologies (Dynetek 2002)

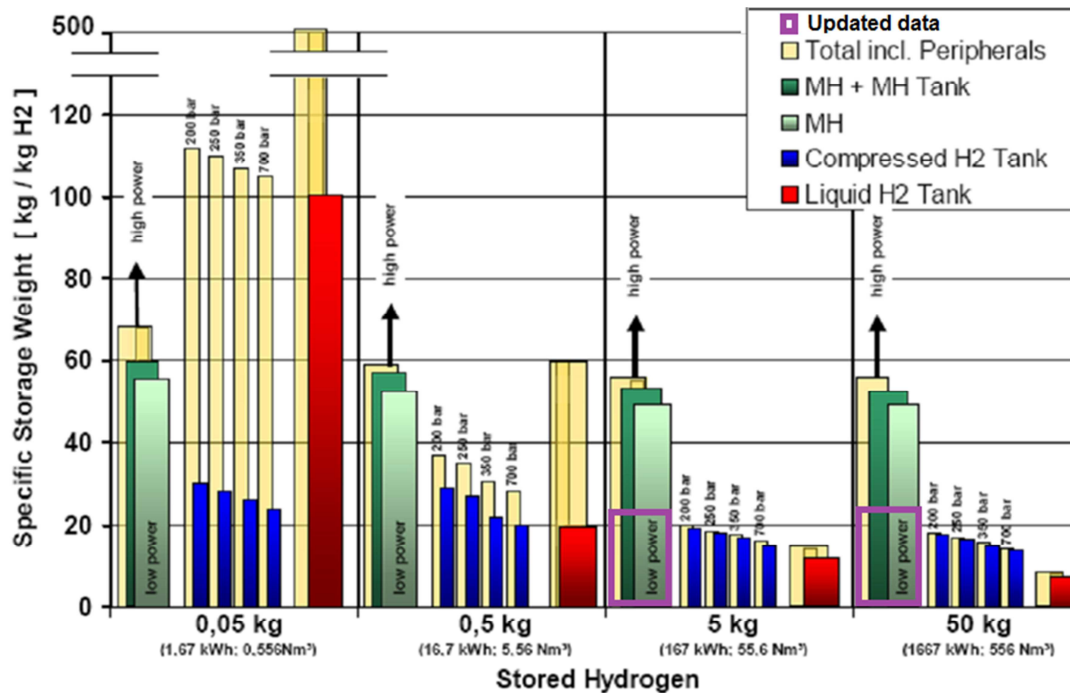


Figure 20- Specific Storage Mass of Different Technologies (DyNETek 2002), updates (Hydrogen Program Report 2009)

Cost of storage technologies

According to the U.S. Department of Energy Hydrogen Program Annual Progress Report (2009) and investigation conducted by Lasher, Sinha, Chin and MCKenney (2009) currently the cheapest technology of storage hydrogen on board of vehicle is Liquid hydrogen tank. Figure 21 presents cost structure of all feasible methods of storage hydrogen.

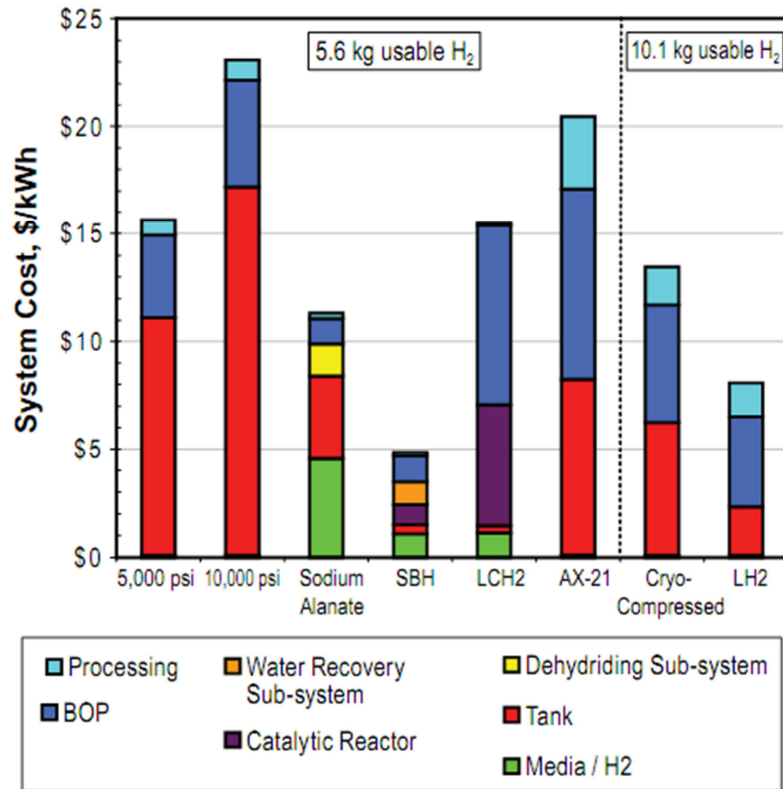


Figure 21- Cost structure of on-board hydrogen storages (Lasher, McKenney, Sinha and Chin, 2009)

However, this comparison does not give an answer which technology will be the most economically efficient for the final user because prices of hydrogen itself under different forms varies. The comparison of ownership cost under the same lifetime for all technologies and for gasoline have been prepared and presented in the Figure 22. Ownership cost is the sum of hydrogen storage devices cost and fuel cost.

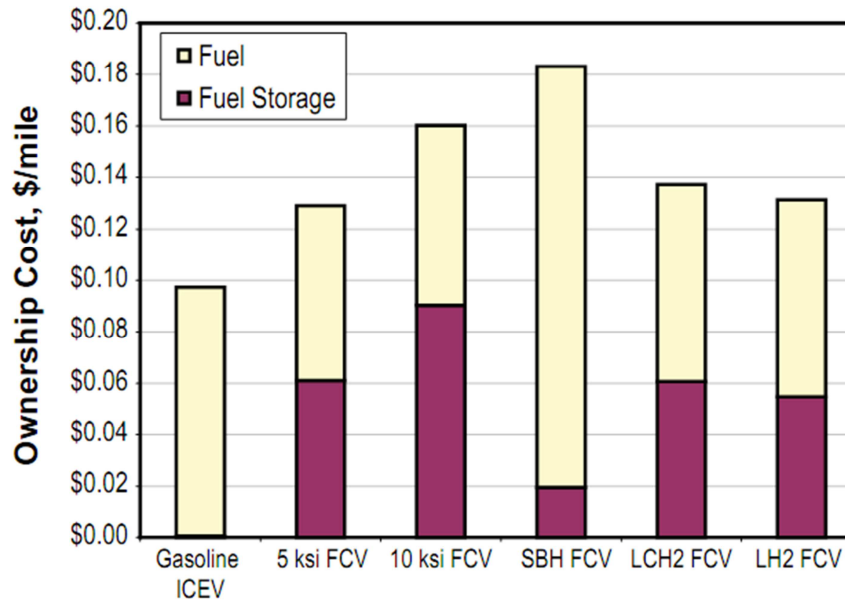


Figure 22- Comparison of ownership cost for different technologies (Lasher, McKenney, Sinha and Chin, 2009)

As it can be obtained from Figure 22 compressed hydrogen under pressure 5 000 Psi (approximately 35 MPa) and liquid hydrogen are two the cheapest options. Ownership cost of fuel is very important factor for freight transportation business because it important factor determining profits.

3.7.5 Preferable technology for hydrogen storage

Compressed hydrogen seems to be the most suitable technique for hydrogen truck application. However, high pressure technology for storing around 50kg in terms technical properties, especially volumetric density is not as good as liquid hydrogen. The ownership cost of those two technologies is very similar. Finally, taking into consideration whole hydrogen storage process from producing hydrogen under required form, cost of storage devices, refueling and transportation infrastructure the most efficient and sustainable method seems to be compressed hydrogen.

3.8 Non fossil fuel refrigerated semi-trailer designs

3.8.1 Introduction for unconventional refrigerated semi-trailer designs

Since diesel oil is not used for the powertrain in a hydrogen fuel cell truck it seems to be pointless to use conventional fuel for refrigeration unit for semi-trailer. In order to provide energy for chiller it is possible to use many approaches. This section is devoted to investigation of the most suitable technology for refrigeration unit.

3.8.2 Refrigeration unit powered by electricity

As it was characterized before current conventional refrigeration units have two sources of torque for compressor – internal combustion engine for road operation and electric motor for stand-by operation. Technologies which use compressor and works on the principle of reversed thermodynamic cycle are very well known and relatively cheap due to big scale production.

Similar refrigeration unit can be designed without internal combustion engine and then electric motor will perform as main source of torque for compressor. Electricity can be harness from the same fuel cell that provides energy for drivetrain.

This solution gives following advantages: decrease the costs of refrigeration unit makes system relatively not complicated and allows working system without truck during stops. Moreover, this solution is good in terms of performance of whole power system because fuel cell can work constantly on higher load and during the peak demands refrigeration unit can be automatically switched off. Thermal dynamic of chilled goods is very slow so periodically stops of compressor should not have influence on temperature in semitrailer.

3.8.3 Refrigeration unit with absorption chiller

Usage of absorption chiller in refrigeration unit is second approach which is feasible for refrigeration in transportation. Since fuel cell produce roughly about 50% of heat that thermal energy can be used by absorption chiller to produce required chill. Quantity of waste heat would assure enough energy for refrigeration needs even with very poor absorption chiller efficiency. Advantage of this solution is that mainly waste heat is used so overall system efficiency increases, moreover there very silent during operation. Very complicated system and relatively expensive components are the disadvantages of this solution. What is more operation during stops and operation without truck would not be possible without doubling system with electrical chiller.

3.9 Overall design for a fuel cell truck technology

This section consist preliminary concept design of powertrain for heavy duty vehicle powered entirely by hydrogen.

Investigation conducted in section 3.4.3 pointed that the most suitable technology for fuel cell is high temperature PEM. To fulfill power requirements maximum power of electrochemical electricity generator should be at the level of 350 kW. Assumption was made that the performance of hydrogen fuel cell powertrain will be at least the same as the performance of conventional diesel power train on the basis of following reasons:

- Efficiencies achieved by fuel cells are in general higher than for internal combustion engines
- Relationship between efficiency and load is more flat for fuel cells which mean that high performance of those devices is available in the range spectrum of loads
- Efficiency of conventional driveline is comparable with hub wheel motors
- Thanks to electrification of powertrain and associated with it capability of better energy management including energy buffer it might be possible to reduce

maximum power of fuel cell. Less powerful fuel cell can be cheaper in production. Not substantial improvements of efficiency are expected after reduction of power because of general capability of fuel cell good performance under wide range of loads

According to factors for state of art fuel cell available on the market in 2009 (Ahluwalia & Wang 2010) fuel cell is described by following specifications. Content of platinum is estimated to be 150 – 200 g (content of Pt in FC 0.57 - 0.42g/kW) mass of the stack 200 kg (power density for stack 1.77 kW/kg, power density of system is estimated to be 0.5 kW/kg).

Technology for hydrogen storage was chosen to be compressed hydrogen at 35MPa. To obtain roughly estimation of hydrogen storage quantity it was assumed that conventional truck average consumption is about 35 liters per 100 kg. Next assumption was made that fuel cell powertrain is the same efficient as conventional. Energy content in 1l of diesel is approximately 10 kW in order to assure 500km range energy stored in hydrogen must be equal to 1750 kWh (53 kg of H₂). Using energy gravimetric and volumetric energy densities mass and volume are respectively equals 1000 kg and 2.6 m³ for compressed hydrogen tanks.

For propulsion two units of SM700/3 wheel motors were chosen. According to Table 7 mass of each device equals to 725 kg.

Prior investigation indicated supercapacitors as probably the most suitable technology for buffer. To guarantee good operation of system buffer should be rated at least 20% of fuel cell power which is 70kW. To obtain such power estimated weight of pseudocapacitors is about 12 kg. However, to maintain reasonable energy buffer (equal to energy produced of full power by in fuel cell in 2 min) the quantity of supercapacitors must be increased then estimated weight will be 400 kg.

The preliminary hydrogen fuel cell truck design is shown on the graph below.

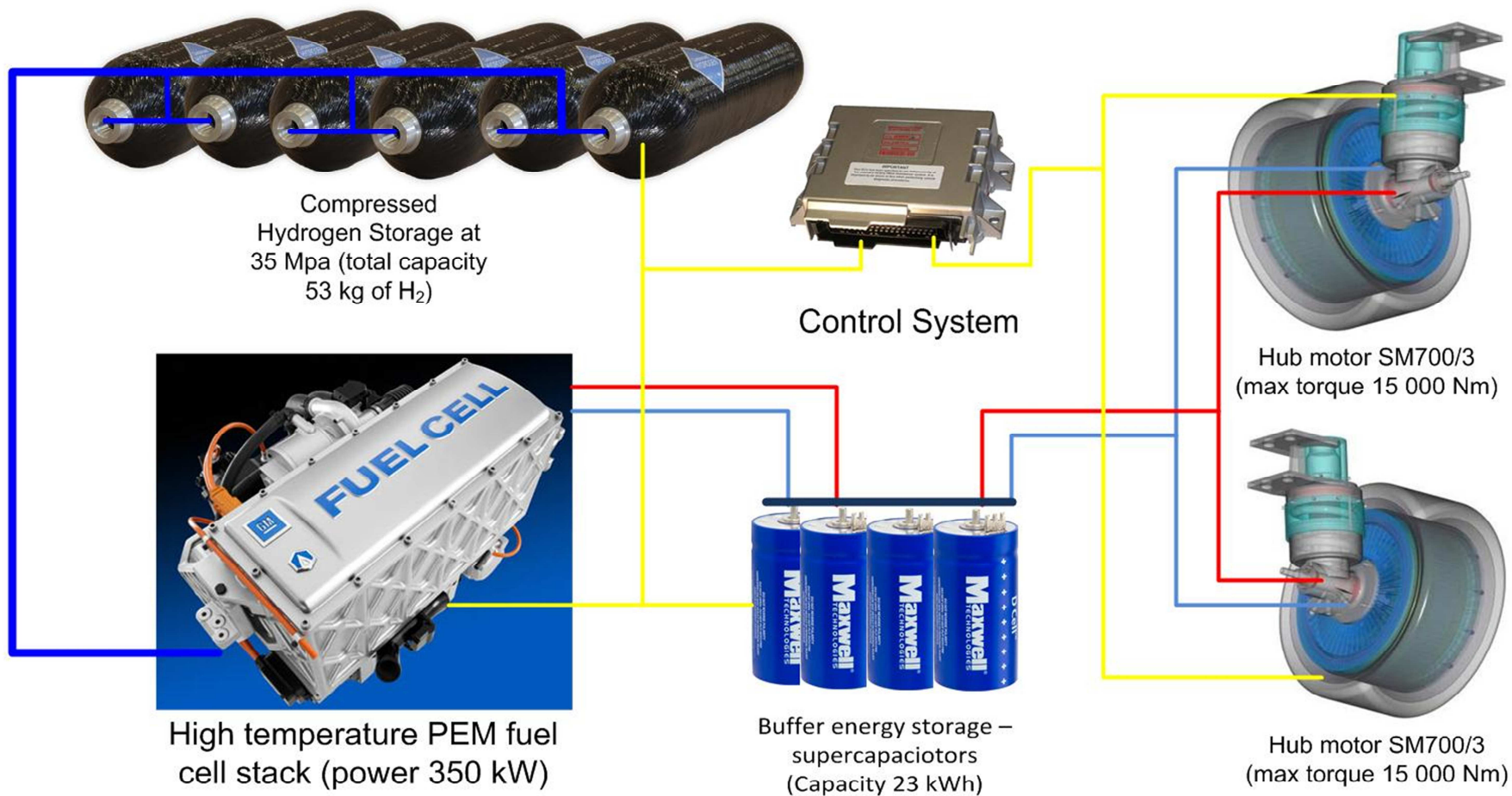


Figure 23- Preliminary design of full-scale hydrogen fuel cell truck

4 SMALL-SCALE MODEL OF HYDROGEN FUEL CELL TRUCK

4.1 Introduction to small-scale model of hydrogen fuel cell truck

In order to get familiar with fuel cell technology, gain more experience in system controlling and optimizing, expose the biggest challenges of proposed design and get experimental data which can be further used for scaling up, a comprehensive design of a small-scale model of hydrogen fuel cell truck has been completed as a part of this project. System components have been ordered. Unfortunately, some of them had not arrived before this thesis was completed, so the model has not been assembled as yet. However, some of the components that have arrived have been tested.

Firstly, the technical parameters of model are measured and presented. Then, the comprehensive design and components of fuel cell powertrain are chosen and presented. Measurement of fuel cell stack performance was conducted.

4.2 Small-scale model parameters

A small-scale model which consisting a body, chassis and battery power train have been purchased from Japan Company Tamiya – which is one of the largest producer in the world of model kits and radio controlled cars.

The 1/14 scale model of Scania R470 Highline have been chosen among other trucks. In this model the aerodynamic body is precisely reproduced even structural details like cabin which tilts forward separately from fenders is reproduced. The ladder frame chassis is made of aluminum channel other elements of plastic. Suspension consists of metal leaf springs and coil spring dampers. All those similarities of body are very important for further process of scaling-up and comparison with current conventional diesel trucks.

Originally model was powered by battery pack (7.2 V, 2400 mAh Tamiya Racing Battery Pack).



Figure 24- Scania R470 Highline 1/14 scale model (Tamiya 2010)

4.2.1 Drivetrain

Drivetrain of small-scale model is similar to conventional full-scale trucks, consist of electric motor, 3-speed gear box, transmission axle and differential mechanism. Thanks to 4-channel transmitter and electric servo gear shifting is possible during running. The overall design of drive train is placed below.

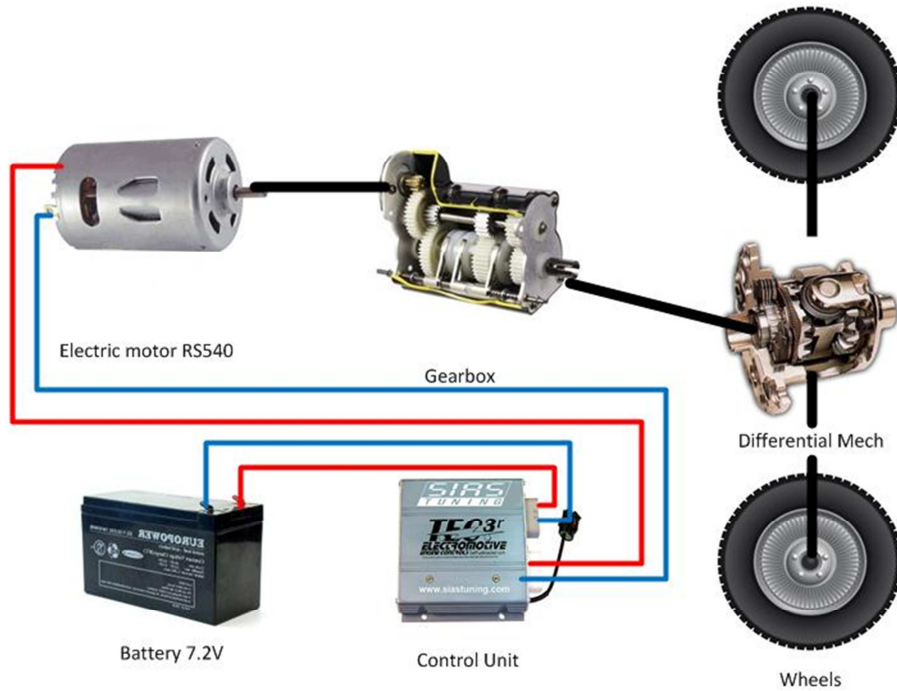


Figure 25- Drivetrain of Tamiya small-scale truck model

Required torque by drivetrain is produced in central electric motor type RS 540. Motor RS540 is carbon brush motor type. Beside radio control models this type of motor is used for vacuum cleaners and electrical screw drivers. Figure 26 and Figure 27 presents respectively dimensions and performance of RS 540 motor.

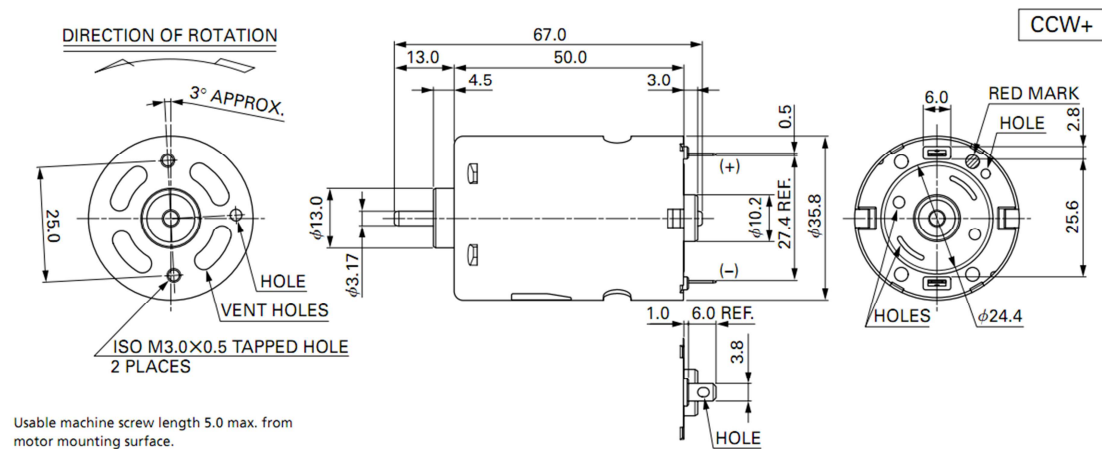


Figure 26- Dimensions of electrical motor RS 540(Mabuchi Motor 2010)

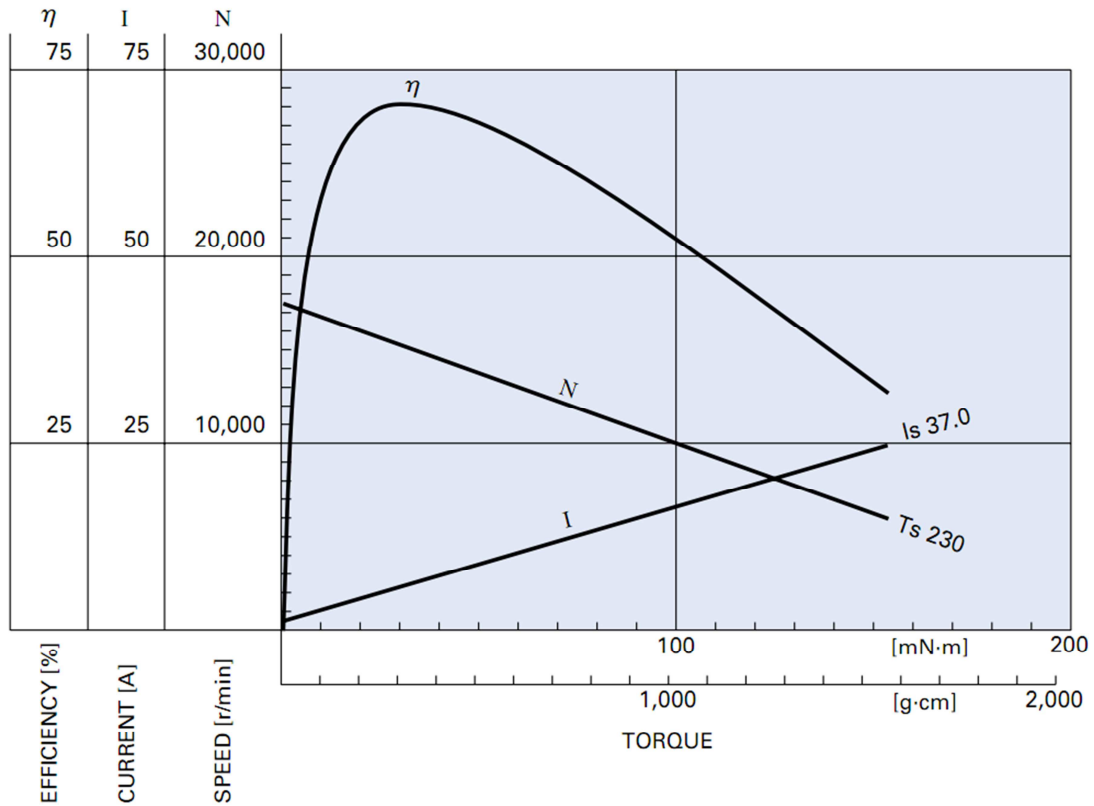


Figure 27- Performance of electric motor RS 540 (Mabuchi Motor 2010)

4.3 Measurements

In order to find out what is the required power of fuel cell which would replace battery pack some of measurements must be done. According to Figure 27 powered required by electric motor changes with torque. Fuel cell stack which is going to replace batteries needs to deliver power to electric motor and also for auxiliaries systems like lights, servo, control unit and data acquisition system.

In order to measure the peak power required by truck was tested on different gears with different speeds on different inclinations. Figure 28 presents connections of measurement devices during test.

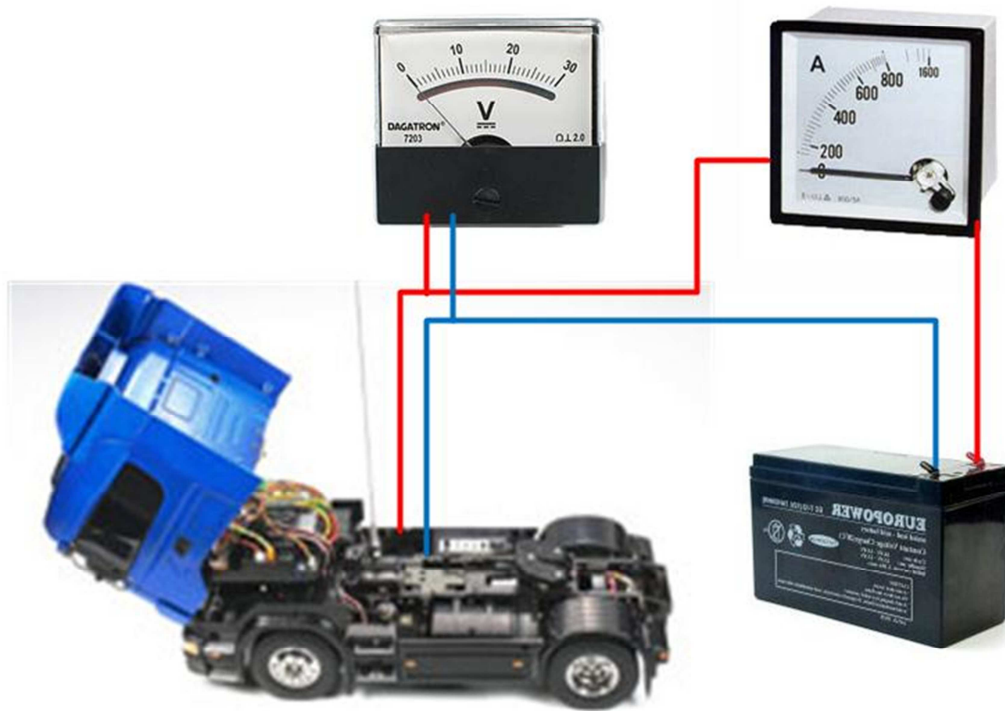


Figure 28 – Electric circuit diagram during measurement

Power measurement shown that maximum power of truck model powertrain and auxiliaries is 55 W.

4.4 Fuel cell

4.4.1 Fuel cell technical parameters

In order to fulfill power requirements two 30W fuel cells have been chosen. Those fuel cells have been designed and manufactured by Horizon Fuel Cell Technologies Company, which offers the wide range of PEM fuel cell systems in the range from 10W to 5kW. Chosen units are low temperature PEM fuel cell because only this technology among PEM fuel cells is available on the market. According to manufacturer those units can work without external humidification system they are so-called self-humidified. Self-humidification process is possible for small power units with precise control system. Lack of necessity of external water management system makes this particular fuel cell similar in application conditions to high temperature PEM fuel cell investigated in section 3. Table 8 and Figure 29 present technical specification of chosen fuel cell stacks.

Table 8 - Technical parameters of H-30 Verizon fuel cell (Verizon 2010)

Type of fuel cell	PEM
Number of cells	12
Rated power	30 W

Output voltage range	7 – 14 V
Weight (with auxiliaries)	235 g
Dimensions	64x80x48 mm
Reactants	Hydrogen and Air
Rated H ₂ consumption	420 ml/min
Hydrogen pressure	0.3-0.4 Bar
Controller weight	88.8 g
Max stack temperature	55° C
Hydrogen purity	99.999% dry H ₂
Start-up time	30 s
Efficiency of system	40 % at full power

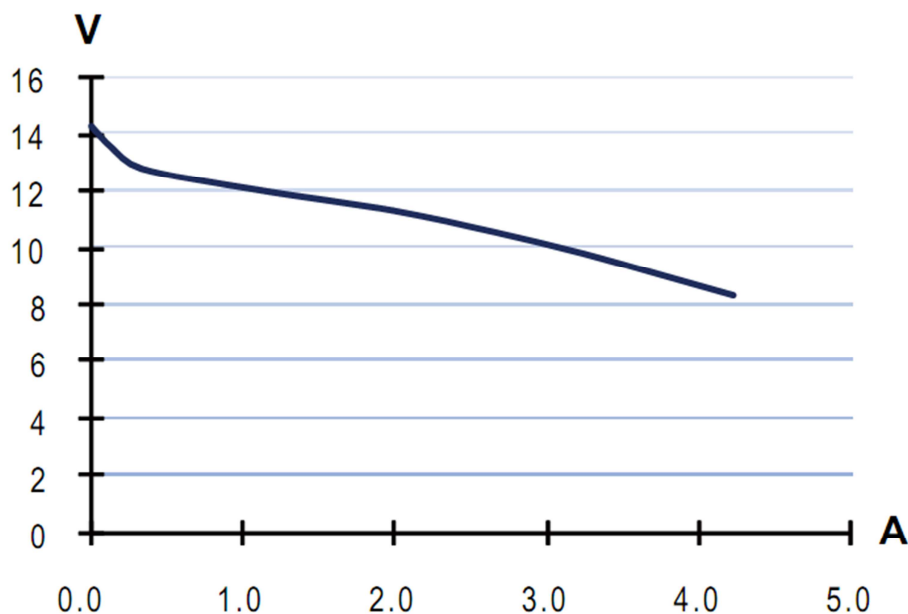


Figure 29- Fuel cell voltage in relation with current for H30 Verizon fuel cell (Verizon 2010)

4.4.2 Polarization curve measurements

Polarization curve describes the relationship between the voltage and the current of the stack over time. Polarization curve of all PEM fuel cell has similar shape, which is caused by losses which occur in particular intervals. Three regions can be distinguished on polarization curve graph. Those regions are presented and described below.

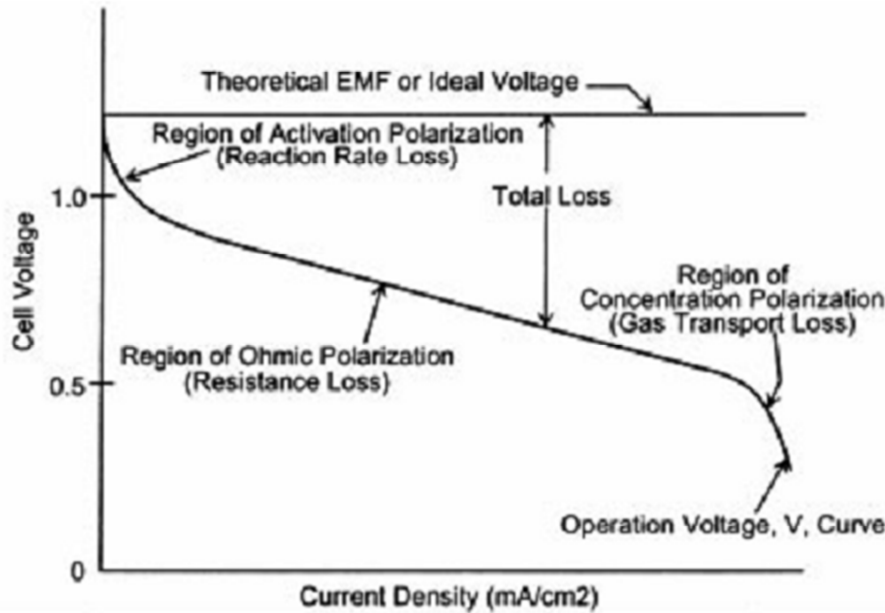


Figure 30- Typical polarization curve for PEM fuel cell

Activation losses region – those losses are typical for low temperature fuel cells. They are basically losses of overall voltage at the expense of forcing the reaction completion. Tafel Equation describes mathematically these losses.

$$V = A \ln \left(\frac{i}{i_0} \right)$$

$$A = \frac{RT}{2\alpha F}$$

Where: R is the ideal gas constant, T is temperature, α is charge transfer coefficient, i_0 exchange current

In order to reduce those losses there are several things that can be done, there are listed below (Rayment & Sherwin, 2003):

- Increases of operating temperature – at high temperatures activation losses are relatively small, due to fact that the value of i_0 increases two order of magnitude over the span of temperatures.
- Increase catalytic presence – there are three different ways to achieve it: usage of rougher catalyst (greater contact area, reaction can proceed faster), increase the operational pressure (still pressure at the anode side must be higher than cathode side) or implementation of more effective materials (only Palladium has higher i_0 than platinum – research of new materials is essential)

Ohmic losses Region – those losses occur in every electronic device and are associated with electron resistance flow in bipolar plates. In order to reduce those losses it is necessary to use highly conductive electrodes. It is also important to try to keep the distance which electrons must travel as short as possible, since losses are proportional to the distance. (Rayment & Sherwin, 2003)

Mass transport losses region – those losses are the most pronounced at high current densities. They are resulted from not enough rates of supply reactants for reaction. Mass transport within fuel cell is limited if it reach the max then further transport is not possible.

One of important way to minimizing mass-transport losses is very effective water management for PEM fuel cells. Too much water can restrict gas access and result in higher losses, too less water will dry off the membrane. It is very hard to maintain saturated, but not flooded state, thus complicated water management system is needed (Darling & Perry, 2000). Moreover it is important that materials of which diffusion layer consist should have high diffusion coefficient and should be the thinnest as possible.

In order to check if particular device provided by manufacturer perform as it is expected suitable survey stand was created.

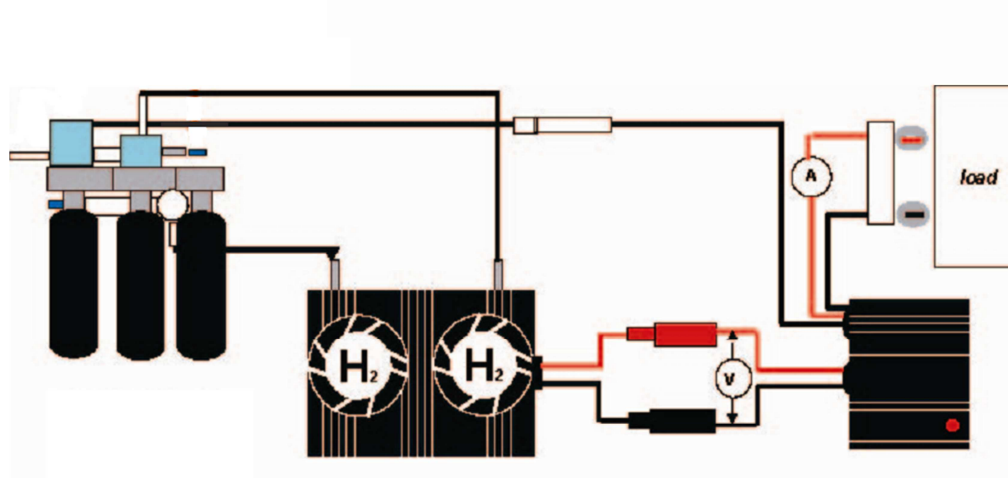


Figure 31- Electric circuit diagram for polarization curve measurement (Horizon 2010)

Below it can be found the polarization curve which was obtained from conducted measurement in comparison with polarization curve which was obtained from manufacturer data.

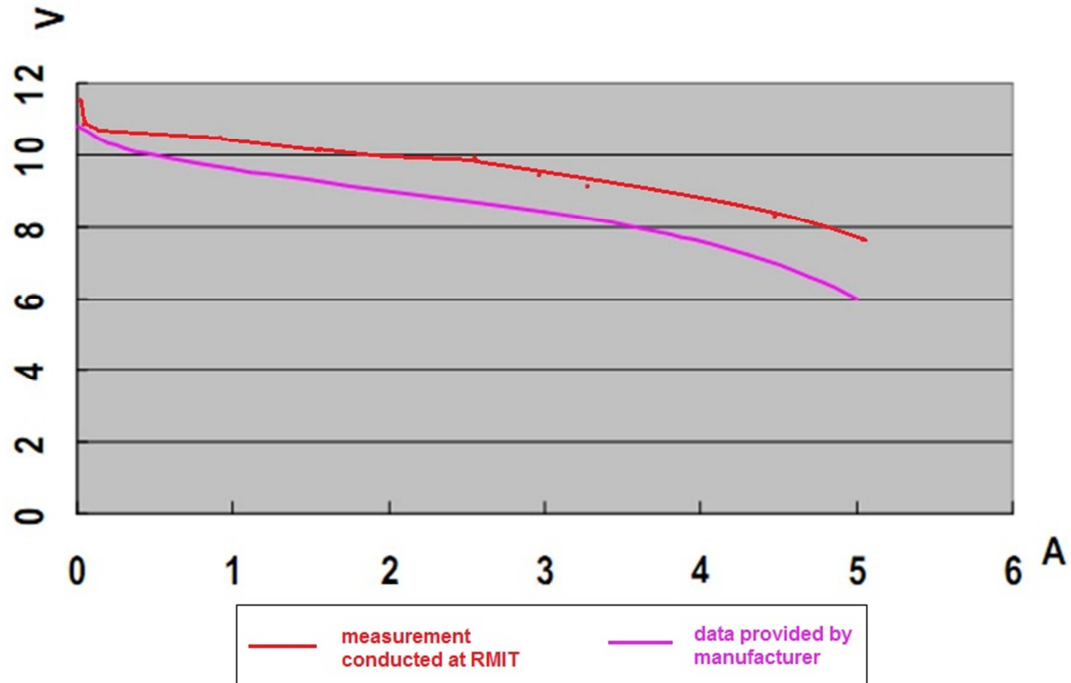


Figure 32- Comparison of polarization curve obtained from measurement and manufacturer data

4.4.3 Elements of fuel cell system for model truck

Fuel cell system beside fuel cell consists of some additional devices which are necessary for operation of whole system. Those elements are following:

- Control unit – controls the purging and short circuit of the stack
- Purge valve – this valve is controlled by control unit for purging water and redundant hydrogen from the fuel cell
- Pressure regulator – lower the pressure from metal hydride canisters to required pressure by fuel cell

4.5 Hydrogen storage

According to Figure 19 and Figure 20 metal hydride hydrogen storage technologies are the most suitable for storage small quantities (about 0.05kg) of hydrogen. Moreover, these technologies are market available for small-scale solutions. Company Horizon sales the Metal Hydride Canisters which are able to storage 20 normal liters (1.8g) of hydrogen.

Table 9 presents technical parameters of metal hydride canister:

Table 9- Metal Hydride Canisters Technical Parameters (Verizon 2010)

Storable H2 volume	20 SL
Storable H2 mass	1.8 g
Mass of metal hydride	130 g
Dimensions	25.4 x 105 mm
Mass	160 g
Cylinder type	Aluminum Alloy
Valve type	Brass screw-on valve
Pressure at 20C	8 Bar

Metal hydride composition is presented on chart below:

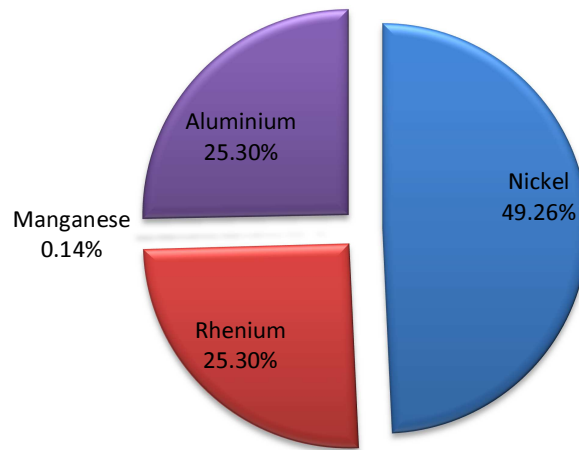


Figure 33- Canister Metal Hydride composition (Horizon 2010)

In order to release hydrogen from metal hydride some heat must be added to the canister. Both fuel cells are supposed to consume less than 1.5 slpm for such small flow rates heat absorbed from ambient would be enough. To make sure that quantity of heat is enough canisters will be located neat to exhaust of fuel cell stacks to provide more heat.

Hydrogen is release at the pressure 8 Bar. This pressure must be reduced to 1 Bar in order to supply fuel cell. Special designed pressure regulators are used.

4.6 Data acquisition unit

Task for data acquisition unit

For research purpose acquisition system has been used to control operating parameters of truck drivetrain. System is able to passing by wireless connection in real time information like:

- speed of the truck
- hydrogen consumption
- operating temperature of stacks
- fuel cell voltage and current
- pressure of hydrogen released for canisters
- temperature of metal hydride stacks
- voltage and current of RS540 electric motor
- voltage and current of fuel cell fans

4.6.1 32-channel transponder

Main component of data acquisition system is 32-channel transponder from The National Instruments which is capable of sending all measured information by wireless network. Device is capable of 32 single-ended or 16 differential analog inputs. Channels have programmable input ranges of ± 200 mV, ± 1 V, ± 5 V, and ± 10 V. Minimum Voltage Range Accuracy equals to $157 \mu\text{V}$.

4.6.2 Hydrogen flow meter

In order to measure consumption of hydrogen in real time hydrogen flow meter has been implemented. Among flow meters available on the market the CMS0200 from AZBIL Yataake Corporation was chosen. Flow meter was calibrated to be capable of measuring hydrogen flows in the range of 0-1 slpm. Expected maximum flow of hydrogen equals to 0.92 slpm according to the manufacturer of fuel cell stacks. Accuracy is expected to be 1% of fuel scale.

4.6.3 Pressure sensor

In order to assessing the quantity of hydrogen remaining in the canisters pressure parameters must be controlled. Pressure of released hydrogen is directly dependent of quantity of hydrogen remaining in the storage. Relation between those parameters will be provided by manufacturer of metal hydride storage.

Pressure transmitter 22IC Series was implicated to the system. Pressure range is 0 to 10 Bar. Expected maximum pressure from canisters is 8 Bar. Accuracy equals to 0.25% of full-scale. Transmitter is connected do the transponder what allows to control pressure at real time.



Figure 34- Gems Pressure Transducer 22IC series

4.7 Comprehensive design of small-scale hydrogen fuel cell truck model

Figure 35 shows the whole design and connections between components of small-scale hydrogen fuel cell truck model.

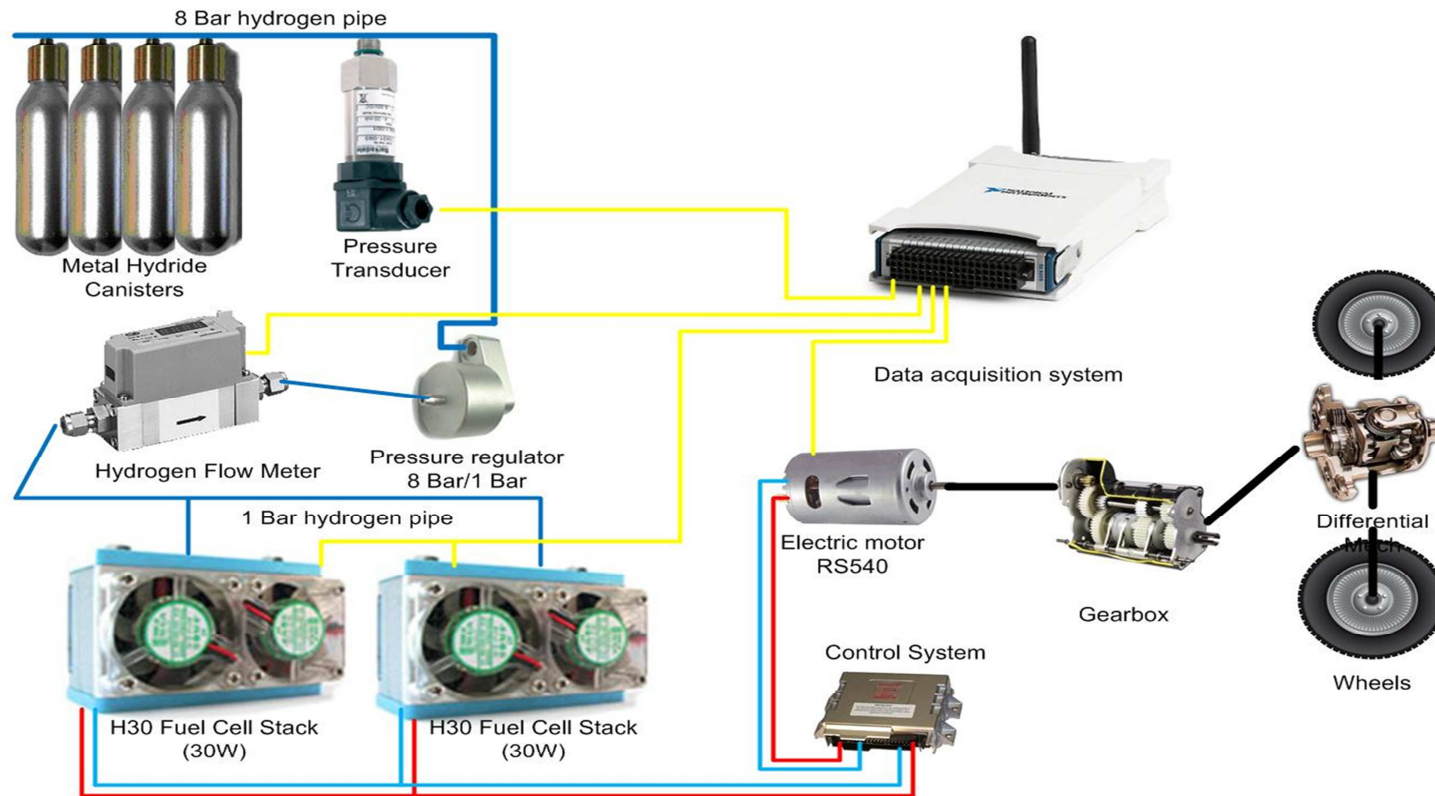


Figure 35- Design of small-scale hydrogen fuel cell truck model

4.8 Accommodation of system components for small-scale hydrogen fuel cell truck model

Small-scale truck model has not been designed originally to be powered by fuel cell. To accommodate fuel cell and other devices involved in the project some originally placed components of the model have been changed, removed or relocated. Place of assembly power system was chosen to be under the cabin of the truck. Data accusation system has been placed in the trailer.

Software modeling has been used to find out the best layout for the system elements. The possible layouts are shown on the Figure 36 and Figure 37.

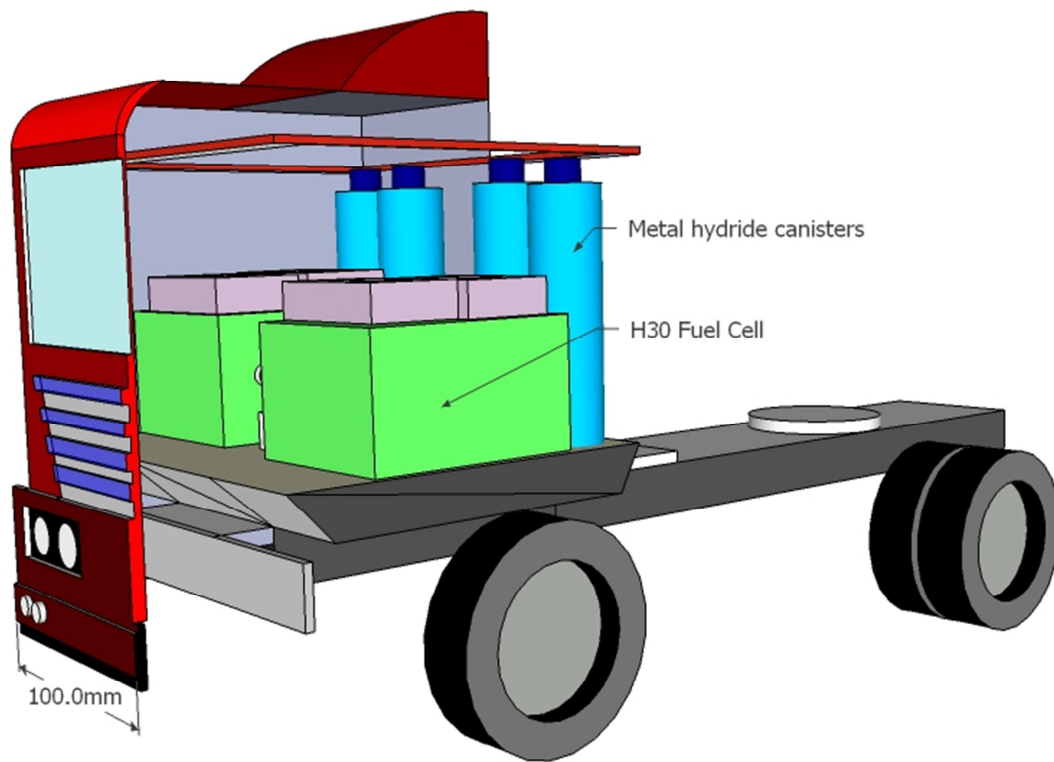


Figure 36- Layout of fuel cell power system in small-scale model truck (vertical canisters layout)

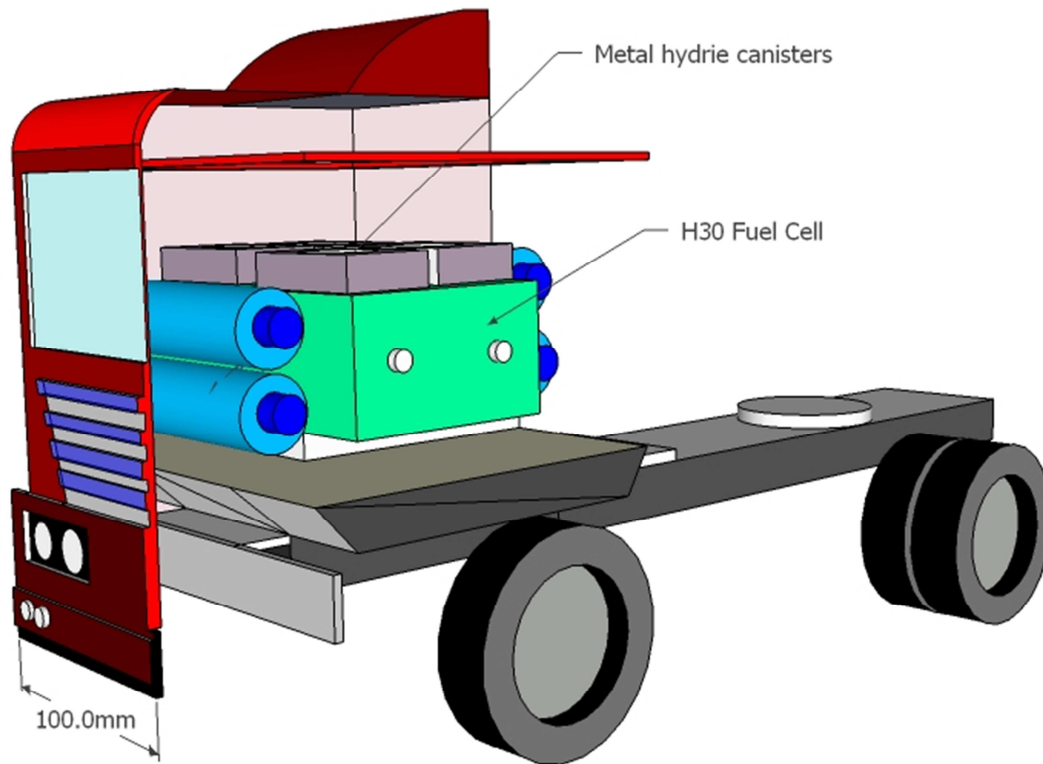


Figure 37- Layout of fuel cell power system in small-scale model truck (horizontal canisters layout)

The layout with horizontal canisters has been chosen because of more efficient usage of space. Moreover, in this layout canisters are provided with waste heat more effective than for vertical layout. Accommodation of metal hydride storage near to exhaust increases their temperature which has positive impact on flow rate of release hydrogen.

Beside fuel cell and canisters other elements of driveline must be placed under the cabin like control unit for fuel cell, pressure regulator and elements for data acquisition system like pressure transducer and hydrogen flow meter. During operation of fuel cell in cabin compartment temperature will increase up to 50°C. The humidity of the air due to exhaust of products of electrochemical reaction will be relatively high. Those conditions could have negative impact on electronic components placed nearby the fuel cell. In order to solve those issues special cage has been designed to separate humidity from the control and measurements units. Moreover, according the advice of manufacturer after operation of fuel cell it must be storage in air tight container to prevent drying of membranes. Cage assembling makes easier remove stack out of model truck to storage.

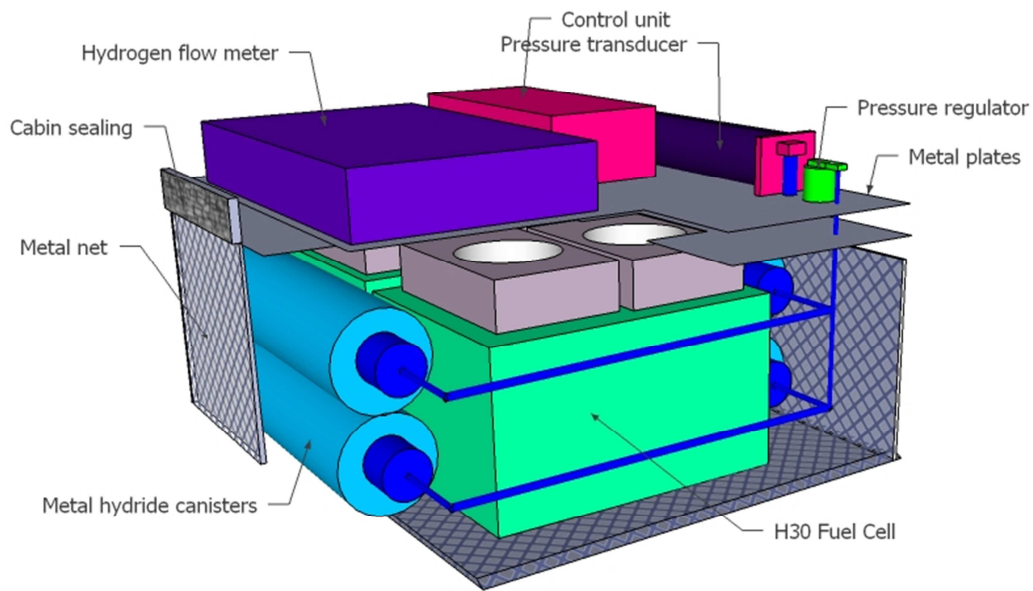


Figure 38- Cage assembly of fuel cell system for model truck

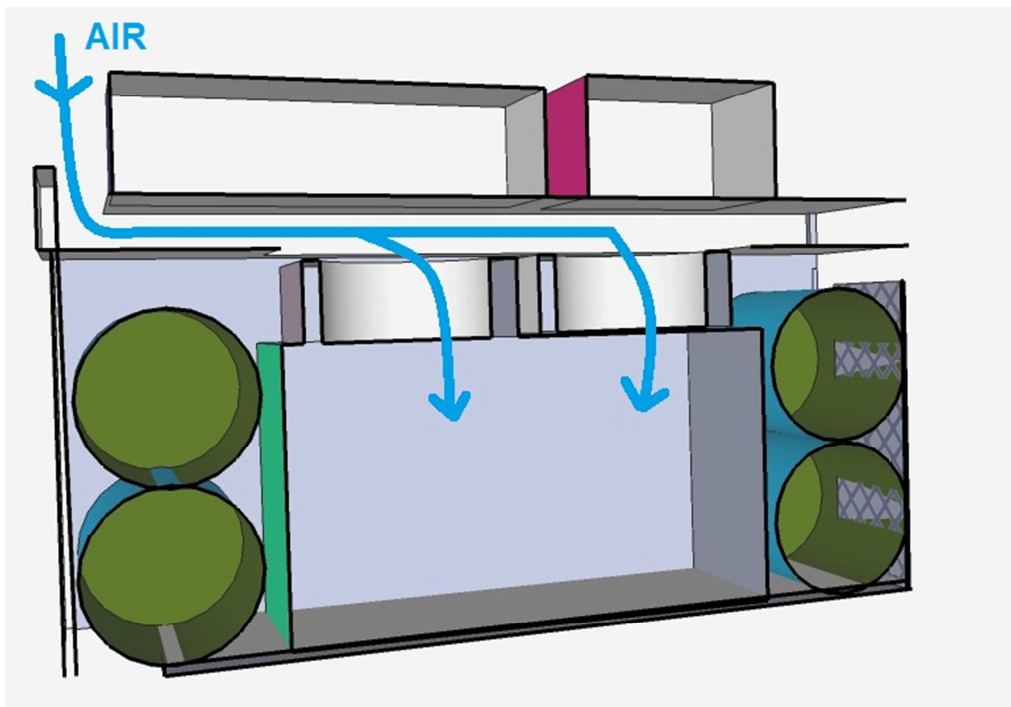


Figure 39- Air flows through the cage assembly

To provide sufficient ventilation some of the cage walls can be made of metal net. Space between metal plates above the fuel cell is designed to supply stacks with fresh air and cooling down the electronic elements mounted to the upper surface. Truck cabin will be modified to separate fuel cell and electronic compartment.

5 COMPARATIVE EVALUATION OF HYDROGEN FUEL CELL TRUCK AND A DIESEL TRUCK

The preliminary design of hydrogen fuel cell truck was presented in the chapter 3. In order to assess feasibility of this design comparison in terms of mass of the components must be done. Volume of driveline elements is not so important as for passenger cars because in truck there is potential to accommodate all necessary components (always cabin roof is at the lower level than semi-trailer it gives opportunity to mount hydrogen tanks, moreover absence of conventional driveline gives additional space). The most important factor seems to be mass of the drivetrain since total truck mass is strictly limited all over the world. Table 10 summaries and compares powertrains of hydrogen fuel cell truck and conventional diesel truck.

Table 10 - Gravimetric comparison of powertrain components for different technologies

MAN TGX Diesel Truck (D2676 Engine)		Hydrogen Fuel Cell Heavy Duty Truck Design	
Component	Mass [kg]	Component	Mass [kg]
Diesel Engine	1050	Fuel Cell	200
Gearbox	500	Hydrogen tanks (with H ₂)	1000 + 53
Propulsion elements	1000	Buffer	400
Fuel tank (with fuel)	50 + 150	Wheel motors	2 x 725
Range	500 km	Range	500 km
TOTAL MASS of conventional diesel power train	2750 kg (15.2 % of average conventional truck mass*)	TOTAL MASS of hydrogen fuel cell preliminary design truck	3 100 kg (17.2 % of average conventional truck mass*)
Gravimetric power density of drivetrain (without fuel tank)	7.29 kg/kW	Gravimetric power density of drivetrain (without hydrogen tanks)	5.84 kg/kW
Gravimetric energy density of drivetrain	1.57 kg/kWh	Gravimetric energy density of drivetrain	1.77 kg/kWh

* Conventional heavy duty truck mass equals to 18 000 kg

As it can be observed from Table 10 masses of propulsion components for conventional and hydrogen fuel cell truck are comparable for the same range which is 500 km.

Gravimetric power density of hydrogen fuel cell truck is comparison to conventional powertrain is much better because of all devices associated with energy production are lighter.

Gravimetric energy density of powertrain is insignificantly greater for hydrogen fuel cell truck design. For extended ranges differences in gravimetric energy density will be more visible due to much better capability of storage energy in liquid carbohydrates.

Driveline based on the fuel cell would be heavier about 350 kg than conventional diesel. Relatively to average truck mass of 18 tonnes it is acceptable value. Some mass reductions can be expected for hydrogen truck design because of absence of fossil fuel generator for semi-trailer.

The comparison shows that hydrogen fuel cell truck is feasible moreover using the unconventional drive train have no negative influence for limit payload of the truck.

The most important advantage is that preliminary designed truck not causing pollution like CO₂, NO_x, SO_x. Particle emission is not reduced to zero level because this pollution is associated with trucks wheel movement. Moreover, cooling needs for hauling can be fulfill without using fossil fuel.

Electrification of drivetrain gives opportunity to introduce better management system which can lead to the reduction of energy use and increase of efficiency.

Currently, the biggest challenges for fuel cell technology for heavy duty trucks are the durability and cost. According to information in section 3.8 between 150g (5.4 oz) and 200g (7 oz) platinum is needed to construct fuel cell of power about 350kW. Current market price of platinum on New York Stock is approximately 1820 US/oz (25 Jan 2011) which makes the cost of needed platinum for 1 fuel cell in range of 10 000 USD - 13 000 USD.

6 POLAND SITUATION

According to Central Statistics Office (GUS 2009) in Poland at the end of 2009 there was registered about 2.6 million of trucks. About 1.2 million have capacity load above 1 000 kg more than 63 thousand are equipped with closed, cooled box.

Below there is presented contribution of air pollution in 2008 (in Poland) of light and heavy duty vehicles.

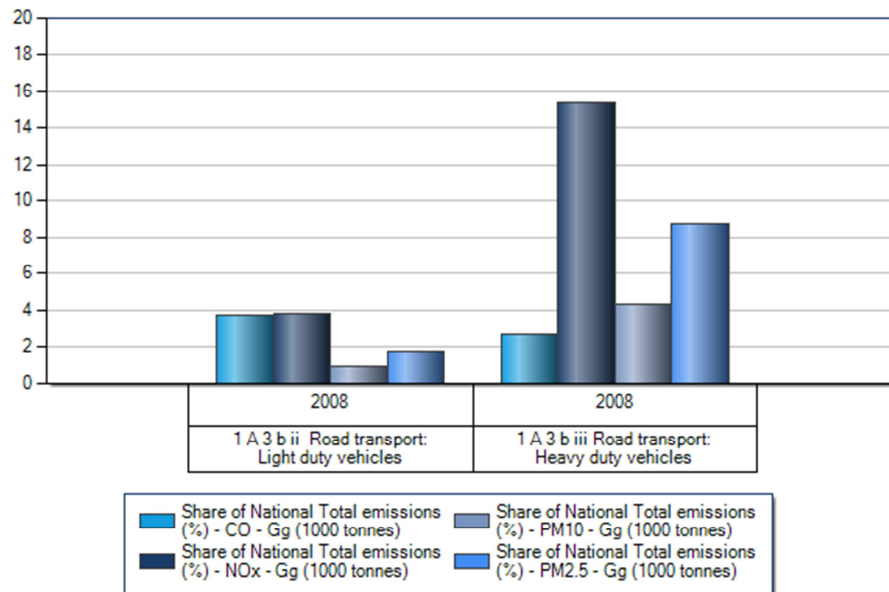


Figure 40- Share of National Total Emission for Poland from light and heavy duty trucks (EEA 2008)

As it can be seen from the graph heavy duty road transport is substantial pollution maker in Poland.

It is possible to reduce those pollutions almost to zero level if all trucks would be replaced with FC truck and if we assume hydrogen production from renewable energy sources. Those actions would help Poland to fulfill European Union requirements about emission.

Currently there is no country in the world which solved problem with emission from road freight. Poland as a member of European Union is obligated to pursue to reduce the emission to the lowest level as possible.

One of the grater barriers of introducing hydrogen technologies in Poland is lack of government interest in popularization of this energy carrier. Without public support it is not possible to start demonstrative project that are very import in terms of persuading potential future users for this technology. Moreover, without those activities no hydrogen refueling station will be built. Lack of hydrogen infrastructure will lead to no interest of user to buy hydrogen powered vehicles.

So far in Poland there is no infrastructure for hydrogen at all. Poland's hydro and wind potential make possible to use those two sources to produce hydrogen without any

associated emission. Furthermore, it is also possible to use biomass for this purpose since government wants to strongly follow this way which in does not seem to be ideal solution as it was stated before in this thesis. Since electricity production in Poland comes mostly from coal-fired power plants and electricity prices differ during peak on and peak off hours it is possible to use surplus electricity during night to produce cheap hydrogen. Poland has unique possibility to use salt caverns located in south of Poland for mass storage of hydrogen. Currently similar caverns are used in Poland to store natural gas and liquid fuels.

Those reasons forcing to research for alternative drivetrain designs for countries like Poland which can be used before hydrogen refueling infrastructure will be built. Alternatives should focus on the most efficient usage of current available fuels with implementation of hydrogen technologies.

One of the most feasible solutions is application of fuel on-board reforming system. However, this solution doesn't lead to cut off the fossil fuels. Furthermore, because of reforming possible not substantial efficiency improvements are expected.

Among currently methods of reforming two were considered: partial oxidation and auto-thermal reforming as the most suitable for automotive applications. For auto-thermal reforming water (what caused need of additional water tank) which is converted to steam and oxygen is required. Despite this fact auto thermal reformers are considered as the best solution for reforming of diesel oil for automotive applications. According to Karatzasa and Nilssona (2008) this method is very promising because of high efficiency (up to 75%), low system complexity and relatively quick start-up. The biggest disadvantage of this type conversion is hydrogen purity which is insufficient for direct use in PEM fuel cell. Some purification system must be implemented which made system more complex and more expensive.

Due to facts mentioned above, full-scale fuel cell heavy duty truck powered by diesel oil is feasible but this design doesn't give any profits in terms of energy use and pollution emissions.

It seems to be the best way for Poland to setting up demonstration projects and invest in refueling infrastructure.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This master thesis gave the answers for the research questions placed in the section 1.2.

It was proved that design of hydrogen fuel cell truck is feasible. The investigation reveals the most suitable technologies for no emission hydrogen heavy duty truck:

- High temperature PEM fuel cell for electricity production
- Compressed hydrogen tanks for energy storage
- Wheel motors for propulsion instead of classic driveline
- Supercapacitors as a technology for energy buffer

Usage of those components for powertrain makes this design comparable in terms of gravimetric power density with conventional truck.

Advantages of unconventional hydrogen fuel cell solution for truck powertrain are following: zero tailpipe emission of gases like CO₂, NO_x, SO_x, possibility of implication of better energy management which can lead to increase of efficiency and energy savings. Still the challenge of high price and durability of technology remains.

Refrigeration semi-trailers can operate with fuel cell truck. Instead of producing energy to power the compressor in separate generator energy can be provided from fuel cell which gives electricity for propulsion. This solution leads to remain the quality of products storage at the same quality level with better efficiency since bigger units are always more efficient than small.

Absence of refueling infrastructure in Poland prevents from direct introduction of hydrogen fuel cell truck technology. To make it possible on-board reforming system must be involved. Use of fuel conversion system leads to dramatic losses on efficiency and does not stop pollutions from haul trucks. To implement this technology to Poland some governmental support is needed for building refueling infrastructure in strategic points in the country.

Comprehensive design of small-scale truck model with data acquisition has been completed. All components have been ordered. Model hasn't been assembled because of delays of components arrivals.

7.2 Recommendations

In order to finish project some further work must be done:

- Firstly, model truck must be completely assembled
- Further, surveys and calculations should be done in order to obtain the optimal size of energy buffer
- Series of tests and software modeling should be conducted to figure out the system efficiency at wide range of loads, speeds and under universal driving cycles
- Calculations and tests which would lead to scaling of results obtained for small-scale model should be the next step of project. Small-scale truck body is identical as the full-scale truck, so air tunnel could be used for

- As a summary of all those steps the comparative evaluation of performance can be done and potential of efficiency and energy use improvements can be assessed between hydrogen fuel cell and conventional diesel trucks
- Next phase of project might be construction of the next small-scale model according to designs presented in chapter 3. This step would allow evaluating the advantages of wheel motors as future of vehicle propulsion

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