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Fuel Cell Electric Tractor FCTRAC: Powertrain, Thermal System, Hydrogen Storage, and Performance

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In the FCTRAC project, a fuel cell electric tractor is developed based on the existing diesel vehicle STEYR 4130 Expert CVT. After the FCTRAC project is presented, the paper introduces the developed fuel cell electric powertrain architecture designed to deliver comparable working performance to the donor vehicle. The description of the thermal system focuses on the challenging heat dissipation of the fuel cell stack. The design of the 700-bar hydrogen storage system is discussed, considering vehicle framework conditions. Finally, the paper addresses the test bench validation of the FCTRAC powertrain. It confirms the simulative development approach and demonstrates operation comparable to the donor vehicle with 95 kW constant load at 35 °C ambient temperature without derating.

Keywords
Hydrogen, Fuel Cell Electric Powertrain, Agricultural Tractor, Thermal System, Hydrogen Storage System

The global efforts to limit climate change by reducing greenhouse gas emissions are defined by legally binding climate targets. The most relevant are the Paris Agreement (UNFCCC 2018) and, locally, the European Green Deal (European Commission 2019). These legislations influence the development of all key economic sectors. The economic sector mobility is one of the main drivers of climate change and must become sustainable to achieve the climate targets. The vast majority of CO_2 emissions results from mobility on land (IEA 2023a).

The Fit-for-55 legislative umbrella, among others, specifies emission targets for the mobile sector in the EU: From 2035, only cars or light commercial vehicles with zero-emission powertrains can be registered (European Parliament and Council 2023). Based on the current legislative status, these are exclusively battery electric or fuel cell electric vehicles that emit no CO_2 exhaust gas emissions. For heavy-duty vehicles, the Council of the EU adopted the regulation on reduction of CO_2 emissions by 90 % by 2040 compared to 2021 limits (European Council 2024). Off-road and non-road vehicles (like agricultural tractors) are still not restricted with or proposed for comparable strict EU-wide targets. However, as meeting the climate targets is legally binding, off-road and non-road mobility will face similar requirements in the future.

The spectrum of requirements for agricultural tractors is vast and the requirements are demanding. Figure 1 shows the timely mission distribution of a 110 kW tractor utilized at mixed farms of 50 – 200 ha size. Mixed farms are here defined as a mixture of crop farms and other types of farms whose individual contribution margin does not exceed 50 % (Eckstein 2017).

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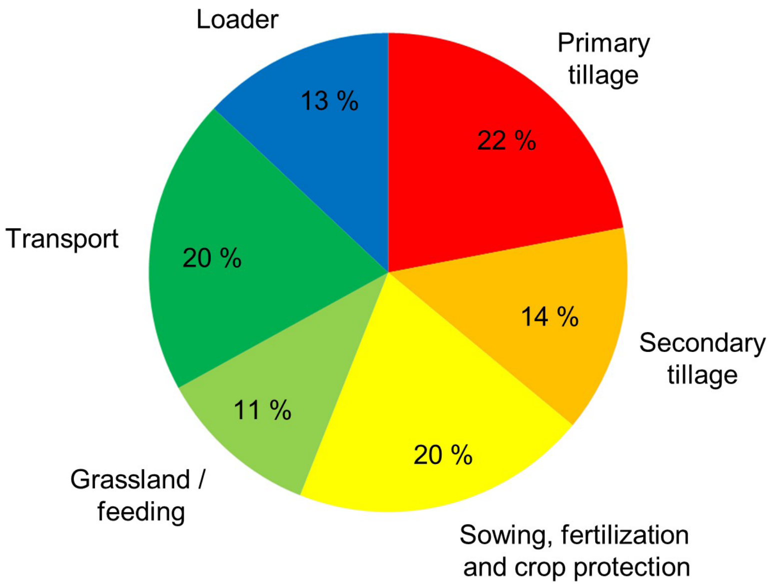

Figure 1: Average mission profile in percentage, vehicle class: 110 kW, farm size: 50 - 200 ha

Agricultural work very often takes place under difficult operating conditions. Primary and secondary tillage require tractors to operate at low speed and permanently high power, which demands a powerful propulsion system, thermal system, and sufficient energy on board to achieve autarchy. Considering sowing, fertilization, and crop protection, tractors need to have a good driver's field of view to avoid plant damage and be lightweight to reduce soil compaction. This requires a light and compact powertrain for good packaging characteristics and lightweight. At the same time, a high payload is essential for implements or loader tasks. For transport tasks, tractors must pull trailers in regular road traffic and achieve good drivability. Powertrains must, therefore, enable precise control for field work at low speeds but also allow high dynamics and speeds for road transport. The powertrain must be able to provide high performance at all speeds. Tractors are very flexible and, thus, are used not only in agriculture and forestry but also in the municipal sector, at airports, in mining, or at construction sites. Tractor powertrains must work reliably and persistently for all applications, considering harsh environmental conditions – like dust, dirt, or extreme temperatures.

Developing a zero-emission tractor is challenging and far more complex than developing a passenger car or truck due to the above mentioned requirements. Worldwide, manufacturers present zero-emission tractors in different technical stages: prototypes, small series, or series. Nevertheless, zero-emission tractors still do not meet all agricultural requirements, especially in the medium to high-power segment. Due to their low energy density, battery electric tractors have either little autarchy or high weights (Mocera et al. 2023, Scolaro et al. 2021), sometimes combined with poor visual axis (Eilbote 2022). Hydrogen storage systems for mobile applications and, thus, powertrains that aim at high autarchy, achieve significantly higher volumetric and gravimetric energy densities than comparable battery electric powertrains (Klell et al. 2018). A few fuel cell electric tractors have been developed. These prototypes are not commercially available. They aren't able to fully meet agricultural requirements or to achieve performances comparable to conventional diesel vehicles (Patrico 2012, Quick 2009). Luoyang Research Institute for Intelligent Agricultural Equipment Co., Ltd. (CHIAIC) and Luoyang advanced manufacturing industry R&D base of Tsinghua University's Tianjin Research

Institute for Advanced Equipment presented the ET504-H, an unmanned fuel cell electric demonstrator tractor (Hekkert 2020). The fuel cell and battery deliver a maximum power of 37 kW to the driveline. The HELIOS fuel cell electric tractor was developed in the course of the project H2Agrar by AGCO GmbH and partners (Breu 2023, Nöss et al. 2023). This prototype is based on a conventional diesel tractor and powered by a 100 kW fuel cell and a high-voltage battery. The hydrogen storage is placed on the cabin roof while high-voltage battery, fuel cell, or radiators are below the engine hood.

Project FCTRAC

In the FCTRAC project, a fuel cell electric tractor is developed from an existing diesel vehicle. This FCTRAC vehicle aims to fulfil the requirements of agriculture and to achieve comparable performances to a conventional-powered vehicle. The main development goals are a compact and robust design with a good driver's field of vision, continuous operation at maximum power (of the e-drive) with high ambient temperatures (35 °C) even at stationary applications, sufficient energy on board, and fast and local hydrogen refuelling. Because hydrogen infrastructure is not sufficiently available, especially in rural areas, the FCTRAC project provides the BioH2Modul for local and flexible hydrogen supply (Figure 2).

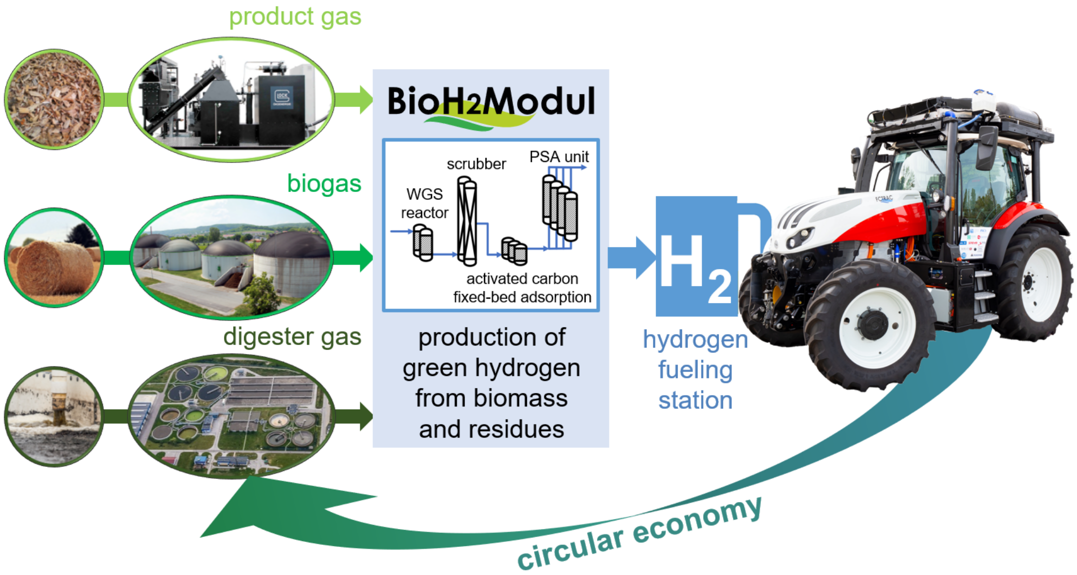

Figure 2: FCTRAC project concept

The BioH2Modul is developed to provide hydrogen from three feed gases typically available in rural areas: product gas from the gasification of wood chips, biogas, and digester gas. The hydrogen production capacity is 3 kg/h and meets ISO 14687. Further information on the BioH2Modul can be found in Gubin et al. (2023).

The Austrian Climate and Energy Fund funds the FCTRAC project. The Institute of Powertrains and Automotive Technology of TU Wien is the project coordinator. Several Austrian partners are involved: AVL List GmbH, CNH Industrial Österreich GmbH, Engineering Center Steyr GmbH & Co KG, GLOCK Technology GmbH, HyCentA Research GmbH, SoHaTex GmbH, and the Institute of Chemical, Environmental and Bioscience Engineering of TU Wien. The project started in 2020 and has a planned duration of four years.

Fuel Cell Electric Powertrain

The objective is to develop and build the fuel cell electric powertrain with comparable performance to the donor vehicle, a STEYR 4130 Expert CVT. This means a constant maximum power of 95 kW, which has to be delivered at ambient temperatures without derating, even at stationary applications. The development was not only performance-oriented, but also driven by packaging, weight balance, safety, and robustness/durability requirements. Figure 3 shows the resulting powertrain system architecture.

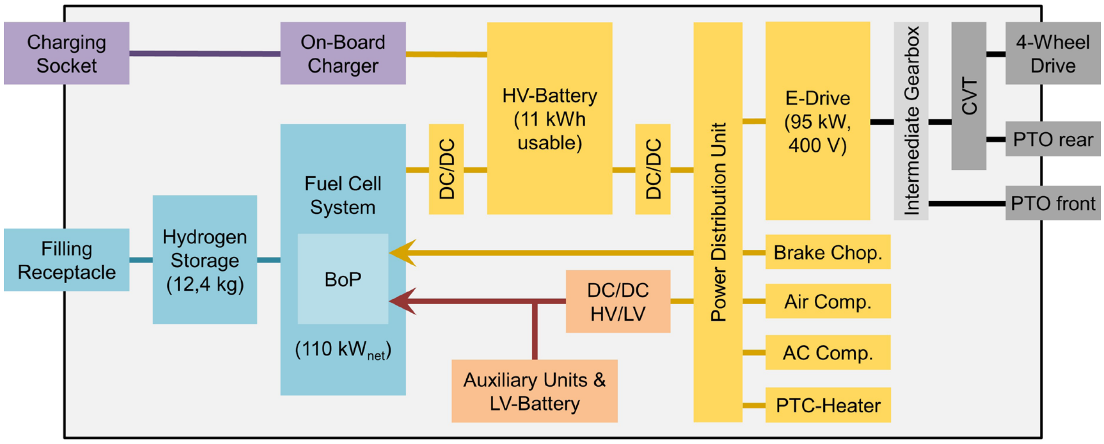

Figure 3: System architecture of FCTRAC powertrain

The primary energy provider is the proton-exchange membrane (PEM) fuel cell system (FC system) with 110 kW-net power. This electrochemical energy converter generates electrical power (DC) from high-purity hydrogen and ambient air, cleaned through an active carbon filter, releasing water vapor saturated air, condensation water, and negligible amounts of hydrogen into the environment via the exhaust. The FC system consists of the FC stack as the energy converter and the Balance of Plant (BoP) components that supply the FC stack. The FC system is supplied with hydrogen from the 700-bar high-pressure storage system. To increase durability, the applied automotive FC system is operated less dynamically with a limited power rate of 20 kW/s.

Therefore, a high-voltage lithium-ion battery (HVB) supports dynamics, enables electric-only operation, and powers the vehicle during startup and shutdown. The HVB has an NMC chemistry and 11 kWh of usable energy. It allows for a short time the maximum discharge power of 69 kW / charging power of 28 kW. The HVB has a nominal voltage of 260 V. A Type 2 charging interface and an on-board-charger allow external recharging of the HVB with one phase at 7 kW. FC system and HVB are serially coupled to the power distribution unit (PDU) by DC/DC-converters. The voltage of the PDU is fixed at 400-V-level due to consumers like e-drive, air conditioning compressor, and air compressor to supply the pneumatic system. Therefore, the load-depending voltage of the FC stack (approx. 360 - 560 V) has to be decreased to the HVB level and then increased to the PDU level. This solution results from the lack of suitable buck-boost converters.Via DC/DC-converters, the PDU powers the 12 V and 24 V low voltage networks and, thus, the electrical auxiliaries of the donor vehicle and the FC powertrain like fans, pumps, and electronic control units. The low-voltage auxiliary consumers have a maximum constant power of approx. 8 kW. More than half of this is provided to the fans. The e-drive (permanent-magnet synchronous motor) can constantly provide 95 kW and powers the donor vehicle's continuously variable transmission – CVT (for the 4-wheel drivetrain and rear power take-off (PTO)) and the front PTO, both via an intermediate gearbox. The intermediate gearbox (gear ratio four) matches the e-drive speed to the CVT.

Fuel Cell System and Cooling

To design the thermal system of an FC electric powertrain, a detailed understanding of the FC system and its cooling demand is necessary. In the case of the widely automotive applied PEM FC, the stack, built up by electrically connected cells in series, is continuously fed with gaseous high-purity hydrogen on the anode side and filtered ambient air on the cathode side with the pressure of approx. 1 - 4 bar. An electrically insulating electrolyte (polymer membrane) separates the cathode and anode sides. Hydrogen diffuses on the anode side towards the electrolyte and is oxidized by a catalyst to two protons and two electrons. The protons are transported through the electrolyte to the cathode. The electrons cannot pass and move through the outer electric circuit to the cathode, driven by the electric potential difference of the anode and cathode reactions. Hence, chemical energy is directly converted into electrical work (independent of the Carnot efficiency). At the cathode, water results from protons, electrons, and catalytically reduced oxygen from the air. The proton transport requires the electrolyte to be humidified by water without flooding the diffusion channels. This complex process requires operation temperatures of approximately 80 °C for state-of-the-art PEM FCs.

The efficiency of the FC stack is significantly dependent on the load, next to factors like operation temperature, humidity of the electrolyte, and ageing. Ageing (also called degradation) reduces FC stack efficiency and voltage. It appears due to various reasons like too high temperature and dynamics, insufficient hydrogen supply and humidity, or hydrogen/air containing harmful gases like CO or sulphur compounds. Due to inherent losses, the FC stack efficiency decreases with increasing electrical power (Figure 4).

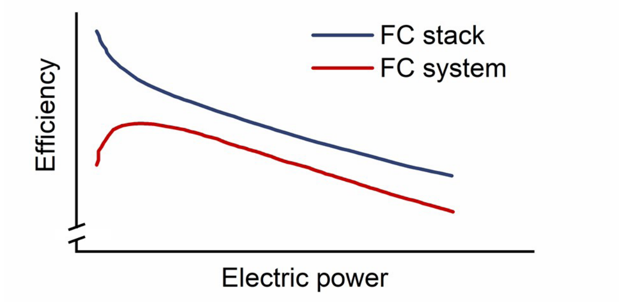

Figure 4: PEM fuel cell efficiency: stack and system (derived from Hofmann 2023)

The BoP supply the stack with media such as hydrogen and humidified ambient air; it includes the sensors, actors, and the control- and thermal system. The primary BoP power consumers are the air compressor and the hydrogen recirculation pump. The relative fraction of BoP power demand decreases with increasing stack power. The stack efficiency and the corresponding BoP power demand determine the FC system efficiency. At low loads, the BoP consumes a significant part of the stack power. At high loads, the stack efficiency is low due to the inherent losses. Consequently, a PEM FC system reaches maximum efficiency in the medium power range (Figure 4).

Uniform stack and cell conditions, like hydrogen and temperature distribution at the electrolyte, are essential to reduce ageing and achieve high efficiencies. Every cell of a FC stack is directly liquid-cooled to achieve a uniform temperature. Because the cells are life parts (electrically conducted), low conducting coolant (approx. <10 µS/cm), deionized components, low ionic-emission materials, and the integration of an ion exchanger are necessary for the stack coolant circuit.

The FC brings two challenges to developing the thermal system in mobile applications. First, the FC system almost only dissipates the waste heat through the cooling circuit. Heat dissipation via exhaust gases is insignificant. Figure 5 compares the energy flows of a PEM FC system and an internal combustion engine (ICE) with equivalent power at a high load.

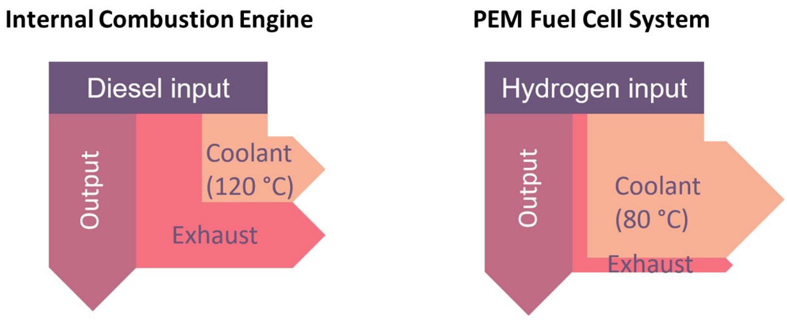

Figure 5: Energy flows of an internal combustion engine and a PEM FC system at high load

ICEs and PEM FC systems have similar efficiencies at high loads (Kufferath et al. 2021 and Pietruck et al. 2021). The ICE dissipates the heat in similar shares to the thermal system and the exhaust, whereas the FC system dissipates almost exclusively to the thermal system. Especially at high loads, with a reduced FC stack efficiency, very high thermal loads have to be dissipated. This leads to a significantly increased load onto the thermal system compared to a conventional ICE. A detailed comparison that discusses many aspects of PEM FC and ICEs is available in e-mobil BW (2021).

Second, the operation condition of the PEM FC stack demands a coolant temperature of approximately 80 °C (Hoogers 2003). This results in a reduced temperature difference to the ambient air compared to a conventional ICE with a maximum coolant temperature of 120 °C (Van Basshuysen et al. 2017). Thermal transmittance, surface area, and temperature difference of liquid and gas-side define a heat exchanger's heat transfer. Therefore, a reduced temperature difference results in increased heat exchanger surfaces. The heat transfer coefficient for gasses is generally one or two orders of magnitude lower than that for liquids. Hence, the heat transfer surface on the gas side must be significantly larger than on the liquid side. However, the limitation of the heat dissipation of liquid-air thermal systems is generally on the air side (Shah et al. 2003).

Agricultural applications like tillage or bailing have high fouling potential. Therefore, agricultural heat exchanger fins have reduced compactness, spray cooling, which is under consideration for heavy-duty applications (Rathberger et al. 2023), cannot be applied, and cleaning strategies like reversed fan rotation are necessary.

Considering the increased thermal load at a reduced temperature difference and the fouling potential, large heat exchanger areas and high fan powers are necessary to guarantee sufficient heat dissipation, especially for challenging tractor applications such as constantly high loads when stationary.

Thermal System Architecture

Tractors often operate at low speeds, high loads, and high ambient temperatures. Therefore, the thermal system of FCTRAC is designed for stationary operation with maximum power at ambient temperatures up to 35 °C without derating. This boundary selection allows FCTRAC to operate at usual Austrian (Central European) ambient temperatures without thermal restrictions.

The development of the thermal system is conducted in the KULI simulation environment, coupled with the vehicle longitudinal dynamics model in Matlab Simulink. The models are parameterized with test bench measurement data, literature values, and test cycles like DLG PowerMix (Gubin et al. 2023). Figure 6 shows the developed architecture of the thermal system.

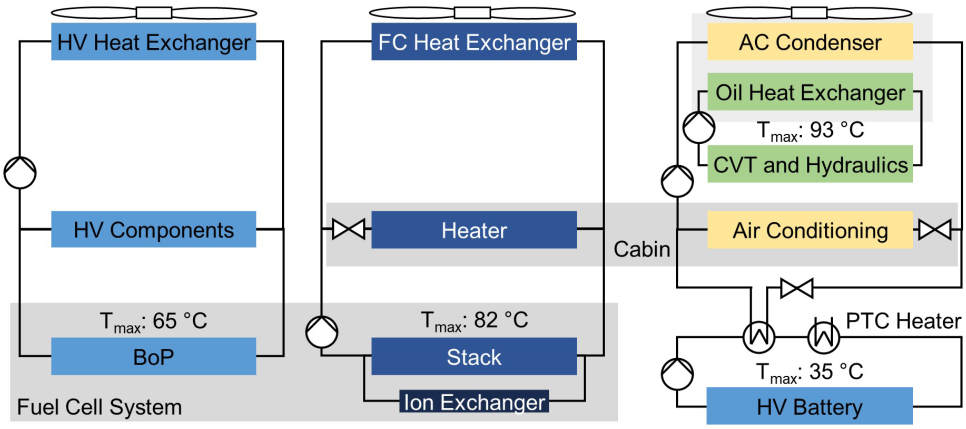

Figure 6: Architecture of FCTRAC thermal system

The FCTRAC thermal system consists of five coolant circuits. The components of the FC are divided into two cooling circuits. The directly cooled components of the FC stack (live parts) are integrated into a separate cooling circuit with low-conducting coolant and an ion exchanger. The FC stack operating temperature should be above 30 °C and must not exceed 82 °C to provide ideal operating conditions for the electrolyte avoiding condensation or evaporation of water. The thermal simulation that considers the ageing effects of the FC stack and, thus, end-of-life efficiencies, predicts a maximum thermal load of 168 kW. This results in a heat exchanger volume 2.3 times larger than the one of the diesel donor vehicle's ICE and 3.15 kW of installed fan power. The heat exchanger does not fit below the engine hood and is placed on a roof structure above the cabin (Mayer et al. 2023). The FC stack waste heat is the largest thermal load and has the highest cooling temperature level, apart from the oil circuit. Therefore, it is applied for cabin heating. The BoP components of the FC and a total of 11 HV components of the powertrain are distributed in the HV cooling circuit to five parallel branches according to packaging, pressure drop, and flow rates. The circuit's maximum temperature is 65 °C. The HV heat exchanger dissipates up to 20 kW of waste heat with 1.15 kW fan power.

Due to the packaging, the AC (air conditioning) condenser and the oil heat exchanger are in series on the air side and supplied by a 0.6 kW fan. The oil heat exchanger dissipates up to 12 kW from the CVT and the hydraulic system. Next to the driver cabin, the HVB is cooled by the AC system. The AC condenser dissipates 10 kW, to which the highly efficient HVB contributes only a maximum of 2 kW. A 5 kW PTC heater in the HVB circuit allows the HVB cells to operate in a performance-optimal temperature window. In a worst-case scenario, the FCTRAC thermal system dissipates more than 210 kW of waste heat.

Compressed 700-bar hydrogen storage system

Current hydrogen storage systems do not reach the volumetric and gravimetric energy storage density of conventional liquid fuel tank systems (Schwaderlapp et al. 2022, Klell et al. 2018). However, compared to a state-of-the-art automotive HVB-pack, the gravimetric energy density is significant higher (Klell et al. 2018). Hydrogen is currently stored either liquid or gaseous in vehicles.

Generally, liquid storage at cryogenic temperatures (-253 °C) achieves a higher energy density than gaseous storage. Since it is impossible to thermally insulate the hydrogen tanks entirely, after some days approx. 5 % of the hydrogen mass evaporates per day in current cryogenic storage systems, depending on the ambient conditions (Hergott et al. 2023, Stepan et al. 2023). Therefore, cryogenic storage systems are ideal for vehicles with constant power demand that can consume the evaporated hydrogen (e.g., refrigerated trucks). Currently, there are almost no cryogenic storage systems on the market. The corresponding refuelling station infrastructure is non-existent, except for very few prototypes.

High-pressure storage allows the permanent, technically tight storage of gaseous hydrogen. Storage system pressures are 350 bar or 700 bar, with higher pressures allowing increased volumetric storage densities. To reduce weight, in the automotive sector, type 4 tanks made from plastic and surrounded by carbon fibres are often used instead of steel tanks (type 1) or mixed forms (type 2 and type 3). Filling the storage system at a hydrogen refuelling station takes about the same time as filling a diesel vehicle. The refuelling station infrastructure is currently being set up in most industrial countries. For example, there are currently around 250 publicly accessible 700-bar hydrogen refuelling stations in Europe (IEA 2023b), around 90 in Germany, and fewer than 10 in Austria (H2Mobility 2024).

When designing the hydrogen storage system, the overall vehicle concept must be considered. On the one hand, it is important to maximize the amount of energy stored on board to achieve a high level of autonomy. On the other hand, compact vehicle packaging with good driver's field of view and low weight must be achieved. A 700-bar hydrogen storage system with type 4 tanks was developed for the FCTRAC vehicle. This kind of storage system is state-of-the-art in passenger cars and heavy-duty applications.

The storage system is placed on a roof structure together with the fuel cell heat exchanger above the cabin (Mayer et al. 2023). The four type 4 pressure tanks (diameter 410 mm, length 1050 mm) with a storage volume of 312 L and an empty weight of 236 kg enable the storage of 12.4 kg of hydrogen. This corresponds to 413 kWh of energy and an energetic diesel equivalent of approx. 42 L. The hydrogen storage system is designed for refuelling at public hydrogen refuelling stations next to the BioH2Modul. It meets the SAE J2601 requirements.

The FC system is supplied with a constant hydrogen pressure level of approx. 10 bar via stainless steel lines and a pressure regulator. The filling level of the storage system can be detected via high-pressure sensors. The hydrogen storage system also has various safety systems, including hydrogen sensors and thermal fuses on the tank valves.

Testbench Validation of Powertrain and Thermal System

Aside from the simulation environment, development, testing, and additional validation of the hydrogen storage, powertrain, and thermal system are conducted through test bench measurements at the Institute of Powertrains and Automotive Technology at TU Wien. Figure 7 shows the test setup.

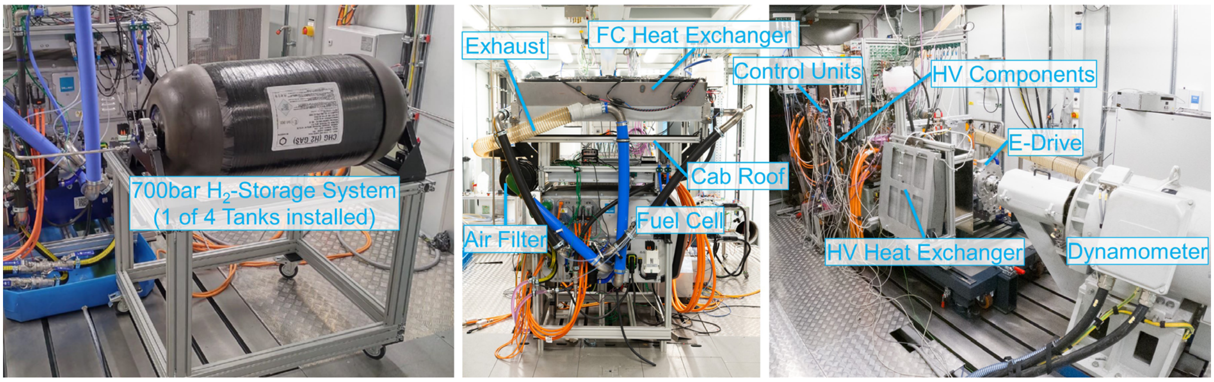

Figure 7: Test bench setup of hydrogen storage system, powertrain, and thermal system at IFA, TU Wien

The powertrain (Figure 3) and the thermal system (Figure 6) are assembled entirely similarly to the vehicle setup (except for the AC and hydraulic cooling circuits). The 12 V and 24 V low-voltage networks of the powertrain system are set up. Other low-voltage components – mostly of the donor vehicle – are represented by battery emulators. Vehicle components with significant influence on the airflow, like cabin roof or cover grille, are integrated. A single-tank hydrogen storage system is set up for the test bench tests, corresponding to the vehicle system in terms of components, function, and safety. The system can be continuously supplied via the test bench hydrogen supply or filled at a 700-bar hydrogen refuelling station. The powertrain control and operating strategy, including energy and thermal management as well as the monitoring and safety functions, are provided by two electronic control units with partly redundant functions (Hybrid Control Unit and Safety Control Unit). Software development and validation are conducted at TU Wien.

Test bench conditioning allows test operation at ambient temperatures from −7 to +45 °C. The highly dynamic dynamometer maps the load of the CVT. Next to stationary and dynamic tests, typical agricultural load cycles like the DLG PowerMix are also applied (Back et al. 2011). Figure 8 shows the selected results of a cultivator cycle (Z1G, 100 %) at 35 °C ambient temperature.

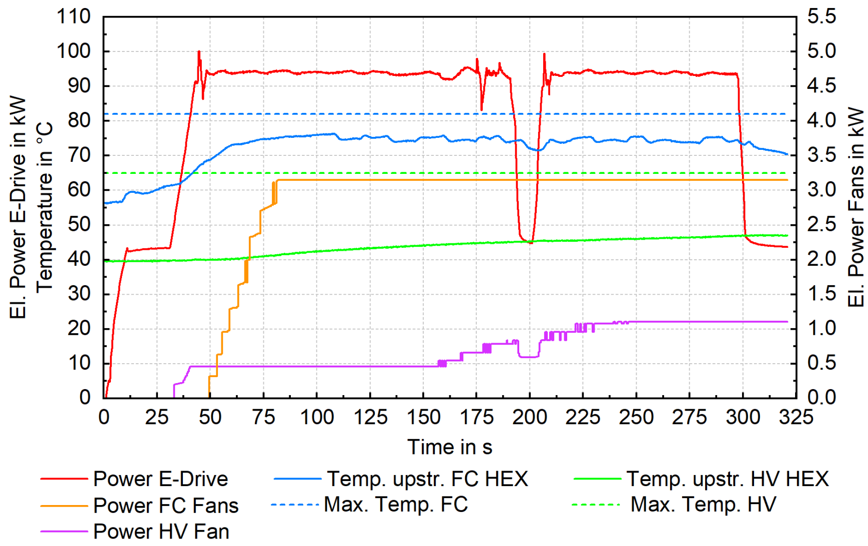

Figure 8: Test bench measurement: cultivator cycle (Z1G, 100 %) at 35 °C ambient temperature

The thermal system enables a constant load of 95 kW without derating at 35 °C ambient temperature. The FC system is the primary energy provider. The HVB supports the transient operation with high efficiency and, therefore, neglectable waste heat. The temperatures of the FC stack and HV components remain below the defined limits of 82 °C and 65 °C, respectively. The temperature of the HVB circuit (not shown) remains constant at approx. 35 °C. The total electric fan power reaches 4.25 kW at a maximum. Derating appears at further increased ambient temperatures. A measurement at 45 °C ambient temperature shows approx. 15 % derating at a constant load.

The test bench measurements show that the developed powertrain system can deliver maximum performance at high ambient temperatures, achieving a power comparable to the diesel doner vehicle. Dynamic operation corresponding to road driving is also reproduced on the test bench. Here, driving dynamics comparable to those of the diesel vehicle are achieved.

Conclusions

This paper presents the fuel cell electric powertrain for the agricultural tractor FCTRAC, focusing on thermal system, hydrogen storage, and performance. FCTRAC is based on a diesel donor vehicle, a STEYR 4130 Expert CVT, with a constant power of 95 kW. The primary energy provider of the FCTRAC is the proton-exchange membrane fuel cell system with 110 kW-net power. A 11 kWh (usable) high-voltage lithium-ion battery supports dynamics, enables electric-only operation, and powers the vehicle during startup and shutdown. The e-drive can constantly provide 95 kW at 400 V. It powers the donor vehicle's CVT. Compared to an internal combustion engine, the fuel cell leads to an increased amount of waste heat at high loads, a reduced temperature difference to the environment, and, finally, a heat exchanger volume 2.3 times larger than the heat exchanger of the donor vehicle's internal combustion engine. The FCTRAC thermal system consists of five coolant circuits with different temperature levels, mass flow rates, and insulation requirements. A 700-bar hydrogen storage system with 12.4 kg of hydrogen capacity is developed and placed on a roof structure above the cabin together with the fuel cell heat exchanger. 12.4 kg of hydrogen corresponds to 413 kWh of energy and an energetic diesel equivalent of approx. 42 L. The hydrogen storage system is designed for refuelling at public hydrogen refuelling stations next to the BioH2Modul, which provides hydrogen locally at the place of tractor operation. Development, testing, and additional validation of hydrogen storage, powertrain, and thermal systems are conducted through test bench measurements at the Institute of Powertrains and Automotive Technology at TU Wien. Next to stationary and dynamic tests, typical agricultural load cycles like the DLG PowerMix are applied. The thermal system enables a constant load of 95 kW without derating at 35 °C ambient temperature.

Based on the presented work, the vehicle operation strategy is developed. Varlese et al. (2024) show the development of a robust machine-learning-based energy management strategy utilizing statistical analysis of real-farming scenarios and considering efficiency and durability. After the successful vehicle registration (single type approval), the next step in the FCTRAC project is the demonstration phase, where the FCTRAC vehicle will perform demanding everyday agricultural work, powered with sustainable hydrogen from the BioH2Modul. The FCTRAC vehicle is discussed with a focus on vehicle design and architecture by Mayer et al. (2024).

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