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Reformed Methanol Fuel Cells as a Climate-neutral Drive for Commercial Vehicles

Hydrogen is considered a sustainable energy carrier for the transformation towards climate-neutral mobility. The safe handling of hydrogen and its storage in the vehicle are technically highly demanding. Expanding the hydrogen refuelling infrastructure is also a challenge. A possible remedy can be the use of methanol as a hydrogen carrier, as it can be produced, used and easily stored in a climate-neutral way. This article by Gumpert and the Technical University Ingolstadt presents a reformed methanol fuel cell for commercial vehicles and its potential for promoting sustainable mobility.

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The partial or complete replacement of fossil energy in the transport sector requires alternative energy carriers. Currently, battery-electric drives are mainly developed for this purpose. Due to the lower energy density of lithium-ion batteries currently available on the market, the suitability of these batteries for energy intensive use by heavy commercial vehicles is limited. **FIGURE 1** compares the gravimetric and volumetric energy densities of hydrogen storage systems, batteries and gasoline currently discussed for mobility. The achievable values for the energy source are shown as orange bars and the complete storage system as blue bars. Compared to gasoline, chemically bonded forms of storage such as ammonia and methanol have significantly lower energy densities, but they have significantly higher energy densities compared to pure hydrogen systems. As a result, key performance charac-

teristics such as range and payload can be achieved.

If chemically bound hydrogen in the form of Liquid Organic Hydrogen Carriers (LOHC) or methanol is used for the transport sector, the existing refuelling station infrastructure can be converted with comparatively little effort. The “chicken-and-egg” problem associated with hydrogen mobility, which requires the construction of refuelling stations with acquisition costs of more than one million euros per unit [1], does not apply to the same extent to the use of methanol.

Methanol is a chemical compound with the half structural formula CH_3OH . As described in the following chapters, methanol can be produced carbon-neutral by synthesising hydrogen and carbon dioxide. The high availability of wind and solar energy in some regions of the world can be utilized for production. A comparison of the

average specific wind power of the windiest area of Germany (595 W/m^2) and southern Chile (5454 W/m^2) [2] (10 % of the windiest land area is taken into account in each case) emphasizes the need for spatial separation of production and use. Haru Oni, the pilot plant for the production of e-fuels such as e-methanol, is also located in southern Chile [3]. Methanol is already being imported on a large scale today. Total imports to Europe in 2021 amounted to over 2 billion US dollars [4]. This equates to more than 4.5 million t methanol.

As an energy carrier liquid at room temperature, methanol is easier to handle than hydrogen. It is possible to fill conventional filling stations with methanol without a great effort for conversion. Pure-methanol-based powertrains (M100), while rare at present, are already being used on the roads, particularly in China.

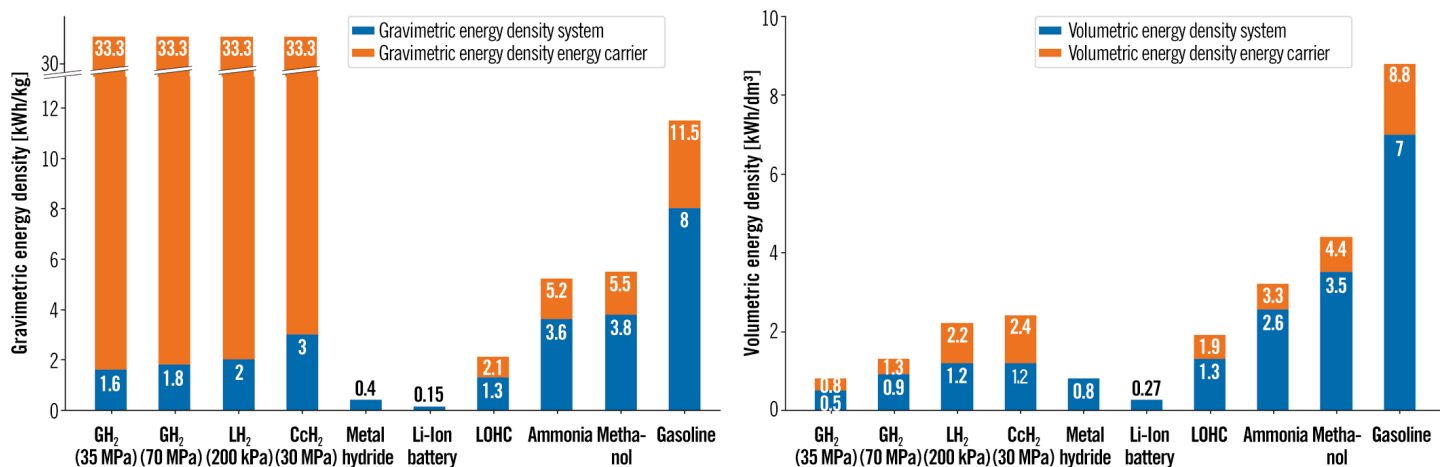


FIGURE 1 Gravimetric (left) and volumetric (right) energy density of energy storage systems in the transport sector (the illustration only considers the storage and not the efficiency of the energy conversion; GH₂: Gaseous Hydrogen; LH₂: Liquid Hydrogen; CcH₂: Cryo-compressed Hydrogen) © Gumpert

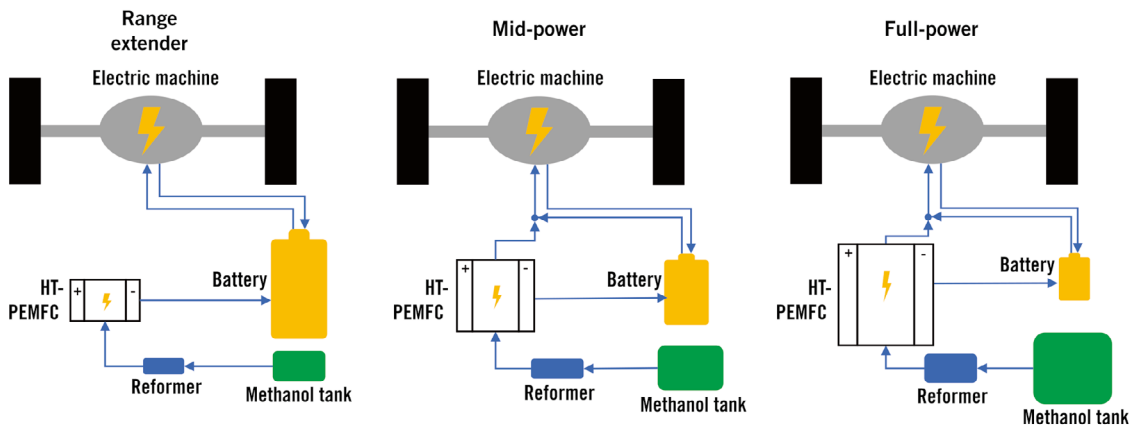


FIGURE 4 Sizing configurations for RMFC vehicle systems (© Gumpert)

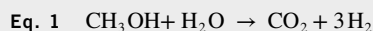
obtained from biomass, whereby several concepts are available for the production process: gasification-based production, reformer-based production from biogas and production from the pulping cycle in pulp mills. The biomethanol synthesis processes are identical for all concepts. First, the raw materials are cleaned multiple times and converted into a synthesis gas. This is then synthesized into “green” methanol [8, 9].

Electrolysis with renewable electricity is the basis for e-methanol. E-methanol can be produced through various production paths. The most common path uses hydrogen produced by electrolysis with renewable electricity and synthesises it into methanol in a catalytic reaction with CO₂. Alternative synthesis processes produce the synthesis gas from CO and H₂ with the addition of renewable electricity, water and CO₂ during electrolysis and convert this to e-methanol in the subsequent step. Direct electrochemical conversion of CO₂ and water is also possible [8]. If the CO₂ is taken from the air, the e-methanol is referred to as “green” e-methanol [8]. When it originates from exhaust gases, e.g. from industrial plants, “blue” e-methanol is produced [8].

VEHICLE CONCEPT USING REFORMED METHANOL FUEL CELLS

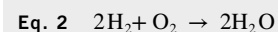
Vehicles equipped with Reformed Methanol Fuel Cells (RMFC) are identical to fuel cell vehicles using pure hydrogen as fuel in terms of basic functionality. They differ primarily in the hydrogen storage method. Vehicles powered by

pure hydrogen typically store the hydrogen cryogenically or under high pressure and feed it directly into the fuel cell without any conversion processes. Vehicles with RMFC have methanol stored in the tank instead. This can be stored at ambient temperature and ambient pressure. Vehicles with RMFC also use hydrogen in the fuel cell. The hydrogen must first be extracted from methanol in an exothermic reaction known as steam reforming. In the reformer, a mixture of water and methanol, previously produced and vaporized in the evaporator, is fed across a catalyst with the addition of further heat. As described in Eq. 1, this results in a reformat containing the main constituents hydrogen and CO₂:



The purity of the reformat is significantly lower than that of pure hydrogen for conventional hydrogen vehicles. By using a High-Temperature Polymer Electrolyte Fuel Cell (HT-PEMFC) which is less sensitive to impurities in the anode gas, the reformat can be used as an educt. In an additional step, a portion of the reformat is thermally utilized in the reformer in order to maintain its operating temperature.

As with low-temperature PEMFC, the hydrogen in the HT-PEMFC reacts with the oxygen from the ambient air according to Eq. 2 to form water, releasing electrical energy to drive the vehicle.



To avoid having to carry additional water for the reforming process, in



FIGURE 5 RMFC transporter prototype on the roller dynamometer (© Gumpert)

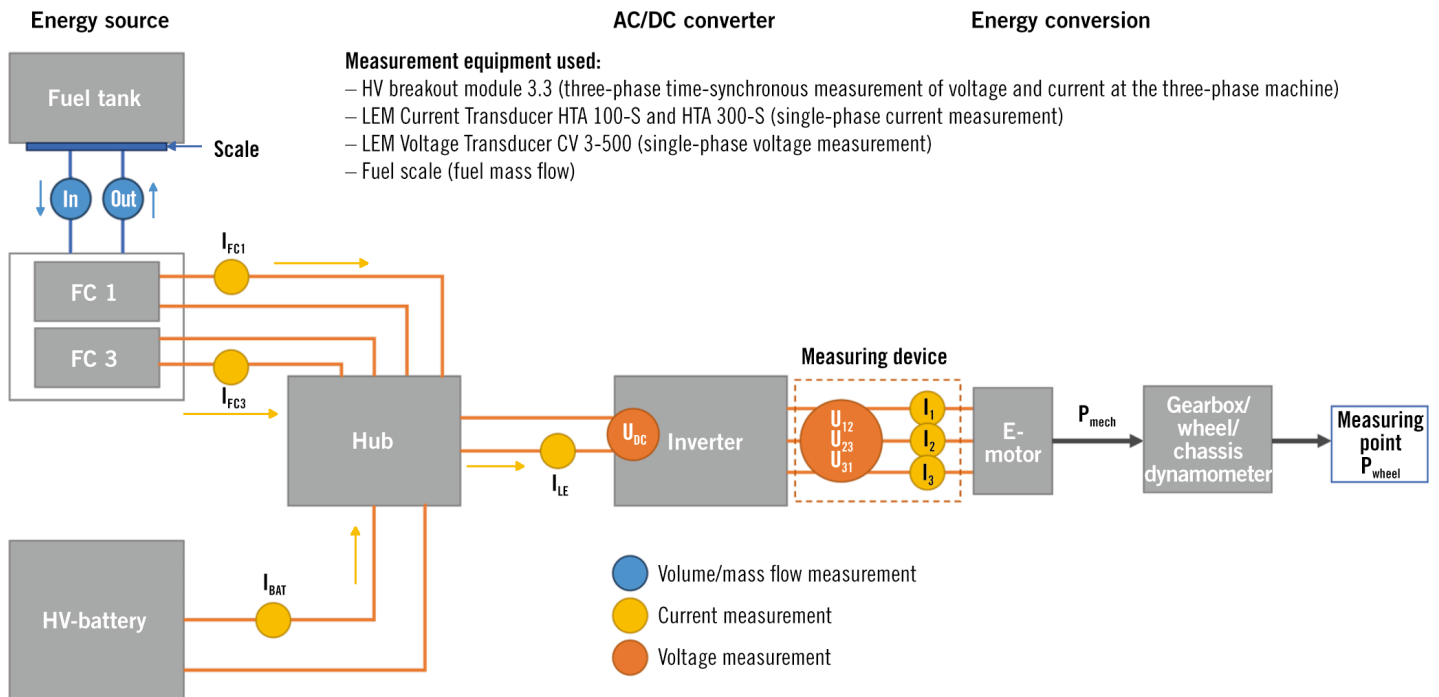


FIGURE 6 Electrical test bench design for stationary RMFC efficiency measurements (© Gumpert)

recent RMFC vehicle concepts the water produced at the fuel cell is partly collected at the condenser unit. The water is then used to form the water-methanol mixture in the evaporation process. As shown in **FIGURE 3**, the further structure of an electric vehicle with RMFC is similar to that of a conventional fuel cell vehicle. The electrical energy generated in the fuel cell is fed into a separate power electronics unit, which converts the output voltage of the fuel cell for the traction battery and the electric motor. Depending on the current driving condition and the battery's state of charge, the power is distributed to the drive system and the traction battery. During recuperative braking, the energy generated in the e-machine is fed back into the traction battery. The methanol tank can be refueled using a dedicated fuelling nozzle. The battery can also be charged at a charging station via a charging socket.

For the design of the powertrain in commercial vehicles, various types of RMFC drive systems can be considered. These are usually divided into fuel cell-dominant drives and battery-dominant range extender drives. Depending on the design, the fuel cell power, stored fuel, and battery capacity can be varied, **FIGURE 4**. Range

extender fuel cell systems draw the power needed in operation solely from the battery. The fuel cell does not provide adequate power to drive the vehicle alone in most driving conditions. It charges the battery and does not feed any power directly into the powertrain itself.

A so-called full-power fuel cell system is designed to cover the required power of all driving conditions with the fuel cell. The fuel cell directly supplies the electric motor. A large fuel tank and a powerful fuel cell are used for this concept. The battery is mainly used to start the fuel cell and to store the energy fed back by recuperation and only requires a small capacity.

So-called mid-power systems represent a gradation between the aforementioned designs. They are capable of covering a large part of the driving conditions using the fuel cell. The fuel cell power is fed either into the battery or the drivetrain. Driving conditions with high power requirements, such as driving uphill, are supported by the battery. For greater flexibility, a High-Voltage (HV) charging connection can also be installed to charge the vehicle battery. The right dimensioning of the fuel cell and battery system depends on the anticipated utility profile of the respective commercial

vehicle. It can ideally be determined using simulation models.

Fuel cell electric vehicles have fewer wear parts than comparable vehicles with internal combustion engines, which can reduce the maintenance effort and hence the operating costs. The reliability and durability of fuel cells in vehicles still have considerable development potential. It is expected that a long service life will be achieved in the future [10].

APPLICABLE VEHICLE CLASSES

Due to the higher efficiency of battery electric vehicles, it is reasonable to primarily equip vehicles in urban areas and for short-distance travel with this topology. RMFCs are useful for applications with high daily energy demand. It is not possible to give a general threshold value above which the use of RMFCs makes sense due to the highly variable load profiles in the commercial vehicle sector. Vehicles such as garbage trucks or agricultural harvesters often have very high energy consumption even without long daily distances. The use of RMFCs can also make sense for light commercial vehicles if they are used for longer distances on a daily basis. Buses and agricultural or forestry machines are

also conceivable applications. A stronger configuration of the fuel cell system can also ensure operation outside areas with electric charging infrastructure, if required. As the fuel cell system can remain active and charge the battery even when the vehicle is parked, it is possible to operate such vehicles in remote regions for longer periods of time.

EXPERIMENTAL INVESTIGATIONS ON THE OPERATING BEHAVIOR

To evaluate the new drive concept, a prototype based on the electrically powered MAN eTGE van was built, **FIGURE 5**. The core element of the conversion was the installation of four identical RMFCs, each with a rated electrical output of 5 kW. Hydrogen is produced by an upstream reformer. The fuel cells are connected directly to the drivetrain and battery in a mid-power configuration. The cell stack is operated at 160 to 180 °C and carries a mixture with the volumetric blend of 60 % methanol and 40 % in a separate tank.

The drive motor, drivetrain and traction battery remain mostly unmodified. To analyze the energy flows, high-pre-

cision ammeters and voltmeters, a power measurement system for three-phase applications and a fuel scale were installed. The measuring points and the measuring technology used can be seen in detail in **FIGURE 6**. Since no torque measurement was possible at the output of the drive unit, the determined efficiencies of the electric motor also include the losses from the drivetrain. In this configuration, the test vehicle was used to carry out stationary measurements on a chassis dynamometer at various speeds and loads and with a full payload. During these tests, two out of four fuel cells were active with an average total output of 6.5 kW. **FIGURE 7** shows the efficiencies resulting from the energy balances in the vehicle (tank to wheel) for selected operating points. The efficiencies measured at 8 and 19 kW wheel power represent important operating points of this vehicle at 50 and 80 km/h of the driving resistance curve on level ground.

For assessing the energy flows and efficiencies, the fuel cell and reformer are considered as a single unit. The unit also includes the other peripherals such

as the electric drive of the auxiliary units like the fan, coolant and fuel pump. The water exits the system in gaseous form, which is why the net calorific value is used as consideration parameter. This also enables a good comparison with combustion engines. The net calorific value of anhydrous methanol amounts to 19.9 MJ/kg. When water and methanol are mixed, the volume is reduced by a factor of 0.9637. Considering the evaporation enthalpy of the water content, the mixture has a calorific value of 9.69 MJ/kg. This value can be used to calculate the supplied fuel energy based on the measured fuel mass. The efficiency of the battery was set approximately to 100 %.

When evaluating the overall efficiency, it must be taken into account that it depends on the power split between the battery and fuel cell. In purely battery-electric driving mode (operating point on the right-hand side of **FIGURE 7**), overall efficiencies of up to 88.7 % and up to 34 % (not shown) in pure fuel cell mode are possible. For these reasons, overall efficiencies of 40.3 % to 78.9 % were measured with an active fuel cell. As expected, the efficiency of the elec-

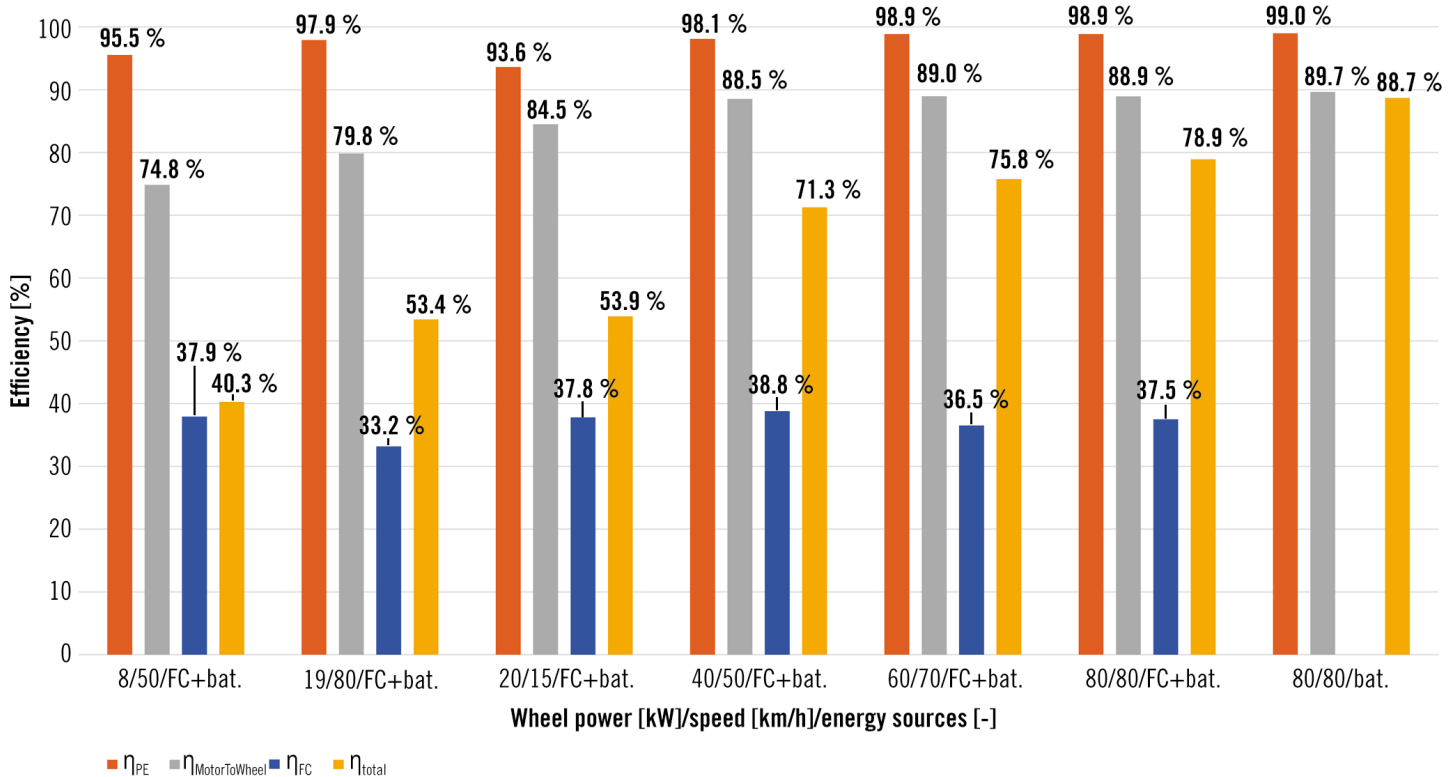


FIGURE 7 The influence of the fuel cell efficiency on the overall system is proportional to the share of energy supplied by the fuel cell in relation to the total energy (bat.= battery) © Gumpert

tric motor is load and speed dependent. Considering the losses, the efficiency of the drivetrain is at a familiar level for electric vehicles. This also applies to the efficiency of the power electronics with a consistently high efficiency of up to 99 %.

For further analysis of the new drive concept, an electric drive with battery and the fuel cell technology described previously was set up on a functional test bench, **FIGURE 8**. The measurements on this test bench are primarily used to analyze the fuel cell to support modeling and simulation and subsequently enable targeted further development. The measurement technology used was adopted from the test vehicle described above.

The efficiency of the RMFC was first analyzed in stationary operation at different loads. **FIGURE 9** (top) shows the measured efficiency of the fuel cell over the power output as a ratio to the maximum power. The optimum point is reached close to 50 % of the maximum output and decreases to 40 % at nominal output (equivalent to 75 % of the maximum output). For an efficient operation, this behavior must be considered in the control strategy.

Another research question concerned the starting behavior of the fuel cell. As the fuel cell system must first be heated to operating temperature, a cer-

tain amount of time passes before it is ready for operation. For the RMFC used here, this means a period of about 30 min until electrical energy is supplied and a further 9 min until stationary operation is reached, **FIGURE 9** (center). Integrating the energies up to the change in current direction at the fuel cell, the fuel cell system consumes 0.513 kWh of fuel energy and 0.439 kWh of electrical energy from the battery during the start-up process. The shorter the subsequent stationary operating phase of the vehicle, the more this energy consumption reduces the efficiency of the fuel cell and thus of the whole vehicle. A parameter variation was carried out to illustrate the influencing variables on the ratio of transient to stationary fuel cell efficiencies, **FIGURE 9** (bottom). In addition to the start-up energy, the start-up time and the electrical output of the fuel cell were varied. For the base scenario, 95 % of the stationary efficiency is achieved after 150 min. Improvements are mainly possible by reducing the required start-up energy, but also by increasing the electrical power of the fuel cell under identical conditions. This transient operating behavior must be addressed in the further development of the fuel cell to increase the actual efficiency and to expand the application range of this drive concept.

CONCLUSION AND OUTLOOK

This article provides an overview of methanol as a climate-neutral fuel and its use in commercial vehicles with reformed methanol fuel cells. Vehicles equipped with this technology first convert the methanol into hydrogen on board and then feed it into a HT-PEMFC. They also contain a traction battery whose energy content can be varied depending on the configuration of the overall system. The use of RMFCs in vehicles is particularly useful when their operating phases last over a longer period. This applies both to vehicles with high continuous loads as well as to vehicles with standstill phases and alternating loads. The potential of RMFC technology increases with higher vehicle weight and energy requirements. The technology is therefore particularly interesting for the transportation and heavy-duty sector.

Due to its advantages in terms of distribution, infrastructure and system energy densities, methanol can usefully complement conventional battery electric vehicle technologies. The development potential on the path to series maturity of RMFC drives lies mainly in the fields of further development of operating strategies, performance scaling and start-up performance.

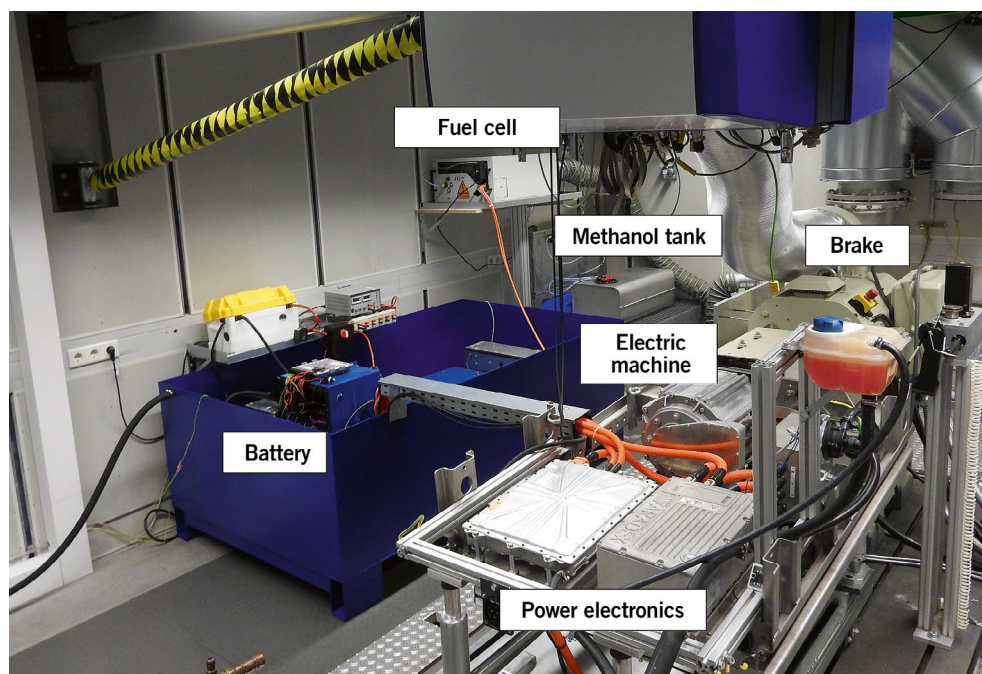


FIGURE 8 Test bench for measuring the transient operating behavior of the RMFC (© Gumpert)

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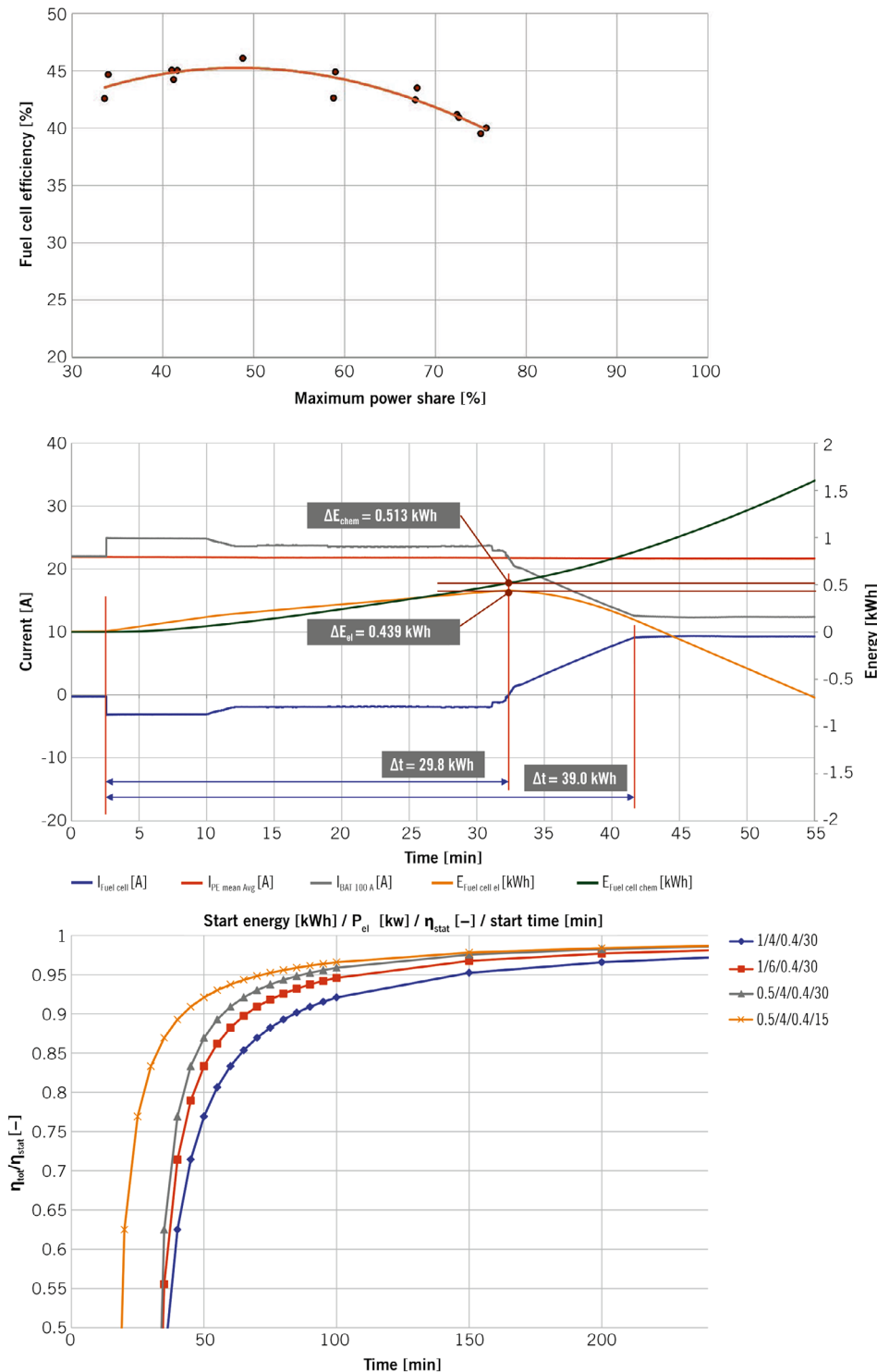


FIGURE 9 RMFC efficiency over load (top), RMFC cold start behavior (center) and RMFC efficiency considering the starting behavior (bottom) © Gumpert

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