Battery Electric Tractor Development

Benno Pichlmaier
Dr.-Ing.
Director of Global Research & Advanced Engineering
AGCO, Marktoberdorf, Germany

Markus Ehrl
M.Sc., Dipl.-Ing. (FH)
Director of Electrification
AGCO, Marktoberdorf, Germany

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Benno Pichlmaier and Markus Ehrl

AGCO, Marktoberdorf, Germany

Abstract. *This distinguished lecture will provide an overview of battery electric tractor design principles. An introduction to the Fendt e107 battery electric tractor development will be presented, such as the project history, basic concept considerations, general opportunities of electrification for agriculture, and the transition from a proof of concept in research to a series development. Key focus will be on the feasibility and technological building blocks. A key design choice for battery electric tractors (BETs) is whether to use shared components with combustion engines (conversion design) or develop a unique (purpose design) tractor with substantial drivetrain changes. The battery and its management system (BMS) determine many of the BETs essential functions and performance. Unlike refueling a traditional fuel tank, charging a BET battery requires specific additional aspects and has to deal with global infrastructure variations like voltage levels and charging standards. Additionally, managing component temperature ranges necessitates careful thermal system design. Electrical systems over 60 volts also require specialized safety measures for production, service, and repair.*

Keywords. *Battery electric tractor (BET), Battery pack, Charging, Conversion design, Electric drivetrain, Electric energy, Electrification for agriculture, Purpose design, Safety, Thermal management.*

Although the diesel engine (with renewable fuel) will remain a dominating power source for large tractors in the years to come, battery electric drives are showing a high potential for greenhouse gas reduction and energy efficiency improvements in smaller utility tractors. A cradle-to-grave product carbon footprint (PCF) comparison between the Fendt e107 V Vario (battery electric) and the Fendt 207 V Vario (diesel) demonstrates the advantage: If the Fendt e107 V Vario is charged with electricity from renewable sources, its CO_2 footprint becomes lower than the combustion engine tractor after less than 900 hours of use, despite a higher carbon intensity from production and disposal or recycling. After 3,500 hours, the electric tractor has only half of the CO_2 footprint vs. the combustion engine tractor (Fendt, 2023).

Beyond aspects of greenhouse gas reduction, there are plenty of additional opportunities to advance agricultural mechanization with new ideas and fresh thinking given the progress of electric drive systems and battery technology, e.g., energy savings in complex (hydraulic and mechanic) implement drivelines, a more precise and dynamic controllability of field processes, and more energy independence for farmers with their own electricity supply from solar, wind, or biomass.

History

Electric or electrified tractors are not a new idea. “Probably the first attempt to use electricity to power field equipment was in 1894, when the Zimmermann company in Germany demonstrated its self-propelled electric ploughs […]. Small-scale commercial success came in about 1900 when Brutschke electric tractors were used for ploughing in Germany” (Williams, 2019) (fig. 1).

Already back then, one of the main benefits was the use of locally, self-supplied, and independent energy at low cost. In this case it was surplus electricity from a nearby sugar beet processing factory being provided to the electric tractor with overhead power lines instead of a mobile battery.

With the invention of robust diesel engines, a period of abundant fossil fuel at relatively low cost and little worry about environmental impacts, there was no interest in alternative drive trains. Today we see more and more severe impacts of climate change and understand the role of greenhouse gas emissions from fossil fuels as a root cause. There is a clear push to find sustainable and economically viable mobile energy sources with a low carbon footprint.

There are numerous examples of agricultural machine electrification activities in the early 2000s. The development of a compact 140 kW electric power drive system dedicated to use in agricultural equipment started at AGCO in 2001 with the so-called MELA project (Szajek et al., 2004). This research also addressed safety concepts for higher voltage systems, integrated cooling solutions for implements and a continuously variable electric power split transmission proof of concept. Prototypes of a diesel-electric self-propelled sprayer and a tractor with a fully integrated 130 kW generator for a 700 V power supply to auxiliaries and implements were subsequently developed, as shown in figure 2 and table 1 (Pichlmaier et al., 2014). From about 2005 onwards, multiple electric tractor and implement prototypes were developed by machine manufacturers to research opportunities and challenges of electrification (Breu et al., 2013; Stöhr et al., 2015). All these projects helped to build know-how across the agricultural industry and drove fruitful exchange and intense collaboration across the industry with the aim to enable the next technology chapter for farm mechanization.

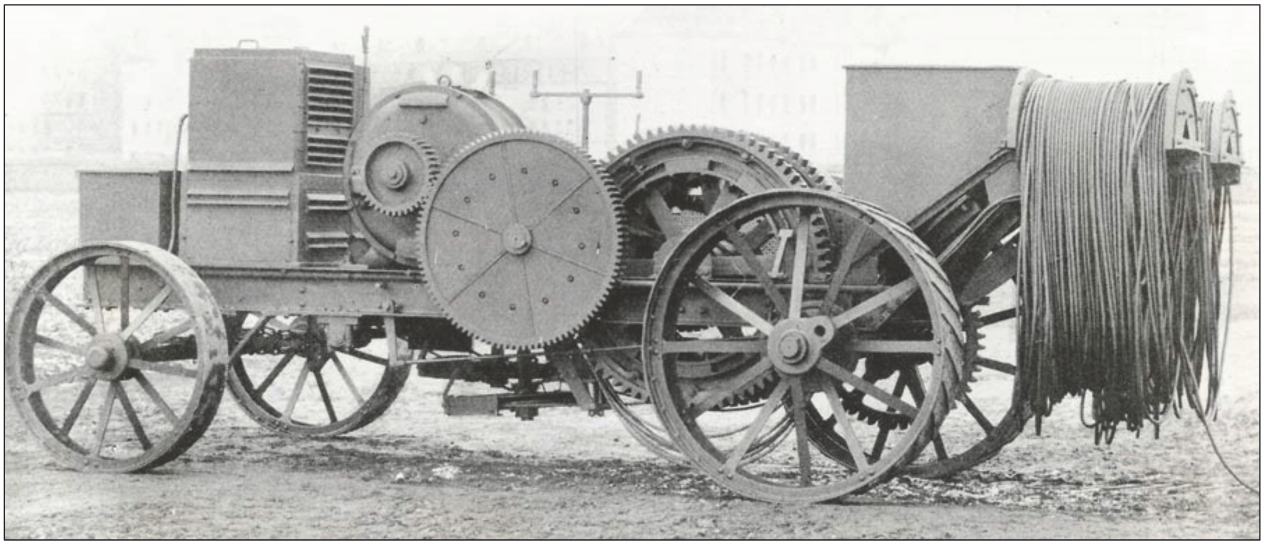


Figure 1. Brutschke electric cable tractor (Williams, 2019).

Figure 2. MELA, electric tractor transmission system, 2004 (left); eRoGator, electric sprayer with wheel-hub drives, 2010 (middle); Fendt X Concept, electrified tractor with 130 kW power generator, 2013 (right).

Table 1. Timeline of AGCO key high-voltage electrification projects and their technology focus, leading to the "BETTI" battery electric tractor concept and subsequently the Fendt e107 series version.

Project	Mela	eRoGator	X Concept	eFormer	Betti
Publication	2007	2009	2012	2015	2017
Description	Initial research on e-power drives	Sprayer with electric hub drives	Electrified tractor w 130 kW generator	Electric rake with two direct drive motors	Battery electric tractor concept
Key Technology Focus	Compact PMSM motor, coil cooling	SR motor and drive controls	Power dense generator	Integrated torque motors	Battery system and charging
	High voltage safety insulation concept	Electric wheel drive system	Integrated 700 V DC powerbus	Sensorless motor controls	Thermal management
	High performance mobile inverters	Thermo-management	Electric implement supply	Implement operation via app	Energy mgmt. and recuperation

Parallel to the technology and machine concepts, a "High Voltage Group 7" was initiated and officially started within AEF (Agricultural Industry Electronics Foundation) in 2011 to define necessary standards like voltage level, communication protocols, and physical interface designs for electrified tractor-implement systems. It is remarkable that the agricultural industry had already anticipated the need for higher power and voltage levels at that early time, creating a future-proof standard—it is only in recent times that these 700–800 V levels are becoming the new norm in automotive, driven by high-power fast charging needs and the cost reduction opportunities due to lower electrical currents and thus smaller diameters in wire harnesses.

Drivers and Opportunities

With the push to decarbonize the mobility and transport sector, substantial investments were allocated to electric drive as well as battery technology development, especially in the automotive sector with significant progress: Volumetric energy density of batteries has already made a leap and is anticipated to progress even further, weight came down significantly, robustness is proven at a viable cost, and–not least–the decarbonization of electric grid power around the world from coal, oil, and gas towards renewable sources makes great strides. The recent IRENA (International Renewable Energy Agency) report (IRENA, 2024) presents a cost comparison between fossil and renewable energy: "Renewable power is increasingly cost-competitive with fossil fuels–81% of renewable capacity additions in 2023 produce cheaper electricity than fossil fuel alternatives": Francesco La Camera, Director-General IRENA (fig. 3). The costs of battery storage projects declined 89%, from USD 2,511 per kWh to USD 273 per kWh between 2010 and 2023, the second critical building block and enabler for reliable, affordable, green electricity. A recent interesting indicator for the cost of grid storage systems came out of China in December 2024: The Power Construction Corporation of China (PowerChina) has attracted 76 bidders for its unprecedented tender of 16 GWh. The bids have attracted prices averaging USD 66.3 per kWh (Parkinson and Hill, 2024).

The concept work to design a fully electric, battery-powered tractor started in 2014 within AGCO/Fendt. While a common opinion at that time was that batteries would not provide sufficient onboard energy for practical agricultural tractors, there were three main drivers and perspectives that motivated a closer look:

- Global: Reducing greenhouse gas emissions and mitigating climate change requires alternative, clean energy powertrain solutions.
- Farmers: Opportunity to greatly benefit from the use of their own farm-born energy from solar, biogas, and wind with lower energy costs and better energy (and cost) independence.
- Manufacturers: Tightening emission regulations leads to growing challenges in terms of cost as well as the packaging of exhaust aftertreatment systems, in particular for small tractor platforms.

Battery electric tractors offer several benefits to farmers in field operations, in forestry, in greenhouses, for livestock, as well as for municipal use cases. As an outlook, electrification also supports the adoption of advanced solutions for improved productivity, efficiency, and sustainability on the implement and process side. An overall summary of the benefits and opportunities can be clustered as follows:

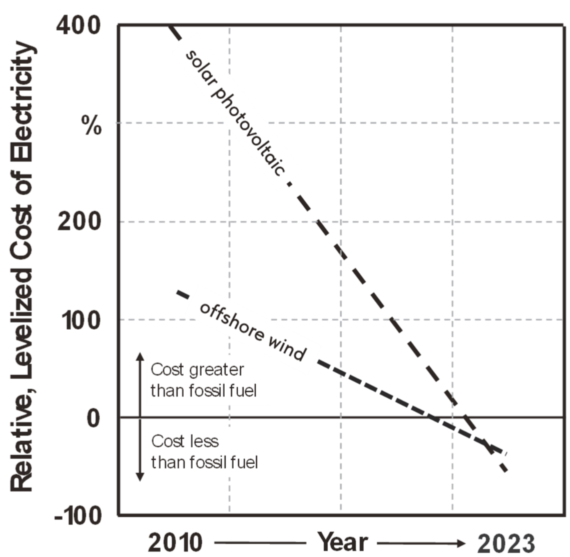


Figure 3. Levelized cost of renewable electricity (LCOE) production vs. fossil fuel. Development from 2010 to 2023 (IRENA, 2024).

- Environmental Benefits
  - Zero local emissions: for municipal use cases, in greenhouses and close to livestock.
  - Low noise: unique opportunities for electric tractors in residential areas.
  - Lower CO_2 emissions: during operation, down to zero when using renewable electricity.
  - Reduced product carbon footprint over lifetime.
  - Less risk of oil spillage or leakage, especially in forestry and field operations.
- Operational Benefits
  - Superior driving dynamics and strong torque from zero rpm.
  - Full compatibility with conventional implements while saving energy and CO_2.
  - Comfortable driving experience with low noise and vibrations.
  - Opportunities for more precise field operations with electrified implements (future).
- Economic benefits
  - Less maintenance: oil, filters, exhaust fluid, fewer moving parts, and less wear.
  - Reduced energy costs: significant advantage when using farm-born electricity.
  - Highly efficient driveline and energy recuperation.
  - Green production of food as a unique advantage and opportunity for premium pricing.

The environmental and economic benefits are driven by the high efficiencies of electric drive systems across a broad operating window. However, the full Well-to-Wheel (WtW) chain needs to be considered to assess various pathways. It is important to mention that values highly depend on tractor use, electricity production, infrastructure, load cycles, drivetrain design, and many other influencing factors and parameters; thus, the following values cannot be generalized. Also, the only focus on efficiencies is not necessarily an indicator of total sustainability (e.g., product carbon footprint). An indicative direction is presented in figure 4. The diagram is built around a reference diesel tractor with a 50 kW rated, mechanical crankshaft power.

With a diesel driveline, the biggest energy loss is at the thermal combustion process in the tractor diesel engine, with typically less than 40% efficiency (at full load) considering auxiliary systems of the engine. Full load WtW for the diesel tractor here is at 28%. For the electric tractor operated from grid electricity, the worst scenario is a fully fossil energy production system with the dominating thermal conversion losses (comparable to the diesel engine) taking place at power plants burning gas, coal, or oil. Since modern, large power plants still achieve relatively high efficiencies (here 38% Well-to-Battery including losses from grid transport and battery charging), the overall WtW efficiency can still be close to or even better than with a diesel tractor (here indicated at 30%). More renewable sources in the grid help to further boost WtW efficiencies. The best case is direct solar or wind electricity from on-farm production: it comes with almost negligible electricity transportation losses and

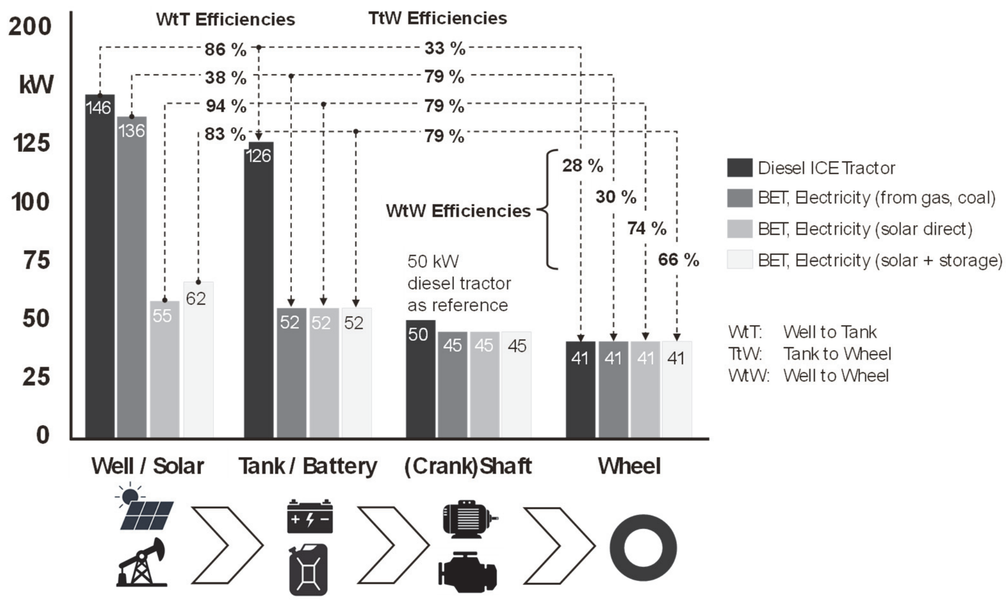


Figure 4. Well-to-Wheel efficiency indications for various energy pathways of a battery electric tractor.

delivers excellent WtW efficiency of approx. 74%, including charge/discharge losses and state-of-the-art electric drive systems. Even with an additional intermediate storage step (e.g., a stationary battery to manage demand and supply disparities), efficiencies are still about double (~66%) compared to the fossil energy path (grid or diesel) in the given system boundaries.

An energy cost comparison can be derived from such an efficiency table if using local up-to-date values for diesel and electricity on the input side and calculating towards the same amount of energy delivered at the wheel to pull implements (similar for PTO and hydraulics or mixed operations).

Feasibility Considerations

The fundamental challenge for battery electric tractors is the high energy demand of agricultural machines and the relatively low energy density of battery systems. The first aspect to research is thus the understanding of limits and influencing factors concerning the maximum possible on-board energy storage with a battery versus requirements from tractor use cases.

A very basic indicator used at the beginning to enable a research & development decision was the comparison of volume, weight, and cost for the complete diesel engine system (including the engine itself, air intake system, exhaust gas aftertreatment, fuel tank, and all related components) with state-of-the-art and anticipated battery-electric drive systems. The results indicated (in 2014) that at least a 50 kWh battery pack would be a feasible equivalent if the diesel engine system were to be replaced. At the same time, a significant positive trend for cost as well as technical parameters of batteries was already foreseeable and on its way for the upcoming decade.

Duty Cycles and Energy Storage

While duty cycles greatly vary across global use cases, figure 5 shows an indicative average relation between three standard tractor horsepower levels (50 kW, 150 kW, 300 kW) and daily operating hours as well as engine load factors (λ). This was derived from telemetry fleet data, simplified and consolidated to enable an analysis of battery electric tractor feasibility.

Engine load factor (λ) is defined as the utilized actual power relative to the installed rated engine power:

$$\lambda = \frac{P_{actual}}{P_{rated}} \tag{1}$$

The engine load factor as well as daily operating time directionally increases with rated engine power. This “law of growth” provides a first indication of opportunities and

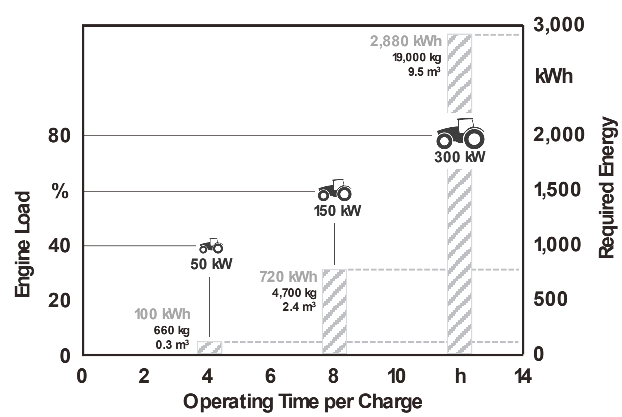


Figure 5. Electrical energy storage requirements for typical operating parameter sets of small-, medium-, and high-horsepower tractors. Estimates of battery volume and mass.

limitations for battery electric tractors looking at the respective energy needs and related battery size (volume, weight). Intermediate charging during the day was not included to develop a solid baseline. Not surprisingly, high-horsepower machines show high values for battery weight and volume; still, the growth rate over horsepower is surprisingly significant and not linear but close to a cubic relationship: a growth factor of 6 in power from 50 kW to 300 kW driving a factor of 33 volume increase, and factor of 30 weight increase (see values in fig. 5).

The battery weight and volume requirements relative to the gross (diesel) tractor weight and overall volume provide a more detailed perspective. Two diagrams can be developed: Figure 6a shows relative battery mass as a percentage of gross vehicle weight (conventional diesel tractor of the same power class). Figure 6b presents the battery volume relative to a tractor reference volume. A key challenge for the battery installation is the available space on a standard tractor. Different from automotive, the volumetric challenge is more difficult to solve than the gravimetric challenge (weight).

Due to large tires (incl. steering, suspension), visibility requirements, and cab for the operator, only a small portion of the total vehicle geometry is available for components and systems. From the side, top, and front views, a maximum of half of the outer tractor dimensions are usable as (gross) installation space. It is thus proposed to define the simplified reference volume $V_{reference}$ as follows:

$$V_{reference} = \frac{1}{8} * L * W * H \tag{2}$$

with L, W, and H being the overall outer dimensions of the tractor from its standard data sheet.

Because of increasing engine load factor (duty cycle, mentioned previously) and at the same time, increasing daily operating hours, there is a steep total increase of energy demand from low to high power tractors beyond the proportional growth according to nominal engine power. While it is obvious from this relative comparison that a 300 kW tractor (battery weight alone = 1.7 times the weight of the complete diesel tractor) will not be feasible, the lower power range with tractors around 50 kW is a practical possibility.

To generalize the question of whether a battery electric energy system and drivetrain is a realistic solution for a tractor of a specific power class, the data behind figures 5a and 5b is being combined with agronomic aspects (acceptable weight to avoid soil compaction) and packaging considerations (battery design flexibility vs. space claim of combustion engine, aftertreatment system, tank, etc.). The following paragraphs provide suggestions for a power limit assessment.

Volumetric Energy Density

Approximately 20% or less of the previously established reference volume is suggested as a realistic range for the battery volume in low horsepower tractors (0–50 kW), decreasing to 14% for high horsepower tractors (200 kW+) (fig. 6a). This is a consequence of over-proportional growth of tires with increasing power and thus less available space within the frame. Looking at today's battery pack densities of approximately 300 Wh/l standard tractors with 50–60 kW nominal power are feasible (solid line). With expected progress of battery technology and here volumetric density towards 600 Wh/l in 2030+, 100 kW tractors are within technical reach. A light gray hatched area outlines the expected additional installation space once a shift to purpose design architectures will take place (see chapter "conversion and purpose design"). E.g., if combined with robotics and autonomy technology, it is obvious that today's packaging limitations can theoretically be overcome by utilizing the cabin's space claim for energy storage. Tractors with 150 kW and even higher nominal power could be electrified (technical feasibility, volumetric density). An example of a purpose-design machine concept is a tractor integrating a 1,000 kWh battery with a cab-optional architecture (Van Erkelens, 2022).

Gravimetric Energy Density

In addition to the volumetric constraint, there is a gravimetric limitation. For low horsepower tractors (20–50 kW), a battery weight of max 20% of the reference tractor weight will lead to an acceptable total mass when offsetting with the

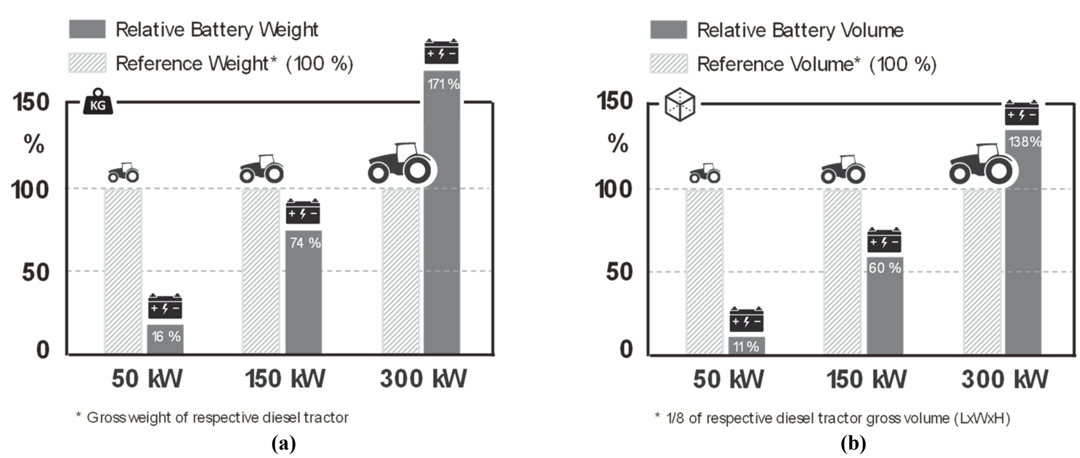


Figure 6. (a) Weight of battery vs. weight of comparable diesel tractor and (b) volume of battery vs. reference volume of comparable diesel tractor.

removed components from the diesel tractor. A slight increase towards 25% for high horsepower tractors (200 kW+) is acceptable since optimum tractive effort and wheel slip require additional ballast when performing heavy tillage, which is the critical use case for the overall battery energy demand (fig. 7, right). When considering a 300 Wh/kg energy density vs. approximately 150 Wh/kg today, 100–120 kW tractors will become a technical possibility.

Advancements in Battery Technology

Figure 8 presents an example of a 2016 study predicting climbing production volumes and correlating cost reductions driven by on-road applications (Randall, 2016). Values until 2015 are actuals; values from 2016 to 2030 are forecasts as predicted back in 2016. Today (2024) the global battery production is at 495 GWh p.a. for transportation (almost triple vs. the prediction from 2016). Expectation for 2030 is an annual production demand of 1,745 GWh (Li, 2021).

Since agriculture alone does not drive significant production volumes for battery cells and systems, on-road applications are and will still be the enabling trend. A study from 2021 summarizes expected volumetric as well as gravimetric energy density development of batteries at the cell level out to 2030 and takes already achieved improvements into account. Both parameters are expected to further advance significantly (König et al., 2021) (fig. 9).

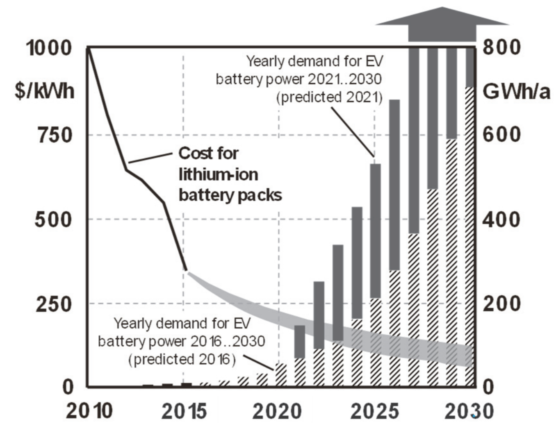


Figure 8. Global cost and demand prediction for electric vehicle batteries (Randall, 2016; Li, 2021, modified).

Conversion Design and Purpose Design

The starting point for the transition to electrification in vehicles is usually a conversion design concept based on existing platforms: most components of the diesel tractor driveline and other defining elements will be kept the same or similar, while the prime power source and energy supply convert to electric. For example, the diesel engine and all related systems will be replaced by an electric engine and battery. Transmission, axles, interfaces, general layout, etc. remain close to the original layout with minor adjustments.

"Purpose design" is a more radical approach: the whole vehicle architecture and the driveline are being developed and dedicated to battery electric optimization from scratch. This comes with higher costs and risks; for example, replacing a transaxle with its drive functionalities and structural tasks by electric wheel drives and alternative frame designs requires a completely new development and additional solutions for PTOs and hydraulics.

An exemplary comparison of a central drive design (conversion) vs. a distributed design (purpose) can be seen in figure 10. For a central drive design, the 50 kW installed electric motor power can be distributed mechanically as needed to front PTO, to the rear PTO, hydraulics, and rear wheels via transaxle (mechanical differential locks in the front and rear axle to shift side to side). In the case of a distributed drive system, the possibility to control torque and speed individually for all consumers provides new functional features. Packaging flexibility can be gained in the central frame area. However, as mechanical power distribution and differential locks are removed with the axle's bars, the torque transfer to individual wheels has to be replaced by over-sizing electric drive components. In critical use cases (tillage, slopes, etc.), each rear wheel might need to deliver up to 60% of the total tractor power. Also, the rear power takeoff (PTO) is expected to deliver full engine power. Combining these requirements with the other remaining auxiliaries and key functional drives (hydraulics, front PTO, and front axle), the total installed power of electric machines and

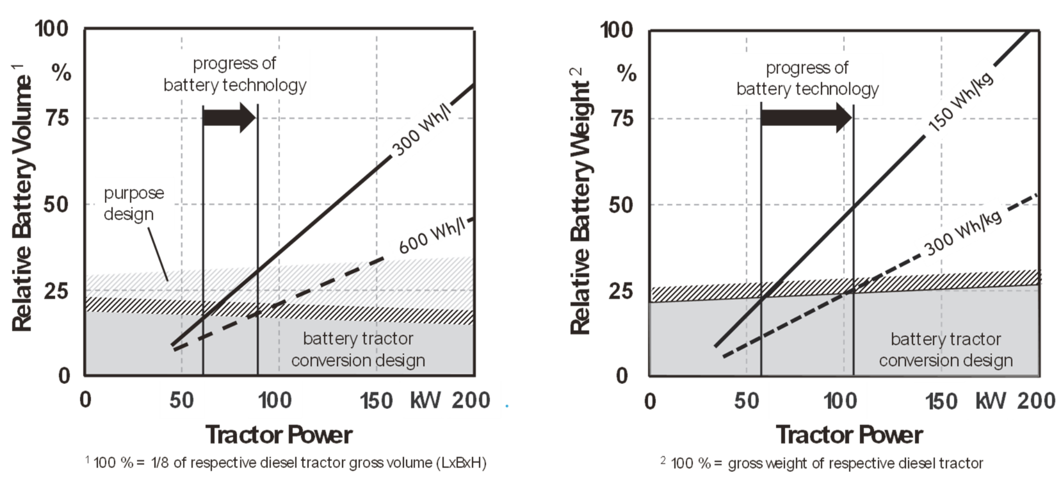


Figure 7. Limits of battery tractor feasibility considering installation space (left) and considering weight (right) of the battery at pack level.

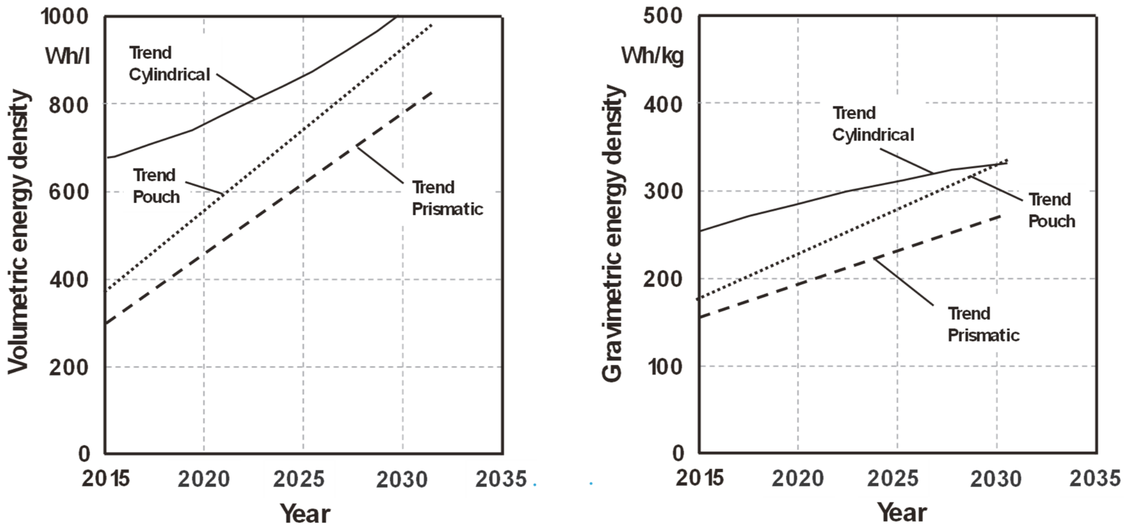


Figure 9. Development of volumetric (left) and gravimetric energy density at cell level between 2010 and 2030 (König et al., 2021, modified).

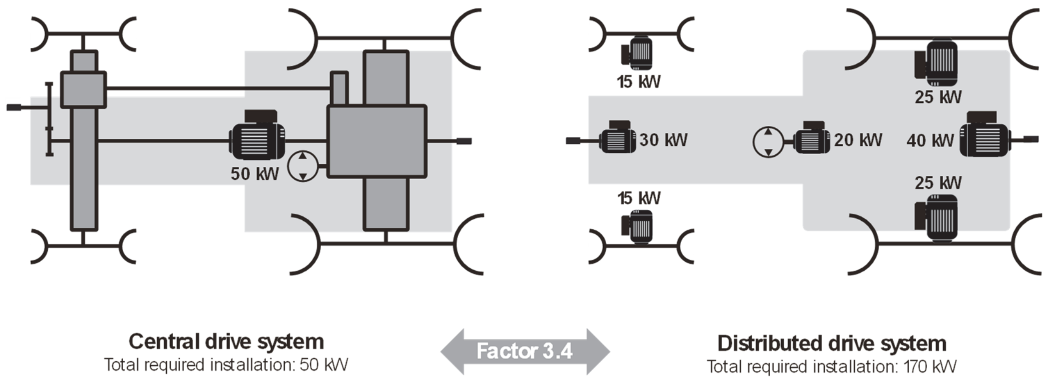


Figure 10. Comparison of central drive vs. distributed drive concept.

respective inverters sums up to more than 170 kW in the case of a tractor with 50 kW nominal power (table 2). This is a factor of 3.4 compared to the central drive solution with its single 50 kW (like in a standard diesel ICE layout) and has, as such, substantial consequences for the total system cost. A functional advantage of the distributed electric drive system is the possibility to parallelize power flow and allow for higher total performance. For example, provide full power to the traction drive and the same to the PTO for implement drives. The operating range, however, will be significantly reduced in such cases and will not be sufficient for permanent field work. Short time boosts around 10%–20% (seconds to a few minutes) are possible and do not affect overall operating time significantly. Flexible speed and torque management can be an advantage for specific operating conditions like tight turns with full steering angle at high pull.

Table 2. Required power installation for electric drives - central vs. distributed concept. Absolut power values and percentage of nominal tractor engine power.

Nominal Tractor Power	Central Drive (conversion) 50 kW	Distributed Drive (purpose) 50 kW
Rear PTO	-	40 kW (80%) + 10 kW boost
Rear wheel (each)	-	2 x 25 kW (2 x 60%)
Front wheel (each)	-	2 x 15 kW (2 x 30%)
Front PTO	-	30 kW (60%) + 10 kW boost
Hydraulic pump	-	20 kW (40%)
Total required installation	50 kW	170 kW

Concept Requirements

Voltage level

One of the first key decisions for the design of a battery-electric tractor (BET) is the operating voltage level. Table 3 shows the used nominal system voltage of typical industries today.

Urban public transportation systems or powerful special machinery like mining dumper trucks are using voltage levels of 1,500 VDC or up to 3,000 VDC. These kinds of systems are dedicated designs for special use cases and normally produced in low volumes. Also, the key semiconductor components in these designs are very specific and high cost.

The voltage level of up to 800 VDC is typically used by all types of off-road vehicles and long-haul trucks and buses. More recently, automotive high-end/high power vehicles are moving from 400 VDC to 800 VDC, especially to allow boost charging of up to 350 kW and thus reduce charging stop times.

The standard voltage level in small- and medium-sized cars is 400 VDC. This voltage level has the most volume behind it and allows the assumption to be the most cost effective.

Table 3. Typical use of nominal voltage levels per industry.

Typical Industry Use	Nominal Voltage
Metros, Trams, Mining Construction Equipment	1,500 VDC / 3,000 VDC
Construction Equipment, Off-Road Vehicles, Truck and Bus, Automotive Drivetrain (High End)	800 VDC
Automotive Drivetrain (Standard)	400 VDC
Automotive Auxiliary Drives, mild hybrid	48 VDC

In the lower end, the 48 VDC level is commonly used for automotive auxiliary drives and is widespread in mild hybrid cars. The major advantage of this voltage level is that the safety requirements are as low as for classical 12/24 VDC systems. 48 VDC was selected by the automotive industry to stay under all circumstances below 60 VDC, which is worldwide defined as the safe level for all human beings.

To select the most appropriate voltage level to design a BET, the power range of the vehicle is of high importance. Figure 11 shows the necessary current flow for power levels in dependence on the selected voltage. The higher the voltage, the lower the necessary current flow to reach the same power.

The current flow is a major design parameter for the interconnection (cable harness) of all drivetrain and auxiliary components. The following list shows that a design for minimized current flow is very beneficial:

- Connectors with high current capability are very rare, expensive, and have high space needs.
- Current flow restrictions can have severe impacts:
- Strong cable heat-up, connector melt-down, efficiency losses, and power restrictions.
- The cable diameter strongly drives the specified and allowed bending radius. This leads to challenges in overall vehicle system cabling.
- If cable weight exceeds certain limits, the production line faces challenges to attach harnesses to the vehicle.

Moreover, the operation at lower current results in smaller, lighter components and longer component life. A basic guideline for voltage level selection for agricultural tractors is to use 400 V for the power range of 20 kW to 50 kW. For 50 kW and above, the selection of 800 VDC is most appropriate. For lawn mower-sized vehicles up to subcompact tractors below 20 kW, the choice between 48 VDC and 400 VDC depends less on technical reasons but more on strategic, platform, or service requirements.

To meet the proposals of the AEF working group "High Voltage," 700 VDC +/- 10% is the recommended voltage level for all agricultural tractors (e.g., to enable future-proof implement compatibility with the defined electric power take-off interface).

Further, fundamental requirements for a proof of concept (PoC) battery tractor development were defined at an early stage of the process at AGCO/Fendt and are summarized in table 4. These requirements could basically be kept as the project moved forward to industrialization in a series development project leading to the Fendt e107 battery electric tractor platform.

Drivetrain Architecture

Figure 12 presents a system schematic of major drive system components (simplified) of the Fendt battery electric tractor concept. A central electric permanent magnet synchronous motor is connected to a continuously variable transmission, distributing the mechanical power to front wheel drive, a hydraulic pump, the rear PTO, and the rear axle. The electric motor offers a direct output shaft to the front PTO gear. Cooling components are installed in front of the battery. A thermal management system provides all required cooling and heating. Two fan drives operate at 12 VDC and supply the respective heat exchangers. A power distribution unit, which interlinks the high-voltage components, is fixed next to the CCS2 (Combined Charging System Type 2) connector on the left vehicle side that offers AC (22 kW) and DC (80 kW) charging. For AC charging, an onboard charger is installed on top of the battery housing. A DC/DC converter powers the 12 VDC circuit and charges a small 12 VDC battery used to buffer this low-voltage circuit and support the startup process of all electronic systems.

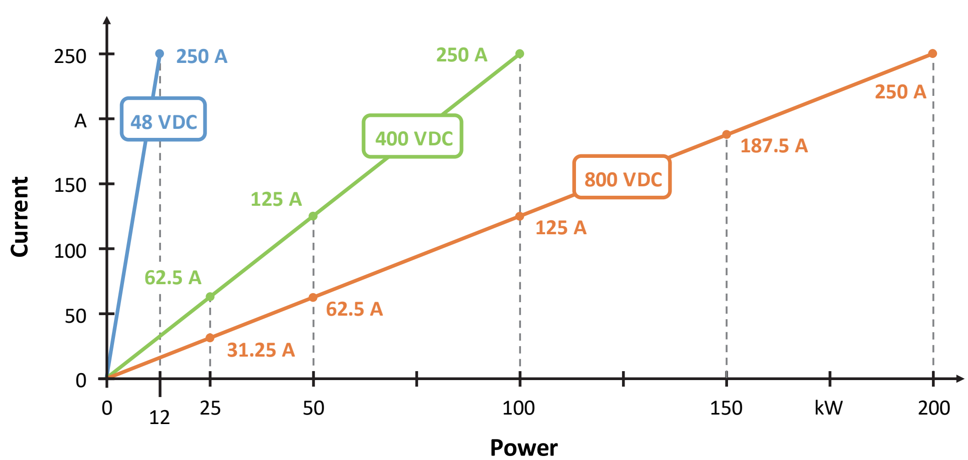


Figure 11. Power vs. current flow.

Table 4. Selected key requirements for a Battery Electric Proof Of Concept (predecessor of the Fendt e107).

Requirement	Value
Power	50–60 kW (expand below existing Fendt 200 series)
Implements	Compatibility with all current implements; evaluate electric supply (700 VDC)
Charging	Matching typical infrastructure (e.g., 400 V, 3-Phase), fast charging option
Range	Minimum 4 hours for a typical duty cycle
Weight	Max 10% above comparable diesel tractor
Drive System	Vario CVT conversion design (high efficiency, best cost, market acceptance)
Carbon Footprint	Significant life cycle reduction of at least 50% to comparable diesel
Other	Energy recuperation, remote app for pre-conditioning (cab, battery)

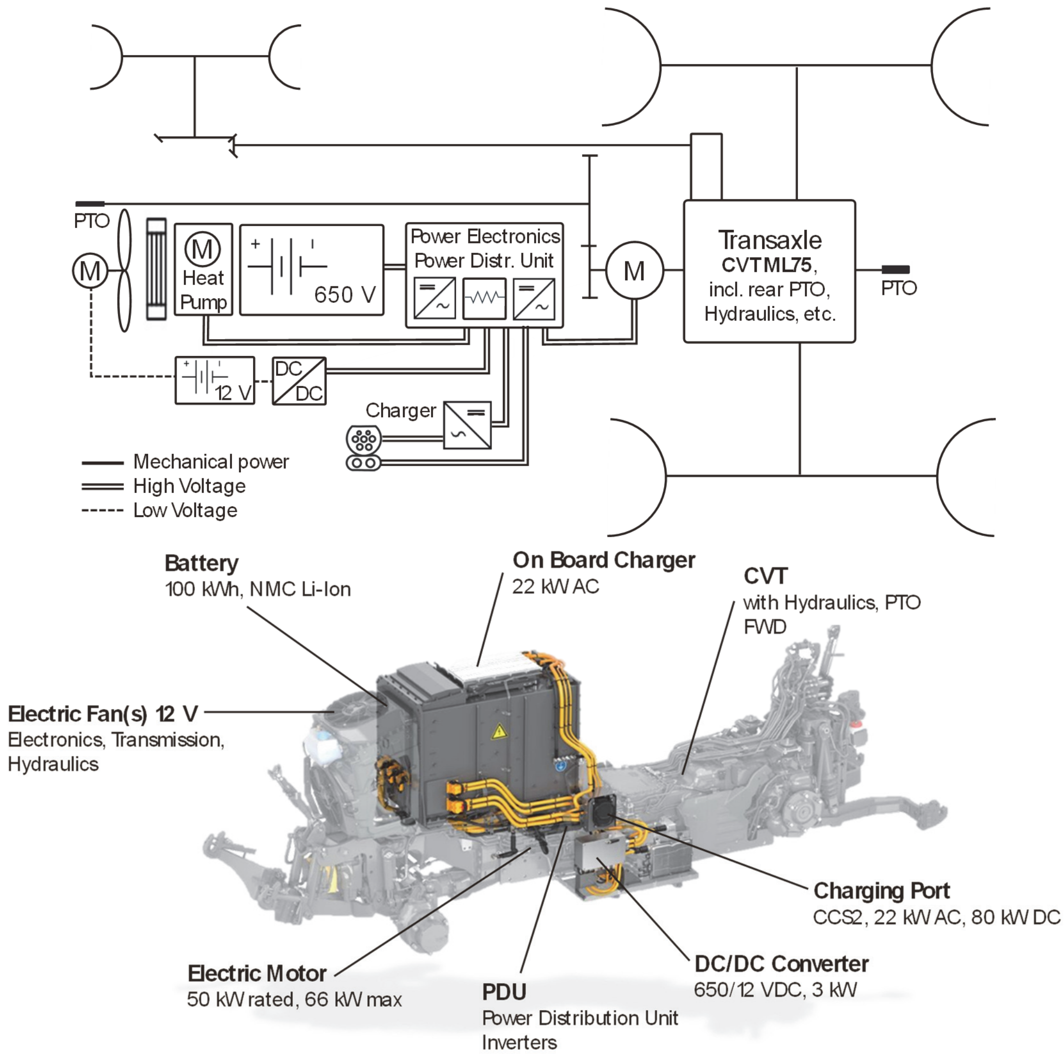


Figure 12. Simplified drive and energy system layout of the Fendt battery tractor concept (top) and the Fendt e107 tractor structure with location of the main electric components (below).

Electric floor, window, and seat heating provide a comfortable, yet efficient conditioning of the cabin (not in schematic). A high-efficiency heat pump system was tested to analyze the technology for tractors.

Feasibility Conclusion and Outlook

Combining the proposed relative weight and volume limits and considering a technical battery development according to forecasts (600 Wh/l and 300 Wh/kg at pack level), battery electric tractors with 100 kW rated power will become technically feasible. Purpose design architectures will open new opportunities to push these limits further out to 120 kW and beyond. The cost for battery systems, electric drives, and high-voltage components will define commercial viability while infrastructure (grid, chargers, green electricity) will likely be a limiting factor approximately until the end of the 2030s for many regions. A high DC link voltage level of 700 VDC +/- 10% is recommended at least for 50 kW and higher nominal power to enable electric tractor-implement connections according to the AEF standard. Starting the transition to battery electric tractors with a conversion design approach provides a reliable and cost-effective design while unlocking efficiency benefits and ensuring compatibility with existing implements.

Technical Modules and Design Principles

Battery

Over the past years, lithium-ion based batteries have improved greatly in performance hand in hand with significant cost reductions. However, many applications, including agricultural tractors, still demand higher energy capacity, less weight, lower cost, longer life cycles, improved safety, and stable supply chains.

The battery is the major component of a battery-electric drivetrain and influences directly or indirectly most of the performance parameters of the overall vehicle. As the design of a battery is very complex, this paper shall only cover some important battery design aspects.

Cell Chemistry

The selection of a lithium-ion battery cell chemistry is one of the most important decisions in an early design phase. The cell chemistry defines many parameters like total capacity, power output, cycle life, cost-effectiveness, thermal stability, or availability of rare-earth metals in the supply chain. There is no clear standard for cell chemistries, as this is well-protected knowledge of worldwide cell manufacturers.

Basically, the cathode material is defining the name of the cell chemistry, whereas today's anode material is typically graphite. There are two main chemistries in mass production for EVs today:

- NMC – Lithium Nickel Manganese Cobalt Oxides.
- LFP – Lithium Iron Phosphate.

Another chemistry is currently entering mass production and is expected to take a significant role:

- LMFP – Lithium Manganese Iron Phosphate

Table 5 shows a comparison of generic design parameters of NMC, LFP, and LMFP chemistries. For high-end applications, NMC is still the standard, whereas LFP becomes a dominating chemistry, particularly in the Chinese EV market.

Agricultural tractors have a very high energy demand due to the nature of their operation. On the other hand, space, especially combined design volume, is extremely scarce due to the limitations caused by implementing mounting interconnections like front-hitch, rear-hitch, or front-end loader consoles. Therefore, a typical agricultural tractor design only allows in a limited volume to add battery capacity (see chapter "feasibility considerations"). These boundary conditions are a strong driver towards NMC cell chemistry with its superior energy density.

As battery technology is a key future market, high research and development efforts are spent on a worldwide level. Therefore, there are several promising chemistries to come, like solid-state, sodium-ion, or silicon-anode, just to mention a few. After industrialization, the future will show which emerging chemistries will be the right choice for agricultural machinery.

Cell Format

Besides the chemistry of the cells, the cell format is another key decision in the design phase. There are three main cell formats in mass production:

- Cylindrical (e.g., 18650, 21700, or 4680)
- Prismatic
- Pouch

Each cell format has its unique strengths and weaknesses, making them suitable for different applications. Decisive performance indicators are energy density, heat dissipation, number of welding connections, space optimization, complexity of assembly, durability, mechanical stress, thermal extension, and more. Figure 13 illustrates the shape of each cell format.

The electric car manufacturers are using all types of cell formats in their products today. For commercial vehicles like trucks, buses, and larger construction equipment, there is a clear trend towards the prismatic cell format. One reason behind this is the need for large battery capacities per vehicle, ranging from 100 kWh up to 600 kWh for long-haul trucks. A prismatic cell has the capacity of multiple cylindrical cells in one stable package, which is a valuable advantage in the production process of large-sized batteries. Another advantage is the cuboid shape, which allows the available volume to be as efficient as possible in combination with an efficient cooling (and heating) system.

A superior cell format for battery electric tractors cannot be defined today. Every cell format seems to be packageable in a way that the appropriate requirements towards vibration, shock resistance, and others can be fulfilled, of course with variations in effort-benefit ratio.

Battery Pack

A typical modular setup of a battery is to design out of single cells a battery module with dedicated properties. N battery modules in serial or parallel interconnection form a battery pack, which is basically the battery. All battery modules can be placed in one or more housing units to optimize volume, weight distribution, or other factors, which are

Table 5. Generic comparison of NMC, LFP, and LMFP battery cell chemistries.

Parameter	Unit	NMC	LFP	LMFP
Nominal Voltage	VDC	3.6–3.7	3.2–3.3	3.5
Energy Density	Wh/kg	150–250	90–160	160–180
Cycle Life	n	1,000–2,000	2,000–4,000	3,000–5,000
Safety	-	medium	high	high
Cost	-	medium to high	low	medium
Thermal Stability	-	medium	high	high
Typical Applications	-	EVs, power tools, medical devices	EVs, stationary energy storage	EVs, stationary energy storage
Charge / Discharge Rate	-	medium	high	high

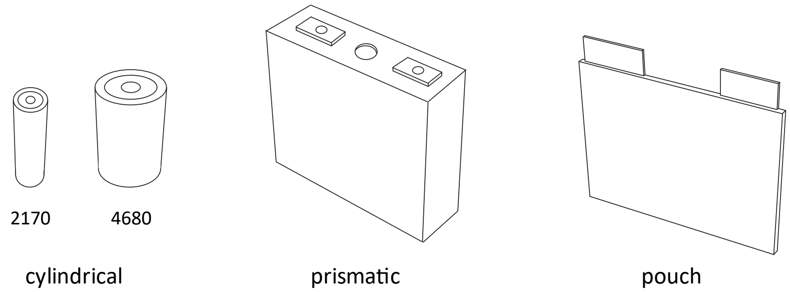


Figure 13. EV battery cell formats.

important for the design of agricultural tractors. Figure 14 illustrates an exemplary setup of a battery pack with a resulting nominal voltage of 648 VDC. The nomenclature for serial and parallel connection of cells is the following:

$$\begin{aligned} &|\text{number of single cells in series}|\ \text{s} \\ &|\text{number of parallel connections}|\ \text{p} \end{aligned} \quad (3)$$

The connection of cells inside a pack is heavily dependent on the requirements of the overall system. The automotive industry is typically not using cell-to-module-to-pack setups, rather than cell-to-pack designs to optimize cost and production. This high level of optimization is very expensive and needs a very high production volume to become efficient.

Due to the restricted design volume for batteries in agricultural tractors, a maximized battery capacity seems to be only achievable with specifically designed battery packs. Nevertheless, the optimization of battery capacity might not always be the main focus. Another possibility is to "build the tractor around the battery pack," which has the potential to catch limitations for other requirements.

An exemplary battery pack, consisting of NMC cells in 180s1p configuration, is depicted in figure 15. The different colors show normal operating voltage levels in green, exceeding operational limits in light and dark orange, and very critical values in light and dark red.

The resulting operating voltage level in dependency of technical state-of-charge is shown in table 6. The overall system needs to strictly stay between lower and upper operation voltage limits over the whole lifetime (green color area). In case of undervoltage, being equal to a deep discharge, there is a high risk for irreversible damage and enduring capacity loss. Even more critical is the overcharging of NMC chemistries, which yields with high probability to an excessive thermal runaway.

Battery Power Delivery

The rated power of agricultural tractors is generally measured on the power take-off (PTO). Combustion engine design tractors typically provide power directly from the crankshaft by belt drive to auxiliary consumers like cooling fan, air compressor, climate compressor, alternator, or water pump. These auxiliary drives normally cannot be disconnected and are part of the rated power measurement.

In a battery electric tractor drivetrain, selected auxiliary consumers are electrified as well and can be switched as needed on an individual basis. From a battery power delivery point of view, the auxiliary drives also need to be supplied in addition to the rated power. As an example, a BET with rated power of 50 kW and an additional power requirement of 10 kW for auxiliary consumers' needs to provide a continuous power of 60 kW.

The battery as well as the overall electric power distribution network needs to be designed and capable of providing the full power over the full range of TSoC. Figure 16 illustrates the inverse correlation between voltage and current at constant power. Especially the design to fully cover the current flow is critical; otherwise, a derated power at lower TSoC levels will be the consequence.

An inherent property of agricultural tractors with internal combustion engine (ICE) is the supply of full continuous power until the last drop of diesel is used. To ensure the same

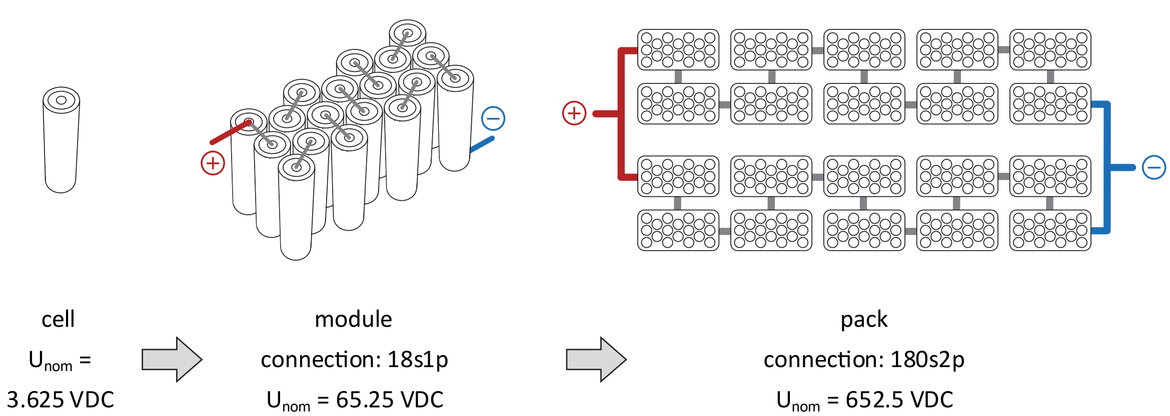


Figure 14. Example of cell connection inside a battery pack.

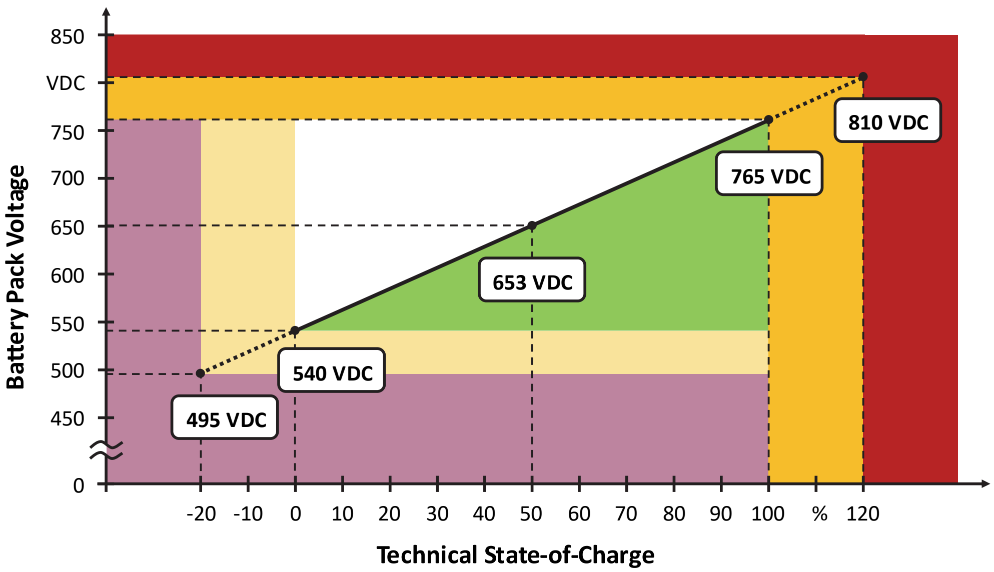


Figure 15. Voltage level vs. TSoC of exemplary 180s1p NMC battery pack.

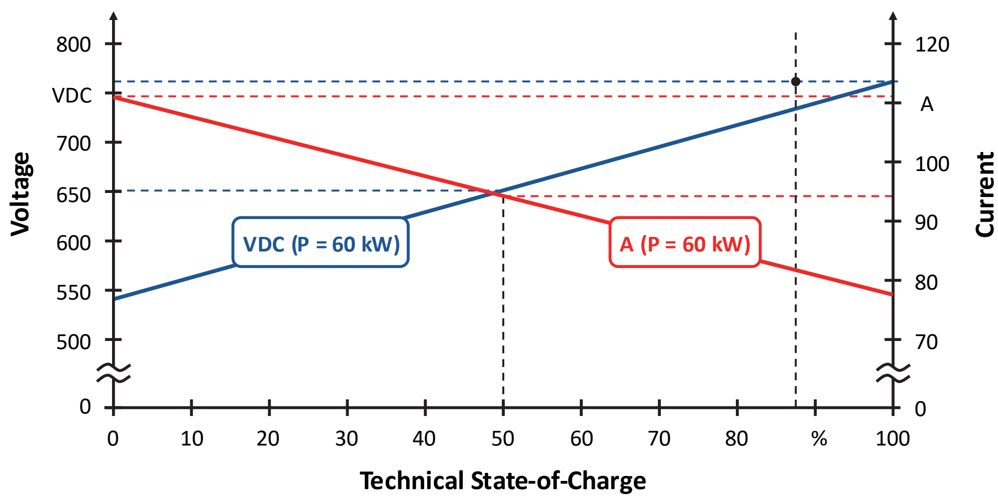


Figure 16. Current and Voltage vs. TSoC for constant power delivery of 60 kW.

Table 6. Voltage levels of NMC cells and pack at different Technical SoC (TSoC).

Technical SoC	NMC cell	180s1p Pack	Note
-20%	2.75 VDC	495.0 VDC	Critical undervoltage, high risk for irreversible damage and capacity loss
0%	3.00 VDC	540.0 VDC	Lower operation voltage limit
50% (nominal)	3.63 VDC	652.5 VDC	Nominal voltage
100%	4.25 VDC	765.0 VDC	Upper operation voltage limit
120%	4.50 VDC	810.0 VDC	Critical overvoltage, high risk for thermal runaway and component damage

behavior with battery electric tractors, the overall design needs to especially take care of low TSoC values and hence high current flows. In real-world operation of BETs, a new technical symptom could occur, where tasks like plowing or seedbed cultivation cannot be done with equal performance over all states of charge of the battery.

Lifetime Energy Throughput

To cover the full lifetime of a tractor with a single battery, the calculation of the total lifetime energy throughput is important. Table 7 shows key parameters to roughly calculate the operating lifetime energy throughput of a 50 kW sized tractor resulting in 200,000 kWh.

In addition to this basic calculation, a percentage markup of 5% is recommended to cover additional energy consumption like battery heat-up in cold conditions, battery self-discharge, cabin preconditioning, and likewise. This ends up in an overall lifetime energy throughput of 210,000 kWh and is a key specification parameter for the battery.

The reuse of a passenger car battery in agricultural tractors is not recommended as the energy throughput is by factors smaller in comparison to a tractor. Table 8 shows a basic calculation of a typical medium-sized passenger car with

Table 7. Tractor (50 kW) lifetime energy calculation.

Tractor Parameters	Unit	Value
Design lifetime	hours	8,000
Continuous power	kW	50
Average load factor	-	0.5
Operating lifetime energy throughput	kWh	200,000

Table 8. Passenger car (medium-sized, 100 kW) lifetime energy calculation.

Passenger Car Parameters	Unit	Value
Design travel distance	km	250,000
Continuous power	kW	100
Average energy consumption per 100 km	kWh	20
Operating lifetime energy throughput	kWh	50,000

100 kW installed power. The lifetime energy throughput in this particular comparison is only 1/4th of the tractor. The major difference is the average load factor, which is way smaller in a passenger car compared to an agricultural tractor which is designed to pull heavy loads all day long.

Charging Cycle Life

The last battery design aspect to be considered in this paper is the battery charging cycle life. Based on the lifetime energy throughput, the charging cycle capability of the battery is a main influencing factor for the overall tractor lifetime expectation (N. N., 2024).

The cycle life of a battery is the number of charge/discharge cycles before its capacity significantly degrades. Neither the value of significant degradation nor the end-of-life of a battery are standardized values in this context. In literature (Engel et al., 2019), it is suggested to define end-of-life if the battery no longer maintains 80% of total usable capacity and has more than a 5% self-discharge rate over a 24-hour period.

A full charging cycle is defined to be one complete discharge and one complete recharge of the total battery capacity. To count charging cycles, fractions of cycles can be summed up to full charging cycles. The cycle life is a complex parameter of a battery, as several environmental conditions like temperature, age, charging speed, cell balancing, and more do have significant influence. In the following, the NMC chemistry is in focus, but many generic parameters are basically valid for all chemistries.

An exemplary BET with 50 kW rated power and 8,000 operating hours has an energy lifetime throughput of 210,000 kWh, as calculated before. Covering the whole lifetime with a single battery of 100 kWh capacity results in 2,100 full charging cycles. A battery with a capacity of 50 kWh requires 4,200 charging cycles, whereas a 150 kWh battery requires only 1,400 charging cycles. This simple calculation shows clearly how important the interaction of battery size, chemistry, and cycle life is to cover the tractor's lifetime expectation as well as for the value preservation of used machines.

The cycle life of a battery is surely defined by the chemistry, but also other conditions do have an important impact. Table 9 shows influencing factors as well as the corresponding responsibility.

A key role is played by the Battery Management System (BMS) of the battery in combination with the thermal management of the tractor. The BMS is the control and monitoring electronics of a battery and needs to ensure a safe and secure operation over its lifetime. A wide range of functional safety requirements (e.g., based on ISO 25119 for agricultural tractors) are to be implemented in the BMS, like prevention of overcharge, deep discharge, or overheating. Also, cell monitoring and periodic rebalancing of cells are the responsibility of the BMS. Intelligent algorithms with the BMS help to mitigate some of the negative effects of fast charging by monitoring and managing the temperature, voltage, and current during charging in dependence on SoC.

Besides technical solutions, the user can also influence the cycle life of a battery to a strong degree. Especially the charging behavior is of great importance. Whereas the gentle speed of AC charging is ideal for overnight use, DC fast charging is suited for fast recharge cycles during the working hours. Whenever time allows for charging with moderate speed, this is the right choice to maximize cycle life. Another influencing factor in control of the user is the ambient temperature whilst charging. Of course, this is also considered by modern BMS control algorithms, but only the user can move the tractor under cold or hot environmental conditions to other locations like buildings or out of direct sunlight.

Charging

Unlike refueling a traditional fuel tank, the charging of EV batteries requires interacting with external infrastructure and handling associated versions of charging standards. The worldwide electrical grid varies by many parameters, like single-phase or three-phase design, voltage levels, alternate current frequencies, and many other design and legal requirements. To cover all regions of the world with one design is principally not possible, but an intelligent split of system parts allows for the design of single modules as region-specific variants.

State-of-the-Art

The charging of BEVs can systematically be split into two technical solutions:

- Alternate Current (AC) charging, and
- Direct Current (DC) charging.

Figure 17 shows a representative charging infrastructure from grid to BET via the CCS2 standard. Both AC and DC charging options are technically represented in this setup.

For AC charging, a Wallbox or special cables are connected to the household/operational infrastructure. An On-Board Charger (OBC) is used as a counterpart on the vehicle-side. The OBC is an AC/DC converter to provide direct current to the battery. Typical charging power levels of OBCs are 11 kW or 22 kW.

DC charging represents the fast-charging option and currently reaches power levels of 50 kW to 350 kW. In this case, the AC/DC converter is part of the Electric Vehicle Supply Equipment (EVSE). The vehicle needs to communicate due to ISO 15118 via Control Pilot (CP) and Proximity Pilot (CP) and must take care of locking the charging plug and switching the DC charging contactors safely under all conditions.

Table 9. Influencing factors on battery cycle life.

Influencing Factor	Description	Responsibility
Overcharging	It needs to be technically ensured that charging is stopped at the upper voltage level.	BMS
Optimal SoC	Ideally, the battery is kept within the range of 20% to 80% SoC.	User
Proper Temperature	The battery needs to stay within recommended temperature range of +15°C to +25°C.	BMS / Thermal Management
Deep Discharge	In dependence on cell chemistry, a deep discharge usually harms the battery significantly.	BMS / User
Balancing	Cell balancing is a specific operational mode to influence the voltage of single cells. All cells shall be on an "as equal as possible" voltage level.	BMS
Storage when not in use	If not used for longer periods, the storage of a battery is recommended at around 50% SoC in normal ambient temperature conditions.	User

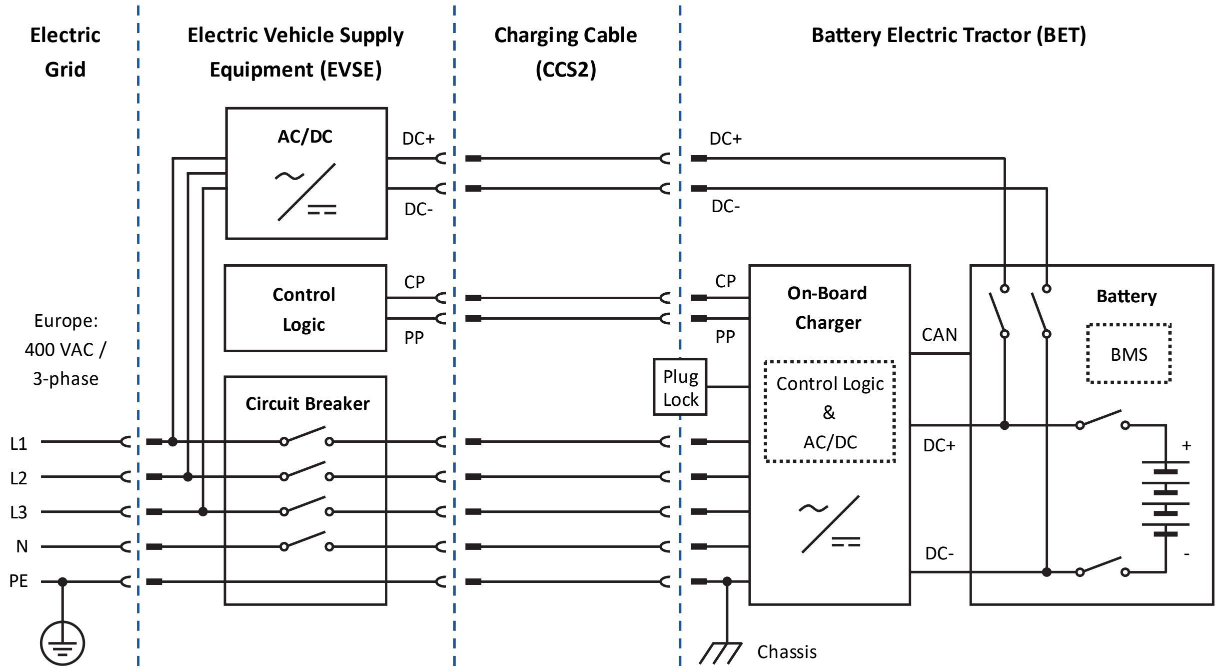


Figure 17. Representative charging infrastructure from grid to BET via CCS2.

Charging Standards and Connectors

With the growing importance of BEVs over the past decade, the charging infrastructure has evolved in parallel. Spread over the world's major automotive industry regions—North America, Europe, Japan, South Korea, and China—several worldwide standards for charging infrastructure and connectors were specified. Table 10 shows the most important system parameters, like connector interface, voltage, current, and power levels for AC charging.

For DC charging, often called rapid (> 50 kW) charging or ultra-rapid/high performance charging (> 150 kW), table 11 provides a worldwide overview.

Especially Tesla, with its full focus on electric cars and charging infrastructure, has set in NA and partly in Europe a quasi-standard. The Tesla connector with different communication (from CAN to CP/PP) is currently in standardization (SAE J3400) to become the publicly called North American Charging Standard (NACS). Besides Tesla's company-specific charging infrastructure, other NA carmakers launched their products based on Combined Charging System Type 1 (CCS1). Based on broad automotive industry support, it is likely that NACS will become the dominant standard in NA over the next few years.

In Europe, the Combined Charging System Type 2 (CCS2) is the widespread standard for AC and DC charging. CCS2 is legally mandated for DC charging in the European Union.

Asia needs to be split into China and Japan/South Korea. Whereas Japan and South Korea have adopted CCS1 for AC charging, the CHAdeMO association (TEPCO, Nissan, Mitsubishi, Subaru, Toyota, etc.) specified its own DC charging standard. The current version (CHAdeMO 2.0) supports a charging power of up to 400 kW. China, with its increasingly strong role in EVs and battery technology, has defined its own standards for both AC (GB/T 20234.2-2015) and DC (GB/T 20234.3-2015) charging. GB/T 20234.3 is the legally mandated DC fast-charging standard in China.

Public Charging Stations vs. Farmyard Charging

Agricultural farm equipment and machinery are used in rural areas. Refueling of today's ICE machinery is almost always done at the farmyard, or even fuel is transported to the field to maximize runtime in main working seasons like spring seed. Therefore, it is also an important requirement to charge battery electric tractors at the farmyard rather than at public charging stations.

Table 10. Worldwide charging standards and connectors for AC charging.

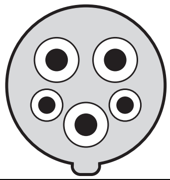
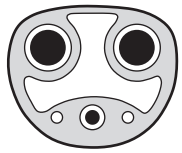
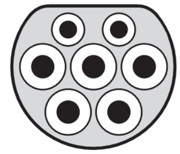
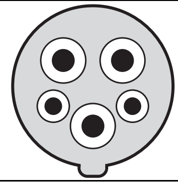
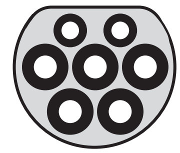
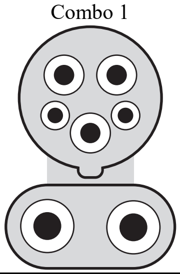
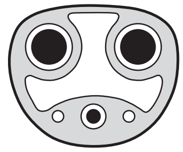
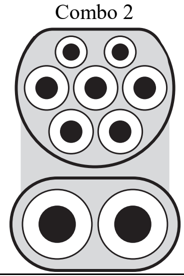
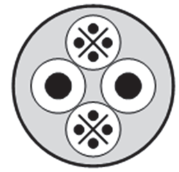
	North America	North America	Europe	Japan / Korea	China
Name and Standard	Combined Charging System Type 1 (CCS1) SAE J1772 / IEC 62196-2	North America Charging System (NACS) SAE J3400	Combined Charging System Type 2 (CCS2) IEC 62196-2	Combined Charging System Type 1 (CCS1) SAE J1772 / IEC 62196-2	GB/T 20234.2 - 2015
Connector Interface					
Communication	CP / PP	CP / PP (Tesla: CAN)	CP / PP	CP / PP	CC / CP
Number of Phases	single phase	single phase	single or three phases	single phase	single phase
Max Voltage	120 VAC / 240 VAC	240 VAC / 277 VAC	240 VAC / 400 VAC	120 VAC / 240 VAC	250 VAC / 440 VAC
Max Current	80 A / 80 A	48 A / 80 A	16 A / 63 A	80 A /80 A	32 A / 63 A
Max Power	9.6 kW / 19.2 kW	11.5 kW / 22.1 kW	3.8 kW / 43 kW	9.6 kW / 19.2 kW	8.0 kW / 27.7 kW

Table 11. Worldwide charging standards and connectors for DC charging.

	North America	North America	Europe	Japan / Korea	China
Name and Standard	Combined Charging System Type 1 (CCS1) SAE J1772 / IEC 62196-2	North America Charging System (NACS) SAE J3400	Combined Charging System Type 2 – CCS2 IEC 62196-2	CHAdeMO 2.0	GB/T 20234.3 - 2015
Connector Interface	Combo 1 		Combo 2 		
Communication	CP / PP	CP / PP (Tesla: CAN)	CP / PP	DCP / PP and CAN	CAN (SAE J1939)
DC Lines	DC+ / DC-	DC+ / DC-	DC+ / DC-	DC+ / DC-	DC+ / DC-
Max Voltage	1,000 VDC	500 VDC or 1,000 VDC	1,000 VDC	1,000 VDC	750 VDC to 1,000 VDC
Max Current	500 A	not specified / (105°C limit)	500 A	400 A	250 A
Max Power	350 kW	> 250 kW	500 kW	400 kW	250 kW

To install a farmyard charging station, the available electric infrastructure and the necessary investments and installation expenditures are fundamental. AC charging with up to 22 kW can be covered by the existing infrastructure without large investments in most regions of the world.

DC charging is very likely to be limited to lower power levels of 40–80 kW without upgrading the electrical infrastructure.

Generally, the energy supply to EVs and BETs on a farmyard level is very individual, and the most suitable solution largely depends on given boundary conditions like the capability to self-produce energy with photovoltaic or biomass power plants and available storage capabilities.

Thermal Management

The thermal management of a BET differs significantly compared to ICE tractors. ICE cooling circuits typically run on a water-glycol mix with a temperature of ~10°C below the water boiling point of 100°C. The following list shows some typical characteristics of ICE cooling circuits:

- Passive cooling principle against ambient temperature.
- All auxiliary components are designed to cope with temperatures up to water boiling point.
- Cooling circuit components like the fan, water pump, and air-conditioning compressor are belt-driven and work only when ICE is running.

- High cooling power demand due to high waste heat of ICE.
- High load/fast switch-off scenarios may stress and overheat components.
- Waste heat is reclaimable for cabin heating under cold environmental conditions.

In summary, the cooling system and auxiliary components of ICE-based tractors have matured over decades and are a decisive system to allow continuous high-load operations.

The thermal management of battery electric tractors also plays a key role in ensuring safe operation and allowing full performance under all environmental conditions. The battery, as the heart of a BET, can also be considered a chemical power plant. A dedicated temperature band, ideally between +10°C and +30°C, is required to ensure proper chemical reaction in the form of electron flow between anode and cathode. Besides the specific temperature requirements of the battery, the overall thermal management of all power electronics components can be listed as follows:

- Active cooling of battery to always ensure temperatures lower than +40°C.
- Power electronic components like inverters, electric motors, or DC/DC converters can be operated in passive cooling circuits.
- Thermal management components like electric fans or water pumps can independently be switched on and off.
- Additional heating power demand due to missing waste heat of the overall system.
- High load/fast switch-off scenarios can be handled.
- Battery and cabin pre-conditioning possible.

Figure 18 illustrates an exemplary active cooling and heating circuit for the battery of an electric tractor. To actively cool the system, the same system components as for air conditioning can be used. These are a chiller, a condenser, a compressor, and an expansion valve. A water pump is necessary to circulate the cooling fluid, typically water-glycol, through the batteries cooling plates. As demanded, two 3-way-mixing valves enable the system to switch between heating and cooling. In addition to that, one or more temperature sensors need to be installed for proper closed-loop temperature control.

To prevent the duplication of major system components for air conditioning and battery cooling, an intelligent interconnection via additional valves is recommended.

Other Aspects

Besides the mentioned design aspects of a BET, the in-vehicle safety needs to be covered by standardized lifecycle management processes around Functional Safety (FuSa) and technical safety of the high-voltage system.

There is a broad range of national and international standards, like ISO 25119 or ISO 26262 for FuSa or ECE-R100 Rev. 3 for the type-approval of vehicles with electric powertrains. ECE-R85 covers the measurement and approval of the net power of electric drive trains.

Drivetrain technology over 60 VDC also requires specialized safety measures for production, service, and repair. Here is a subset of important aspects:

- Risk assessment for production and maintenance areas.
- Regular training of employees.
- Creation of new organizational structures and processes.
- Ensuring that only qualified personnel work on high-voltage systems.
- Installation of dedicated firefighting tools and measures.
- Special first aid equipment and training.
- Creation of restricted areas in workshops.
- and more…

Overall, companies that step into the design of battery electric tractors do not only face technical challenges but also need to trigger an evolutionary development process of the overall organization.

Battery Tractor Specifications

In 2024, with the launch of the Fendt e107 vineyard tractor as well as the e107 standard tractor ready for serial production, farmers can benefit from the advantages of battery electric tractors (fig. 19). Feasibility parameters were identified, and advancements of battery technologies materialized as forecasted. It was key that the challenging journey from research concept to an industrialized product was started early. The technical data of the e107 standard tractor are summarized in table 12.

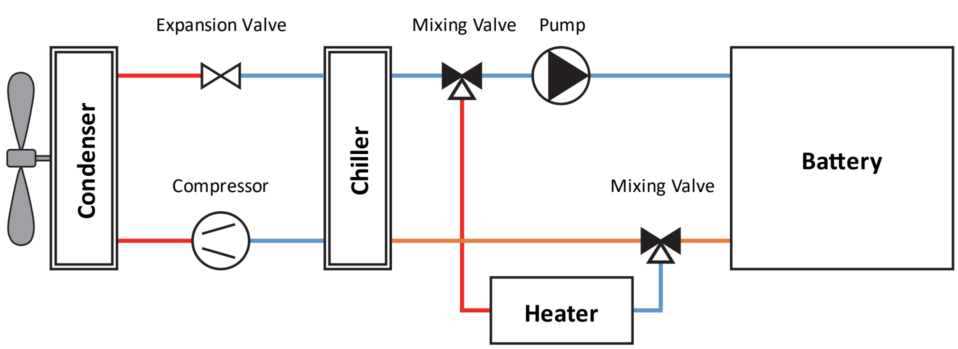


Figure 18. Exemplary active cooling and heating circuit for the battery of an electric tractor.

Table 12. Technical data of the battery electric standard tractor Fendt e107 S.

Feature	Value	Unit	Comment
Rated power (ECE-R85)	50/68	kW/hp	eco
Continuous power (ECE-R85)	55/75	kW/hp	dynamic
Peak power (ECE-R85)	66/90	kW/hp	dynamic+
Battery capacity	100	kWh	92 kWh usable
Operating range on one charge	5	h	approximation with typical use
Max. AC charging	22	kW	onboard charger, Type 2 CCS
Max DC charging	80	kW	fast charging, Type 2 CCS, 45 min 20%–80%
Driveline	CVT ML75	-	MFWD, energy recuperation
Speed range	0.02–40	kph	0.02–25 kph reverse
Rear PTO	540/540E/1,000	rpm	ground PTO as option
Front PTO	1,000	rpm	
Max. hydraulic flow	113	lpm	load sensing: ~200 bar
Overall width	2,163	mm	with standard tires
Overall length	4,119	mm	
Overall height	2,568	mm	
Turning radius	4,200	mm	
Empty vehicle weight	4,400	kg	
Max. operating weight	7,500	kg	incl. payload
Carbon footprint reduction	69	%	e107 V, GER green electricity mix vs. diesel.

Figure 19. Fendt e107 battery electric tractor.

Conclusion

Although the diesel engine—with renewable fuel—will remain a dominating power source for large tractors in the years to come, battery electric tractors have arrived and demonstrate a high potential for greenhouse gas reduction and energy efficiency improvements. The presented example (Fendt e107 Vario) provides a calculated product carbon footprint reduction of approx. 69% compared to its diesel counterpart with an opportunity for further improvements (e.g., battery production with green electricity). Battery electric tractors have various advantages, e.g., high efficiency, low maintenance, and the opportunity to directly use electricity produced at the farm. Combining the proposed relative weight and volume limits and considering a technical battery development according to forecasts (600 Wh/l and 300 Wh/kg at pack level), battery electric tractors with 100 kW rated power are technically feasible. Purpose-design architectures will open new opportunities to push these limits further out to 120 kW and beyond. The cost for battery systems, electric drives, and high-voltage components will define commercial viability, while infrastructure (grid, chargers, green electricity) will likely be a limiting factor approximately until the end of the 2030s in various regions. A high DC link voltage level of 700 V +/- 10% is recommended for 50 kW and higher nominal power to easily enable future electric tractor-implement connections according to AEF standards and keep electric currents low. Starting the transition to battery electric tractors with a conversion design approach provides a reliable and cost-effective design while unlocking efficiency benefits and ensuring compatibility with existing implements. There are various charging standards across global regions, e.g., the CCS2 for Europe and the NACS for North America. The current situation at typical farms requires pragmatic solutions—like 22 kW AC charging—that can be locally installed. Managing battery health and thermal load in all conditions is critical for longevity. High-voltage safety on the machines is highly important and has technically been solved with automotive progressing into electrification as consumer products as well. Sales teams must be equipped with all necessary context and education about electrification needs (e.g., charging systems, duty cycles, total cost of ownership calculations, etc.) to provide the best product recommendations to farmers. It is paramount that the service organizations are being qualified with intense high-voltage trainings and equipped with necessary tools to enable maintenance as well as repair of electric- and non-electric systems on a tractor with high-voltage components and high-energy battery storage.

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