Sparking a vineyard revolution

Powering up the potential of electric tractors

Electric cars are a hot topic. Interest has also been growing in the possibility of electric tractors. In this article AWRI Senior Engineer, **Dr Simon Nordestgaard**, reviews recent developments.

Introduction

In vineyards, electric tractors would facilitate the use of renewable energy and could end up being cheaper than diesel tractors. They would also likely be quieter and easier to maintain. Powering tractor implements electrically instead of by a mechanical PTO (power take-off) or hydraulics would allow for more precise implement control and improved energy efficiency. However, there are technical and cost challenges to realising these benefits. This article assesses the status of tractor electrification, together with the prospects for alternative fuels such as hydrogen and methane.

Battery-electric tractors

Prototype tractors powered solely by batteries were displayed at major industry trade shows in 2017 by John Deere and AGCO-Fendt. The 50 kW Fendt e100 tractor (Figure 1) is of a size and capability that might be suitable for grapegrowers and is therefore of particular interest.

Figure 1. Fendt e100 tractor prototype as presented at Agritechnica 2017 (50 kW, 100 kWh battery)

A technical challenge with battery-electric vehicles is the low energy density of batteries relative to diesel (Table 1), which means that large heavy batteries are needed to achieve equivalent operating time/range before recharging/re-filling. The approximate battery size and cost needed for different operating times and categories of tractor is explored in Figure 2. Twelve hours of operation is currently not feasible on a single charge, as the battery would weigh more than the tractor in some scenarios. The battery needed for four hours of operation by a 50 kW tractor (such as the Fendt e100) is more reasonable though.

The cost of batteries is another major challenge. A battery that would provide four hours of operation would cost around half the price of a complete diesel tractor of the same rated power (Figure 2). In September 2020, Fendt announced that current battery prices would make their e100 tractor too expensive to be competitive and therefore series production of the e100 has been delayed

Table 1. Energy storage properties of different fuels (Estimates from sources including: the NIST Chemistry WebBook, Sundén 2019 and Pickel 2019. Practical energy density = energy density x engine efficiency.)

	Diesel	Methane (200 bar)	Hydrogen (700 bar)	Lithium-ion battery
Density (kg/m^3)	830	157	39	3,000
Specific energy (MJ/kg)	45	56	120	0.5 (0.15 kWh/kg)
Energy density (MJ/L)	37	8.8	4.7	1.6 (0.45 kWh/L)
Engine type	Combustion	Combustion	Fuel cell-electric	Battery-electric
Engine conversion efficiency	40%	40%	60%	90%
Practical energy density (MJ/L)	15	3.5	2.8	1.5

Units of Energy and Power

Energy: The capacity to perform work

- Energy can take many forms, e.g. mechanical, electrical, chemical, and thermal
- The SI unit of energy is the joule (J)
- Unit prefixes are often used (e.g. 1 kJ = 1,000 J and 1 MJ = 1,000,000 J)
- Electrical energy is confusingly typically described in units of kWh (1 kW of power used for 1 hr):

1 kWh = 3,600 kJ [1 kJ/s x 1 h x 3,600 s/h = 3,600 kJ]

Power: The rate of conversion of energy (e.g. from electrical to mechanical)

- The SI unit of power is the watt (W), which is equivalent to the conversion of 1 joule of energy per second (i.e. 1 W = 1 J/s)
- Unit prefixes are often used (e.g. 1 kW = 1,000 W = 1,000 J/s = 1 kJ/s)

	Small vineyard (50 kW, 3 t, A$80,000)		Large vineyard (80 kW, 4 t, A$120,000)		Broadacre (380 kW, 14 t, A$500,000)	
Operating time	4 hrs	12 hrs	4 hrs	12 hrs	4 hrs	12 hrs
Battery capacity	100 kWh	300 kWh	160 kWh	480 kWh	760 kWh	2,300 kWh
Battery mass	0.7 t	2 t	1 t	3 t	5 t	15 t
Battery volume	0.2 m^3	0.7 m^3	0.4 m^3	1 m^3	2 m^3	5 m^3
Battery price	A$40,000	A$120,000	A$60,000	A$190,000	A$300,000	A$900,000

Figure 2. Theoretical battery mass, volume and price for different tractor categories and operating times before recharging (Estimates are based on data in Table 1, an assumed 50% of rated power utilisation and an A$400/kWh battery price – that is, a slightly more premium battery than the current mass-market average shown in Figure 3. Approximate power, mass, and price of diesel tractors for different tractor categories are included for reference, but tractor images are illustrative only and prices are author's estimates. Battery mass and volume analysis concepts based on Pickel 2019, which had been adapted from AGCO-Fendt.)

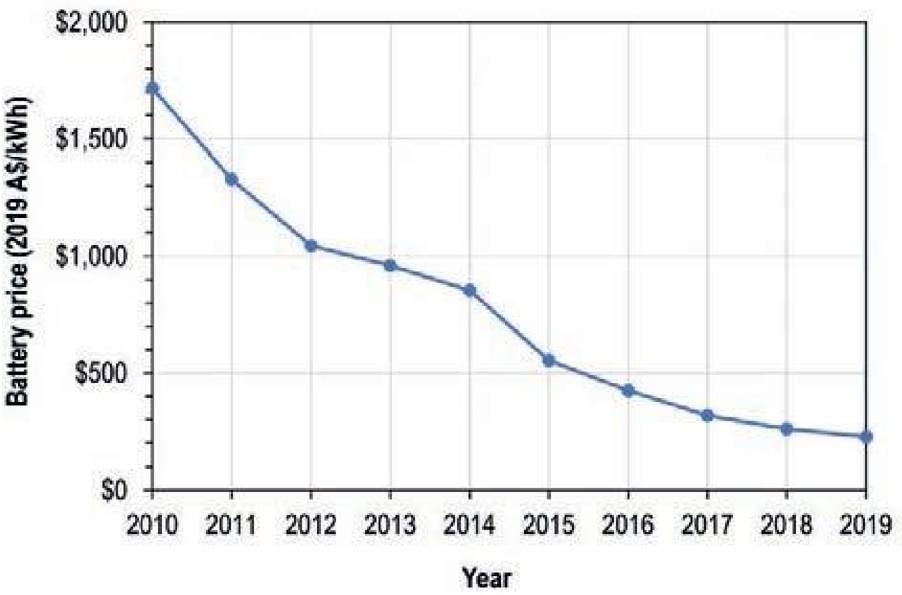


Figure 3. Average lithium-ion battery pack prices over time (Data adapted from BloombergNEF 2019.)

until 2024 (Zevenbergen 2020). Battery prices have fallen dramatically over the last 10 years (Figure 3), and it seems likely that this will continue, although the rate of fall does seem to be decreasing. The future price of batteries will likely be determined by battery developments in the automotive sector. For example, at its heavily publicised 'battery day' in September, Tesla introduced several initiatives to try to reduce battery prices and increase their energy density (Tesla 2020).

Other technical challenges that Fendt has addressed include the cooling requirements for the batteries and electrical systems and noise reduction. While in initial tests their battery-electric tractor was quieter overall than a diesel tractor, noise from the transmission and hydraulics became more pronounced in the absence of noise from a diesel engine and this needed to be managed (Christiansen 2020).

Figure 4. Tecnoma Voltis electric straddle tractor

Battery-electric straddle tractors

The Fendt e100 is not the only battery-electric tractor expected to be on the market soon. Rigitrac, a small Swiss manufacturer, displayed its own 50 kW battery-electric tractor in 2018 and has advised that it is intended to enter production in 2021, with some exports possible in 2022.

There are also a small number of battery-electric straddle tractors already in use in vineyards. Kremer and Tecnoma both received innovation awards at the 2013 SITEVI trade show for their battery-electric straddle tractors and the Tecnoma Voltis (Figure 4) entered commercial production in 2015. Around 10 units have been sold. Most of them are being used in Champagne.

While the e100 uses the same hydrostatic-mechanical power-split continuously variable transmission (CVT) as on Fendt's diesel tractors, the Tecnoma Voltis uses an electric CVT with an electric motor in each wheel. The electric CVT is likely to be more efficient than the hydrostatic CVTs used on straddle tractors and other over-the-row equipment such as harvesters (vehicles where mechanical transmissions are not practical because of the location of the engine relative to the wheels).

The use of electric CVTs for vehicles is not a new idea. Some large mining dump trucks have had generators driven by diesel engines that power wheel motors since the 1960s (Haddock 1998) and electric transmissions have also been common on diesel trains. The high torque at low speeds is useful as is the ability to easily supply power to motors located at different places on vehicles with complex layouts.

Figure 5. Charging socket on Fendt e100 in 2017

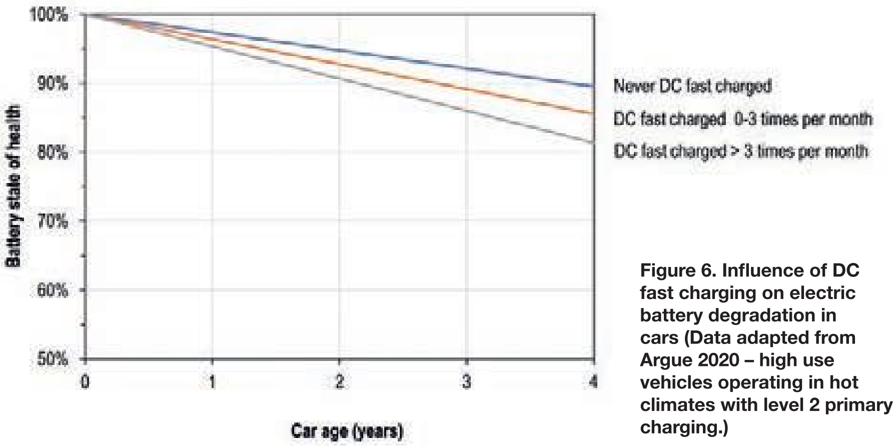


Figure 6. Influence of DC fast charging on electric battery degradation in cars (Data adapted from Argue 2020 – high use vehicles operating in hot climates with level 2 primary charging.)

Battery charging and degradation

Like many battery-electric vehicles, the Fendt e100 can be charged relatively slowly using an AC power point or more quickly by a DC fast charger (i.e. like a Tesla Supercharger). Fendt's proposed AC charging solution operates at 22 kW (~3-phases x 230 V x 32 A), which allows the 100 kWh battery to be charged in around five hours (100 kWh/22 kW). This would be suitable for overnight charging, provided there is 3-phase 32 A electricity available at the site. Fendt's proposed DC charging solution operates at 140 kW (700 V x 200 A), which allows for the battery to be charged to 80% in around 40 minutes (80% x 100 kWh/140 kW). This could be suitable for a lunchtime recharge, but requires access to a DC fast charger, of which there are very few in Australia. Potentially a site could have multiple batteries and the flat tractor battery could be swapped with a charged battery, but the battery size would likely make this too inconvenient to be performed regularly, although John Deere did display a large hybrid-concept tractor in 2015 where a 50 kWh battery could be mounted on the front hitch (Pickel 2018).

Therefore, if a site wished to achieve more than four hours of use from the Fendt e100 tractor each day, they would likely need to install their own DC fast charger – perhaps even a faster charger than 140 kW that draws electricity from stationary batteries charged by solar panels. Regular DC fast charging would also likely degrade the battery more quickly, such that over time the battery would be able to hold less and less energy after a charge. Fleet data for electric cars has shown that while all batteries degrade over time, those batteries that are DC fast charged more often degrade more quickly (Figure 6). The impact would likely be even more pronounced in relation to time for heavily used tractors since they might be being fast charged almost every day. There is continuing work in the automotive sector to try to develop batteries that can be recharged huge numbers of times, without much degradation (and therefore maintain their range/operating time between recharges). The prospect of 'million-mile batteries' that can last a million miles before needing to be replaced is often discussed in the media. It should also be noted that with DC fast charging, the charging time is usually presented for an 80% battery charge, because while the charging speed might be close to 140 kW up to 80% charge, the speed decreases as the battery gets fuller to allow for it to be filled up without degrading the battery excessively.

Even without a DC fast charger, the Fendt e100 may still be workable for some vineyards. There may be customers that only need their tractor for less than four hours per day. The four hours per day is also based on an assumption of 50% rated power utilisation (Pickel 2019). The true hours of usage will depend on the task – it could be more or less. The delay of e100 series production until 2024 may also allow for some further improvements in battery energy density and battery life before launch. Given the interest in the automotive sector in electric vehicles, in the longer term it seems plausible that battery-specific energy might triple (e.g. from 0.15 to 0.45 kWh/kg) and batteries might not degrade as quickly, in which case the battery specified for four hours of operation in Figure 2 would give twelve hours of operation and the speed of charging would then become almost irrelevant, as overnight charging would be sufficient.

Grid-connected electric tractors

To investigate tractor electrification and manage issues with battery energy density, in 2018 John Deere demonstrated a prototype that is connected to the grid ▸

Figure 7. John Deere grid-connected prototype electric tractor with cable reel

by a cable that is wound and unwound on a reel as the tractor travels across the field (Figure 7).

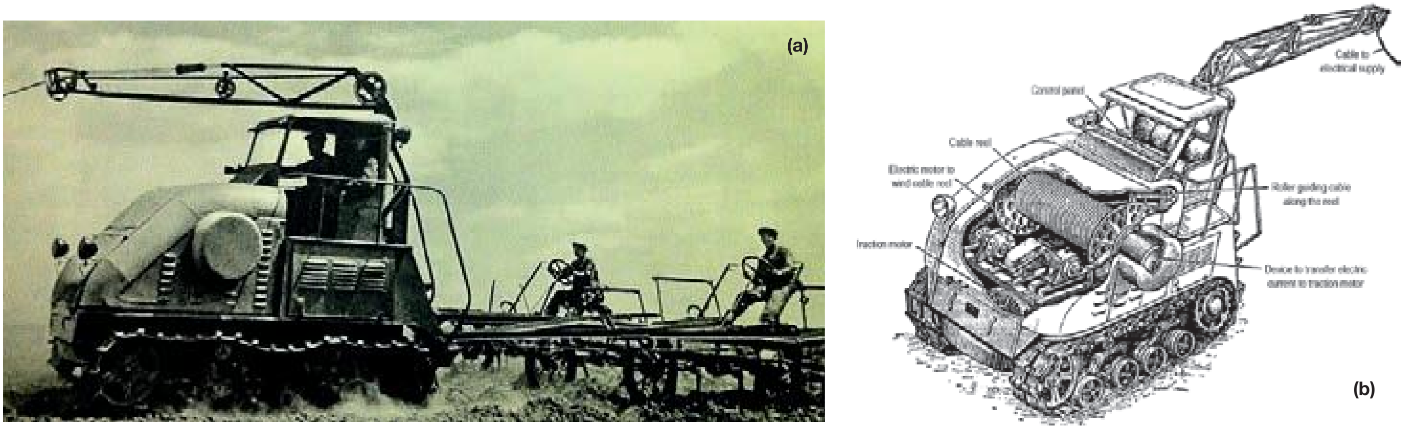
As John Deere acknowledges, similar principles have also been used for tractors in the past. In the late 1940s, grid-connected electric tractors with cable reels were developed in the Soviet Union (Figure 8). A mobile sub-station would raise a tower that would connect to overhead high voltage transmission lines, and electric tractors would then connect to the sub-station. These grid-connected tractors are even demonstrated in a 1951 Soviet film: *Dream of a Cossack* (https://www.youtube.com/watch?v=T7LJwkBoeAQ). The tractors were expensive and faced ongoing issues with wear to the reel cable. They were abandoned in the 1950s in favour of diesel tractors. The discovery and exploitation of oil fields in Kazakhstan reduced diesel prices and together with it the desirability of powering tractors with electricity (Jedlička 2019, Beloyar 2020). Similar equipment was also developed in New Zealand in the 1930s, but only eight machines were built, and these stopped being used in 1943 (Ashburton Guardian 2014).

This principle does not seem practical for Australian farms – particularly for vineyards where the cable would be likely to get caught on grapevines.

Synergies between electrification and autonomy

Vehicle electrification and autonomy are both widely seen as technologies of the future. There are potential synergies between them. Operating time and

Figure 8: Soviet grid-connected electric tractorwith cable reel: (a) operating, and (b) schematic



charging speed are currently weaknesses of battery technology. However, these are not such big problems if the battery-electric vehicle is autonomous and can operate day and night and automatically travel between the field/vineyard and the charging station only when needed. Domestic-grade electric lawnmowers already operate in this manner (Nordestgaard 2020).

Hydrogen fuel-cell electric tractors

A fuel cell is an alternative to a battery for powering electric vehicles. A fuel cell is similar to a battery, except that is run by a constant supply of hydrogen instead of needing to be charged (Figure 9). The specific energy of hydrogen is much higher than a lithium-ion battery, although, even at 700 bar (the fuel tank pressure in modern hydrogen fuel cell vehicles such as the Toyota Mirai), the energy density is only slightly better than a lithium-ion battery (Table 1). Practically, this means that the hydrogen tank will weigh a lot less than lithium-ion batteries but will still take up a large volume. If the fuel cell itself is included, the system volume is likely to be only slightly smaller than when using batteries. Fuel cells are generally seen as being a preferable way to use hydrogen as a fuel compared with combustion engines, partly because combustion engines are far less efficient and would therefore require even larger hydrogen tanks.

The major advantage of a hydrogen fuel cell compared with a battery, is that a hydrogen tank can be refilled very quickly – much like a diesel vehicle. However, hydrogen is currently much more expensive than electricity and unlike electricity there is not yet distribution infrastructure in place. Storing hydrogen on a farm would also not be as easy as storing diesel, or even liquefied petroleum gas (LPG). To handle 700 bar pressure (around 690 x atmospheric pressure), expensive tanks are typically needed. In cars, carbon fibre tanks are used that contribute significantly to the cost of the vehicle. Different strategies to distribute hydrogen are currently being explored that may help to limit the required investment in infrastructure. One strategy is to inject a small percentage of hydrogen into the natural gas distribution system (<10%), which can then be purified from the natural gas at destination, while the un-purified natural gas is used as normal. Transporting higher concentrations of hydrogen, however, potentially presents risk of pipe embrittlement and rupture. Converting hydrogen to ammonia to allow easier transportation (e.g. for export on ships) is another alternative (COAG Energy Council 2019).

As the world seeks to tackle climate change, a compelling benefit of hydrogen compared with burning fuels such as diesel is that the only waste product is water (Figure 9). The hydrogen itself can also potentially be produced from the electrolysis of water, using electrolysers (essentially a fuel cell in reverse) and this is the idealised future technology. ▸

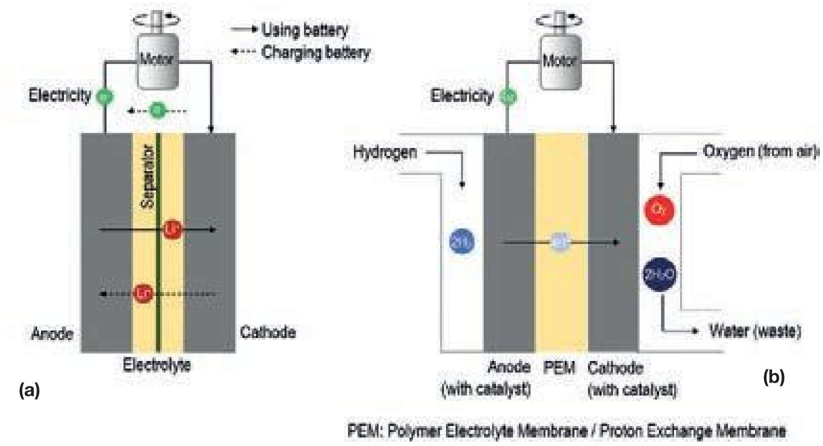


Figure 9. Operational principles of: (a) lithium-ion battery, and (b) hydrogen fuel cell

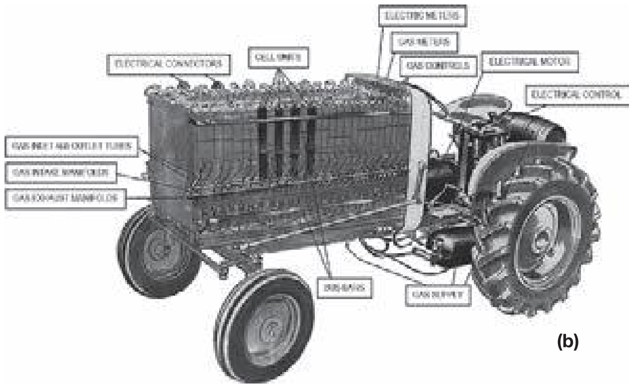


Figure 10. Allis-Chalmers fuel cell tractor from 1959: (a) original trial video, and (b) schematic (J & L Video's Allis-Chalmers Archive Project 2019)

Just like battery-electric vehicles, how renewable the hydrogen is will depend on how the electricity used to make it was generated. If it is produced from electrolysers powered by renewable electricity it is called green hydrogen. Currently, only around 0.1% of hydrogen is produced by water electrolysis (IEA 2019). Most hydrogen is still produced by steam-reforming of natural gas. There are also major energy inefficiencies in using electrolysers and fuel cells, which means that much more initial renewable energy is needed for green hydrogen production compared with using batteries for energy storage (debatably twice as much, Baxter 2020). Therefore, the availability of large quantities of very cheap renewable energy is critical if hydrogen is to be a feasible energy storage solution.

The above considerations mean that there is much debate about whether hydrogen fuel cells or batteries are the future (they could also co-exist). The topic of using hydrogen as an energy storage medium has been considered for a very long time – the term 'hydrogen economy' was coined in the early 1970s (Gregory 1973). Slow progress on the development of hydrogen infrastructure and vehicles has made many people cynical about whether it will ever become a mainstream technology, particularly given recent successes with battery-electric vehicles. Elon Musk (notably a battery manufacturer with a vested interest) has referred to fuel cells as 'fool sells' and as being 'staggeringly dumb' but many other vehicle manufacturers are still pursuing the technology.

Interestingly, a tractor was the first fuel cell vehicle ever to be made, back in 1959 by Allis-Chalmers (Figure 10), although it never went beyond a prototype. This 15 kW tractor had 1,008 fuel cells and used propane instead of hydrogen as the fuel. Even at that time, the promotional material for this vehicle described how engineers saw the value in fuel cells and discussed using off-peak electricity to produce hydrogen that could be stored, transported and used at will in fuel cells (Allis-Chalmers 1960). In 2009, New Holland displayed a prototype hydrogen fuel cell tractor at a trade show (Figure 11), which was further developed and displayed again at another trade show in 2011. The 2009 prototype was a nominally 50 kW tractor with a fuel tank that held up to 2.4 kg of hydrogen at 350 bar. The 2011 prototype was a larger 100 kW tractor with a tank that could hold 8.2 kg of hydrogen (at 350 bar). The 2011 prototype could operate for longer than the 2009 version – up to three hours, depending on load (Fuel Cells Bulletin 2012). New Holland subsequently shifted from developing a hydrogen tractor to developing a methane tractor instead. John Deere staff have commented that 20 years ago that they saw hydrogen as the likely near future tractor technology, but that is not the case now (Koerhuis 2020).

Whether hydrogen powered land-based vehicles have an opportunity to establish themselves as a mainstream technology will probably depend on how quickly competing battery manufacturers can increase battery energy density and life, while reducing prices. Hydrogen does have benefits in terms of weight and speed of refuelling and there has been recent interest in hydrogen fuel cells for long-haul trucking on major highway routes, which would require a relatively small number of hydrogen refuelling stations and would foster the establishment of a broader hydrogen distribution network.

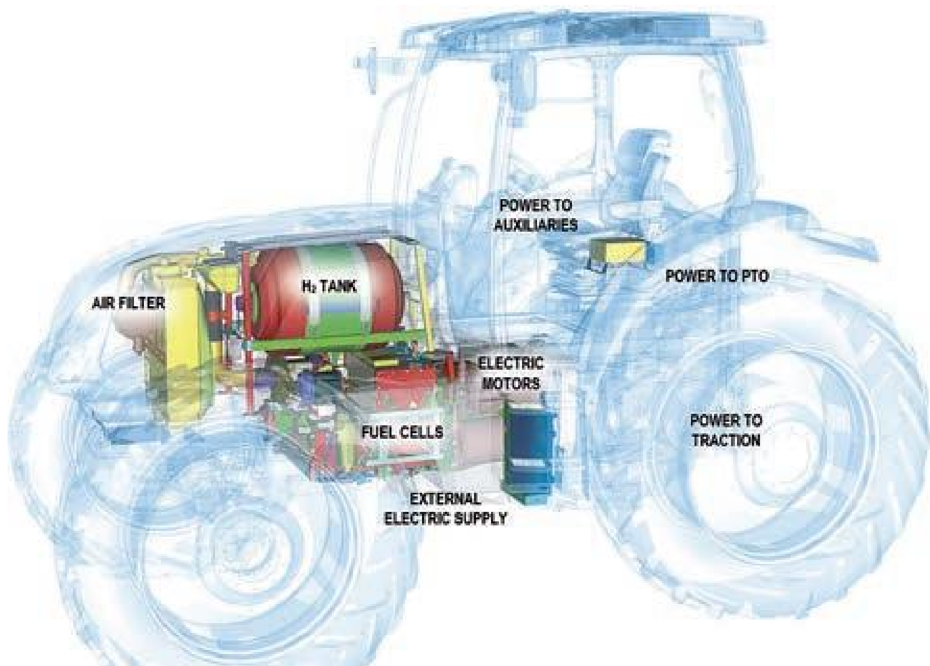


Figure 11. Schematic of New Holland hydrogen fuel-cell tractor prototype from 2009

Figure 12. New Holland methane-fuelled tractor in front of anaerobic digestors that produce biogas, which can be refined into biomethane

Methane/compressed natural gas (CNG) tractors

Natural gas is predominantly methane. It has long been used to fuel internal combustion vehicles in some countries, mainly in the form of CNG. In Australia, CNG vehicles have primarily been buses and trucks that return to a base for refuelling, where there is a dedicated system for compressing natural gas from a mains supply (Gas Energy Australia 2020). However, countries like Italy and Germany, have a large network of publicly accessible CNG stations (NGVA Europe 2020).

At recent trade shows, New Holland displayed a methane-fuelled tractor (Figure 12), which is set to enter series production in 2021 and be available in Australia from 2022. The methane tractor also replaces the hydrogen tractor as part of New Holland's 'energy-independent farm' concept. Biogas can be produced from organic waste in an anaerobic digestor and then potentially further refined to produce biomethane of a purity suitable for running tractors or other natural gas fuelled vehicles. However, these techniques are likely more applicable to larger farms or groups of farms, probably with livestock, than they are to vineyards. Such a set-up would be a lot more effort than installing solar panels and batteries and using that electricity to charge a tractor.

One benefit of powering a vehicle with biomethane is that the carbon dioxide produced during combustion is usually not counted in greenhouse gas emissions accounting. This is because it is reasoned that the carbon dioxide is being produced from sources that at origin had previously removed a similar amount of carbon dioxide from the atmosphere (e.g. crops). Fugitive emissions of methane, however, are counted as greenhouse gases.

Electric implements

Mechanical PTOs and hydraulic pumps are the established means of powering tractor implements. However, electric power would likely be far more energy efficient than hydraulics for this purpose. Hydraulic implements are at best 50% efficient, as evidenced by the energy lost to heat in the hydraulic oil that then needs to be cooled (Renius 2020). Electric motors can also be controlled much more precisely than hydraulic motors.

Several attempts have been made historically to establish the powering of implements electrically from tractors. In the 1950s, International Harvester (which later became the IH part of Case IH) offered 'Electrall' tractor-mounted generators. These were designed to power both implements like balers and also to serve as a back-up farm generator in an era when electricity supply in rural areas could be unreliable. It was ultimately unsuccessful, partly because IH introduced live mechanical PTOs at about the same time, which went on to become very popular (Allen 2018).

Over the last 20 years, tractor manufacturers such as AGCO-Fendt and John Deere have performed several

Figure 13. John Deere electro-mechanical power-split CVT with electric power for external implements: (a) schematic, and (b) illustrating external power being used to drive wheels on the rear two axles of the trailer, improving traction (adapted from John Deere)

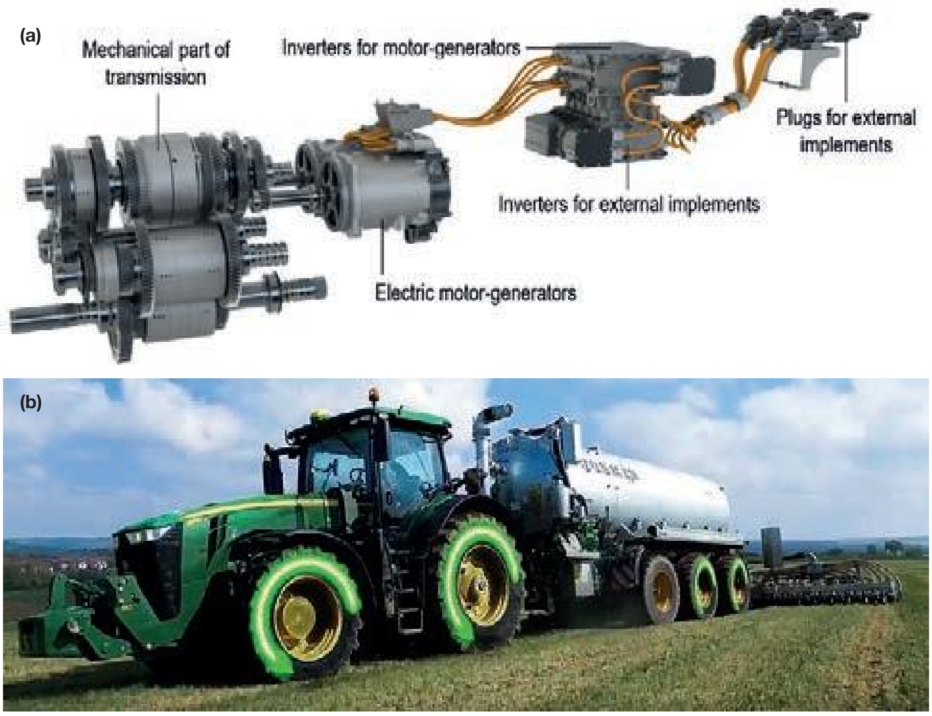


Figure 14. John Deere single axle concept vehicle

research and development projects on this topic (Buning 2010, Breu 2013, Pickel 2019). The work on powering tractor implements electrically has therefore been going on much longer than efforts to power tractors themselves with batteries. For clarity it is also worth noting that battery-electric tractors are not limited to working with electrical implements; for example, the Fendt e100 has a mechanical PTO and hydraulic connections just like a standard tractor.

All current tractors have some electrical systems, but they are not sufficient to power major equipment. For example, on a large Fendt tractor the alternator produces less than 4 kW (Pichlmaier et al. 2014) and ISOBUS (the standard protocol for communication between tractors, software and implements of major manufacturers) can only supply 700 W at 13V (Rahe and Resch 2017).

In 2007, John Deere released the E-Premium tractor, which used a crankshaft generator to power auxiliaries (fan for engine cooling, air conditioning compressor, etc.) as well as providing single-phase (230 V) and 3-phase (400 V) external power points. It was not commercially successful (Pickel 2018); however, its development led to discussions between suppliers about standardising interfaces and in 2011 a working group at the Agricultural Electronics foundation (AEF) was established. These discussions are still ongoing, but it is generally expected that two new standard electrical interfaces will be established for electrical connections between tractors and implements (Rahe and Resch 2017, Pickel 2019, Renius 2020):

1. High voltage AC/DC for electric traction drives or similar (up to 150 kW)
2. 48 V DC for most other applications

Some of the reasons for the relatively slow development of electrical tractor implements is a 'chicken-or-egg' scenario: there is little point having an electrical supply on the tractor if there are no implements to use it and no point developing electrical implements if there is not an easy supply of power. There has also been debate on topics such as whether inverters to control implement motor speeds should be on the tractor or the implement (Rahe and Resch 2017).

There are already some implements with electric motors that have their own generators. In the wine industry, Greentech multi-head axial fan canopy sprayers use electric motors that are powered by a generator driven by the tractor PTO. In the past, some Pellenc trimmers and pruners also used electric motors, but these were switched back to hydraulic motors because they were more expensive than the competitors. John

> Vehicle electrification and autonomy are both widely seen as technologies of the future. There are potential synergies between them.

Deere also already sells broadacre seeding equipment that takes advantage of the precision control possible with electric motors to place seeds with an accuracy of ±1 cm at 20 km/hr (Pickel 2019).

While powering implements electrically may be more efficient than using hydraulics, many implements are actually only used for part of the year and do not actually use large amounts of energy, so the absolute diesel savings from these increased energy efficiencies are not huge and have not been sufficient to cause a shift to electric implements. The main use of energy in a tractor is from driving/traction (Rahe and Resch 2017) and this has been the focus in some recent developments.

Electro-mechanical CVTs and electrical power take-off for external traction

At Agritechnica 2019, John Deere presented an electro-mechanical power-split CVT that provides electrical power take-off, particularly aimed at powering axle motors on trailers to increase traction and therefore have a meaningful effect on overall tractor energy use (Figure 13). Furthermore, John Deere claims that the transmission itself is more energy efficient.

A standard hydrostatic-mechanical power-split CVT (such as the Fendt Vario) variably splits engine power into a fixed mechanical path with high efficiency and a hydrostatic path with moderate efficiency. It allows for a higher total efficiency and continuously variable power transmission. The John Deere transmission replaces the variable hydrostatic component with a variable electrical component. Since the hydrostatic system is replaced with an electrical system, John Deere claims that it is more efficient (Pickel 2019).

While electro-mechanical power-split CVTs have been researched since at least as far back as 1998 (Buning 2010, Breu 2013, Pickel 2019), this most recent design is not just for a concept vehicle. John Deere's 8R series tractor (~170-300 kW) will be fitted with this transmission from 2021 (Pickel 2020). Other transmission manufacturers such as ZF are also offering similar systems. It is not clear if similar transmissions might appear also on the smaller tractors that are used in vineyards. If batteries can improve sufficiently, that step might be skipped and smaller tractors might go straight to using a battery with a fully electric CVT and wheel motors, which presumably could be just as efficient as a power-split CVT since electrical energy in the battery is only being converted to mechanical energy once (at the wheel motors).

The ability to power wheels on external implements does present interesting opportunities that blur the line between the tractor and the implement. For example, at Agritechnica 2019, John Deere also presented a concept tractor with only a single axle, with an implement with a powered axle behind (Figure 14).

Conclusions

While the launch of the Fendt e100 tractor has been delayed until 2024 because of the price of batteries, there is still much promise for tractor electrification. Automotive sector developments will likely keep pushing battery prices down and energy density and battery life up, making battery-electric tractors increasingly feasible. Increased autonomy of tractors or other agricultural robots may also facilitate electrification. At this stage, hydrogen fuel cell tractors seem unlikely, but they could still come to fruition in the longer-term if battery technology does not improve sufficiently.

Electrically powered implements will likely be adopted in the longer term, but these will probably only become common once many tractors have an electrical power take-off and following a long transition period of tractors having this in conjunction with a mechanical PTO and hydraulics.

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Disclaimer

Readers should undertake their own specific investigations before trialling or purchasing equipment. This article should not be interpreted as an endorsement of any of the products described. Manufacturers should be consulted on correct operational conditions for their equipment.

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