Methane-Fuel cell-CCS-Drive: the emission-free working machine

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Kurzfassung

Unumkehrbare Folgen der globalen Erwärmung müssen zum Erhalt der aktuellen Klimabedingungen verhindert werden. Dazu muss jede Branche ihren Beitrag leisten, CO_2e Emissionen einzusparen. In diesem Artikel werden zunächst die Einflüsse auf die Treibhausgasemissionen von mobilen Maschinen beschrieben. Anschließend wird der nachhaltige Kraftstoff *verflüssigtes Methan* als Alternative zum Dieselkraftstoff für mobile Maschinen diskutiert. Maschinenkonzeptvarianten mit verflüssigtem Methan nach dem Prinzip des Morphologischen Kastens werden vorgestellt. Zum Schluss wird ein Konzept für eine emissionsfrei arbeitende Maschine vorgeschlagen, beschrieben und exemplarisch auf einen Bagger angewendet. Das Konzept besteht aus einem Antrieb mit nachhaltig hergestelltem verflüssigtem Methan und einer Brennstoffzelle sowie einem CO_2-Abscheidungssystem.

Schlagworte: Emissionsfrei arbeitende Maschine, Einflüsse von Treibhausgasen von mobilen Maschinen, verflüssigtes Methan, Brennstoffzellenantrieb, CO_2-Abscheidungssystem

Abstract

Irreversible consequences of the global warming must be prevented in order to preserve the current climate conditions. Therefore every sector has to make their contribution to reduce CO_2e emissions. In this article first the influences are described on greenhouse gas emissions of mobile machines. Afterwards, the sustainable fuel called *liquefied methane* is discussed as alternative to diesel fuel for mobile machines. Machine concept variants with liquefied methane according to the principle of the morphological box method are then presented. Finally a concept for an emission-free working machine is proposed, described and applied exemplary on an excavator. The concept consists of combining the sustainable liquefied methane with a fuel cell drive and a carbon capture system.

Keywords: Emission-free machine, influences of greenhouse gases for mobile machines, liquefied methane, fuel cell drive, CO_2 separation system

1 Introduction

In order to prevent irreversible consequences caused by the global climate change, greenhouse gases must be reduced. Until 2050, the EU requires emissions to be reduced by at least 80 % compared to 1990's levels. [1]

The climate policy goals that Germany wants to achieve by 2050 have not yet been set. Under consideration are until 2050 reductions goals of greenhouse gas emissions of 80 %, 85 % or 95 %. [2]

A reduction target of 95 % means that under consideration of non-reducible greenhouse gas sources, such as methane from animals, no fossil-fuelled mobile machine may be operated by 2050 [2]. Assuming the service life of mobile machines is max. 18 years [3], the sale of fossil fuel-powered mobile machines will have to cease latest on 2032 in order to reach the decarbonisation in 2050.

For these reasons sustainable climate friendly mobile machines are necessary. In the following chapters concepts of how a sustainable climate-friendly mobile machines could look like will be presented. First the basics about the influences on greenhouse gas emissions of mobile machines will be explained. Then the selection of an adequate sustainable fuel will follow. Based on this selection, a drive concept design methodology for mobile machines for this fuel will be developed. Then the description of the best solution will follow by combining three main aspects enabling the elimination of greenhouse gases: sustainable fuel, fuel cell drive and an adapted exhaust after treatment system capturing carbon. At the end this concept proposal will be applied exemplary on an excavator.

2 Influences on CO2e emissions of mobile machines

The analysis of the CO_2e emitted during the life cycle of a mobile machine indicates that over 80 % of all CO_2e emissions are released during their use and 10 % to 14 % CO_2e are emitted during the manufacturing of the machines [4]. According to the Pareto principle, the focus will lay on the 80 % of greenhouse gas (CO_2e) emissions emitted by mobile machines during its use.

It is not unusual that a mobile machine can in a same day be driven by various operators, work in different locations and environment conditions as well as have different working processes with different objectives for different applications. Table 2.1 describes exemplary a typical half day of work for an excavator on a construction site.

Table 2.1: Exemplary half day of work for an an excavator

Time	Excavator Activity	Excavator driver	Environment
6:58-7:06	Warming-up phase	Driver 1	Dark & cold
7:35-7:48	Transformation of an overburden into a platform	Driver 2	Fog & wet soil
7:48-8:00	Workplace & buckets preparation		
8:00-8:46	Excavation of canal	Driver 3	
8:58-9:07	Transport of pipe		
9:07-9:18	Excavation of canal with bucket 1 (1.6m³)		
9:18-9:36	Excavation of canal with bucket 2 (0.7m³)		
9:36-9:41	Distribution of grit stone with bucket 3 (gripper)		
9:41-9:48	Inserting the pipe into the canal		
9:48-10:11	Distribution of grit stone with bucket 3 (gripper)		
10:11-10:20	Distribution of earth with bucket 3 (gripper)		Sun & soil not so wet anymore
10:20-10:27	Transport&insert of concrete connector into the canal		
10:27-10:42	Distribution of grit stone with bucket 3 (gripper)		
10:42-10:57	Transport of bucket 4		
10:57-11:04	Distribution of grit stone with bucket 3 (gripper)		
11:04-11:44	Distribution of earth with bucket 3 (gripper)		
11:44-11:51	Transport&insert of pipe		
11:51-12:00	Excavation of canal with bucket 2 (0.7m³)		

Additionally, soil parameters, environment and construction site change each day. Further a construction site is always unique and work processes need to be adapted. Mobile machines are therefore not designed for one type of processes in one kind of environment and construction site. The amount of CO_2e emissions varies depending on the machine's activity, its application and environment. These are the reasons, why a mobile machine cannot be examined in isolation but have to be considered in its process. In order to achieve a sustainable CO_2e reduction, an overall view of the mobile machine with its process and its various influences is indispensable. In [5] saving potentials of CO_2e emissions of mobile machines are identified and can be summarized as follows: machine efficiency, process efficiency, operation efficiency, use of alternative fuels to fossil diesel and construction material efficiency. Additionally, to these CO_2e reduction potentials, another potential has been identified, which is *CO_2e capture and storage*. These pillars can not be considered individually, but in their interrelation and interdependence to each other. Their combined effect influences the CO_2e emission of a mobile machine.

These CO_2e reduction potentials, categorised in pillars are described individually in the following text.

The CO_2e emissions are influenced by the machine efficiency, which depends on the machine technology and the machine maintenance state. If the technology in the machine, such as engine, transmission, hydraulics, electric, etc. are in total more efficient together, less CO_2e will be emitted. A bad state of the machine increases the fuel consumption and so the CO_2e emissions. The machine condition state varies depending on the service regularity and its age. [5]

The CO_2e emissions are also influenced by process efficiency. A major influence in this category is the construction site organization, depending on it, the amount of subprocesses necessary to complete the construction work can be reduced or increased. Further process assistant features can contribute to process efficiency. The influence level of these features depend on the driver (expert, normal, beginner) and its experience. In addition, the influence of these measures can vary depending on the construction site complexity level, which is dependent on the weather, the available construction time and the available construction site freedom. [5]

During construction observations, process-related idling was identified as additional influence. An example was observed during road maintenance in Karlsruhe. After the paver had laid the binder course, manual work was necessary to bridge the gap between old and new course. During this time the paver was at idle in order to maintain the temperature for the following subprocess: laying of the driving course. This idle time is being characterised as unavoidable process-related idling. [6]

Operation efficiency also influences the CO_2e emitted by a mobile machine. It is characterised by the influence of the machine driver and the avoidable idle time. A machine driver is exposed to different influences as his physical and mental state, his training level and the ergonomic of his workplace as well as the view and the temperature in the cabin. Another aspect is the *avoidable* idle time. This is the time where the engine is unnecessary switched-on and the machine does not work. This idle time can increase or decrease depending on the engine state (switched-on or switched-off). The engine state is actuated automatically or by the operator. [5]

The CO_2e emission are in direct relation with the fuel consumed, because the amount of CO_2 emissions emitted during combustion by a fuel depends on the amount of carbon atoms contained in the fuel [7]. Alternative fuels have different compositions as diesel and therefore have the potential to reduce the greenhouse gas emissions. In order to determine the CO_2e emission impact of alternative fuels a well-to-wheel analysis is necessary. The well-to-wheel analysis is a methodology to quantify the amount of CO_2e emissions during production (well-to-tank) and combustion of the fuel (tank-to-wheel) [8].

Mobile machines are in direct contact with the construction material. For a correct CO_2e impact analysis the material used from the resource extraction to the construction site has to be considered. By using less construction material or recycle material CO_2e emissions are reduced. In conclusion material efficiency has to be considered and can be improved through production improvements, use of recycling material, use of alternative materials, etc. .

An additional influence on CO_2e emissions of mobile machines is the installation of a *CO_2e capture and storage* system. This system will permit to catch or reduce the CO_2 emission before they are released into the air and so reduce the locally emitted greenhouse gas emissions (CO_2e). Nowadays three capture possibilities exist for power plants: *pre-combustion*, *oxy-combustion* and *post-combustion*. In pre-combustion technologies, the CO_2 is captured before combustion takes place. In the oxy-combustion technologies, the combustion takes place with oxygen (O_2) instead of air. Air comprises not only oxygen but e.g. also nitrogen (N_2). Post-combustion technologies describe the separation and storage of CO_2 from the exhaust gas, after the combustion process. [9]

For mobile machines the main focus lays on pre- and post-combustion technologies.

The CO_2e reduction potentials are described by the combined total efficiency of the six pillars described above and shown in Figure 2.1. These six pillars are widely interrelated and cannot been assessed as stand-alone since construction machines are contributing to multiple processes by various operators in changing environments. An efficiency increase on a small scale can therefore lead to a reduction in the whole construction application.

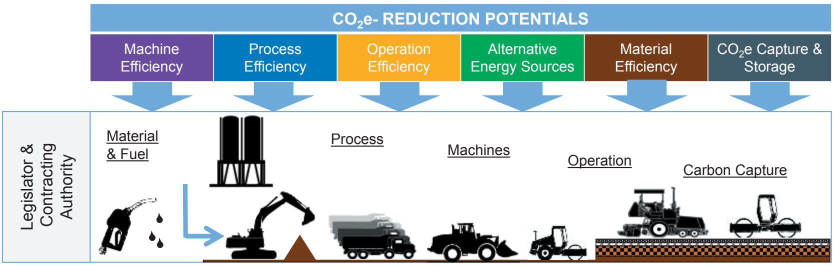

Figure 2.1: Six main CO2e reduction potentials for construction equipment

3 Methane as sustainable fuel for mobile machines

One possibility to reduce greenhouse gas emissions is to use an alternative energy carrier to diesel (alternative energy sources pillar). In order to choose an adequate alternative an analysis about its calorific value, its gravimetric and volumetric energy densities is necessary. In [10] different energy carriers were examined. Hydrogen was found to be not an option for mobile machines because of its volumetric value, see Table 3.1. An efficiency of 0.34 and 0.5 are assumed for an internal combustion engine (ICE) and for a fuel cell (FC), respectively [10,11]. The energy of 500 l diesel is equivalent to 2,104 l liquid hydrogen in an ICE drive concept and 1,431 l with a FC drive concept. Such a tank volume would be too big for a mobile machine. Further hydrogen reduces the strength, ductility and service life of many metallic materials (hydrogen embrittlement) [12].

Batteries are not an interesting alternative to fuels because of their gravimetric energy density. In [13], a battery for a combine harvester equivalent to the energy of 500 l diesel (0.415 t) has been calculated and would have a weight of 29 t.

Geimer and Ays identified in [10], sustainable liquefied methane as the most promising alternative fuel for mobile machines. In Table 3.1 can be seen that the volume as well as the mass of liquefied methane are in an acceptable range, lightly higher than diesel.

Table 3.1: Comparison of methane and hydrogen with diesel fuel [10] [11] [14] [15]

	Concept	Density of fuel [kg/l]	Calorific value of fuel [MJ/kg]	Volume of fuel [l]	Mass of fuel [kg]
Ref.	Diesel & ICE	0.83	43.2	500	415
Gas	CH_4 (0°C, 200 bar) & ICE	0.141	50	2,543	359
Gas	H_2 (700 bar, 25°C) & ICE	0.039	120	3,802	149
Liquid	CH_4 (-167°C, 1 bar) & ICE	0.423	50	848	359
Liquid	CH_4 (-167°C, 1 bar) & FC	0.423	50	601	254
Liquid	H_2 (-253°C, 1 bar) & ICE	0.071	120	2,104	149
Liquid	H_2 (-253°C, 1 bar) & FC	0.071	120	1,431	102

$^*\eta_{ICE} = 0{,}34;\ \eta_{FC} = 0{,}5;\ \eta_{Reformer} = 0{,}75$

Methane is liquefied by a temperature of -167 to -157°C at 1 bar and has a calorific value of 50 MJ/kg. Depending on the purity of the natural gas or biogas corresponding to the percentage amount of CH_4 molecule, the calorific value varies between 39 to 50 MJ/kg.

Table 3.2 shows the amount of greenhouse gas emitted during its production, also called well to tank (WtT), and during its conversion into mechanical energy, tank to wheel (TtW). The sum results to the total greenhouse gas emissions, also called well to wheel emissions (WtW). In case sustainable energy carriers are used, the TtW emissions (local emissions) are assumed to be zero, they correspond to the CO_2e absorbed from the atmosphere for e. g. during the growing process of the plant [16]. Mobile machines can only be operated with liquefied methane if the infrastructure is available. In [17] was shown on the example of Karlsruhe that such infrastructure is already available thanks to the existing natural gas network and the biogas plants. Methane or natural gas are nowadays transported in Germany in gaseous form via pipelines or in liquid form via maritime delivery, via rail transport with tank wagons or via road tankers. Liquid methane is first stored in depots or storage facilities before it is distributed. Power-to-methane plants or biomethane plants can also serve as depots, only the installation of additional liquefaction system would be necessary. [18]

Table 3.2: Well to wheel analysis of liquefied methane

	[g CO_2e/MJ]		
	WtT	**TtW**	**WtW**
LNG fossil	19.0	56.0	75.0
LNG from wind power-SNG	12.3	56.7 *(process with fraction diesel)*	13.0
		56.6 *(Otto process)*	12.9
		0.06 (fuel cell)	12.3
LBG liquid biomethane	31.3	56.7 *(process with fraction diesel)*	32.0
		56.6 *(Otto process)*	32.9
		0.06 (fuel cell)	31.3
Diesel	15.3	74.0	89.3

The refuelling possibilities of mobile working machines with liquid methane can take place either via direct refuelling of the machine by a tanker truck, via the delivery or filling of a stationary container or via the company's own liquefaction plant on the premises. As soon as their own liquefaction plant is available, the machines can divert the liquid methane from the natural gas network. The refuelling process may only take place in well ventilated places and must be carried out by persons wearing safety clothing to prevent cold burns. [18]

4 Methane drive concept design methodology for mobile machines

Figure 4.1 shows according to the morphological box method possible machine concepts with liquefied methane. First, the primary energy converter needs to be selected. With liquefied methane, not only internal combustion engines as the Otto engine, diesel gas engine or gas-diesel engine can serve as primary energy converter but also fuel cells [19]. Four different types of fuel cells were therefore identified: the proton-exchange membrane fuel cell (PEMFC), the phosphoric acid fuel cell (PAFC), the solid oxide fuel cell (SOFC) and the molten carbonate fuel cell (MCFC).

The MCFC and the PAFC are recommended to be used as central power generation source for an amount of machines. PEMFC and SOFC can be installed as primary energy converter in mobile machines. The main advantage of SOFC is its smaller dimensions and lower weight while requiring less power. In contrast, the PEMFC requires an external oversized reformer for low power output, which takes up a large volume and weight. When the power requirement reaches a certain value, the advantage of the high power density of the PEMFC outweighs the advantages of SOFC. [20]

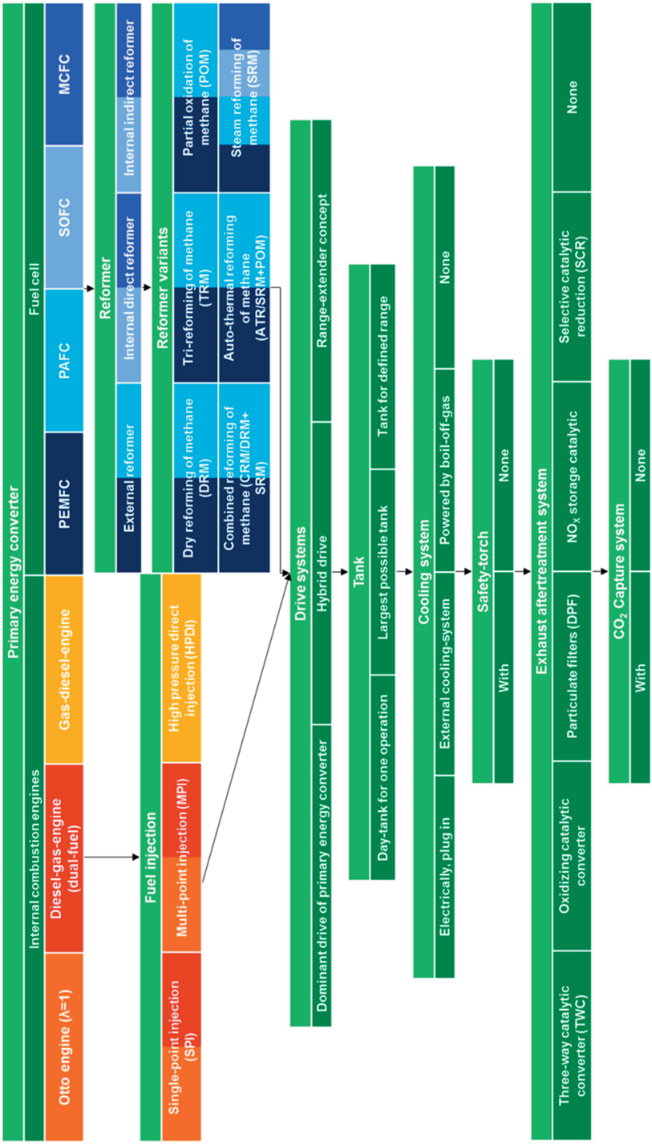

Figure 4.1: Machine concepts variants with liquefied methane according to the morphological box method

Fuel cells work with hydrogen, therefore methane is converted with a reformer into hydrogen. Depending on the fuel cell type an external, internal direct or internal indirect reformer can be installed. An external reformer is an independent component, not integrated in the fuel cell. An internal reformer is integrated in the fuel cell. When the conversion happens with a separated catalyst, the process is called internal indirect reforming and when the conversion into hydrogen happens directly at the anode, the process is called internal direct reforming. [20]

For methane different reforming technologies are available where water and/or oxygen and/or carbon dioxide react with methane into hydrogen and carbon monoxide. Six existing technologies were identified: steam reforming, dry reforming, partial oxidative reforming, combined reforming, auto-thermal reforming and tri-reforming [21].

In order to increase the hydrogen production the water shift reaction takes place directly after the reforming process [22].

Then, depending on the machine type and its application the drive system has to be chosen. The most common drive system for mobile machines is a dominant drive of the primary energy converter. Alternatives are the range-extender concept or other hybrid drive concepts.

Afterwards the right tank size has to be chosen. Therefore, it has to be clarified if the machine requirements impose a minimum tank volume for one operation day or for a defined range or if the largest possible tank is requested. Methane needs to be stored in a special tank, where temperature is of -167 to -157°C at 1 bar in order to be liquid because it is gaseous at atmospheric temperature and pressure. If the machine has long standstill time, a cooling system is necessary to extend the holding time before evaporation of the fuel takes place. The cooling system can be an external system or integrated in the mobile machine. It can be powered with electricity or by boil-off-gas. A security measure could be a safety-torch or a small burner which burn any evaporated gas before it is released in the atmosphere.

Finally, depending of the choice of the primary energy converter different exhaust aftertreatment systems are necessary. Not only conventional systems but also a CO_2 capture system can be adopted in order to reach zero pollutant emissions.

5 Adapted exhaust aftertreatment system capturing carbon

CO_2 capture and storage (CCS) technologies are considered by [2] to be the solution to the global warming problem. The CO_2 emissions are captured and stored instead to be released into the atmosphere. Actual application focus lay on large scale and stationary sources of CO_2 such as power plants [9].

Huang investigated in [9] different existing technologies for CO_2 capturing and developed adapted solutions for mobile machines. The best proposed solution can be seen in Figure 6.1. In the CO_2 capture system, first the exhaust gas is being cooled down to 60°C. This may happen with a gas cooler or with air from the atmosphere by using a turbocharger. Then CO_2 is captured with one of the two activated carbon filters and finally the CO_2 free exhaust gas is released into the air. When the filter is fully charged with CO_2, the exhaust gas is led via the 3-way valve to the other filter. Meanwhile the first filter is being heated to 120°C to desorb the CO_2. It will later be cooled down to 30°C and compressed into liquid (200 bar) in order to be stored in a tank. This means that if one activated carbon filter is in adsorption state, the other filter is in desorption state. As soon as the tank is full, it can be emptied, the CO_2 can then be sold and transferred to an external system for other utilisations, e.g. in order to produce e-fuels. [9]

6 Exemplary application on an excavator

Using sustainable liquefied methane as fuel is considered to be climate neutral because CO_2 from the atmosphere is absorbed for e.g. during the growing process of the plant and then released in the atmosphere by converting chemical energy into mechanical energy. If in addition the emission produced during the conversion of chemical energy in mechanical energy is captured and stored in the underground and so not released in the atmosphere, the system is not climate-neutral anymore but emitting negative CO_2e, which would mean the technology cleans the atmosphere.

In Figure 6.1 exemplary is shown on an excavator the technology combination of sustainable liquefied methane as energy carrier with a PEMFC fuel cell range extender drive concept and with the carbon capture system described in chapter 5.

A fuel cell is a primary energy converter providing "high electrical and overall efficiencies with limited environmental impact" [23]. This compact technology emits no noise, has no moving parts and produces no vibration. In addition, fuel cells have an electrical efficiency of 50 to 65 % and a total efficiency of over 80 % [11]. As fuel cell a PEMFC is selected because of its high energy density and efficiency [20]. For the exemplary excavator the range-extender drive concept is chosen so that load fluctuations impact as little as possible the fuel cell and so mostly the battery.

The energy carrier liquefied methane flows through a heat exchanger and enters gaseous the external reformer. There the steam reforming process takes place. The fuel methane reacts with the water vapour to produce syngas or synthesis gas which consists of hydrogen (H_2) and carbon monoxide (CO). The reaction is described in (6.1) [14].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta H^\circ = 206 kJ \cdot mol^{-1} \qquad (6.1)$$

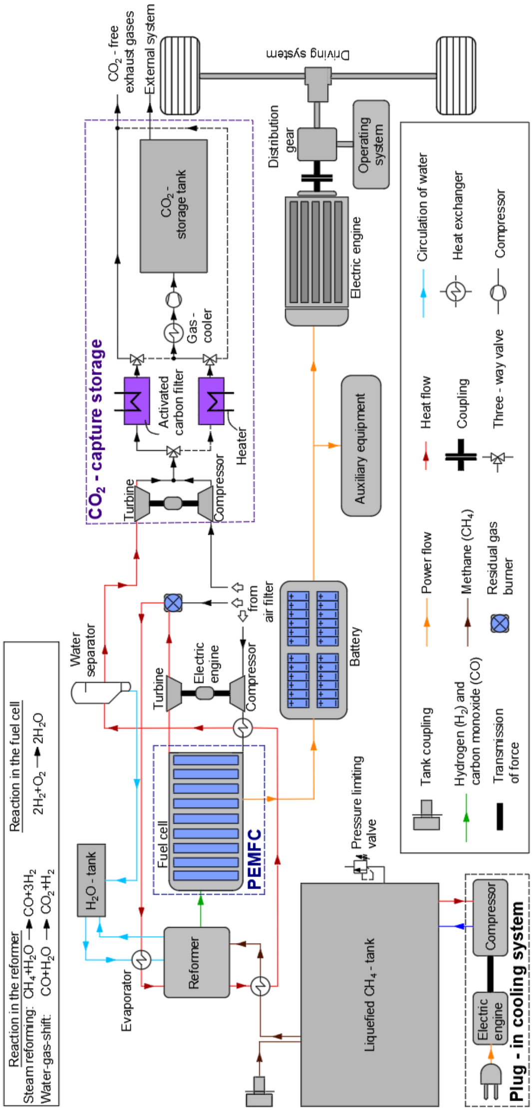

Figure 6.1: Machine concept for mobile machines

Afterwards to increase the hydrogen production, follows the water gas shift reaction like in (6.2).

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H° = -41\ kJ.mol^{-1} \tag{6.2}$$

The products of the reaction flow into the fuel cell in order to produce electricity for the traction drive. For efficient use of the chemically bound energy, residual gases left in the exhaust gas leaving the fuel cell are burnt. The heat of the exhaust gas is then used for the heat exchangers, reformer and H_2O separator. Finally, in the exhaust gas only O_2, CO_2 (low approximately 0.8 g/kWh) and because of the residual gas burner very low (< 10 ppm) of CO and NO_x are left [24]. Subsequently in order to reach zero emissions, the CO_2 needs to be continuously separated with a capture system and stored. The carbon capture system solution adopted for this exemplary excavator cools down the exhaust gas with air from the atmosphere via a turbocharger and adsorbs CO_2 through an active carbon filter system was.

Table 6.1: Approximated volume and weight calculation for an conventional 30 t excavator versus a CH_4-FC-CCS drive excavator for a same energy output of 6,340 MJ [10] [11] [14] [15] [26]

Concept		Fuel	Tank	Drive		Exhaust gas aftertreatment System	CCS	Total
Diesel excavator (30t)	Volume [m³]	0.52	negligible	Engine:	0.79	0.33	-	**1.6 m³**
	Mass [kg]	432	26	Engine:	715	140	-	**1,313 kg**
CH_4-FC-CCS-drive excavator	Volume [m³]	0.49	0.55	FC: Battery: Reformer:	0.73 0.67 2.59	-	0.98	**6.0 m³**
				Total:	3.99			
	Mass [kg]	264	426	FC: Battery: Reformer:	475 603 720	-	162-888 (CO_2-tank emtpy-full)	**2,650 kg to 3,376kg**
				Total:	1,798			

$^*\eta_{ICE} = 0{,}34;\ \eta_{FC} = 0{,}5;\ \eta_{Reformer} = 0{,}75$

The combination of these described technologies are estimated to weight 1.3 t with an empty CO_2 tank to 2.1 t more with a full CO_2 tank (4.5 to 6.9 %) and to need 4.4 m³ more space than conventional excavators (see Table 6.1). The conventional exhaust gas aftertreatment system is replaced with a CO_2 capture and storage system.

7 Economical aspects

The organisation for Economic Cooperation and Development (OECD) states that direct damages and indirect consequences such as adaptation measures due to global warming cost today 30 €[1] per t of CO_2e and in 2020 60 € per t of CO_2e [27]. In the case of a diesel excavator with e.g. a service life of 10.000 hours and a fuel consumption of 30 l/h, this would correspond to 954 t of CO_2e emissions and 28.620 € or in 2020 to 57.240 €. The described innovation in Figure 6.1 will cost less than direct damages and indirect consequences due to global warming. Consequently, it becomes clear that this innovation is quite economical.

8 Summary

The global warming drives the reduction of man-made greenhouse gas emissions. One possibility for mobile machines is the use of sustainable liquefied methane. A drive concept methodology for mobile machines with this fuel was developed in chapter 4. By combining sustainable liquefied methane with a fuel cell drive and a carbon capture system the best climate friendly result is obtained. The structure of this concept has been explained and

[1] 30 € per t CO_2e is a low-end estimate of today carbon costs and is valid for "42 OECD and G20 countries, representing 80% of world emissions" [27].

applied exemplary on an excavator. In summary, this article has proposed a real alternative on how mobile machines can continue to contribute to the reduction of greenhouse gas emissions.

Further work are necessary before this described technology combination can be implemented in a mobile machine such as detailed dimensioning of the components depending on the machine and its application, simulations, adaptations of the operation strategy, etc. .

By capturing and storing CO_2 emissions new business models for mobile machines, construction companies or farmers can be derived.

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