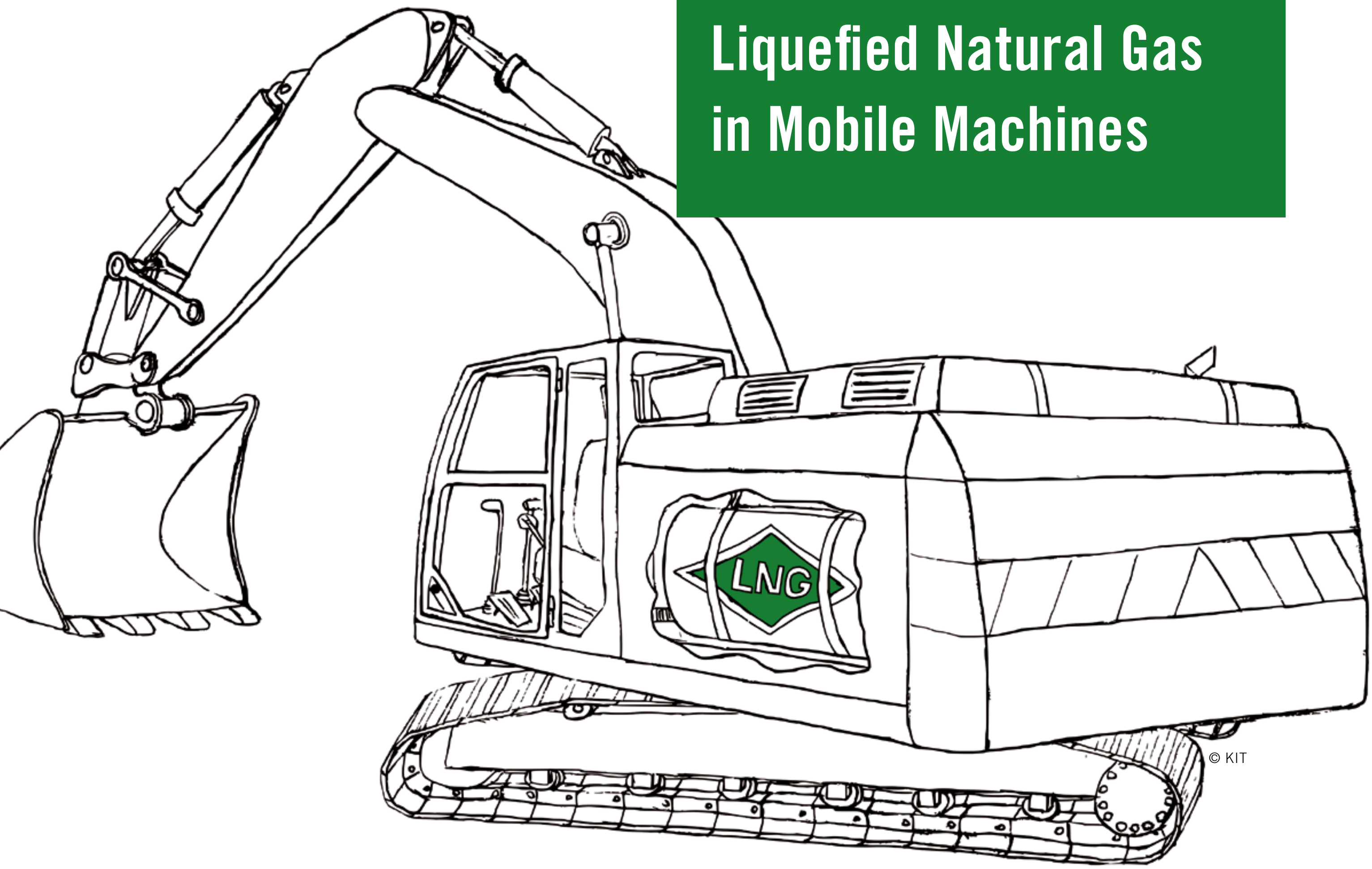
Liquefied Natural Gas in Mobile Machines



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Liquefied natural gas offers many advantages in long-distance truck. At KIT has now examined whether this alternative fuel is also of benefits in mobile equipment. In addition to the characteristics of the fuel, the production as well as the possible tank and combustion processes were analysed. These concrete potentials regarding consumption, and emissions are identified and evaluated for all types of machines.

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MOTIVATION

In autumn 2015, 188 countries of the world submitted climate plans to the United Nations. These plans contain milestones to reduce greenhouse gas emissions, also called CO_2e, and to prevent global warming [1]. The goal defined by the European Union is to reduce the greenhouse gas emission level of 1990 by 40 % until 2030. Another objective pursued by the European Union is emission reduction by 30 % from 2005 to 2030 [2].

The finite resources of fossil fuels which will not cover the world's energy consumption in the long term and the ambitious objectives of the European Union with respect to the reduction of anthropogenic greenhouse gas emissions, cause EU politics to increasingly focus on not yet regulated industries like mobile machines. Fuel consumption and, hence, greenhouse gas emissions can be reduced not only by increasing the efficiencies of powertrains or hybridisation, but also by alternative sustainable energy concepts.

First, the emitted CO_2e of liquefied natural gas and diesel gas fuels are examined and compared to each other. Afterwards possible drive concepts with liquefied natural gas are presented. Finally, these concepts are adapted to the edge conditions of different mobile machines.

ALTERNATIVE FUELS

When using alternative fuels instead of diesel in mobile machines, the calorific value as well as the gravimetric and volumetric energy densities of the fuel have to be considered. A highly promising option for fuelling mobile machines is liquefied natural gas [3]. According to studies, direct combustion of 1 MJ natural gas causes emission of 56 g CO_2e. The corresponding value for 1 MJ diesel is 74 g CO_2e. This corresponds to a reduction of approximately 24 % of the emitted greenhouse gases, assuming the same efficiency during combustion [4]. If the carbon content of the natural gas originates from a source that either regenerates quickly or the use of which does not contribute to source's exhaustion [5], this natural gas is referred to as regenerative fuel or biogas (non-fossil natural gas). The fuel takes the carbon fraction from the air. It is released again into the air, as a result of the fuel's combustion. For this reason, local emissions (tank-to-wheel emissions) produced by the combustion of regenerative fuels are not included in the climate balance.

"When using regenerative fuels, possible methane slip may be considered by the greenhouse warming potential – GWP of non-fossil methane. The HC limit given in Euro Stage IV for mobile machines of 56 kW to 560 kW driving power is 0.19 g/kWh [6]. When converted into MJ, a limit of 0.053 g/MJ results. Assuming that the CO_2e hydrocarbon emissions in the exhaust gas consist of methane exclusively, a maximum permissible CO_2e emission of about 1.5 g/MJ is obtained using the GWP of non-fossil methane. As this value is assumed to refer to the output power of the machine, the maximum permissible emission can also be related to the fuel consumed". [7] When assuming efficiencies of 39 % for the Otto process and 44 % for the diesel-gas process and the gas-diesel process (see chapter state of the art), maximum resulted emissions are respectively about 0.6 g CO_2e/MJ and 0.7 g CO_2e/MJ [7].

SUSTAINABILITY OF PRODUCTION

For a holistic analysis of the sustainability of the energy source (Well-to-Wheel), the production of liquefied natural gas (Well-to-Tank) has to be considered. Conventional and cheaper natural gas production takes place at natural gas storage reservoirs [8]. The total energy consumption for the supply at a refuelling station (Well-to-Tank) is in average 0.23 MJ per MJ of LNG fuel, this corresponds to 19 g CO_2e per MJ fuel. Most of the CO_2e emissions from LNG fuel are caused by liquefaction and sea transport [9]. The production of liquefied natural gas is at first glance of no interest compared to diesel with 15.3 g CO_2e [10]. However, in case of a sustainable production of liquefied natural gas, the Well-to-Tank balance may be more ecological than the one of diesel production. Biomethane is produced by processing the gas formed by anaerobic fermentation of organic waste or from renewable resources with the help of bacterial cultures [11]. For the supply of 1 MJ of liquid biomethane 31.3 g CO_2e are emitted [7]. Synthetic production of natural gas with wind power (SNG) by e.g. the power-to-gas process (PtG) or by thermochemical gasification of biogenic solid gives rise to greenhouse gas emissions of 12.3 g CO_2e per 1 MJ natural gas (PtG) [7].

Liquefied natural gas (-167 to -157 °C, 1 bar)			
Structure of methane	CH_4		
Density	0.43 to 0.47 kg/l		
Calorific value	39 to 50 MJ/kg		
	Well-to-Tank [g CO_2e/MJ]	**Tank-to-Wheel [g CO_2e/MJ]**	**Well-to-Wheel [g CO_2e/MJ]**
LNG fossil	19.0	56.0	75.0
LNG from wind power – SNG	12.3	0.7 (Process with fractions diesel)	13.0
		0.6 (Otto process)	12.9
LBG – liquid biomethane	31.3	0.7 (Process with fractions diesel)	32.0
		0.6 (Otto process)	31.9
Diesel	**15.3**	**74.0**	**89.3**

TABLE 1 Well-to-Wheel emissions of different LNG fuels (© KIT)

When extracting oil, the natural gas is located above the oil. It is released during drilling and usually flared (except in Norway), as feeding this natural gas into the pipeline network is not profitable for the oil companies. Flaring has adverse impacts on the environment and in particular on agriculture and drinking water. Emission of this natural gas without flaring would enhance the greenhouse effect. [8] If this lost natural gas was used as a fuel, the use of fossil natural gas would be more sustainable.

The Well-to-Tank (WtT) emissions, Tank-to-Wheel (TtW) emissions, and total emissions of various liquid methane fuels are listed in **TABLE 1**. **TABLE 1** shows that in spite of the higher Well-to-Tank emissions of liquid natural gas (LNG) compared to diesel, the Well-to-Wheel (WtT) value is still below that of diesel.

STATE OF THE ART

LNG (liquefied natural gas) is stored at about -160 °C, which reduces its (specific) volume by a factor of about 600 compared to the normal gaseous state (temperature = 273.15 °K = 0 °C; pressure = 1013.25 mbar) [12]. Due to the high temperature difference between the interior of LNG tanks and their surroundings, heat inflow into the tanks cannot be avoided. Consequently, constant evaporation of LNG takes place in the tanks. This increases the pressure inside the tanks, unless the evaporating gas is removed. The evaporating LNG is referred to as boil-off gas [12].

LNG tanks are designed such that losses due to the boil-off effect are minimised. To minimise heat inflow, they are provided with a multi-layered vacuum insulation [13], and represent closed systems that do not release any boil-off gas until a maximum permissible pressure level is reached. As a result, LNG tanks have about 1.6 to 2.9 times the weight and at least twice the construction volume of diesel tanks per energy content [7].

Three processes can be distinguished for combustion of natural gas in engines:
- Otto process
- diesel-gas process
- gas-diesel process.

The Otto system is currently the only way to burn natural gas in combustion engines without additional fuel [7]. The (gas) Otto process reaches a power density of about 80 % of that of diesel engines [14]. The average efficiency of gas-Otto engines in commercial vehicles is about 80 % of that of the diesel engine [15, 16]. For compliance of the gas-Otto process with current exhaust gas standards, a three-way catalytic converter is sufficient [17]. Gas-Otto engines produce up to 3 dB(A) less noise than diesel engines [16].

According to the current state of the art, a diesel process cannot be run with natural gas as the only fuel [18]. Diesel-gas and gas-diesel processes require diesel fuel for operation, in addition to natural gas. In particular, in the commercial vehicle sector, the diesel-gas process is also referred to as dual-fuel process, while the gas-diesel process is called HPDI (high-pressure direct injection) process [14, 18]. In the diesel-gas process, the gas fraction is about 60 to 80 %, whereas that of the gas-diesel process is above 90 % [18]. Efficiency and power density of the gas-diesel engine correspond to those of the diesel engine [16]. The data published on the diesel-gas process are con-

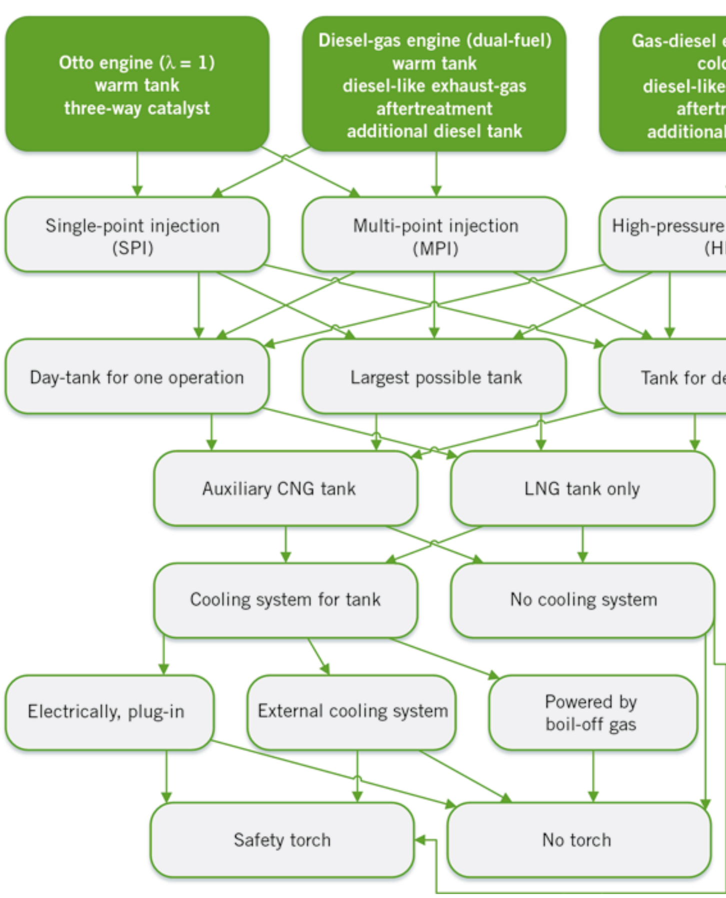

FIGURE 1 Morphological box of possible concepts (© KIT)

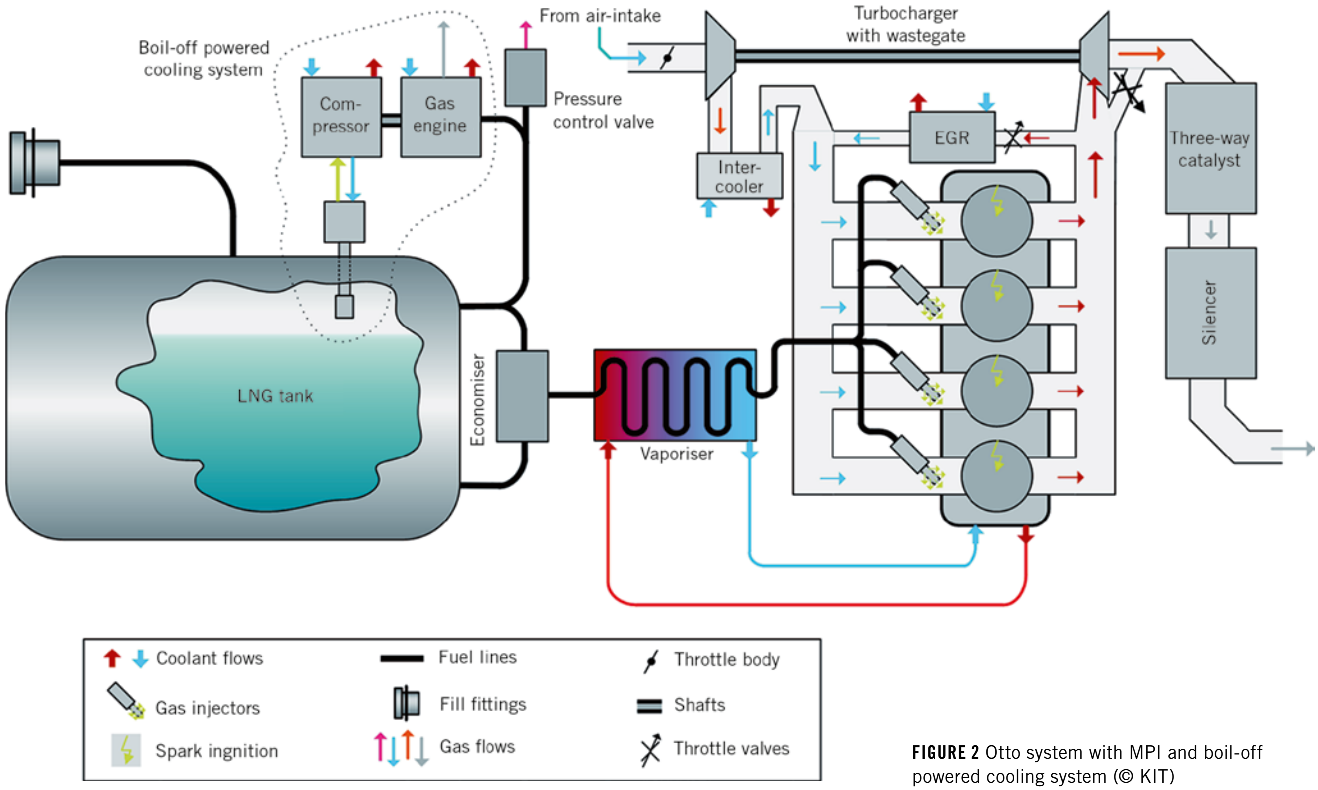

FIGURE 2 Otto system with MPI and boil-off powered cooling system (© KIT)

tradictory [14, 16], but the power density and efficiency appear to be slightly smaller than in the diesel process. For compliance with current exhaust gas standards, both processes with a diesel fraction require the same exhaust gas cleaning systems as used in current diesel engines [18]. When using the diesel-gas process, pure diesel operation is possible without any modifications [14].

TREATMENT OF BOIL-OFF GAS

Boil-off gas that is released into the environment via the pressure relief valve after the dwell time, that is to say at maximum permissible tank pressure, is lost and pollutes the environment. The easiest way to treat boil-off gas is to flare it in an explosion-proof manner. In this way, CO_2e greenhouse gas emission due to boil-off gas can theoretically be reduced by 90 to 93 % [7]. Potential stand-by time of an LNG-driven machine is not extended by flaring. Instead of flaring the boil-off gas, it is also possible to cool the tank and, hence, to reduce the evaporation rate. Such systems may be operated electrically, if power supply is available at the location, where the machine is parked. Alternatively, an engine driven by the boil-off gas may operate the cooling system. A tank cooling system based on boil-off gas can reduce the greenhouse gas emission rate (at an assumed engine efficiency of 30 %) by up to about 99 % and extend the potential stand-by time of the machine by factors of about 3.6 to 11.5 (depending on the system) [7].

The state of the art described and the options to treat the boil-off gas produced result in some variables for which powertrain concepts can be derived. They are represented in **FIGURE 1**. Choice of an engine technology usually also determines the tank technology (with or without fuel pump) and the required exhaust gas cleaning system. Apart from the combustion process, an injection method for the gaseous fuel has to be specified. The construction volume available and machine weight have to be weighed against tank capacity. The mode of operation of the machine has to be considered as well. Apart from the capacity of the tank or tanks, it has to be determined whether a cooling system is needed and how it is to be operated. Finally, it has to be decided whether the machine has to be provided with a safety-flare (if necessary, in addition to the cooling system).

GROUNDSCARE MACHINES WITH OTTO ENGINES

Similar to CNG drives, LNG machines may be driven by an Otto engine. This type of powertrain might be used for such as waste collection vehicles. The reduced noise level of the Otto process is advantageous, as these machines are also operated in residential areas. Based on the assumption that waste collection vehicles are usually operated five days a week at least, no tank cooling system would be required [7]. For longer downtimes, a flare might be installed on the roof of the machine. Due to its place of installation, it would be protected against unintentional contact. As a result of the usual parking locations of these vehicles, the risk of fire is minimised. This powertrain concept is represented schematically in **FIGURE 2**.

ROAD CONSTRUCTION AND SMALLER EARTHMOVING MACHINES

Road construction machines, such as pavers and earthmoving machines, of up to about 20 t service weight are considered. These machines are assumed to be operated for at least one work shift at a

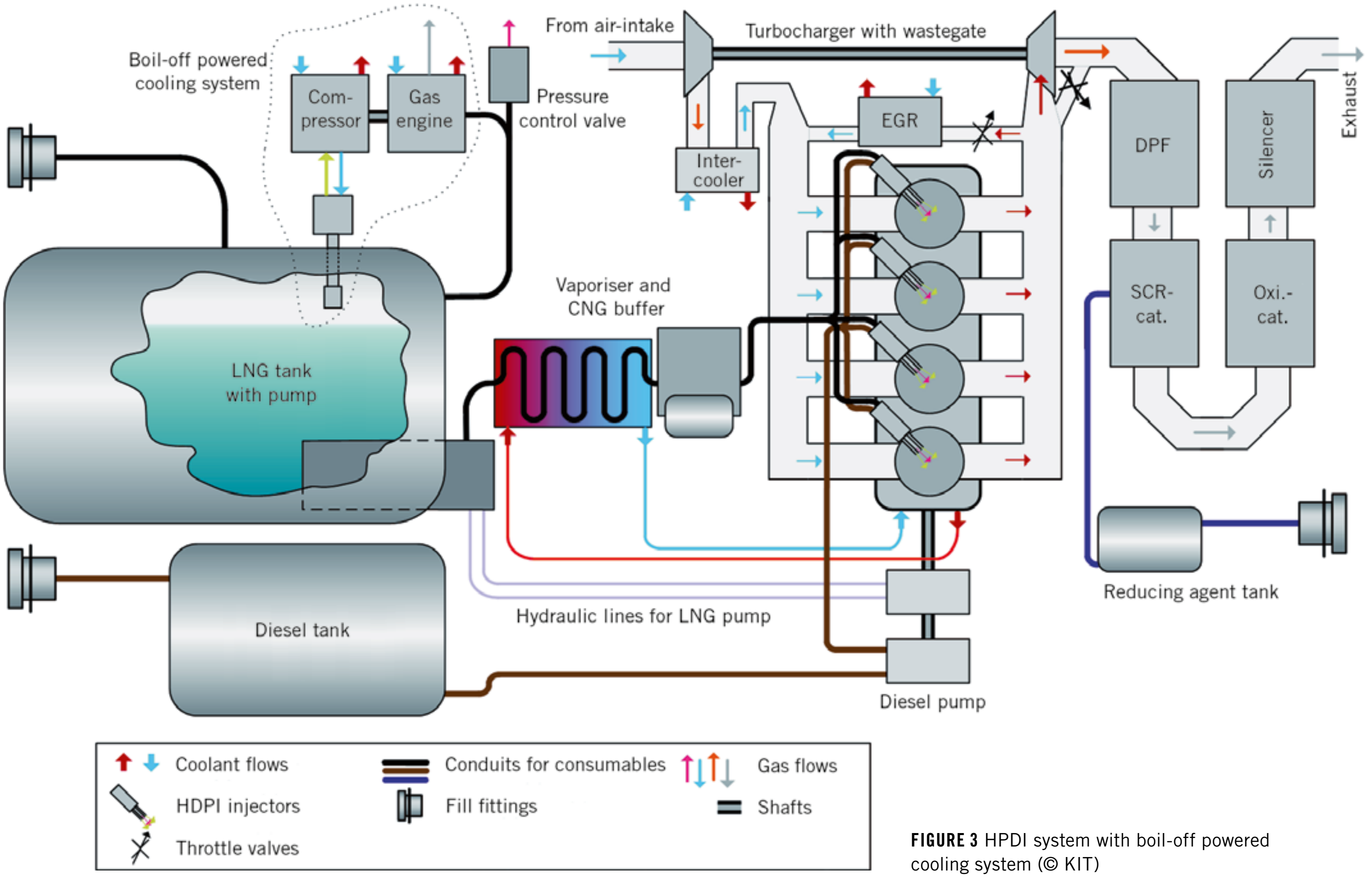

FIGURE 3 HPDI system with boil-off powered cooling system (© KIT)

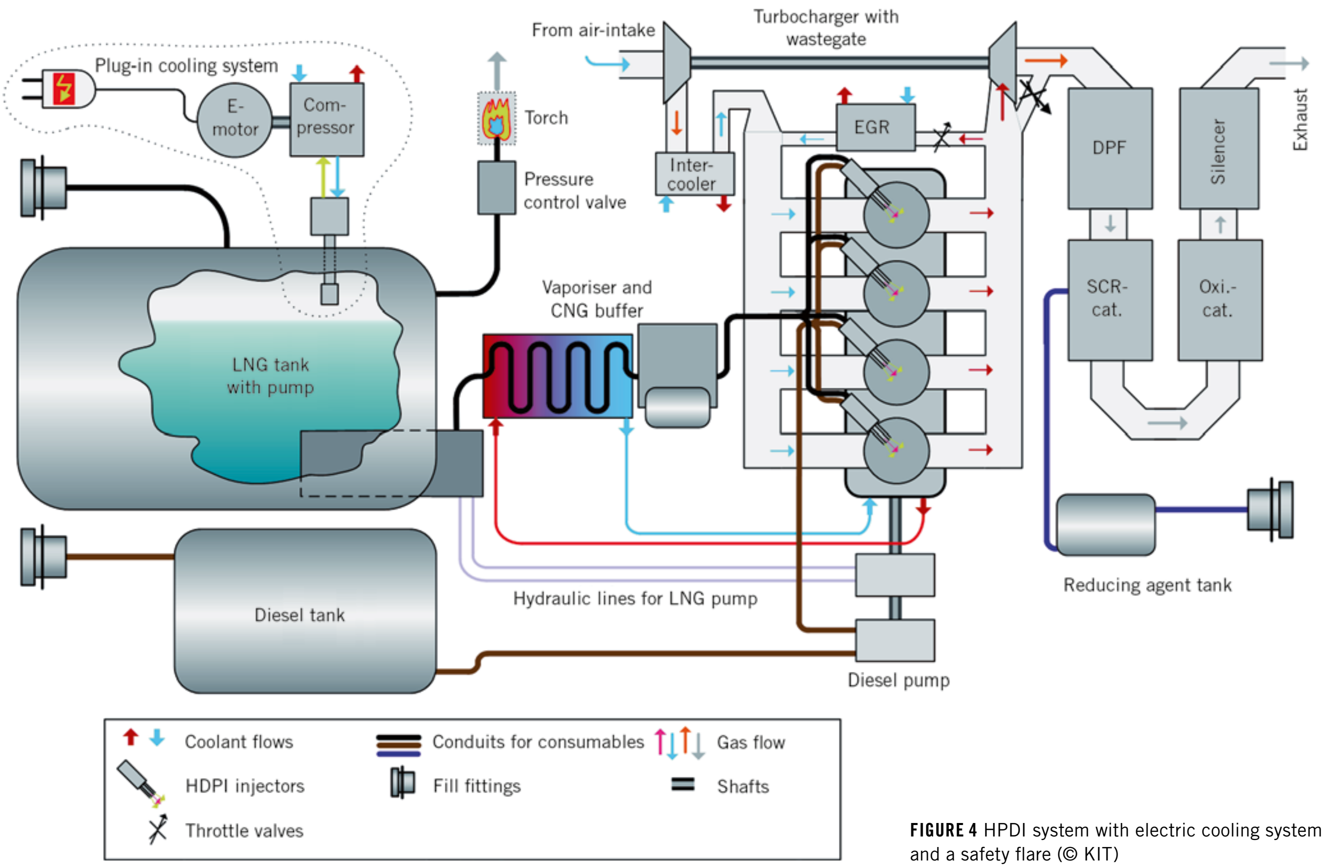

FIGURE 4 HPDI system with electric cooling system and a safety flare (© KIT)

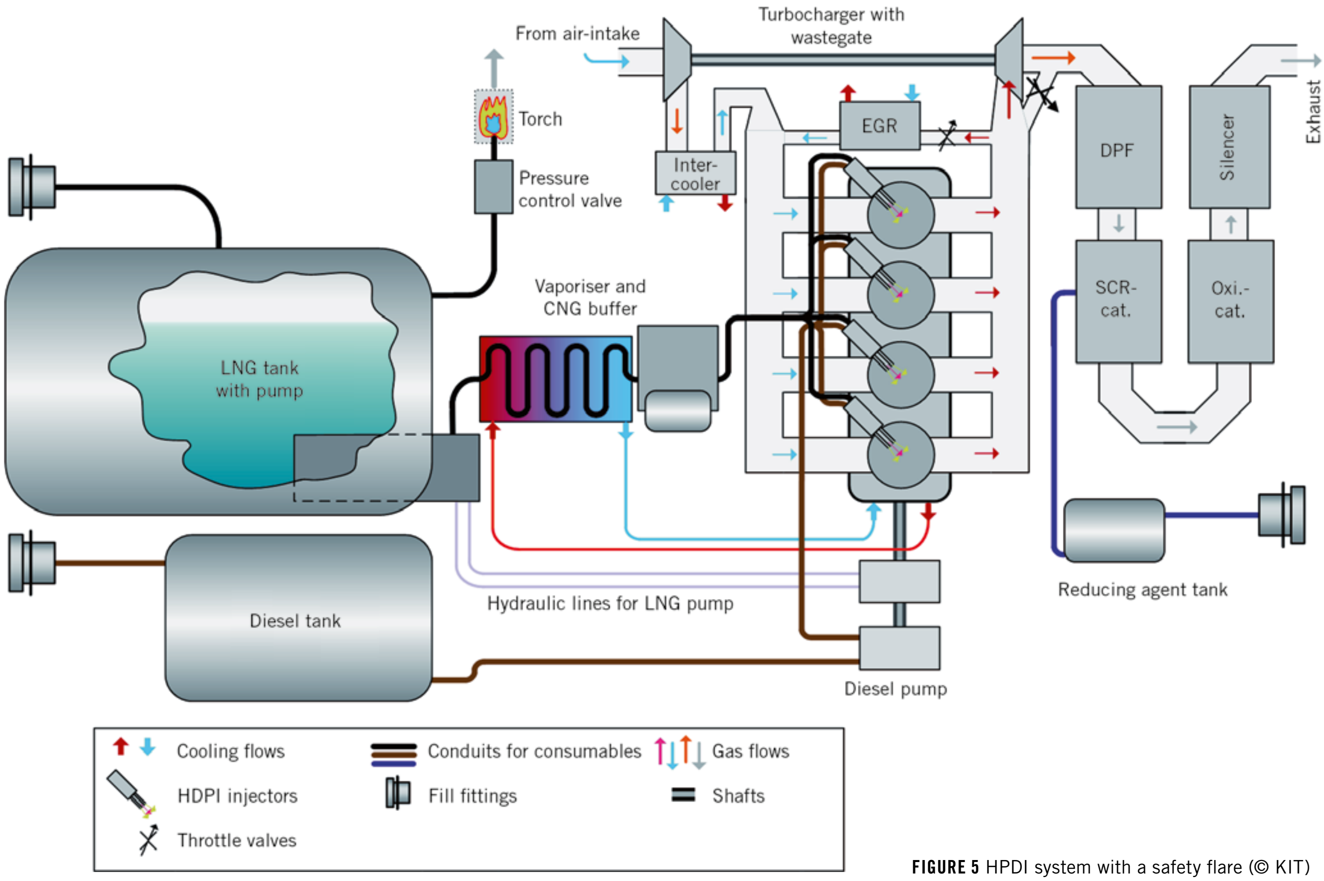

FIGURE 5 HPDI system with a safety flare (© KIT)

time, while downtime periods may last several weeks. The best possible exhaust gas behaviour and maximum efficiency are required. An HPDI powertrain with tank cooling system is envisaged. The tank cooling system is operated with boil-off gas or, as an option for machines parked on municipal builders yards, electrically. Machines with an electric cooling system should be provided with a flare for downtimes without power supply. Due to their slow continuous movements, a potential weight gain would be acceptable for most of the machines. It remains to be checked in detail whether and to what extent the additional weight of the tank system can be compensated by smaller ballast weights in frequently accelerating loading machines. Possible powertrain concepts for these machines are represented schematically in **FIGURE 3** and **FIGURE 4**.

EXCAVATORS AND OTHER MINING MACHINES

Excavators and other big mining machines are provided with high driving powers and are operated for long periods of time. Hence, an HPDI engine appears reasonable due to its efficiency and the possible iesel substitution rates. These machines need a large tank capacity, as they have to be operated at high power for at least one work shift and a special vehicle is required for refuelling such big machines. Potential weight gain of excavators, even of larger ones, would be uncritical. For wheel loaders or transport vehicles, compromises have to be found between tank capacity and weight. It is assumed that such big and expensive machines are run at maximum capacity with minimum downtimes. Consequently, no tank cooling system would be required for such machines. For potential longer downtimes, a flare should be installed. This is not expected to be associated with any risk for the staff operating the machines. The schematic setup of an HPDI powertrain suited for mining machines is shown in **FIGURE 5**.

AGRICULTURAL AND FORESTRY MACHINERY

Similar to the mining machines described above, big agricultural machines are operated at high power and capacity. Here, we consider highly specialised machines, such as forage harvesters, combine harvesters, beet harvesters etc. Due to the high energy turnovers expected, an HPDI drive is envisaged. During the harvesting season, these machines are operated for long times without refuelling. This assumption is based on the fact that the optimal harvesting times are limited. Hence, tank capacities of the machines have to be maximum and sufficient for one day of full-load operation at least. Additional energy consumption by takeover vehicles has to be analysed separately. In case of smaller capacities of the LNG tank, LNG tank trailers for field use might be feasible, if the contamination of the harvested crop by refuelling is eliminated. However, this would possibly require an additional expenditure and soil compaction of the field. It is assumed that such machines are parked for longer terms outside of the season and that power supply is available. If an LNG refuelling station is found directly at the parking location, feeding of the LNG from the machines back into the station may be feasible at the end of the season.

The situation is similar for forestry machines with high driving powers. Again, an HPDI drive is envisaged. Maximum tank capacity has to be provided. For this, a compromise has to be found between the permissible ground pressure and potential operation time. It also has to be taken into account that operation has to be interrupted when the machine has to leave the forest for refuelling. It is assumed that forestry machines also may have longer downtimes. In case of downtimes in the forest, no power supply is available. These machines are to be equipped with a tank cooling system based on boil-off gas. Due to the risk of fire, no flare is planned to be used.

SUMMARY

Stricter requirements of the European Union for reducing anthropogenic greenhouse gas emissions have given rise to the development of alternative sustainable energy concepts.

Within the framework of the present study, technically feasible LNG concepts were found for every common machine type. Discussion of drive concepts for the machines revealed that they should not be considered separately. Other factors, such as the operation environment, infrastructure available, and usage profile of the machines should be taken into account. These factors are of decisive importance to agricultural and forestry machines in particular and they should be analysed in more detail in connection with LNG use. This will give room for meaningful machine operation concepts to be derived depending on environmental conditions. For operation of easy-to-refuel machines with a good surrounding infrastructure, such as groundscare or construction machines, use of LNG is already a real alternative.

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