HYDROGEN POWERED HYDRAULIC POWERPACK

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ABSTRACT

A general challenge in the construction machinery sector is that 90% of the current fleet of machines uses diesel as fuel. In contrast to the positive developments in the field of particle mass and nitrogen oxide emissions, CO_2 emissions are stagnating at a constantly high level. The use of hydrogen fuel cell technology results in CO_2 neutral operation and is in line with current CO_2 reduction policies. A hydrogen driven powerpack is used to generate hydraulic power, which is then used to drive a stationary concrete pump. This paper deals with the transformation of a conventional drive system to a fuel cell drive system. Furthermore, two different fuel cell operating strategies are discussed. The challenge in using fuel cells is that due to the efficiency and the balance of plant components about 50 % of the electrical power is converted into heat. Furthermore, the volumetric energy density of hydrogen currently limits the unrestricted use of the CO_2 neutral fuel. As a result, a sufficiently large cooling system must be kept in place. If the same performance and the same operating time shall be achieved as with a conventional diesel combustion machine, it results an increase of the installation space by a factor up to 8 for a fuel cell drive. For the use of such machines, it is important to ensure that future construction sites have an appropriately prepared H_2 infrastructure.

Keywords: Construction Machinery, Fuel Cell, Hydrogen, Powerpack

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1. INTRODRUCTION AND MOTIVATION

Hydrogen as an energy carrier is playing an increasingly important role in the implementation of future CO_2 neutral drive technologies. The construction industry is currently facing structural changes and needs to deal with the new challenges that come along with it. The new challenges are significantly shaped by legislative regulations, by society and by the increasing awareness of environmental protection. The Federal Republic of Germany has committed itself to reduce greenhouse gas emissions (GHG) by 65 % by 2035 compared to the year 1990. Furthermore, the target is to achieve 100 % greenhouse gas neutrality by 2045 [1].

To achieve this ambitious goal, a change is needed in all social, economic and technical sectors of a society. The current state of the art shows that in construction machinery industry, 90 % of all existing machines still use diesel as a fossil fuel [2]. In order to fulfil all requirements, new ways, systems and machine technologies must be defined, implemented and launched on the market to accomplish the set goal. Driven be the regulation of the European Union (EU) for exhaust aftertreatment, a very large part of the reduction in local emissions has already been successfully achieved in recent years. The following **Figure 1** shows the development of emissions over time between the years 1980 to 2050. The figure is based on the Transport-Emission-Model for Mobile Machinery (TREMOD-MM), Version 5.1, and includes all non-road mobile machinery in Germany. The emission model takes into account the following sectors: Agriculture-, Forestry-, Construction-, Residential- and other non-road mobile machinery (NRMM) industry branches. In this diagram, the temporal course of the particulate mass (PM), the nitrogen oxides (NO_x) and carbon dioxide (CO_2) are shown graphically. During the past few years, the machines have always been adapted to the next exhaust emission stage. That is the reason why there is a significant decrease in PM- and NO_x- emissions. The amount of PM- emissions reduced between 1980 and 2018 by 79 % and the amount of NO_x- emissions by 48 %. Against this positive trend, the CO_2 balance stagnates at a constantly high level over time. As a major driver of climate change, CO_2 will be one of the main challenges for construction machinery [3].

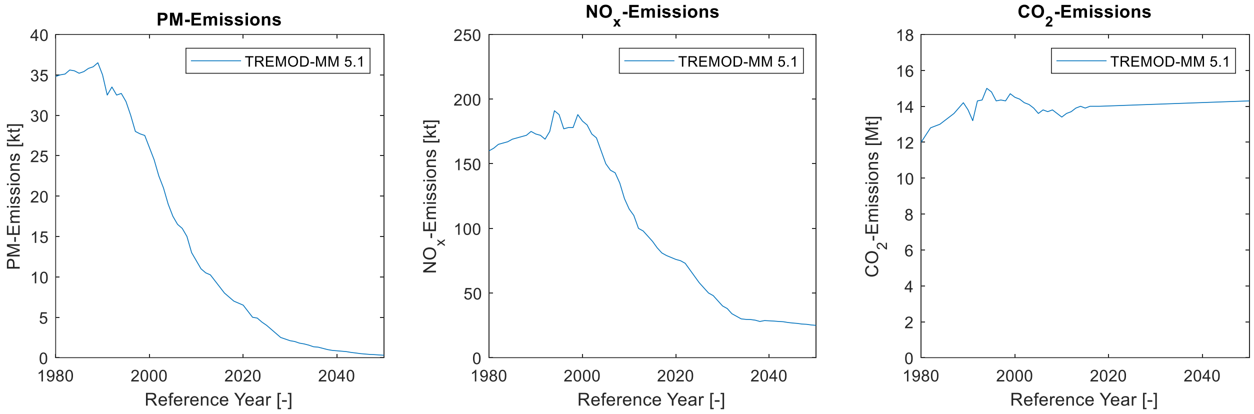

Figure 1: PM-, NO_x- and CO_2- emissions between 1980 - 2050 [3]

This issue must be countered by alternative drive technologies, like battery or hydrogen driven systems. In the low power range up to 80 kW, battery driven machines are available on the market today. For higher power, cable based solutions are the state of the art. The limits here are the available electrical load connection and the cable routes interfering with the construction workflow. The wide range of applications for construction machinery requires outputs up to 1000 kW. Especially the hydraulic power density needs to be maintained for the vast majority of construction machinery. This will not fundamentally change even with the proactive electrification of NRMM.

In the research project “Hydrogen 2 Hydraulics” at TU Dresden / Chair of Construction Machinery, the use of hydrogen together with a fuel cell as a primary power source for hydraulic powered construction machinery is being investigated. The goal is to develop a hydraulic powerpack that provides required hydraulic power with the help of a H_2 fuel cell. A semi-stationary concrete pump is used as an application scenario. Using this machine, the various challenges in the field of H_2 technology are presented in this paper.

2. STATE OF THE ART

A fuel cell is an electrochemical energy converter that converts the internal energy of a fuel into electrical energy and heat. Various types of fuel cells have established their presence on the market. Depending on the fuel cell type, different fuels are used to run the machines. According to this classification, there are fuel cells that use hydrogen (H_2), methanol (CH_3OH) or methane (CH_4) as fuel. Furthermore, the fuel cell types differ in their reaction temperatures. **Table 1** summarizes most common fuel cell types, their fuel and operating temperatures. The functional principle of a fuel cell is explained by using a polymer electrolyte membrane fuel cell (PEMFC) as an example. The reason for that is, because this type of fuel cell has become established in most mobile machine applications and is therefore also used in the research project mentioned above. [4]

Table 1: Fuel cell classification [4]

Fuel cell type	Acronym	Fuel	Operating temperature [°C]
Proton exchange membrane fuel cell	PEMFC	H_2	60 - 160*
*Low temperature PEMFC	LT - PEMFC	H_2	60 - 80
*High temperature PEMFC	HT - PEMFC	H_2	120 - 160
Direct methanol fuel cell	DMFC	CH_3OH	60 - 120
Alkaline fuel cell	AFC	H_2	60 - 80
Molten carbonate fuel cell	MCFC	CH_4	650
Solid oxide fuel cell	SOFC	CH_4	800 - 1000

The core of each fuel cell is formed by two electrodes, the anode (+) and the cathode (-), which are separated from each other by a semi-permeable polymer electrolyte membrane. The hydrogen fuel (H_2) and oxygen (O_2) are continuously supplied to the reaction chambers of each single cell from the outside via the flow channels of the bipolar plates arranged on both sides. Each electrode is coated with an electrolyte consisting of a noble metal layer. This noble layer is usually platinum or a platinum alloy. The electrolyte has a high porosity and consequently increases the active area which is available for the chemical reaction. [4][5]

With the help of **Figure 2**, the functioning of a PEMFC is explained in detail. On the anode side, hydrogen is supplied and diffuses through the Gas Diffusion Layer (GDL) to the catalyst. At the catalyst layer, the hydrogen molecule is absorbed and oxidizes to a positively charged hydrogen proton (H^+) while it releases a negative charged electron (e^-). This reaction is called oxidation and can be written as formula (1). The semi-permeable membrane allows only the protons to diffuse towards the cathode side. The electrons need to take an external by-pass way. As a result of the external electrical flow, electrical work is performed, which can be used. [5]

On the cathode side, the oxygen atom recombines with two electrons and two protons. This reaction is called reduction and can be written as (2). The uptake of the electrons and protons consequently leads to the formation of a water molecule (H_2O), which is discharged to the outside of a cell. The total reaction, shown in (3), is called redox reaction. [5]

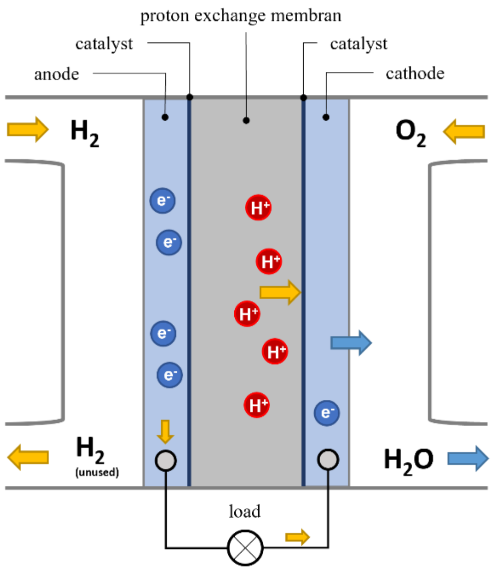

Figure 2: Working principle of a PEMFC [6]

Table 2: Fuel cell reactions

Location	Reaction	Formula	
Anode	Oxidation	$2H_2 \rightarrow 4H^+ + 4e^-$	(1)
Cathode	Reduction	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	(2)
Total	Redox reaction	$2H_2 + O_2 = 2H_2O$	(3)

Each fuel cell has a reversible cell voltage E^0 of 1,229 V under thermodynamic steady-state conditions and can be calculated according to equation (4). The basis of the calculation is the change in the free reaction enthalpy $\Delta_R G_M^0$, the charge number z and the Faraday constant F. [5]

$$E^0 = \frac{\Delta_R G_M^0}{z * F} = 1{,}229\ V \tag{4}$$

The open cell voltage is below the standard potential by an amount of delta E and counts 0.9 - 1,0 V. Under load, the real cell voltage decreases due to further losses with increasing current. The losses can be divided into three main categories. First, activation losses become effective, second, the ohmic resistance becomes stronger with increasing current density and third, gas transport losses occur at maximum power. **Figure 3** shows the typical current-voltage-behaviour of a fuel cell. [7]

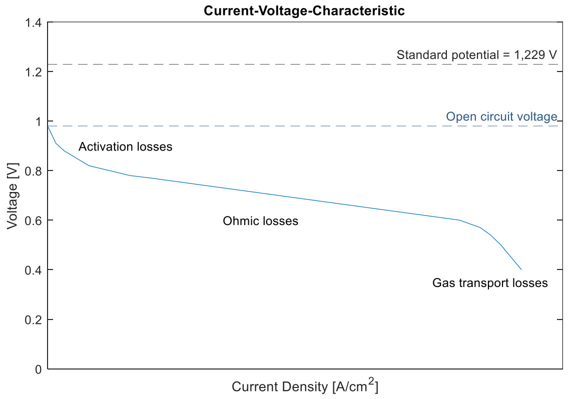

Figure 3: Fuel cell current-voltage-behaviour [7]

3. POWER REQUIREMENT

3.1. Application Scenario

In the project, a hydraulic driven construction machinery is used to test the hydraulic powerpack. For testing, a semi-stationary concrete pump is used. The main drive unit of the present concrete pump is a diesel combustion engine, which will be replaced by an electric motor. The electric motor drives the hydraulic pumps for the working cylinders. As a result, the main aim of this project is to drive the electric motor with a PEMFC. In order to calculate the required hydraulic power for the powerpack, a concrete pressure-power nomogram is utilized. The following boundary conditions are applied to the stationary concrete pump: a concrete flow of 8 m^3/h, a pumping distance of min. 60 m and a max. concrete viscosity of 450 Pa·s/m. This results a required, average net power of 12 kW for the further application, which must be provided by the electric motor. Consequently, the PEMFC must be able to provide the power constantly or partly in combination with a battery. Any power peaks that occur e. g. due to variable load requirements must be compensated by a battery storage system. For the design of an appropriate fuel cell, the characteristic of the entire fuel cell system must be considered.

3.2. Fuel Cell System Design

According to the previous chapter 2.1, the chemical reaction takes place in the reaction chambers of one single cell. Because only a low voltage is achieved with a single cell, several cells are connected into series to form a fuel cell stack. Due to the serial arrangement of the cells, the individual voltages add up and the power increases. By arranging the bipolar plates in the configuration of a stack, a compact design is achieved.

When talking about fuel cells in general, other important components are needed besides the stack. In literature, these components are often referred to balance of plant (BoP) components. Each fuel cell system can be subdivided into the following subsystems with their respective BoP components: Hydrogen path on anode side, air path on cathode side, cooling circuit and electronic control system. As major BoP power consumers the H_2 recirculation pump, the coolant pump and the air compressor must be mentioned. For the design of a fuel cell system according to (5), the self-consumption of the BoP components has to be considered. Consequently, the effective net power P_{FC} of a fuel cell system is defined as the difference between the power of the fuel cell stack P_{Stack} and the power of the BoP components P_{BoP}. [5]

$$P_{FC} = P_{Stack} - P_{BoP} \tag{5}$$

The following **Figure 4** compares the characteristic data curves of the fuel cell stack and the fuel cell system. The graph shows that the highest fuel cell system efficiency (~ 53 %) can be reached in partial load range or in the lower third of power. The power demand of the BoP components is lowest at the point of maximum system efficiency. In the range from low current densities up to the point of maximum system efficiency, the power demand of the BoP components for operating the fuel cell is high in relation to the effective power. This effect is mainly driven by the air compressor, the cooling- and recirculation pump, the heating system and the electronic control units to run the fuel cell system. The effective efficiency of the overall system has it’s minimum at maximum power. At this point the efficiency of the stack is lowest and the power demand of the BoP components is highest. Therefore, for the design of a fuel cell system it is not only important to know the required net power, but also to take into account other consumers (BoP). For the complete functionality of the whole fuel cell system, a special challenge is posed to the cooling subsystem. Since in the worst case at about roughly 50 % efficiency, 50 % of the electric power is converted into thermal losses. For the hydraulic powerpack this effects a massive cooling subsystem, which must be integrated in the body of the machine. Furthermore, the hydraulic powerpack can’t use natural airstream for cooling like on-highway vehicles. Instead, electric powered fans need to be placed in the machine concept.

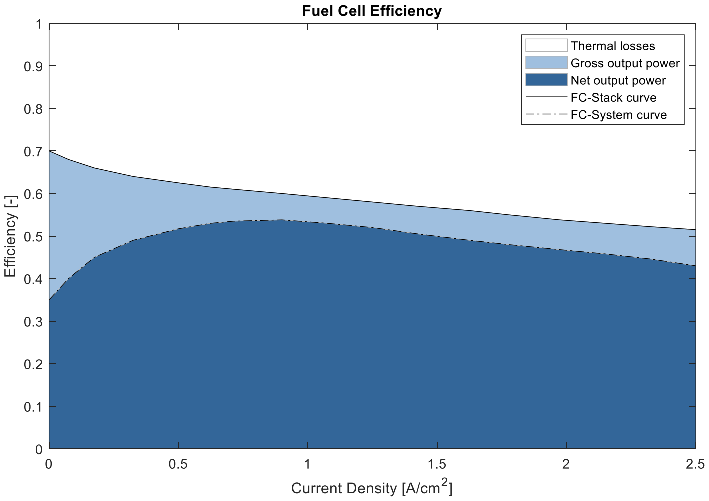

Figure 4: Fuel cell efficiency and losses [8]

Regarding the cooling subsystem it is possible to show the difference between a common internal combustion engine (ICE) and a fuel cell powered vehicle. **Table 3** is used to compare the distribution of the energy conversion in two cases by an example of an effective mechanical power of 10 kW. The internal combustion engine emits 25 % of the total energy via the cooling subsystem. The far greater percentage is dissipated to the environment through the exhaust gas enthalpy. In comparison, only 10 % of the total energy converted in the fuel cell is dissipated to the environment by the air flowing through it. [9]

$$P_{Heat} = \alpha A(\theta_{Fluid} - \theta_{Env}) \tag{6}$$

Due to the operating temperature of 60 - 80 °C of the fuel cell, the temperature gradient to the environment is significantly lower than with a conventional combustion engine, which operates in the range of 80 - 120 °C. According to (6) it means, for the same amount of heat power, a two to four times greater product of αA is required. Based on [10], this effects a two to four times greater fan power for cooling radiators, taking into account the heat transfer surface. This happens especially when the ambient temperature reaches high levels like 40 °C. The temperature range up to 40 °C is a common requirement in the development process for new machines. [5][9]

Table 3: Comparison of energy distribution in an ICE and a fuel cell [9]

	ICE [%]	Example ICE [kW]	Fuel cell [%]	Example FC [kW]
Mechanical/ electrical work	30	10	50	10
Cooling	25	8,3	40	8
Exhaust gas enthalpy	35	11,7	10	2
Friction	10	3,3	-	-
Total	100	33,3	100	20

3.3. Fuel Cell Operating Strategy

The sizing and the choice of the operating strategy of a fuel cell depends on various aspects, including the field of application, the required electrical power and the available resources. There are two main design topologies: efficiency optimized design and cost optimized design. With the help of **Figure 5**, it is shown that the system and stack efficiency of a fuel cell is dependent on the current density. Due to the characteristic curve, it is not possible to achieve the best possible system and stack efficiency at each operating point. In principle, the optimum system efficiency is achieved at low current densities; the lowest efficiency at maximum current density. The same applies to stack efficiency. As the current density increases, the stack efficiency decreases. In contrary, the fuel cell produces the maximum electrical power when the maximum current density is reached.

Efficiency optimized design focuses on achieving the maximum electrical efficiency and the lowest thermal losses of a fuel cell system. To reach this operating point, the fuel cell must be operated at partial load, as shown in the left diagram of **Figure 5**. This operating point can be achieved by either installing more cells or a larger active cell area in order to obtain the same fuel cell performance at a lower current density. The consequence of oversizing is that efficiency optimized fuel cells are more expensive regarding investment than cost optimized fuel cells. Furthermore, due to the larger number of cells and in parallel the larger BoP components, the packaging volume and the weight of the entire fuel cell module increases. In contrast, a cost optimized design focuses on minimizing the manufacturing and investment costs of the fuel cell. In this consideration the operating costs are excluded. Using a cost optimized strategy, it results that the operating point of the fuel cell system has a lower efficiency, the hydrogen consumption is less effectively and more thermal losses occur.

According to the required power, the fuel cell operates at the maximum possible power as shown in the right diagram of **Figure 5**. Contrary to the former strategy, the choice of the cost optimized strategy results in the fuel cell has no power reserves for higher performance requirements. Within the scope of the research project, the cost optimized operating strategy is applied to the hydraulic power unit.

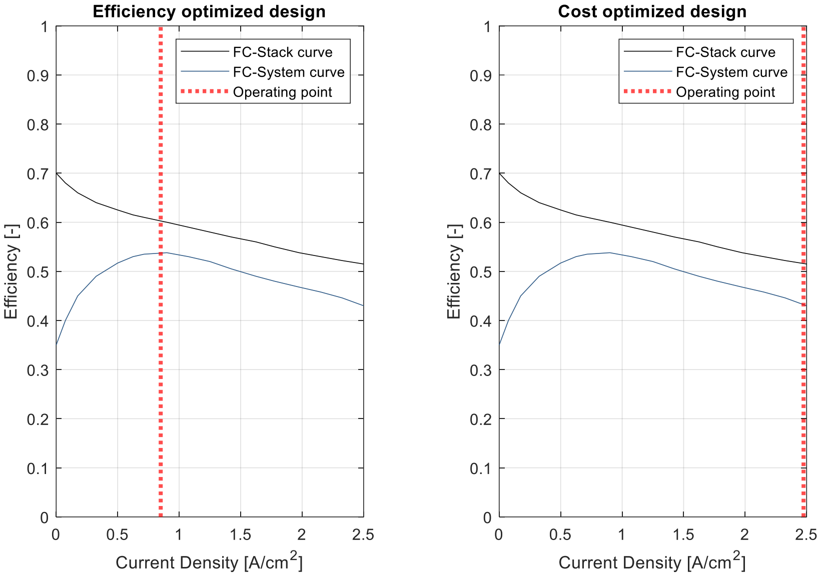

Figure 5: Fuel cell operating strategies

4. SYSTEM ARCHITECTURE

The hybridization of a fuel cell drive mainly differs in the arrangement of the electrical energy storage unit and the energy converter. This results in either a serial or a parallel arrangement of the main components. For the research project, the hydraulic powerpack is subjected to a parallel arrangement according to **Figure 6**. Due to the unavoidable energetic losses during charging and discharging of the battery, a serial arrangement of battery and fuel cell is not considered. The fuel cell system is connected to a DC/DC converter to be raised to the voltage level of the battery system. The chosen concept offers the possibility to increase the state of charge of the battery in case of a power surplus of the fuel cell. Thus, the battery system is charged with the help of the fuel cell when, for example, the powerpack does not have to supply hydraulic power. Within the scope of the research project, a fuel cell system with an effective power of 10 kW is selected. With an average power demand of 12 kW, the fuel cell is undersized, so that the battery system is used to compensate the required power difference and power peaks too.

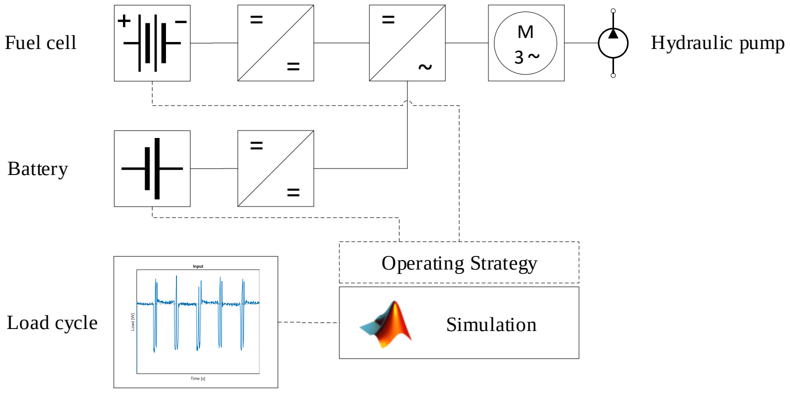

Figure 6: Block diagram of the hydraulic powerpack

The hydrogen infrastructure becomes greater and the hydrogen supply grid grows every year in Germany. However, the current hydrogen infrastructure situation does not allow the machine to be supplied with the sufficient fuel at all locations. This must be taken into account, especially on isolated construction sites. As a solution the consortium of the research project decided to use a battery system with a capacity of 35 kWh. The larger battery capacity of the hydraulic powerpack allows purely electric operation for around three hours. During this time no hydrogen is needed.

5. PROTOTYPE ASSEMBLY

In the prototype application, the powerpack is used to drive a stationary concrete pump. In the first step the goal agreed with the project consortium is to integrate the components of the powerpack into the existing housing of the concrete pump. Subsequently, the main goal is to assemble all the components as a stand-alone solution to provide hydraulic power to other hydraulically operated machines. The most challenging part of the drive modification is to integrate the required components into the existing housing.

The application scenario, stationary concrete pump, is currently driven by a diesel internal combustion engine (ICE) with an output power of 50 kW and an operating time of 8 hours. The following **Figure 7** shows the volume related comparison of switching the machine to hydrogen or battery technology following the same power output of 50 kW and the same operating time of 8 hours. For the comparison, the existing components of the original ICE machine were captured and their volume determined (factor 1). For the hydrogen and battery powered modification, the correspondingly required drive systems were indicated and then the volumes were determined too. Each colored block in Figure 7 corresponds to a converted volume of 150 l.

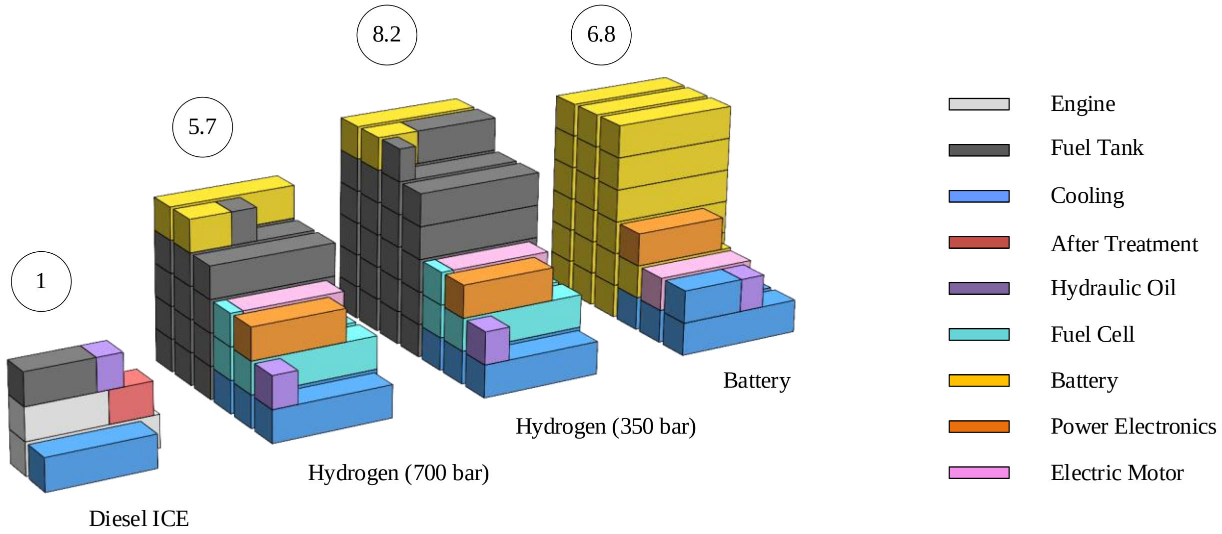

Figure 7: Comparison of installation space for ICE, H_2 350 bar, H_2 700 bar and battery technology

As shown in chapters 3 and 4, the fuel cell converts around 50 % of its power into thermal energy in the worst-case operating point. For this reason, a large cooling system must be installed. In addition, the battery must also be cooled, which is why more overall installation space must be available for the cooling system than for the ICE variant. In parallel to the CO_2 neutral working principle of a PEMFC, another advantage of using hydrogen is the 3 times greater gravimetric energy density compared to the fossil energy carrier diesel. Per kilogram of hydrogen, an energy capacity of 33.3 kWh can be achieved; in comparison, diesel achieves a gravimetric energy density of only 11 kWh/kg. The far greater challenge is to store this amount of energy volumetrically. Under normal pressure, hydrogen has a volumetric energy density of 0.003 kWh/l. To increase the volumetric energy density, gaseous hydrogen is stored in tanks at 350 bar (0.8 kWh/l) or 700 bar (1.3 kWh/l). By comparison, conventional diesel fuel has a volumetric energy density of 10 kWh/l [11]. The storage of the energy content is the main reason why the volumetric factor increases to a factor of 8.2 compared to the ICE variant. The prototypical implementation of the system is in preparation so that initial operational experience can be gathered in the further course of the project.

6. CONCLUSION AND OUTLOOK

The present paper deals with a hydrogen driven powerpack that generates hydraulic power. Against the current developments in the construction industry, the novel machine offers a possibility to work CO_2 neutral when using green hydrogen and in parallel to produce no particles and nitrogen oxides. There are many different types of fuel cells on the market today. For mobile applications the PEMFC is used in most cases. This fuel cell type is therefore used in the research project "Hydrogen 2 Hydraulics" and its functionality is explained in this report. For the selection of a fuel cell system, the influence of the auxiliary consumers (BoP components) at different load points is shown clearly. Based on the presented operating strategies, the operating range of a fuel cell can be adjusted and either an efficiency or a cost optimized variant can be chosen. For a fuel cell with a power of 10 kW, which is used in the research project, the approach of a cost optimized variant is adopted. The volumetric energy density of hydrogen shows that the biggest challenge is the integration of the fuel tanks if a constant operating time is to be achieved as for a comparable, existing diesel application. For the application scenario presented in the paper, this means an increase in the installation space by a factor of 8 under the same boundary conditions. Since the installation space in construction machinery is not infinite, the tank volume must be reduced at the expense of operating time. It is important to note that there won't be an "all fits one solution" for all machines; the use of hydrogen must be re-evaluated for each application and one must be prepared to adapt the requirements taking into account the possibilities and limitations.

NOMENCLATURE

α	Heat transfer coefficient	$W/(m^2 \cdot K)$
Θ	Temperature	K
A	Area	m^2
E^0	Standard potential	V
F	Faraday constant	As/mol
I	Current	A
L	Length	m
p	Pressure	Pa
P	Power	W
$\dot{Q}$	Volumetric flow rate	m^3/h
$\Delta_R G_M^0$	Free enthalpy at standard pressure	J
V	Volume	m^3
W	Energy	Wh
z	Electric charge number	-
BoP	Balance of Plant	
CH_4	Methane	
CH_3OH	Methanol	
CO_2	Carbon Dioxide	
DC	Direct Current	
EU	European Union	

FC	Fuel Cell
GHG	Greenhouse Gas
GDL	Gas Diffusion Layer
H_2	Hydrogen
H_2O	Water
ICE	Internal Combustion Engine
Max..	Maximum
Min.	Minimum
NO_x	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particular Mass
TREMOD-MM	Transport Emission Model for Mobile Machinery

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