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Fuel Cell Electric Tractor FCTRAC: Vehicle Design and Architecture

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Sustainable agriculture demands alternatives to fossil fuels. The FCTRAC project adopts a circular-economy approach, focusing on zero-emission solutions. A fuel-cell-powered electric tractor with 95 kW, derived from a diesel model (STEYR 4130 Expert CVT) was developed. It integrates key components such as a 700-bar compressed hydrogen storage system, fuel cell, electric drive, and high-voltage battery. Leveraging existing driveline technology minimizes costs and development risks of the project. The vehicle achieves comparable performance, optimal visibility, as well as single-type approval for on-road usage. This paper details the vehicle architecture, design, and key integration challenges, advancing the development of zero-emission agricultural machinery.

Keywords
Fuel cell, electrification, hydrogen, agricultural tractor, zero-emission, decarbonization

Achieving the global climate protection objectives outlined in the 2015 Paris Agreement, as adopted by the United Nations Framework Convention on Climate Change (UNFCCC), requires concerted efforts and comprehensive measures (UNFCCC 2018). The legally binding agreement aims to limit the increase in global average temperature to well below 2 °C above pre-industrial levels, with efforts to limit it to 1.5 °C (UNFCCC 2018). Locally, within the European Union (EU), the European Green Deal, adopted in 2020, plays a crucial role in achieving these goals (European Commission 2019). Member states commit to achieving climate neutrality in reporting by 2050, with substantial reductions in greenhouse gas (GHG) emissions by 2030, aiming for at least 50 % and towards 55 % compared to the GHG levels in 1990 (European Commission 2019).

In the context of GHG emissions, heavy-duty motor vehicles account for more than 6 % of the total EU GHG emissions and are responsible for over 25 % of emissions within the EU road transport sector. The EU proposes ambitious targets to reduce CO_2 emissions from new-registered heavy-duty-motor vehicles by 90 % by 2040 compared to the reporting period of 2019. However, type- and non-type-approved off-road vehicles, such as forestry and agricultural vehicles, currently have no comparable prescribed CO_2 emission targets. (European Commission 2023a)

The agricultural sector significantly contributes to the total net EU GHG emissions, accounting for approximately 13.2 % of the total in 2021, excluding the emissions for energy used for agricultural production as it relates to the energy sector (European Commission 2023b). Emissions from agricultural machinery caused by fossil-fuel combustion account for approximately 1 % of total EU GHG emissions (CEMA 2022). To address these emissions, the Committee for European Construction Equipment (CECE) and the Committee for European Agricultural Machinery Association (CEMA) have developed strategies focusing on machine efficiency, process efficiency, operation efficiency, and the use of alternative energy sources (CEMA 2022).

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Alternative fuels, such as compressed or liquefied natural gas (CNG/LNG) based on biomethane, biofuels, such as Hydrotreated Vegetable Oil (HVO) and biodiesel (FAME – Fatty Acid Methyl Esters), and synthetic fuels based on hydrogen, along with electrification, offer possibilities for reducing CO_2 emissions from agricultural and forestry machinery. In addition, battery electric or fuel cell electric powertrains provide a further step towards zero-emission. However, implementing these solutions poses challenges related to vehicle design, infrastructure, and usage, necessitating further research and development efforts (Pretsch 2020).

Examples of Alternative Powertrains for Agricultural Tractors

Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG)

In 2021, New Holland launched the serial production of the CNG-propelled tractor T6.180 Methane Power, providing a rated engine power of 145 hp and a maximum engine power of 175 hp, equivalent to its diesel counterpart (CNH Industrial N.V. 2021). This vehicle features an on-board storage system of 185 liters, equivalent to 32 kg of CNG, with the option to expand it with an additional 270-liters (47 kg) comprehensive front-mounted storage system (CNH Industrial N.V. 2021). A larger model, the T7.270 Methane Power, with a rated engine power of 240 hp and a maximum engine power of 270 hp, equipped with a 1,265-liter storage system equivalent to 219 kg of CNG, was presented for serial production launch in 2024 (CNH Industrial N.V. 2023). Additionally, New Holland presented a prototype of the T7.270 Methane Power tractor in 2022, featuring a temperature-controlled LNG storage system with more than doubled fuel capacity to extend runtime compared to the CNG version (CNH Industrial N.V. 2022a).

Synthetic Fuels – Hydrogen Combustion

The company Blue Fuel Solutions unveiled the H2 Dual Power in 2020, a retrofit solution for a New Holland T5.140 tractor, combining diesel with hydrogen as a dual-fuel configuration (FuelCells-Works 2020). This tractor, with a rated engine power of 130 hp, is equipped with a 470-liter storage system on the roof, containing 11.5 kg of compressed hydrogen at 350 bar (FuelCellsWorks 2020).

JCB presented a mobile hydrogen refueler in 2022, based on a JCB Fastrac 4220 tractor, equipped with a hydrogen internal combustion engine to refill their fleet of hydrogen-powered prototype vehicles directly on-site (Koerhuis 2022).

Electrification – Hybrid

John Deere launched an electro-mechanical hybrid powertrain for their 8R 410 Series tractors in 2023, featuring a stepless variable transmission with two electric machines capable of generating up to 100 kW of electric power to enhance traction performance (Duppong et al. 2019, Deere & Company 2022). Joskin presented a slurry tanker with two electrified axles to increase the traction of the tractor-trailer combination (Duppong et al. 2019).

STEYR Tractor presented the STEYR Hybrid CVT tractor prototype in 2023. Based on the in-2019-presented STEYR Konzept, the prototype provides a maximal power of up to 260 hp and incorporates a parallel hybrid system with two electric machines operating in motor and generator modes (CNH Industrial N.V. 2019, CNH Industrial Österreich GmbH 2023). The tractor based on a STEYR 6175 Impuls CVT includes the combination of a hydro-mechanical continuously variable transmission (CVT) and a hybrid module on the front axle with up to 75 kW and independent wheel suspension (CNH Industrial Österreich GmbH 2023).

Tadus showcased the Tadus Tractor prototype in 2023, featuring a serial-hybrid configuration with electric motors on both front and rear axles, totaling 100 kW of power, and additional electric motors for the hydraulic pump and rear power take-off (PTO) (Böhrnsen 2023).

Electrification – Full Battery Electric

Fendt unveiled the Fendt e100 prototype in 2017, a battery electric tractor with 50 kW power output and a 650 V lithium-ion high-voltage battery (HVB) with a capacity of 100 kWh and a runtime up to five hours (AGCO GmbH 2017, Breu and Pichlmaier 2017). A narrow-track version, the e107 V, based on the Fendt 200 V series, is planned for limited launch in 2024 (Karsten 2023).

CNH introduced the New Holland T4 Electric Power prototype in 2022, followed by the launch together with the Case IH Farmall 75C Electric tractor in 2023 (CNH Industrial N.V. 2022b, CNH Industrial America LLC 2023). These retrofit utility tractors feature a rated power of 55 kW, one electric motor, a carry-over transmission from the internal combustion engine (ICE) model, a 95 kWh usable HVB capacity, and fast-charging (CNH Industrial America LLC 2023).

Türk Traktör presented the New Holland T3 Electric Power in 2024, featuring a maximum power of 75 kW, an 800-V architecture, a 75 kWh HVB, and two electric motors providing power for traction as well as the hydraulic system together with the rear PTO (Van Hattum 2024).

Monarch Tractor initiated production of their MK-V specialty tractor in 2022, featuring one electric motor providing continuous power of 30 kW and up to 55 kW for short periods, as well as driver-assist and driver-optional features (Monarch Tractor 2022).

Further prototypes in the compact/utility segment include the TUMtrac from the Technical University of Munich and the ONOX tractor from Raumideen (TUM 2023, Smits 2023).

John Deere introduced the SESAM prototype in 2016, based on their 6R Series, featuring a 130 kWh HVB installed under the hood, supplying power to two 150 kW electric motors (Lambert 2016). One motor powered the powertrain, while the other was dedicated to the rear PTO, enabling a claimed operating time of four hours in mixed operations (Lambert 2016). In 2022, John Deere unveiled the successor prototype SESAM2, also based on the 6R chassis, providing an increased HVB capacity of 1,000 kWh (Profi 2022). Capable of providing 500 kW to the powertrain and 1,000 kW to external electric machines, this prototype offered a runtime of up to ten hours at 80 % motor load with a fully charged HVB. Due to space constraints imposed by the HVB, it featured a detachable cabin and could be manually or automatically controlled, with or without the cabin (Profi 2022).

Agromec introduced the Agromec 700 Vario prototype in 2023, a retrofit solution based on the Fendt 720 Vario, featuring an 800-V architecture with up to 150 kW power and an installed HVB capacity of 70 kWh (Profi 2023). The available HVB capacity can be increased by a 140 kWh swappable HVB mounted in the front hydraulic power lift, adding a weight of around 2,000 kg (Profi 2023).

Electrification – Fuel Cell Electric

In 1959, Allis-Chalmers showcased the world's first fuel cell tractor powered by a stack of 1,008 alkali cells, providing 15 kW of power (Wendel 1988).

New Holland introduced the NH2 prototype in 2009, featuring a 50 kW fuel cell, and two electric motors for traction and auxiliary functions (Padfield 2009). The NH2, based on a New Holland T6000 tractor, included a 350-bar hydrogen storage tank under the hood, offering a runtime of 1.5 to 2 hours and was built without HVB (Padfield 2009, Deter 2011). A successor to the NH2, based on a New

Holland T6.140 tractor, was unveiled in 2011, equipped with a 100 kW fuel cell system (FCS), a three-gear CVT, and a 12 kWh HVB (Deter 2011). Ten 350-bar hydrogen tanks mounted on the vehicle's sides provided 8.2 kg of hydrogen. The cooling system was installed on the roof as well as behind the cabin on each side (Deter 2011).

E-Ox Tractors, formerly H2Trac, sold a prototype of a fuel cell tractor in 2021, based on their diesel-electric tractor EOX-175, featuring adjustable track width (Future Farming 2021).

As part of the funded joint research project H2Agrar in Lower Saxony/Germany, Fendt presented the Helios prototype in 2023 (AGCO GmbH 2023). This retrofit solution, based on the Fendt 700 Vario Gen6 Series, features a CVT driven by a 100 kW electric motor powered by a 25 kWh HVB and a 100 kW polymer electrolyte membrane (PEM) fuel cell (Nöss and Weller 2023). Hydrogen for the fuel cell is supplied through five hydrogen tanks with a capacity of 4.2 kg each at 700 bar pressure. Retaining components such as the cabin frame, CVT, hydraulics, PTO, brake, and steering system from the donor vehicle, modifications included replacing components directly attached to the ICE with electric counterparts. Additionally, the HVB within the 700-V electrical architecture can be charged via a 22 kW AC on-board charger (OBC). Heating for the cabin is provided by a 6 kW PTC (positive temperature coefficient) heater installed in the airflow of the climatization box under the driver's seat. Up to 15 kW of power can be fed back to the system by recuperation. A braking resistor with a peak power of 50 kW cuts off voltage peaks in the high-voltage (HV) system (Nöss and Weller 2023).

The above examples show the development of concepts and prototypes of tractors to series vehicles with alternative powertrains, including zero-emission options. However, only a few are available as series vehicles, particularly in the battery electric category, and none in the small tractor segment and above with medium to high power demand. Battery electric models in this segment are not suitable due to their low energy density with either low fuel autonomy or high weights and disadvantages due to soil compaction as well as charging time (Scolaro et al. 2021, Profi 2022, Profi 2023). In theory, fuel cell electric powertrains achieve higher volumetric and gravimetric energy densities, but the prototype examples either don't achieve comparable performance with conventional diesel tractors or don't fully meet agricultural requirements like versatility, fuel autonomy, and soil compaction (Moriarty and Honnery 2019, Scolaro et al. 2021). Moreover, cooling the fuel cell is challenging due to the low operating temperature compared to the ambient temperature (e-mobil BW GmbH 2022). Further significant challenges arise from the lack of fueling infrastructure on-farm and in-field, and fuel production in rural areas (Sandaka and Kumar 2023). Addressing these challenges is crucial to achieving the climate targets and fostering a circular economy approach in agriculture.

Project FCTRAC

The FCTRAC project "FCTRAC – fuel cell tractor fuelled with biogenic hydrogen" started in 2020, focusing on retrofitting an existing diesel tractor to develop a fuel cell electric tractor over a four-year period. It aims to fulfill agricultural requirements while achieving performance comparable with conventional tractors. Key goals include designing a compact, robust system capable of continuous operation at maximum power, even in high ambient temperatures, and ensuring sufficient on-board energy storage.

To overcome hydrogen infrastructure limitations, especially in rural areas, the project introduces the BioH2Modul for local and flexible hydrogen supply, using feed gases like product gas from gasification of wood chips, biogas, and digester gas to produce high-purity hydrogen meeting ISO 14687 standards at a rate of 3 kg/h (Gubin et al. 2023). Funded by the Austrian Climate and Energy Fund and coordinated by the Institute of Powertrains and Automotive Technology of TU Wien, the project involves Austrian partners 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.

Selection of the Donor Vehicle

The selection of the donor vehicle for the FCTRAC project was guided by both technological and market-specific considerations. Primarily, current small and medium sized tractors with a power rating of around 100 kW were deemed suitable, given their architecture that segregates the engine and transmission control units, enabling better integration of the new powertrain components. Despite the relatively lower efficiency, the preference for a CVT aimed to mitigate risks associated with the prototype development. Additionally, the chosen vehicle needed to embody versatility and representativeness of the project location in Austria. Consequently, the STEYR Expert platform with a market share of approximately 21 % in 2023 within the STEYR brand in Austria and particularly the STEYR 4130 Expert CVT was selected. The technical specifications of the selected donor vehicle are shown in Table 1.

Table 1: Technical data of the selected donor vehicle STEYR 4130 Expert CVT (model year 2020)

Rated engine power (acc. to ECE R120) in kW	96
Maximum engine power (acc. to ECE R120) in kW	103
Maximum engine torque in Nm	630, at 1,300 rpm
Fuel tank capacity – diesel in liters	180
Fuel tank capacity – diesel exhaust fluid (AdBlue) in liters	19
Design speed in kph	40
PTO standard speed in rpm (shaft)	540 / 1,000 / 540E at 1,969 / 1,893 / 1,546 rpm (engine)
Front PTO standard speed in rpm (shaft)	1,000, at 1,895 rpm (engine)
Maximum hydraulic pump flow rate in liters/min	110, at system pressure of 200 bar
Maximum lift capacity front / rear in kg	2,300 / 5,600
Maximum tire size front / rear	480/65 R28 / 600/65 R38
Weight in selected configuration in kg	6,080
Weight in selected configuration without front loader readiness in kg	5,990
Permitted gross vehicle weight in kg	8,800

Source: Steyr-Traktoren 2023

The Stage V ICE installed in the selected vehicle delivers a rated power of 96 kW. The donor vehicle has a wheelbase of 2,490 mm and the selected configuration includes front hydraulic power lift (HPL), front PTO, suspended cabin, suspended front axle, pneumatic trailer brake system, and front loader readiness, resulting in a weight of 6,080 kg.

Conversion of the Donor Vehicle into FCTRAC

When converting a conventional internal combustion engine vehicle (ICEV) into a fuel cell electric vehicle (FCEV) powered by hydrogen, several subsystems undergo elimination or conversion. Figure 1 provides a generalized overview of this conversion process as applied to the FCTRAC vehicle. In the FCEV, the fuel tank of the ICEV is replaced by a compressed hydrogen storage system (CHSS) and an HVB. The energy released by diesel combustion in the ICEV is converted into mechanical work. In the FCEV, an FCS transforms the chemical energy of hydrogen into electrical energy, subsequently utilized by an electric drive (ED) to generate mechanical work.

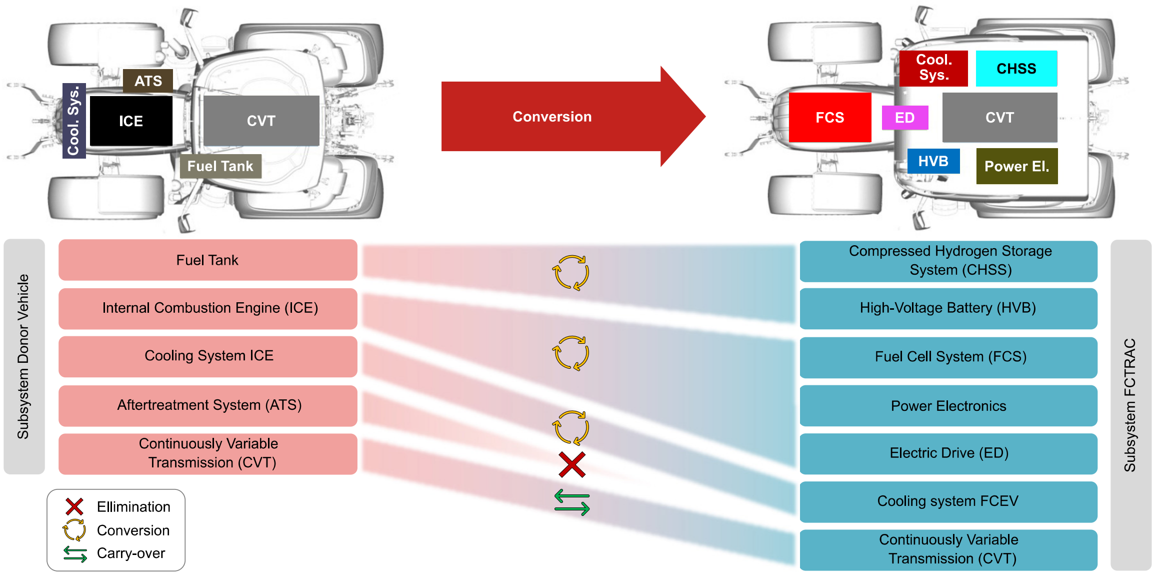

Figure 1: Chosen approach to convert the donor vehicle with an ICE into the fuel cell electric tractor FCTRAC

In the FCEV, the ICE cooling system is substituted by a cooling system that serves the FCS, ED, power electronics, and HVB. The absence of exhaust gases like CO_2, methane, or nitrous oxide from the FCS, which emits hot water vapor, eliminates the need for a complex exhaust gas aftertreatment system (ATS) compared to the ICEV. In the FCTRAC vehicle, the CVT remains unchanged as it is a load-bearing structural element and drives hydraulic pumps. The design and development of the powertrain and vehicle including the system architecture were supported by DLG-PowerMix cycles (Back et al. 2011), the 1D longitudinal dynamics model of the donor vehicle, component topology, and previous tractor development experience. Additionally, seven key performance indicators (KPIs) were established for the prototype vehicle at the project start, as illustrated in Figure 2.

These KPIs include: achieving comparable performance to the diesel equivalent with a rated power of 95 kW and a runtime of up to approximately four hours when operating at about 50 % of its rated power, good driver´s field of vision and functionality with front PTO and HPL, balance between weight and payload with the same gross vehicle weight (within the specified framework conditions), ensuring accessibility to components for servicing or maintenance, compact vehicle dimensions with maximum wheelbase of 2,700 mm, and enabling homologation (single-type approval) of the prototype vehicle for public road traffic.

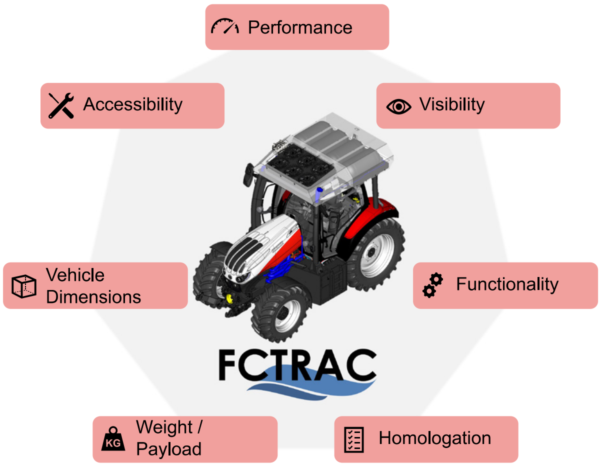

Figure 2: Main key performance indicators for the development of the FCTRAC vehicle

Electrical System Architecture and Main Components

The chosen electrical system architecture, detailed in Figure 3, depicts the integration executed in subsequent Figures 4–9. Hydrogen (H_2) can be filled via the H_2 filling receptacle (A). It is stored in the CHSS (B) across four individual vessels, totaling 12.4 kg (equivalent to a storage volume of 312 liters) at a system pressure of 700 bar. Supplied to the FCS (C) through a pressure regulator, the H_2 maintains a nominal inlet pressure on the FCS of 8 bar.

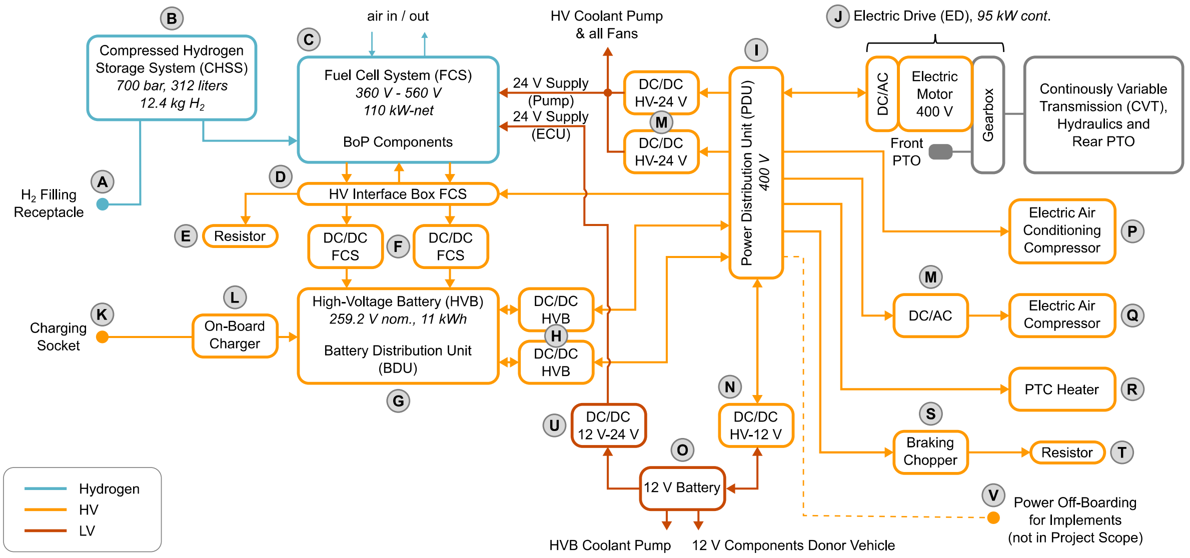

Figure 3: Simplified electrical system architecture of the FCTRAC vehicle

The FCS, featuring a low-temperature polymer electrolyte membrane (LT-PEM) technology, provides an electrical output of 110 kW-net within a voltage range of 360 V to 560 V, dependent on the operating point. Alongside the fuel cell stack, the FCS houses the balance of plant (BoP) components such as air compressor and hydrogen recirculation blower as well as the coolant pump for the cooling system. The first two are supplied via a HV interface box (D), while the latter requires 24 V. During cold starts below 5 °C, a resistor (E) connected to the fuel cell stack, with 5 kW load, heats the stack and coolant.

In the powertrain, the HVB (G) serves as a buffer for the HV system, compensating for the relatively slow load change of the FCS during dynamic load requests from the ED (J). In addition, the HVB powers the vehicle during start-up and shutdown of the FCS. The HVB, divided into battery packs and a battery distribution unit (BDU) with battery management system (BMS), is based on lithium-ion cell technology. With a nominal voltage of 259.2 V and a usable energy of 11 kWh, it achieves peak discharge and charge powers of 69 kW and 28 kW, respectively. The capacity and nominal voltage level for the HVB was primarily determined by two key factors: Firstly, the physical dimensions compared to the available installation space, and secondly, the required capacity based on the simulation results.

The HVB can be independently charged using an OBC (L) and a Type 2 charging socket (K). The OBC supports single-phase charging up to 7 kW and enables purely battery-electric driving. Various DC/DC converters are employed to manage voltage levels, including DC/DC converters (F) in buck mode to reduce voltage from the FCS to the HVB, and DC/DC converters (H) in boost mode to match the powertrain's nominal voltage of 400 V at the power distribution unit (PDU) (I). For cost and availability reasons, parallel-operating DC/DC converters were selected for the prototype vehicle.

The PDU manages power distribution to the ED (J) and electrified auxiliary units. The ED consists of a permanent-magnet synchronous motor (PMSM) with a reduction gearbox (gear ratio four) and an inverter, able to deliver a continuous output power of 95 kW. It is placed at the center of the chassis and directly drives the CVT and the front PTO. The carried-over CVT drives the wheels, the hydraulic pumps, and the rear PTO. Electrified auxiliary units include the air conditioning (AC) compressor (P) with a cooling capacity of up to 5 kW and the air compressor (Q) with a maximum flow rate of 325 liters/min at 10 bar to supply the pneumatic trailer brake system. To power the air compressor (Q), one of the DC/DC converters (M) is equipped with an integrated inverter (DC/AC). Additionally, a 5 kW PTC heater (R) heats the HVB cells at low ambient temperatures. A braking chopper (S) with resistor (T) mitigates voltage peaks during dynamic driving maneuvers. Power off-boarding (V) for electrical implements was considered for future use but not implemented due to the limited commercial availability of electric powered implements.

To meet the performance requirements of the new cooling system, individual radiators with PWM (pulse width modulation)-controlled electrical fans operating at 24 V were applied. The supply of 24 V components and new electronic control units (ECUs) is managed by two 5.6 kW DC/DC converters (M) connected to the PDU (I).

The two new ECUs were implemented with partially redundant functions, ensuring safety, and incorporating three urgent stop switches to enforce a safe state for both the ED and the HV system. One of the two ECUs, called the hybrid control unit, replaced, and emulated the engine control unit of the donor vehicle. The introduction of the 24 V low-voltage (LV) system caused major changes to the existing 12 V on-board power supply system. A 2.8 kW DC/DC converter (N) operating at 12 V substitutes the 200 A / 12 V alternator of the donor vehicle, and a 12 V to 24 V DC/DC converter (U) directly supplies the control unit of the FCS (C). The wet 12 V lead-acid battery, originally with a nominal capacity of 176 Ah, was substituted with a smaller 12 V AGM (absorbed glass mat) battery (O) delivering a nominal capacity of 100 Ah due to the reduced requirements caused by the removed starter of the ICE.

Packaging and Component Integration

The positioning of components on the prototype's roof, detailed in Figure 4, considering the defined KPIs at the beginning of the project, was done due to spatial constraints imposed by the CHSS (B) and the FCS radiator. Both were placed atop the vehicle to accommodate their size and ensure sufficient cooling performance up to an ambient temperature of 35 °C without power derating. Six 24 V pull fans collectively draw 3.15 kW and are installed atop the radiator. The roof also houses the FCS cooling circuit's expansion tank and the ECU responsible for CHSS monitoring and safety functions, including H_2 leakage or accumulation detection.

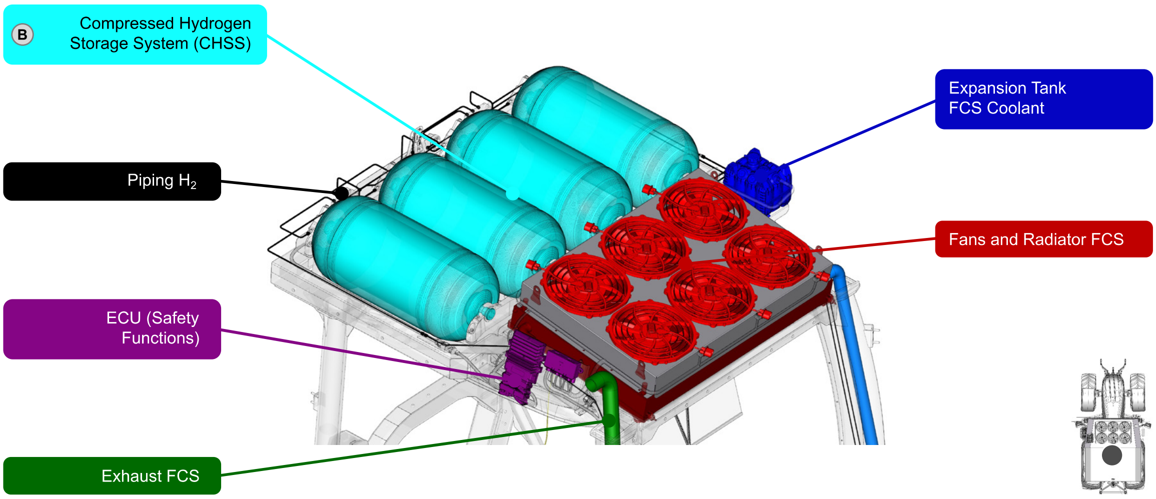

Figure 4: Packaging of the main components of the FCTRAC vehicle on the roof

To meet FCS-manufacturer requirements about potential hydrogen accumulation caused by purging of the fuel cell stack, the FCS exhaust is placed to the roof's right-hand side. Integrating the CHSS and FCS radiator posed challenges, necessitating an additional roof structure (Figure 5) for added weight support and compliance with the type-approved cabin structure and mounts. This structure serves as additional protection in the event of vehicle roll-over incidents and safeguards internal components like hydrogen pipes, cooling lines, and wiring harnesses. Removal of the cabin suspension system and reduction of the maximum tire size were necessary to accommodate increased height and space requirements for the roof structure, ensuring rear visibility is maintained.

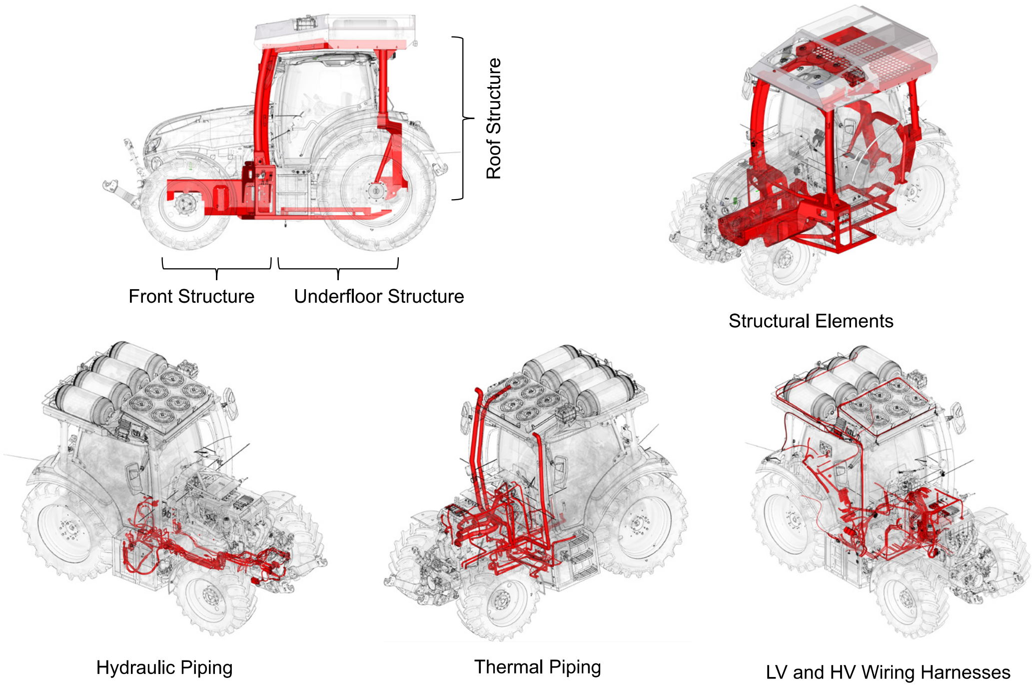

Figure 5: New introduced structural elements for mechanical strength, new hydraulic and thermal piping, and new LV and HV wiring harnesses

Figure 6 illustrates the front end and under-the-hood area, where the ED (J) with integrated intermediate gearbox and inverter substituted the ICE and ATS. It connects directly to the CVT via the retained flywheel (relevant for speed and torque measurements of the carry-over CVT) and provides a shaft to the front PTO.

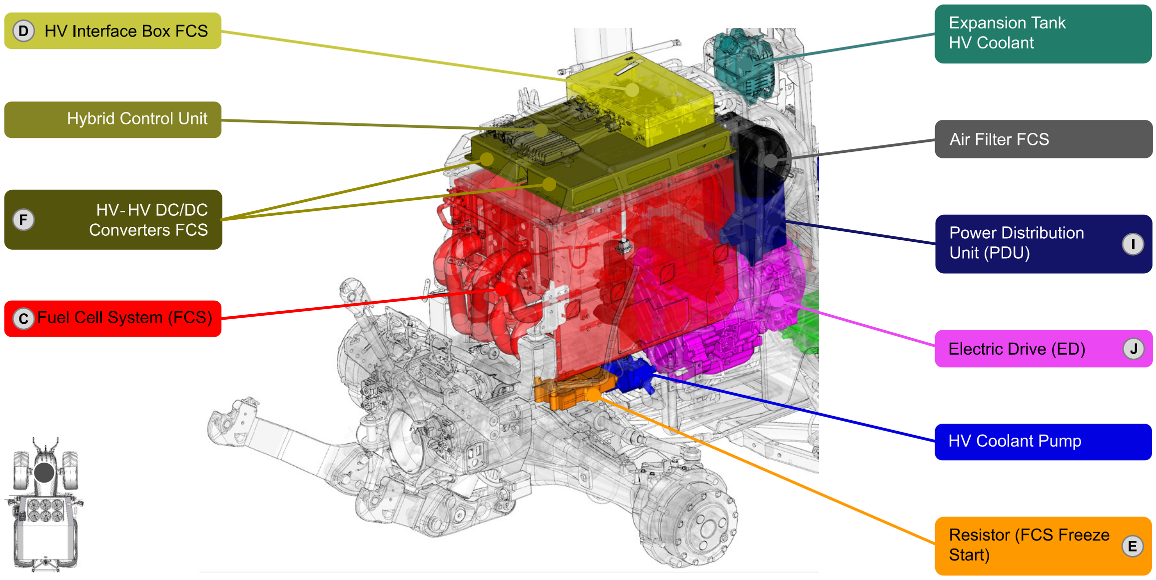

Figure 6: Packaging of the main components of the FCTRAC vehicle under the hood

To compensate for the load-bearing function of the ICE in the donor vehicle, a new load-bearing structural element linking the transmission housing to the front end was developed (Figure 5). This structural element bears resistive forces, torsional and bending moments, and supports internal components while also accommodating the forces and moments of the new roof frame (Figure 5).

The DC/DC converters (F), HV interface box (D), hybrid control unit, and FCS air filter were integrated into a unit connected to the FCS (C) via a carrier structure and mounted on the structural element in a vibration-decoupled manner. This arrangement maximizes the use of space under the hood while minimizing impacts on the shape of the hood. To minimize HV system cable lengths, the PDU (I) was centrally located near the hood support in front of the cabin, with the HV components' cooling system expansion tank positioned above it for accessibility. Within the structural element, space was allocated for the 24 V coolant pump and the freeze-start resistor (E) for the FCS (C).

The space constraints imposed by various components necessitated adjustments such as an increase in wheelbase to accommodate the FCS length, a new front axle support, and a resized hood. The front axle was changed from suspended to unsuspended to simplify development. The option for a front loader was discarded to improve the prototype's payload and to reduce the structural load requirements. This reduced the comparative weight of the originally configured donor vehicle by 90 kg (Table 1).

Figure 7 illustrates the arrangement of components on the left-hand side of the prototype vehicle. The diesel tank and the diesel exhaust fluid (AdBlue) tank were replaced by the HVB (G), divided into two off-the-shelf battery packs, and the BDU (G) with integrated BMS. Access to fuses and electronics is facilitated by a removable cover, including the expansion tank of the HVB cooling circuit located above the BDU. The 12 V battery (O) was placed above the HVB, with charging ports positioned near the cabin entrance due to lack of accessibility. A radiator equipped with a 1.15 kW 24 V pull fan cools HV components (excluding fuel cell stack and HVB) behind the left-side cabin steps. The HVB's installation allows for removal with a forklift after disassembling the left rear wheel, trim parts, and radiator. The H_2 filling receptacle (A) was positioned in the area of the original diesel tank inlet. A manual service disconnect for HV system isolation is located underneath and behind a cover.

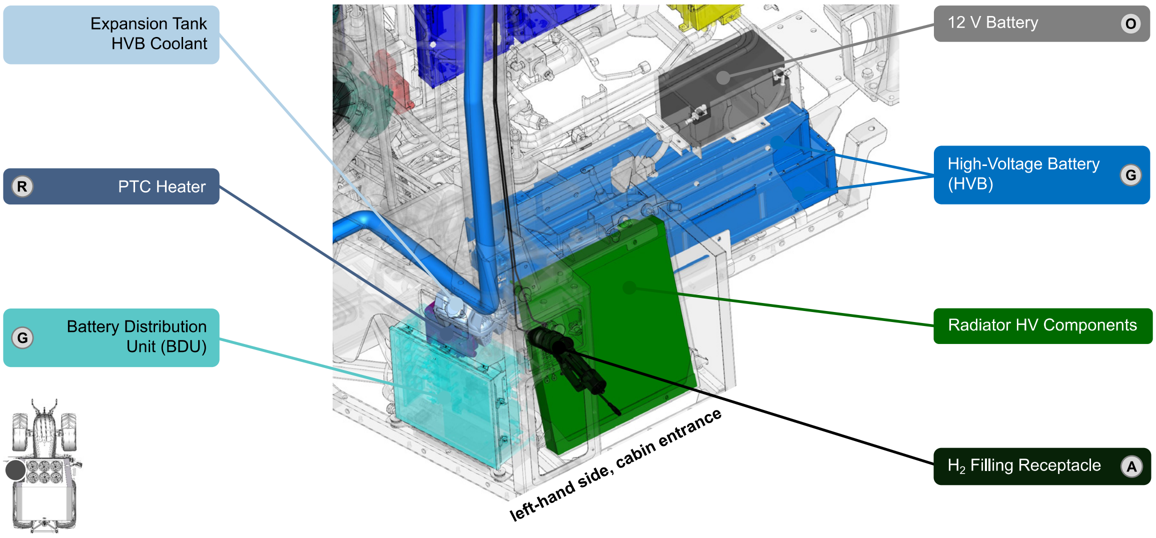

Figure 7: Packaging of the main components of the FCTRAC vehicle on the left-hand side

A main challenge was integrating the HVB due to its size and shape. It was positioned to avoid mechanical damage and potential thermal runaway, protected from side impacts by the rear wheel. This placement necessitated widening the track width by swapping the rims of the rear wheels between the sides, creating approximately 50 mm of additional lateral space.

The donor vehicle's AC condenser, and transmission and hydraulics oil cooler were retained and connected to a unit with a 0.6 kW 24 V pull fan. This unit was installed behind the right-hand side steps (Figure 8). Additionally, the new electric AC compressor (P) and electric air compressor (Q) were positioned there to minimize pipe lengths.

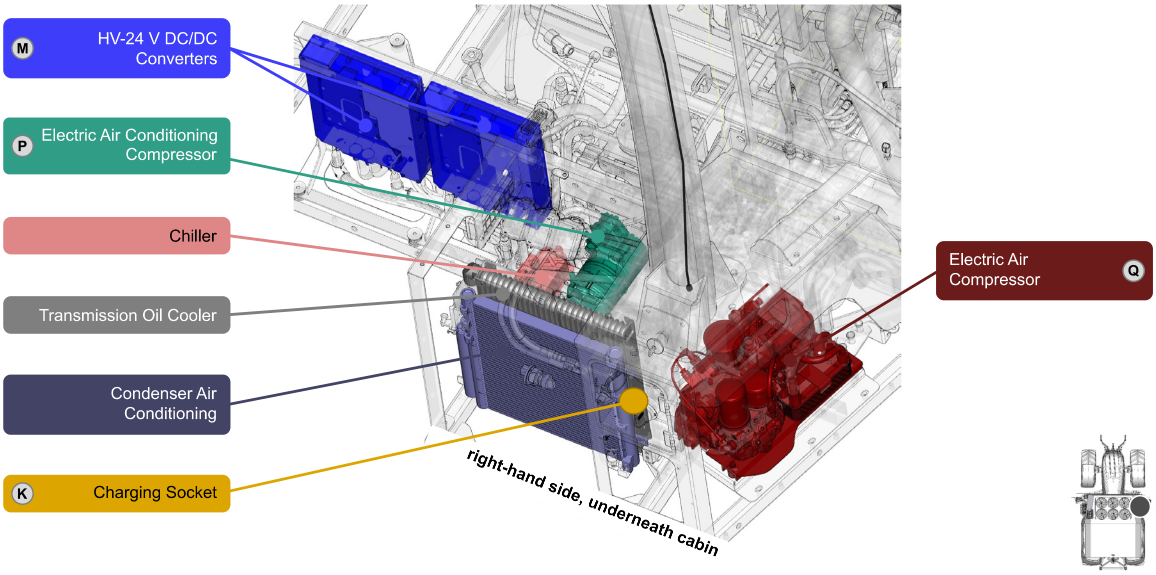

Figure 8: Packaging of the main components of the FCTRAC vehicle on the right-hand side

The cooling for the HVB is achieved through a chiller integrated into the refrigerant circuit, using R-134a refrigerant. Cabin and battery cooling systems operate independently, regulated by shut-off valves. Two 24 V DC/DC converters (M) are located behind the right rear wheel, and the HVB charging socket (K) is placed behind a cover.

The remaining components of the HV system (Figure 3) such as the OBC (L), the HV to 12 V DC/DC converter (N) for the 12 V on-board power supply, and two boost-mode DC/DC converters (H) positioned between the HVB and the PDU were integrated into the underfloor of the vehicle (Figure 9). Their arrangement allows for accessible connections upon removing a panel behind the front axle.

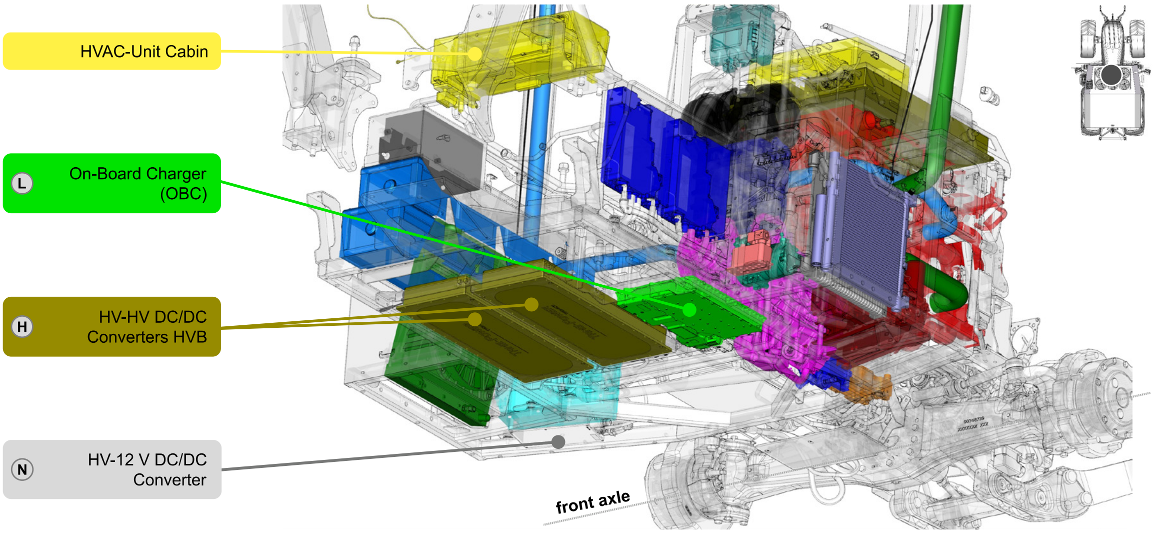

Figure 9: Packaging of the main components of the FCTRAC vehicle in the underfloor

The heating, ventilation, and air conditioning (HVAC)-unit in the cabin was upgraded with an aluminum heater core to replace the copper heater core. This change was necessary because the cabin heating is integrated into the FCS's cooling circuit, requiring specific maximum conductivity of the cooling medium. Exceeding 5 µS/cm at 20 °C results in a decreased insulation resistance between the fuel cell stack high-voltage and the vehicle chassis.

Maximizing ground clearance while providing support for side-mounted components posed a challenge. A frame composed of profiles was designed and attached to the front structure, rear axle, and roof frame structure (Figure 5). The additional weight of the new structural elements included approximately 360 kg for the front structure, 730 kg for the roof structure, and 105 kg for the underfloor structure. Hydraulic lines were rerouted extensively due to the new structure at the vehicle's front and the repositioning of components, resulting in the laying of around 39 m of new hydraulic lines in the prototype vehicle as illustrated in Figure 5. The new piping of the cooling system, totaling approximately 55 m in length, and new LV and HV wiring harnesses, encompassing around 1,025 m of new LV wires, are also depicted. While main LV wiring harnesses for the transmission and the cabin, along with smaller secondary harnesses, could be retained, all other wiring harnesses required redesign and manufacture.

Comparison of the Donor Vehicle with the FCTRAC Vehicle

The conversion process involved replacing or redesigning over 46% (around 3,300) of the donor vehicle´s parts, with the components that were removed or added visualized in Figure 10. This required an expansion of the existing installation space by approximately 3,400 liters, with 2,500 liters allocated to the new roof structure and the space above the cabin.

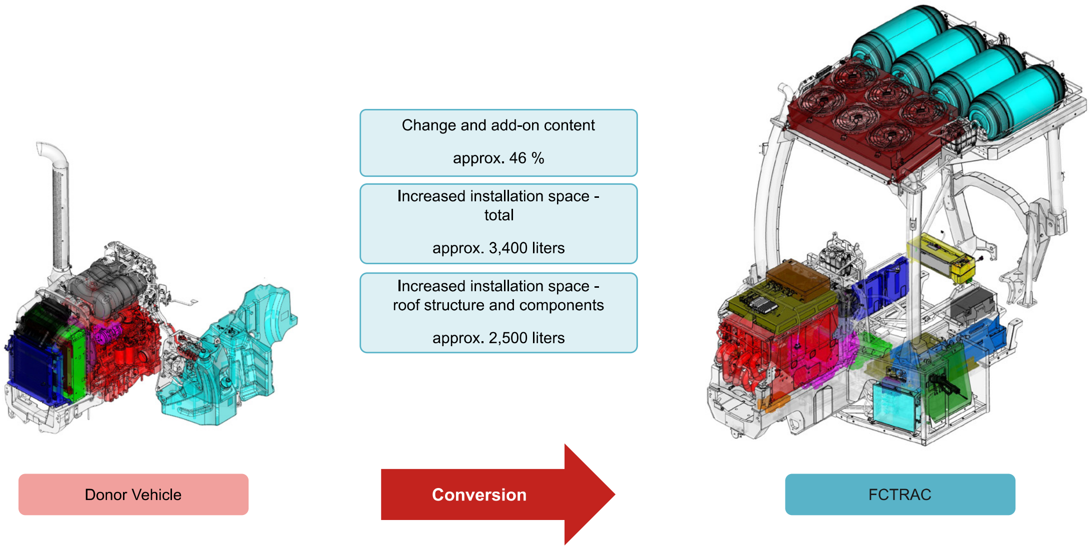

Figure 10: Comparison of the conversion content between the donor vehicle and the FCTRAC vehicle

The cooling system of the donor vehicle, including the condenser for air conditioning, transmission oil cooler (incl. hydraulic), intercooler, and radiator, was cooled by a single pull fan coupled directly to the ICE (Figure 11). In contrast, the FCTRAC vehicle integrates three new coolant circuits with electric water pumps and fans to meet specific temperature and conductivity requirements of components (Konrad et al. 2023). These circuits support the FCS (maximum coolant inlet temperature: 70 °C, roof-mounted radiator), ED, power electronics, auxiliary units (maximum coolant temperature: 65 °C, left-hand mounted radiator), and the HVB (maximum coolant temperature: 35 °C).

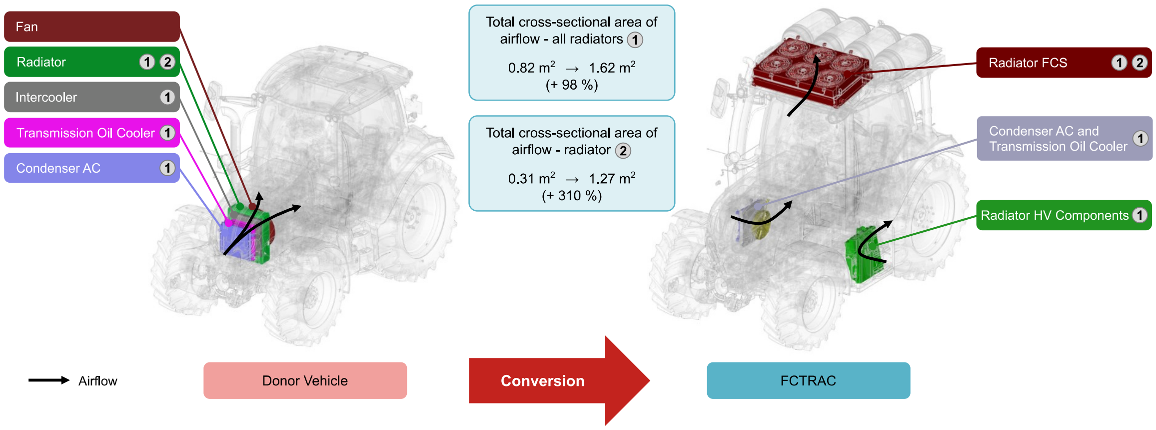

Figure 11: Comparison and packaging of the cooling system donor vehicle with the FCTRAC vehicle

To ensure high performance of the powertrain up to 35 °C ambient temperature without derating, large cooling surfaces are required. The cross-sectional area of airflow through all radiators is twice the size as of the donor vehicle. Furthermore, the cross-sectional area of the FCS radiator was quadrupled compared to the radiator of the ICE. This difference arises from two factors: Firstly, the FCS operates at a significantly lower temperature compared to the ICE, resulting in a smaller temperature difference relative to the ambient temperature. Secondly, the FCS dissipates significantly less heat through the exhaust gas and has therefore a higher heat input into the cooling system.

The roof-mounted radiator draws air from beneath and in front of the cabin, directing it upwards through the roof cover. A protective grille positioned above the fans guards against debris. The radiators on the left-hand and right-hand side of the vehicle draw air through grilles, directing it primarily towards the rear wheels and slightly downwards through the underfloor. The HVB is shielded from heat by a deflector plate. Moreover, the fans can be automatically activated and reversed to clean the radiators of dust and debris.

A direct comparison between the FCTRAC vehicle and the donor vehicle is shown in Figure 12.

Figure 12: FCTRAC vehicle (right) and STEYR Expert CVT (left, model year 2023) in comparison (© STEYR Traktoren)

Table 2 reveals the main differences between both vehicles. The FCTRAC vehicle features an extended wheelbase and length (plus 204 mm), an unsuspended front axle, increased total height (plus 420 mm) relative to the center of the rear axle, and width (plus 30 mm), along with a changed track width (plus 102 mm). The ground clearance relative to the lowest point of the chassis was reduced by 85 mm. This leads to a theoretical reduction of the overall ground clearance of 122 mm considering the smaller selected tires (with rear tires of the type of Firestone Maxi Traction 65 - 540/65 R38 instead of 600/65 R38).

Table 2: Comparison of the donor vehicle with the FCTRAC vehicle

	Donor vehicle	**FCTRAC vehicle**	**Difference**
Wheelbase in mm	2,490	2,694	+204
Overall length in mm	4,397	4,601	+204
Height from center rear axle in mm	2,080	2,500	+420
Width in mm	2,350	2,380	+30
Track width rear in mm	1,730	1,832	+102
Lowest point from center rear axle in mm	-320	-405	-85
Size of front / rear tires	480/65 R28 600/65 R38	440/65 R28 540/65 R38	-
Net weight in kg	5,990	7,352	+1,362
Axle-load distribution front / rear	45 / 55	40 / 60	-
Vertical center of gravity relative to the center rear axle in mm	203	347	+144
Permitted gross vehicle weight in kg	8,800	8,800	0
Energy storage	180 l Diesel 19 l AdBlue	12.4 kg H_2 at 700 bar 11 kWh HVB	-
On-board power supply DC in V	12	12, 24, 400	-

Despite a weight increase of 1,362 kg, the FCTRAC vehicle maintains a payload capacity of 1,448 kg within the same permitted gross vehicle weight of 8,800 kg. The axle-load distribution shifted from 45/55 to 40/60 between the front and rear axle, with the vertical center of gravity shifting upwards by 144 mm (relative to the center of the rear axle). The energy storage of 180 liters diesel and 19 liters AdBlue was replaced by a CHSS with 12.4 kg hydrogen at a pressure of 700 bar and an HVB with a usable energy of 11 kWh.

Conclusions

The FCTRAC project embodies active measures towards sustainable zero-emission agricultural machinery by transforming a conventional diesel tractor, specifically the STEYR 4130 Expert CVT, into a fuel-cell electric vehicle powered by hydrogen. A second scope of the project is the production of high-purity hydrogen from biogenic sources (BioH2Modul). In pursuit of the first goal, specific attention was paid to relevant regulations and guidelines for electric on- and off-road vehicles to fulfill the requirements for type approval of the prototype vehicle.

The retrofitting process involved the integration of key components, including a 110 kW-net fuel cell system, a 11 kWh high-voltage battery, and a 95 kW electric drive, all within a 400-V architecture, effectively replacing the internal combustion engine. The hydrogen is stored in a 700-bar compressed hydrogen storage system with a total storage capacity of 12.4 kg. Notably, the vehicle retained its continuously variable transmission from the donor model, while auxiliary units such as the air conditioning compressor and the air compressor for the pneumatic trailer brake system were substituted with electrical counterparts.

Mechanical and electrical adaptations were implemented at both micro and macro levels to accommodate the electrified powertrain and necessary components of the cooling systems. Significant modifications were made to subsystems, necessitating the redesign or replacement of over 46% of the vehicle's parts. New structural elements were introduced to support new components, while the wheelbase and height were adjusted to meet the installation space requirements.

Following successful implementation and accomplished type approval, the future activities will involve benchmark comparisons with the donor vehicle, and real-world testing in agricultural conditions, utilizing locally produced sustainable hydrogen from the BioH2Modul, which was developed within the project FCTRAC.

From a technical standpoint, opportunities for refinement and optimization have been identified. These include simplifying the electrical system architecture with customized components, exploring higher voltage levels of 700 to 800 V for enhanced efficiency, and adjusting the sizes of fuel cell system, high-voltage battery and compressed hydrogen storage system based on field-test results. Furthermore, tailored electric rear and front axles can substitute the conventional continuously variable transmission to increase transmission efficiency and gain packaging space. Additionally, considerations for alternative storage technologies, such as cryogenic hydrogen storage, can be made. Likewise, the size of the cooling system for the fuel cell system and power electronics needs to be investigated by using techniques such as adiabatic cooling. Future adaptations for autonomous driving offer further possibilities for advancement due to the gain of space for the hydrogen storage system due to the obsolete cabin. The FCTRAC vehicle is discussed with a focus on powertrain, thermal system, hydrogen storage, and performance in the publication by KONRAD et al. (2024).

References

AGCO GmbH (2017): Fendt e100 Vario: The battery-powered compact tractor. Press release 8 September 2017, https://msc.fendt.com/modules/create_pdf/pdf2/7269_web_en-US_2024-03-06_14-13-44.pdf, accessed on 15 March 2024

AGCO GmbH (2023): Fendt shows first hydrogen tractor at German Hydrogen Summit. Press release 27 February 2023, https://msc.fendt.com/modules/create_pdf/pdf2/25089_web_en_2024-03-12_11-09-30.pdf, accessed on 15 March 2024

Back, P.; Hodel, B.; Pirro, P.; Stark, W. (2011): Replication of the DLG PowerMix Tractor Fuel Consumption Test in a Laboratory Environment. In: Agricultural Engineering, Conference Land.Technik AgEng 2011: solutions for intelligent and sustainable farming, VDI-Bericht Nr. 2124, Düsseldorf, VDI-Verlag, pp. 209–216

Böhrnsen, A. (2023): Neuer 100-kW-Elektro-Traktor von Tadus. Profi, https://www.profi.de/aktuell/aktuelle-meldungen/neuer-100-kw-elektro-traktor-von-tadus-31143.html, accessed on 15 March 2024

Breu, W.; Pichlmaier, B. (2017): Electrified Utility Tractor. In: 75th International Conference on Agricultural Engineering, VDI-MEG, 10–11 November 2017, Hanover, VDI Verlag GmbH, pp. 9–14, https://doi.org/10.51202/9783181023006

CEMA (2022): The role of agricultural machinery in decarbonising agriculture. https://www.cema-agri.org/images/publications/position-papers/CEMA_decarbonising_agriculture_27-04-22.pdf, accessed on 15 March 2024

CNH Industrial America LLC (2023): FARMALL UTILITY 75C ELECTRIC TRACTOR, CIH23081601. https://cnhi-p-001-delivery.sitecorecontenthub.cloud/api/public/content/5fde91d7b1cf4223b34039279b86348c?v=c66c2707, accessed on 15 March 2024

CNH Industrial N.V. (2019): STEYR showcases future farming technology with its STEYR Konzept – a hybrid powered concept tractor. Press release 11 November 2019, https://www.cnh.com/-/media/CNHi/cnhicorporate/media/press_releases/2019/november/STEYR-showcases-future-farming-technology-with-its-STEYR-Konzept-a-hybrid-powered-concept-tractor/20191111_PR_CNH_Industrial_STEYR_Concept.pdf?rev=-1, accessed on 15 March 2024

CNH Industrial N.V. (2021): New Holland Agriculture drives forward its sustainable agenda. Press release 23 February 2021, https://newhollandpresskit.btsadv.com/download/nh_presskit/doc/NH_PR02_Clean_Energy_Leader_INB.pdf, accessed on 15 March 2024

CNH Industrial N.V. (2022a): New Holland Agriculture debuts world´s first LNG tractor. Press release 9 December 2022, https://preview.thenewsmarket.com/Previews/CNHA/DocumentAssets/630590.pdf, accessed on 15 March 2024

CNH Industrial N.V. (2022b): CNH Industrial presents first electric tractor prototype with autonomous features. Press release 9 December 2022, https://preview.thenewsmarket.com/Previews/CNHA/DocumentAssets/630670.pdf, accessed on 15 March 2024

CNH Industrial N.V. (2023): New Holland debuts next generation of alternative fuel tractors with Methane Power CNG. Press release 26 September 2023, https://preview.thenewsmarket.com/Previews/CNHA/DocumentAssets/650635_v2.pdf, accessed on 15 March 2024

CNH Industrial Österreich GmbH (2023): STEYR brings hybrid technology closer to production. Press release 7 September 2023, https://preview.thenewsmarket.com/Previews/CNHA/DocumentAssets/648971.pdf, accessed on 15 March 2024

Deere & Company (2022): John Deere offers new Electric Variable Transmission for select 8 Series Tractors, new JD14X engine for 9 Series. Press release 3 March 2022, https://www.deere.com/en/news/all-news/electric-variable-transmission/, accessed on 15 March 2024

Deter, A. (2011): Energieunabhängiger Wasserstoff-Schlepper von New Holland. https://www.topagrar.com/technik/news/technik-news-energieunabhaengiger-wasserstoff-schlepper-von-new-holland-9383780.html, accessed on 15 March 2024

Duppong, S. A.; Kuhl, M.; Delvaux, O. (2019): Production System Optimization with Electrified Powertrain. In: 77th International Conference on Agricultural Engineering, VDI-MEG, 8–9 November 2019, Hanover, VDI Verlag GmbH, pp. 421-426, https://doi.org/10.51202/9783181023617

e-mobil BW GmbH (2022): Systemvergleich zwischen Wasserstoffverbrennungsmotor und Brennstoffzelle im schweren Nutzfahrzeug – Eine technische und ökonomische Analyse zweier Antriebskonzepte. https://www.e-mobilbw.de/fileadmin/media/e-mobilbw/Publikationen/Studien/e-mobilBW-Studie_H2-Systemvergleich.pdf, accessed on 21 August 2023

European Commission (2019): The European Green Deal, COM(2019) 640 final. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, 11 December 2019, Brussels

European Commission (2023a): Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2019/1242 as regards strengthening of the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, and repealing Regulation (EU) 2018/956, COM(2023) 88 final. https://eur-lex.europa.eu/resource.html?uri=cellar:4a3b2136-ad3e-11ed-8912-01aa75ed71a1.0001.02/DOC_1&format=PDF, 14 February 2023, Strasbourg

European Commission (2023b): Pricing agricultural emissions and rewarding climate action in the agri-food value chain. https://climate.ec.europa.eu/document/download/996c24d8-9004-4c4e-b637-60b384ae4814_en?filename=Pricing%20agricultural%20emissions%20and%20rewarding%20climate%20action%20in%20the%20agri-food%20value%20chain.pdf, November 2023, Luxembourg, https://doi.org/10.2834/200

FuelCellsWorks (2020): The First Hydrogen Tractor in the Netherlands. https://fuelcellsworks.com/news/the-first-hydrogen-tractor-in-the-netherlands/, accessed on 15 March 2024

Future Farming (2021): H2Trac sells first EOX hydrogen tractor to Almere City Farm in the Netherlands. https://hydrogen-central.com/h2trac-sells-first-hydrogen-tractor-netherlands/, accessed on 15 March 2024

Gubin, V.; Varlese, C.; Benedikt, F.; Konrad, J.; Müller, S.; Rosenfeld, D. C.; Hofmann, P. (2023): FCTRAC and BioH_2Modul – A Way to Zero Emission Mobility in Agriculture. In: Heintzel, A. (eds) Antriebe und Energiesysteme von morgen 2022, ATZLive 2022, Proceedings, Wiesbaden, Springer Vieweg, pp. 86–104, https://doi.org/10.1007/978-3-658-41435-1_8

Karsten, B. (2023): Electric Fendt Tractor e100 goes into production. Future Farming. https://www.futurefarming.com/tech-in-focus/electric-fendt-tractor-e100-goes-into-production/, accessed on 15 March 2024

Koerhuis, R. (2022): JCB launches mobile hydrogen refueller. Future Farming. https://www.futurefarming.com/tech-in-focus/jcb-launches-mobile-hydrogen-refueller/, accessed on 15 March 2024

Konrad, J.; Varlese, C.; Junger, C.; Krizan, R.; Hofmann, P. (2023): Fuel cell electric tractor powered with biogenic hydrogen. In: 80th International Conference on Agricultural Engineering, VDI-MEG, 10-11 November 2023 in Hanover, VDI Verlag GmbH, pp. 49-55, https://doi.org/10.51202/9783181024270

Konrad, J.; Varlese, C.; Krizan, R.; Junger, C.; Hofmann, P.; Mayer, C. (2024): Fuel Cell Electric Tractor FCTRAC: Powertrain, Thermal System, Hydrogen Storage, and Performance. agricultural engineering.eu 79(3), https://doi.org/10.15150/ae.2024.3314

Lambert, F. (2016): John Deere unveils latest all-electric tractor prototype for zero-emission agriculture. Electrek, https://electrek.co/2016/12/05/john-deere-electric-tractor-prototype/, accessed on 15 March 2024

Moriarty, P.; Honnery, D. (2019): Prospects for hydrogen as a transport fuel. International Journal of Hydrogen Energy 44(31), pp. 16029–16037, https://doi.org/10.1016/j.ijhydene.2019.04.278

Monarch Tractor (2022): Monarch Tractor Launches Production of Founder Series MK-V: The First Commercially Available Electric, Driver-Optional Smart Tractor. Press release 1 December 2022, https://www.monarchtractor.com/news/mk-v-first-commercially-available-electric-driver-optional-smart-tractor, accessed on 15 March 2024

Nöß, C.; Weller, J. (2023): A Fuel Cell Tractor in Operation, Concepts and Field Data. In: 80th International Conference on Agricultural Engineering, VDI-MEG, 10-11 November 2023 in Hanover, VDI Verlag GmbH, pp. 39-47, https://doi.org/10.51202/9783181024270

Padfield, E. (2009): NOW IN VIDEO: New Holland´s fuel cell tractor. Farmers Weekly, https://www.fwi.co.uk/news/environment/now-in-video-new-holland-s-fuel-cell-tractor, accessed on 15 March 2024

Pretsch, S.; Rothbart, M. (2020): Sustainable Agriculture in an Electrified World – Cradle-to-Grave evaluation of different propulsion systems. In: 78th International Conference on Agricultural Engineering, VDI-MEG, 3–4 November 2020, Düsseldorf, VDI Verlag GmbH, pp. 1-8, https://doi.org/10.51202/9783181023747

Profi (2022): Deere tests electric robot tractor. https://www.profi.co.uk/news/deere-tests-electric-robot-tractor/, accessed on 15 March 2022

Profi (2023): Agromec 700 Vario electric tractor: 205 electric horses. https://www.profi.co.uk/test-centre/205-electric-horses/, accessed on 15 March 2024

Sandaka, B. P.; Kumar, J. (2023): Alternative vehicular fuels for environmental decarbonization: A critical review of challenges using electricity, hydrogen, and biofuels as a sustainable vehicular fuel. Chemical Engineering Journal Advances 14, 100442, https://doi.org/10.1016/j.ceja.2022.100442

Scolaro, E.; Beligoj, M.; Perez Estevez, M.; Alberti, L.; Renzi, M.; Mattetti, M. (2021): Electrification of Agricultural Machinery: A Review. In: IEEE Access 9, pp. 164520-164541, https://doi.org/10.1109/ACCESS.2021.3135037

Smits, M. (2023): Start-ups also focus on electric tractors. Future Farming. https://www.futurefarming.com/tech-in-focus/start-ups-also-focus-on-electric-tractors/, accessed on 15 March 2024

Steyr-Traktoren (2023): STEYR Expert CVT. TP01 / SM / 03.19. https://assets.cnhindustrial.com/steyr/assets/Agriculture/Products/Tractors/Expert%20CVT/Brochure/19s0001doo_expert_cvt_8-page_launchflyer_final_low.pdf, accessed on 21 August 2023

TUM (2023): New modular development kit for e-tractors. https://www.tum.de/en/news-and-events/all-news/press-releases/details/new-modular-development-kit-for-e-tractors, accessed on 15 March 2024

UNFCCC (2018): The Paris Agreement. https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf, accessed on 11 March 2024

Van Hattum, B. (2024): New Holland presents 100 % electric T3 tractor. Future Farming, https://www.futurefarming.com/tech-in-focus/new-holland-presents-100-electric-t3-tractor/, accessed on 15 March 2024

Wendel, C. H. (1988): The Allis-Chalmers Story. Sarasota, Florida, Crestline Pub.

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