# DECARBONISING FARM VEHICLES AND FUTURE FUELS

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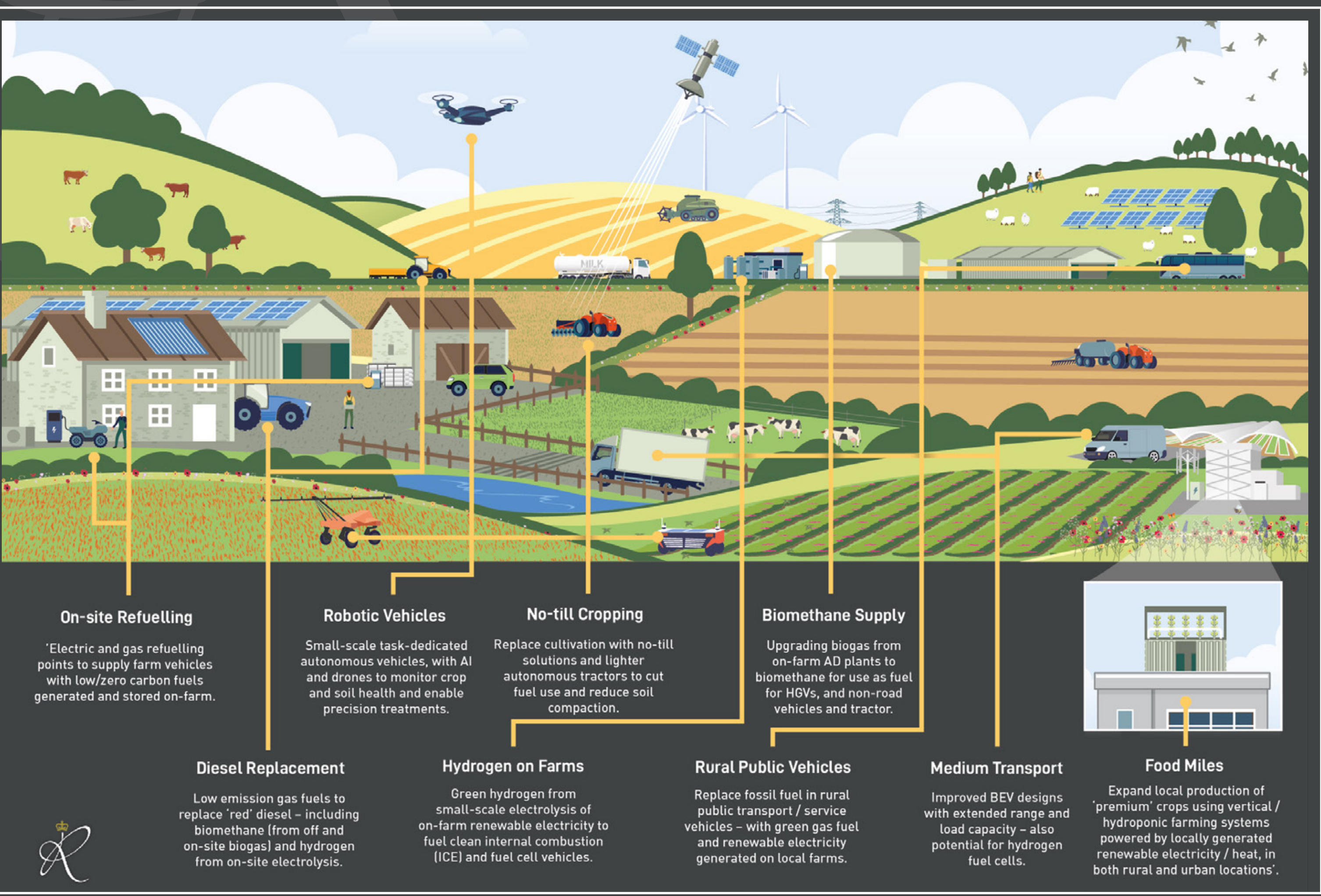

# CONTENTS



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# SUMMARY OF KEY POINTS

1. Policy failure to include agriculture in the replacement pathway for red diesel is a major oversight and should be given greater priority by Government. As a fossil fuel, diesel's time is limited and, like many other industries, agriculture has to figure out what will replace it as the primary fuel for farm vehicles in the next two decades.

2. There are several candidates for farming's 'fuel of the future': electricity, biofuels (as liquid or gas) including on-farm biomethane generation/supply and potentially hydrogen. Wider gas fuel deployment in non-farm vehicles is a priority – in addition to re-thinking farm vehicle design and considering power-to-weight requirements for farm traction.

3. With its higher energy density, gas offers greater potential than electricity for heavy vehicles and machinery. Non-fossil gas fuels are a long-term option for non-road vehicles. To be affordable, low emission fuels should make use of existing engine technology e.g. internal combustion (ICE). This requires Government policy change to boost currently available on-farm fuel technologies such as biomethane and future solutions like hydrogen using on-farm electrolysis.

4. The industry must look beyond increasing farm vehicle size to the use of smaller, more compact, controlled traffic farming systems to prevent soil compaction. Alongside minimum or zero tillage, the role of autonomous and robotic vehicles and machines, along with gantry technology, will increase, running on electric or possibly a hybrid powertrain (e.g. gas and electric).

5. Demonstration is key to farmer adoption and delivering systems change. Field scale trials and on-farm demonstration events for the range of low and zero emission vehicles are an excellent way of encouraging change and should receive external funding support.


*Figure 1: Gas fuelled milk collection tanker (upper left); gas fuelled tractor (upper right); field gantry system (lower left) and robotic field vehicle (lower right).*

# 1. INTRODUCTION: WHAT WILL FUEL THE FARM VEHICLES OF THE FUTURE?

Diesel has been farming's fuel of choice for generations, and the industry was one of the first to pick up on the novel form of propulsion that Josef Diesel[1] introduced around the turn of the 20th century. Now, the future of diesel and other fossil-derived fuels is limited. As with many other industries, agriculture is having to figure out what will replace diesel as the primary farm fuel.

There are several key candidates for farming's 'fuel of the future', with electricity, biofuels (in liquid or gas form) and hydrogen being the most obvious ones. In some people's eyes, one fuel will predominate; others see the future relying on a combination of fuel technologies.

Like other industries, farming is under pressure to limit its climate impact and meet the multiple emissions targets announced in recent years. Already, a number of alternatives to diesel can be produced on farm (such as electricity from hydro, biogas, wind and solar PV, biomass energy, biomethane and in due course, hydrogen). Moving away from fossil fuels gives society a chance to re-imagine energy provision. Individual farms could become modest energy and transport fuel providers in their local area, possibly through private wire arrangements, local fuel dispensing or community supply groups.

Many farms already feed electricity generated on-farm back to the national grid. There is further scope for farms to supply power to communities and co-located businesses. But there will be times when circumstances such as grid restrictions and variable weather conditions mean farm generators will need to use on-site battery storage to make optimal use of their power or alleviate system curtailment[2].

Farms could become clean fuel providers to local communities. As well as representing a new income opportunity, vehicle charging and re-fuelling stations on farms or in local communities could help to avoid 'app-guided' hunts for rural petrol/diesel refilling stations - already decreasing in numbers!

This paper looks at rural supply and use of green electricity, biofuels (either gas or liquid) and hydrogen, all capable of replacing diesel propulsion on the farm of the future. Naturally, there can be a degree of overlap between some of these fuel options and 'dual fuel' systems are being developed.

More farmers are starting to engage in deployment of alternative fuels, including those energy supplies they can produce on farm, such as wind and solar power, biomass or biogas. Future development of zero carbon gas fuels such as hydrogen can help meet the industry's future power needs.

[1] Rudolf Christian Karl Diesel (1858-1913), German mechanical engineer invented the diesel engine, and was awarded a patent in 1892. Higher speed versions were developed in the 1920s for train engines and the 1930s, for trucks and tractors. In 1935 International Harvester introduced the WD 40, the first diesel wheeled tractor.

[2] For power generators, curtailment is the deliberate reduction in output below potential output levels, to balance energy supply and demand or address grid transmission constraints.

The farming industry needs to be engaged in efforts to develop novel gas fuels for use in a range of non-road vehicles. Unlike battery electric vehicles (BEV), internal combustion engines (ICE) running on biomethane, for example, can be provided at a comparable cost to existing diesel units, avoiding inflationary pressure of globally sourced components while using existing infrastructure (with minimal fleet operation and servicing disruption).

Technology change always encourages pioneers - early adopters and leaders who see the benefits and react quickly. They are followed by mainstream users who adopt new solutions once they can be sure of the cost and benefits of change. Finally, the laggards who only move when forced to, either by legislation or economics. Issues impacting on speed of uptake include supply constraints (e.g. availability) and also the ‘life expectancy’ of many older farm vehicles unable to use new fuels or too expensive to convert.

Despite a gulf of 70 years in their manufacture, Massey Ferguson’s T20 and the modern Claas Axion (sustainable tractor of the year 2021, but still using a diesel power train) have a similar chassis but are very different in terms of performance. The drive chain and layout (plus items like three-point linkage) have barely changed. However, new low emission fuel technologies will dramatically alter the design, cost and capability of farm vehicles.

***Figure 2: Massey Ferguson T20 (left) and Claas Axion (right).***

Transition to alternative low and zero emission fuels will take time. A lesson from recent history is the switch to unleaded fuel. Japan led the way, introducing unleaded petrol in 1972 and banning leaded fuel in 1986.  The UK lagged behind: unleaded sales only started in 1986, but only 11% of petrol stations sold it by 1988. The EU only banned leaded fuel in 2000. The last country (Algeria) ended sales in 2021!

## Case study: The time it takes to change – unleaded petrol

Concerns over leaded fuel included health risks from the exhaust. This was a significant concern to drive change, but not at the pace required to mitigate climate change. In 1989, one of 11% of petrol stations selling 'unleaded' fuel was in the outskirts of Coventry. That's where one of the authors bought his first tankful of unleaded petrol, when commuting to his job as RASE Press Officer.

People had concerns as to whether the 'new fuel' suited their car, often asking their garage before switching from 4-star to unleaded! The author, proud to be a pioneer, was not put off by the truck driver who drew up at the next pump and told him he was an expletive "environmental nutcase". He followed that insult with a spectacularly inaccurate prediction: "It will never catch on, mate!"

The author's mother had a similar experience in Chard, Somerset, where repeated requests for the main petrol station to supply unleaded fuel were met with the response "There's no demand for it". In a surprisingly powerful voice, she would reply, "I'm the demand for it!" By the 1990s, there was huge demand, with unleaded fuel promoted as 'the green fuel'. The rest, as they say, is history!

A further issue that will influence diesel replacement fuels is the level of taxation. Several key sectors of the economy have benefitted from 'red diesel', where tax is typically about one fifth of conventional diesel. From April 2022, the construction sector and councils will lose the tax break on red diesel, leaving farming as the last business sector to enjoy this benefit.

If the subsidy were withdrawn, and farmers had to pay the full price for diesel, it would impact heavily on their fixed business costs. In the past 40 years, a frequent complaint from farmers is their inability to pass on their own input cost rises to customers, where they are 'price takers' rather than 'price setters'.

Although there seems little indication of red diesel policy changing in the near future, the GHG emission credentials - and therefore the image of the industry - will be undermined if farms retain this benefit beyond 2030. But to prepare for the likely and eventual withdrawal of the diesel subsidy, farm vehicles should be included in Department for Transport (DfT) initiatives to support new power trains.

# 2. FUELS FOR FARMING'S FUTURE

The choice of new fuels and power trains to replace those currently used on farms will curb emissions in the agricultural sector. Some diesel alternative fuels are already being produced on farm, for example, biofuels, electricity from solar panels and wind turbines - and biogas.

Moving away from fossil fuels provides an opportunity to re-imagine motive power provision on farms, in some cases operating outside the national fuel supply or grid infrastructure. Technology change is underway. Existing and alternative low/zero emission fuel options for farm vehicles are listed below.

***Table 1: Existing and alternative low/zero emission fuel options for farm vehicles***

| Liquid and Gas Fuels Descriptions | Choices of alternative fuels and new power trains requires a clear transition pathway. **Note:** Battery electric vehicles (BEVs) are covered in this report but are excluded in this table which focuses on fuels that can utilise internal combustion engine technology (ICE) in the existing non-road/off-road vehicle fleet. |
|---|---|
| **Petrol** | UK refuelling stations supply E5 grade petrol which contains 5% bioethanol blended with 95% fossil-derived petroleum. The E10 grade which was introduced in September 2021 should cut transport $CO_{2e}$ emissions by 750,000 tonnes/year - equivalent of taking 350,000 cars off the road. The UK may move to E20 grade (containing 20% blend of bioethanol) before 2030. |
| **Diesel** | Regular diesel incorporates renewable biodiesel - with the average blend dispensed with between 3% and 4% biodiesel. It is unlikely that this will change significantly in the coming years. Hence, by 2030 the actual level of biodiesel at refuelling stations is likely to increase to the permitted 7% level. |
| **Biodiesel** | Renewable biodiesel - also called fatty acid methyl ester (FAME) - is produced from waste vegetable oil with methanol. Vehicle manufacturers approve the use of blends up to grade B30 (30%). Several tractor manufacturers offer engine configurations for grade B20 (e.g. John Deere) and some can use higher blends (e.g. Deutz). Pre 2030, some original equipment manufacturers (OEMs) may move to grade B100 fuel blends, although this is unlikely to be available at public refuelling stations. |
| **HVO (Hydrogenated vegetable oil)** | HVO (chemically similar to conventional fossil diesel) is a 'drop-in' fuel that can substitute for diesel with no operational impact. Due to production cost (from vegetable oil which can include palm oil or waste oils), HVO is likely to remain a niche alternative fuel. Although not zero emissions, it can be a cost-effective option and there is no price premium for HVO-powered vehicles. |
| **Biomethane** | Biomethane is the renewable equivalent of natural gas (CNG), produced by removing $CO_2$ from biogas (biogas upgrading). A 'drop-in' fuel for ICE gas engines, compressed biomethane (bioCNG) is derived from organic residues using anaerobic digestion (AD). Gas ICE solutions already commercially available offer affordable power trains for non-road vehicles. The Renewable Transport Fuel Obligation (RTFO) supports its use in heavy vehicles. Gas HGV trucks, already in use, can offer significant well-to-wheel (WTW) emission reductions. Farm vehicles can be run on bioCNG supplied from farm AD sites. |

| | |
|---|---|
| **Hydrogen for ICEs ($H_2$ ICE)** | Hydrogen is proposed as a long-term diesel fuel replacement for heavy vehicles, including in internal combustion engines. However, due to lack of an established $H_2$ fuel infrastructure and high production costs, there is no guarantee that 'green' $H_2$ fuel will become price competitive with bioCNG pre-2030. 'Green' $H_2$ production may be some time off, despite recent ICE development. Future use of $H_2$ fuels in adapted ICEs could facilitate adoption of systems such as $H_2$ fuel cells. Replacement of the ICE on farms with $H_2$ fuel cells (or other battery systems) is unlikely before 2050 - due to rural supply limitations and also the extended life cycle of farm tractors and other machines. |
| **Synthetic Fuels** | Synthetic fuels are at an early development stage. It is possible for industrial processes to combine electrolysed hydrogen with $CO_2$ to produce a synthetic fuel. However, completing this process at scale with a reasonable cost to end-users such as farmers is challenging. At present, synthetic fuels struggle to compete on price against other power solutions. |

***The industry needs to anticipate the loss of its red diesel subsidy by 2030 and a number of OEMs have developed or are developing low emission options. To aid adoption of novel fuels and the different power trains and vehicles covered in this paper, demonstration farms and events are needed to enable farmers and land managers to assess operation and the impact on their farming systems.***

Gas fuels and adapted low emission ICE power trains that do not involve a full 'paradigm shift' will form an important part of the transition to zero-emission farm or rural vehicles. While OEMs develop future options, existing fuels can offer viable diesel replacements in the short to medium term.

## 2.1. Renewable biodiesel

Renewable biodiesel is already used in some farm vehicles. Vehicle manufacturers provide a warranty for FAME[3] blends up to B30. Several suppliers offer engine configurations for B20 (e.g. John Deere and Valtra) and higher biodiesel blends (e.g. Deutz). Before 2030, more OEMs may move to B100 blends.

Diesel ICE powertrains can be converted to higher blends of FAME at the factory or retrofitted (typically costing £6,500 - £8,000). Converted vehicles have been run successfully on B100 and could be used on farms. Biodiesel blends can be stored in and dispensed from existing infrastructure for diesel vehicles at no extra cost, though with more frequent maintenance intervals.

FAME is not a net zero fuel and despite pressure to extend the use of ICE power trains based on novel design solutions, decisions on the future investment in production, storage and on-farm use should factor in the risk that future net zero legislation may not include biofuels.

[3] FAME complies with EU Biodiesel Standard EN14214 and B20/30 with EN16709. Renewable biodiesel has similar properties to fossil diesel and is present (as a very small percentage) in regular diesel. High blend biodiesel usually contains at least 20%. Common blend strengths are B20 (20%), B30 (30%) or B100 (100%). B100 blends need different seals and heating equipment (to prevent it becoming waxy). FAME is intolerant of water, with a limited 'shelf life' compared to fossil diesel.

## Biodiesel tractor – Deutz AG


| | |
|---|---|
| **Supplier and Availability:** | Deutz AG have supplied biodiesel compatible engines to Deutz-Fahr, Same, Lamborghini tractor brands since 2006 |
| **Typical model** | Deutz-Fahr 6G tractor |
| **Engine categories** | Engine series TCD 2.9 / 3.6 / 4.1 / 6.1 / 7.8 / 12.0 / 16.0 compatible with 100% biodiesel / NRMM IV legislation[4] |
| **Typical operating pattern** | Diesel equivalent |
| **Sales and support** | Multiple locations throughout the UK |
| **Additional notes** | Deutz's ICE can operate exclusively with 100% canola oil in compliance with EU emission level IIIB (the valid regulation at launch in 2006/7) or 100% rapeseed oil according to DIN 51605 IIIB. They offer two tanks and the fuel management system to switch between blends[5]. Biodiesel systems also need more frequent maintenance (e.g. filter changes). Fuel storage must be managed with more care than fossil diesel. |

[4] Deutz approves engines for the use of alternative fuels, Deutz, 16 November 2017

[5] Requirements for fuels for Deutz engines, Deutz

## 2.2. Biomethane

Compressed biomethane (bioCNG) is a relatively mature technology. Road going vehicles have been run on methane for several years in the UK. HGV trucks will be the main driver of bioCNG uptake before 2030. Gas ICE vehicles can be up to 25% more expensive to purchase. However, lower cost per unit of fuel can significantly reduce running costs, alongside significant well-to-wheel (WTW) emission reductions.

The Renewable Transport Fuel Obligation (RTFO)[6] scheme allows biomethane to be injected into the gas grid, with an equivalent methane mass (actually CNG) supplied from grid refuelling sites (including those run by CNG fuels). This process is known as 'mass balancing' but is not really suited to rural users.

BioCNG does not need to be grid injected and can be dispensed at farm production sites and can also be distributed to other farms using biomethane trucks. Biomethane can be supplied in a liquid format (bioLNG) but is produced in large refineries. It is not produced in the UK, or appropriate for farm use.

The Climate Change Committee (CCC)[7] and Imperial College London[8] have indicated that without the addition of carbon capture, utilisation and storage (CCUS)[9], bioCNG may not be compatible with net zero by 2050. However, the survival of ICE power trains could be secured, at least in the short to medium term, by offering a significant emissions reduction.

Moreover, action to reduce transport emissions must include transition technologies. Over-focus on developing fully emission-free solutions will delay emissions reduction progress, as stated in the 2020 Cadent[10], which indicated that:

- Rapid deployment of biomethane will cut HGV emissions by 38% over 10 years.
- Waiting for electric/hydrogen trucks will limit the drop over this period to just 6%.

BioCNG (supplied off- or on-grid) could initiate more rapid transport decarbonisation and its use on farm could help reduce methane emissions for livestock farms, if supplied from on-farm biogas plants.

Prospects for bioCNG up to 2050 are dependent on the revision of ICE legislation. The UK will enter a period of highly accelerated decarbonisation between 2030 and 2040. Livestock farmers need to lobby for support for investment in on-farm AD and locally produced gas fuels (including bioCNG) to be used in farm vehicles. Without policy change, gas use as a future transport fuel could be compromised.

[6] The RTFO supports the development and adoption of renewable fuels through production of tradeable certificates (RTFCs). The RTFC value is based on obligation for all fossil fuel suppliers to ensure a proportion of their fuel is renewable. BioCNG is defined under RTFO as an Advanced Fuel.
[7] Technical Note: Biomethane (to support to support the transport chapter of the report 'Meeting Carbon Budgets 2016 Progress Report to Parliament', Climate Change Committee
[8] Biogas emissions could risk Net Zero targets, a recent study warns, Imperial College London, 26 May 2021
[9] Carbon capture, utilisation and storage, IEA
[10] The Future Role of Gas in Transport, Cadent Gas

## Case New Holland Methane Power Tractor

| | |
|---|---|
| **Supplier and Availability:** | Case New Holland (CNH) will launch a methane-compatible commercial version in 2022 |
| **Typical model** | New Holland T6 |
| **Engine categories** | NEF 6.7L engine only (others being developed) |
| **Typical operating pattern** | Diesel equivalent |
| **Sales and support** | Commercial launch in 2022 |
| **Additional notes** | Prototype development began in 2013. Demonstrations have been underway since 2020. New Holland has stated that the 'energy independent farm' (using local bioCNG supplies) is a core strategy for the company going forward[11]. The T6 methane is a key part of that strategy. |

See the full CNH case study.

[11] T6 methane power tractors, New Holland

# 2.3. Zero tailpipe emissions – electric and hydrogen technologies

National requirements are increasingly focused on zero-tailpipe emission vehicles (ZEV) that do not emit greenhouse gases (GHG) or air quality pollutant emissions, e.g. particulates, NOx from the exhaust.

For such vehicles (see Table 2) power is provided by an electric motor with battery generated electricity, or potentially from a hydrogen fuel cell[12] that converts stored chemical energy into electrical energy. Use of battery electric vehicles (BEV) on farms and in rural areas can include some of the vehicles shown below plus a range of smaller task-specific vehicles including ATVs and driverless/robotic vehicles.

***Table 2: Zero tailpipe emission vehicle technologies***

| Technology | Example | Description |
|---|---|---|
| **Battery Electric Vehicle (BEV)** |  | A battery electric vehicle (BEV) stores energy in a battery and delivers its power to the wheels through an electric motor. OEMs are steadily introducing more on-road battery vehicles. Only one BEV 'compact' tractor is commercially available in the UK market (Jan 2022). |
| **Fuel Cell Range-Extended Electric Vehicle (FC REEV)** |  | A BEV with an on-board hydrogen fuel cell (or another renewable power source) to recharge the battery 'on the go' and extend the range. Wheels are powered by the electric motor. The battery can also be recharged by plugging the vehicle into a dedicated charging point. |
| **Fuel Cell Electric Vehicle (FCEV)** |  | Hydrogen ($H_2$) fuel is taking its first steps to commercial availability as a UK transport fuel (initially buses/passenger cars). Compressed hydrogen can be used to power an electric motor by generating electricity through a fuel cell. A small battery can be used for peak power requirements and regenerative braking. |

[12] Fuel Cells, US Department of Energy

### 2.3.1. Electric vehicles (EV)

There are three main types of electric vehicles in common use:

- **Battery Electric Vehicles (BEV)** run purely on electric power, stored in an on-board battery charged from mains electricity (typically at a dedicated charge point) or a battery recharge system located where it is used, including on farms.
- **Plug-in hybrid electric vehicles (PHEV**) are a combination of an ICE power train and rechargeable battery for pure electric-powered driving, or an ICE (powered by fossil fuel, biofuels, biomethane or hydrogen) and electric motor combined.
- **Range-extended electric vehicles (REEV)** have an electric drive train with small generator to charge the battery for longer trips. A type of PHEV, but without the 'plug' to recharge the vehicle. Instead, fossil fuels, biofuels, or hydrogen can power the generator.

When powered by renewably generated electricity, BEVs are classed as a net zero technology. However, charging infrastructure must also be considered for BEVs. Charging infrastructure terminology refers to a range of power outputs as shown in Table 3, with charging speeds, between 'standard' and 'ultra-rapid'. As power available for charging increases, so does infrastructure cost for charging units.

| | AC or DC | Power / kW |
|---|---|---|
| **Standard** | AC | 7-11 |
| **Fast** | AC | 11 – 22 |
| **Rapid** | AC | 43 |
| | DC | 50 |
| **Ultra-Rapid** | DC | 150+ |

***Table 3: Charging Power Categories***

For a rapid or ultra-rapid charging station, installation cost can be significant. There are challenges for on-farm charging and especially rapid charging if there is a weak grid power supply, often the case in farm and other rural locations. To facilitate on-farm EV charging and maximise use of renewable energy generated, on-farm battery storage will help to enable 24/7 flexibility and speed of re-charging.

**Vehicle-to-Grid (V2G):** this emerging technology shown in Figure 3 acts like (and looks similar to) a standard EV charging point, but one in which energy can flow back and forth between the vehicle and mains electricity grid as required. Using EVs as decentralised electric storage resources (i.e. 'batteries on wheels') minimises the need for capital investments in the grid to support ever-increasing demand, while lowering operating costs.

V2G technology is still at an early stage of commercial deployment[13]. However, it represents an opportunity to boost the use of local renewable electricity generation where surplus power is currently exported direct to the grid – and therefore represents a new income stream for the farm business. Batteries used to power farm electric vehicles could provide demand-shifting benefits and reduce the cost of mains electricity. Those BEVs with prolonged downtimes (due to seasonal operation, for example) may be particularly suited to V2G scenarios, storing power as a 'static battery' for on-farm and local power supply.

[13] White paper assesses readiness of V2G technology, Cenex, 18 January 2021

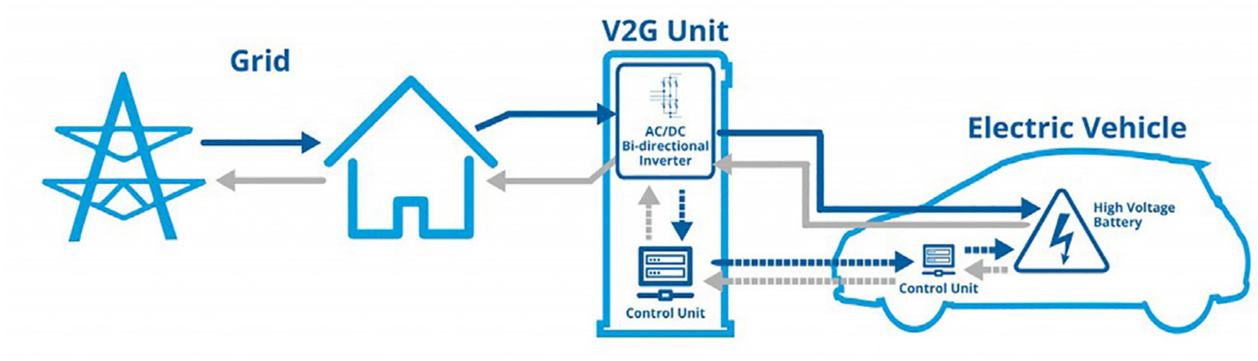



*Figure 3: Vehicle-to-Grid System*

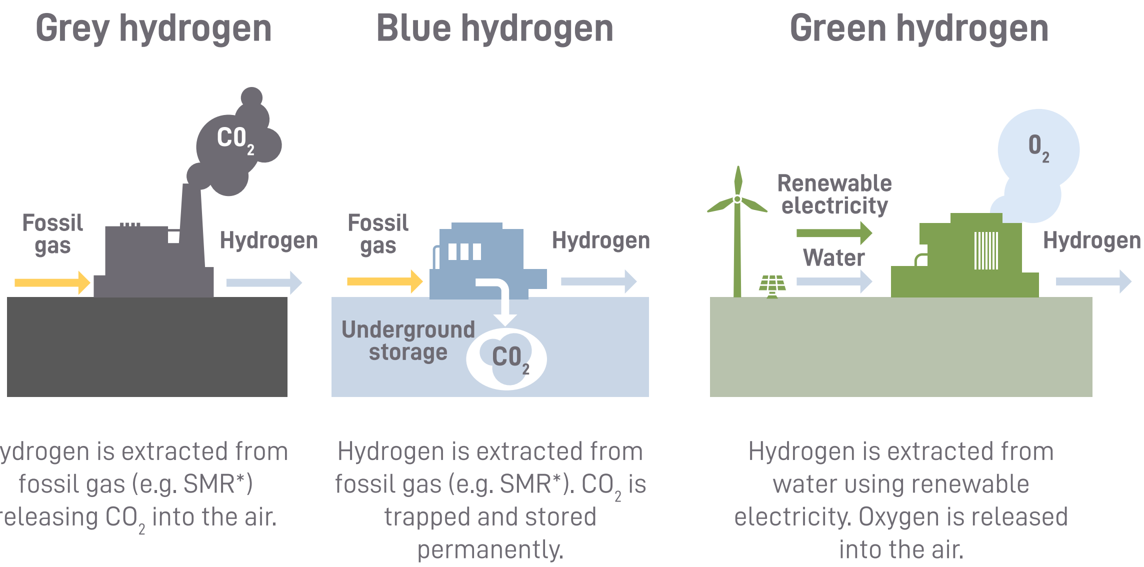
**Limitations of BEVs:** While 'green' electricity is being generated on the farm (via solar panels, wind turbine, biogas combustion) the key impediment to its use as an alternative to diesel is the energy density of batteries. The added weight of batteries needed to provide the necessary power-to-weight ratio for larger agricultural tractors (i.e. >50 hp) limits engine efficiency and damages the soil. Currently, the only commercial BEV tractors are suited for small scale farm and horticultural use (i.e. 'compact' tractors).

## Electric tractor - FarmTrac

| | |
|---|---|
| **Supplier and Availability:** | Reesink Agriculture are Farmtrac's UK distributor |
| **Engine categories** | FT25G model 18.5kW (equivalent to 25hp diesel). – 72 Ah Li-on battery. 3 phase AC induction motor |
| **Typical operating pattern** | Charge cycle 0 -100% is 8 hrs for a full charge (5 hrs 20 – 80%) and can run for up to 6 hours under operational use. |
| **Sales and support** | Shown at LAMMA 2020, commercially available in the UK |
| **Additional notes** | 450kg lift capacity. Minimal noise and vibration. On-board battery charger. 3 range transmission. Selectable 4WD. Independent 540 rpm rear. BBC Countryfile reviewed the tractor here. |

## 2.3.2. Hydrogen

Hydrogen can be utilised either in an internal combustion engine (ICE) or in a fuel cell (FC) to drive electric powertrains. Green hydrogen (see Figure 4) can be produced by using surplus renewable energy, such as solar or wind power, to power the electrolysis process which splits water ($H_2O$) into hydrogen and oxygen atoms.




**SMR: steam methane reforming*

***Figure 4: Types of hydrogen: grey, blue and green***

Based on real-world observations of road-going fuel cell vehicles by Cenex, fossil fuel derived hydrogen can achieve up to 50% reduction in GHG emissions when used in a fuel cell (compared to an equivalent diesel vehicle). Similar GHG emissions reduction should be possible in agricultural equipment powered by fuel cells, should these become commercially viable. If powered by renewably generated 'green' hydrogen, fuel cells would be considered a 'net zero technology'.

On farm generation of green hydrogen (via an electrolyser) may be possible should sufficient renewable electricity (e.g. solar, wind or CHP) be available as a power source. An example of a UK manufactured small scale containerised electrolyser and hydrogen storage system can be found on the ITM Power website. However, the capital costs currently for such a system will be high.

Hydrogen is part of bus fleet conversion plans in cities like Aberdeen, but is not a commercial proposition in rural situations or on farms. Practical drawbacks include lack of infrastructure to refuel hydrogen vehicles, but such issues are not insurmountable. Although bulk hydrogen can be difficult to handle, small volumes can be dispensed from onsite fuel stores.  While blue hydrogen combustion in an ICE is not regarded as a net zero technology, it could meet farming's need for affordable solutions. However, the prime user of blue hydrogen is likely to be heavy industrial hard-to-decarbonise sectors.

Manufacturer JCB is developing a hydrogen-fuelled internal combustion engine ($H_2$ ICE) as an alternative to using fuel cells, reinforcing the need for a transitional approach to diesel replacement (see JCB case study). Their $H_2$ ICE back-hoe loader will be commercially available in 2022.  They have plans to extend this engine to vehicles for farm use, but diesel could remain a farm fuel for some time.

Such a transitional approach makes the case for expanded use of biomethane in ICEs along with other gas engine technologies, where their non-inflationary impact (using standard ICE components) offers a key benefit in terms of cost and availability.  Further development of these existing technologies will enable time for production and deployment of green hydrogen.

The potential of hydrogen as a farm transport fuel is hard to assess. Agriculture deploys a wide range of vehicles and platforms but has a small energy use in comparison. Hence, the option of locally produced biomethane is a much more realistic option to initiate the decarbonisation pathway. Until electrolysers are much cheaper, local generation of hydrogen will not be viable.

While hydrogen storage and biomethanisation[14] may be possible to incorporate into larger AD sites, electrolyser technology (like the Enapater system that won the 2021 Earthshot prize) may become small enough, more readily available and cost-effective in time. It is not yet clear if fuel cell technology will be able to compete with advances in battery design over the next decade or so.

[14] Biomethanisation is a biological process carried out by a microbial community where electrolytic hydrogen ($H_2$) is combined with a carbon source (e.g. $CO_2$ from a chimney or the $CO_2$ portion of biogas) to produce biomethane ($CH_4$).

# 3. FUTURE POTENTIAL FOR ELECTRIC VEHICLES

*A vision of battery-powered tractors parked overnight and being re-fuelled, ready for the next day's fieldwork, may seem to be a neat, virtuous, net zero circle. Power could come from renewable electricity, generated by solar panels located on the building's roof, or from an on-farm wind turbine or a biogas combined heat and power unit (CHP[15]) and stored in a large static battery ready to be down-loaded to the tractor!*

While the transition is underway, the hurdle for this vision of 'net zero heaven' is the energy density of batteries that could be fitted into tractors and other vehicles. For 'agricultural tractors' >50 hp, the battery pack required to provide the equivalent power to a diesel engine would be so heavy that energy needed to carry the battery would consume most of the power it produced!

While this is likely to remain an issue, leading manufacturers like John Deere are developing lighter BEV autonomous or 'driverless' tractors. However, the challenge of the power deficit was highlighted on BBC Countryfile in 2020[16] where a 25 hp equivalent compact electric tractor was demonstrated. It was of note that the presenter and farmer Adam Henson was reluctant to even consider the battery technology until it matched the 250 hp available from his current diesel tractor - let alone to meet the power demands of arable farmers using diesel tractors of up to 500 hp.



***Figure 5: The Farmtrac 25 hp equivalent electric tractor (left) and John Deere's prototype autonomous electric tractor (right).***

[15] Combined heat and power (CHP) engines are found on most farm AD plants and the transition to use of biomethane may be impacted by the need to replace biogas CHPs as they reach end of life or AD plants lose their Feed in Tariff (FIT) payment. The FIT on existing AD sites lasts 20 years and after it expires, they will need to find new uses for the gas.

[16] Robert Llewellyn (host of 'Fully Charged') visited Adam Henson's farm (see picture) to test 50 hp electric tractors. When asked if he was interested, Adam pointed to his 250 hp John Deere, commenting to the effect that he needed more power.

Given the level of research and development being undertaken on battery design and power, the rate of progress with electric drive trains will undoubtedly speed up. However, to address the 'weight to power' problem and enable original equipment manufacturers (OEM's) to engineer the 'workhorse' that Adam Henson and other farmers need requires a combination of two things.

Firstly, on-board batteries used to power tractors must be able to deliver sufficient power to undertake farm tasks. Secondly, they need sufficient capacity to operate for a full working day. At busy times like silage making, harvest or drilling, that could mean 16-hour working days - which leaves just eight hours for re-charging the batteries. While this may suit smaller BEV's such as vans, compact tractors or other automatic machines, for heavy vehicles, recharging times are too slow. This is one of the reasons why some OEMs may move from the battery powered tractor option to hydrogen[17].

Pressure to decarbonise the UK's agri-food supply chain provides a unique opportunity to 're-engineer' farm transport. This could include the replacement of engines and fuel tanks with electric motors in vehicles such as the vans that distribute higher value produce. Farms that generate electric power and use it to recharge their EV fleet could earn revenue by installing charging points for neighbours and visitors.

## Viewpoint: EVs - already a fan!

NFU Deputy President Stuart Roberts uses electric power in his car, but not yet in his farm machinery. In his Nissan Leaf, he covers some 20,000 miles a year. On NFU duty, he is well covered for charging points: there is one at the family's Hammonds End Farm, Hertfordshire and there are charging points at NFU headquarters in Stoneleigh Park, Warwickshire.

Other longer trips require more planning - and more time. Journeys that used to be done in one stint are now split to allow re-charging. And charging times can vary: a partial charge from 20% to 80% might take 35 to 40 minutes, so can be worked into a meal or rest break. A full charge can take 5 hours with a 7-kilowatt charging unit. However, Stuart believes utilising renewable electricity generated and stored on farm will become a viable option for farm vehicles, but only once storage capacity, weight and re-charging issues are addressed.

"Scenarios for electric tractors aren't far away, but I would want them to be better proven technology. When it is, I would be ready to jump in. The real question is: can we replace our 200 hp tractor with an electric model or might we have to rely on a fleet of smaller vehicles?"

He thinks moving away from diesel could lead to a new generation of farm machines being produced. Stuart highlights the potential for robotics and digitally operated.

"With my car, a major part of the vehicle is the same as a conventional model, but the engine is an electric motor rather than a combustion engine. So, will the tractor of the future need to look like the machine we are all familiar with now? We might have a different type of vehicle (maybe 'multi-purpose') that can apply fertiliser and sprays, as well as cultivate, sow and even combine the crop".

[17] For more information, see Harry's farm video on a visit to JCB – explaining why they think hydrogen is the best alternative to diesel for heavy machinery and farm vehicles. They also have a range of smaller BEV units, but these are restricted to specific tasks and requirements.

The NFU sees wider adoption of electric power as a key factor in helping the industry to meet its net zero targets. But there are also electricity supply issues, suggests Dr Jonathan Scurlock, the NFU's Chief Adviser on Climate Change. "It could contribute towards the NFU's net zero 2040 goal for farming by helping to reduce emissions. However, the electricity grid and the provision of charging points in rural areas are far from adequate"[18].

An NFU members' survey (May 2019) attracted 131 respondents (5% of whom had an electric car or van). Although self-selecting, they included all farm sizes, regions and sectors and two-thirds of them expect BEV tractors and machinery to become available within ten years. Dr Scurlock comments, "Lower costs and enhanced safety are expected to be selling points, but higher purchase costs, limited range and recharge downtime are seen as possible drawbacks."

Only a quarter of the famers surveyed could accommodate the 100 kilowatt or above electrical load that is needed to facilitate rapid charging. In addition to better battery storage technology, improvements to the rural power supply infrastructure are required if farms, rural businesses and tourism are to make the successful transition to electric vehicles. The NFU is reluctant to set a date for the phasing out sales of diesel tractors and non-road agricultural machinery. They also want government to accelerate the introduction and encourage demonstration of ultra-low emission electric, gas and hybrid tractors.

***For BEVs, in addition to raw material costs for the same power demand, issues such as battery weight and charge time undermine their viability. Battery power is more suited to smaller compact tractors and robotic vehicles. The option of building larger vehicles with batteries powerful enough for the required workloads appears to be an uneconomic proposal at present, and this justifies the retention of ICE power trains using low emission fuels as part of the future.***

[18] NFU responds to consultation on petrol/diesel vehicle phase out, NFU

# 4. THE FUTURE OF GAS FUELS IN FARM MOBILITY

*It is becoming clear that non-fossil gas fuels offer a long-term solution for both heavy and non-road vehicles. BioCNG is an affordable fuel technology that can use existing supply infrastructure and power trains which contain fewer inflationary components than battery powered alternatives.*

The primary contrast with fuel cells is that the gas ICE is cheaper to manufacture, deploy and service. Adapting existing ICE engine and drive train technology limits design, re-tooling and assembly changes, as well as keeping build costs down. This will also use servicing skills already present, based on existing infrastructure. It is also regarded as more robust solution than fuel cell or BEV equivalents.

## 4.1. Biomethane

There is scope for development of grid-enabled refuelling as well as use of existing off-grid biogas plants to supply bioCNG in rural areas. Biogas can be upgraded, compressed and stored on farms. It can be transported to rural sites in tankers (as with diesel), to fuel gas ICE[19] vehicle power trains. Rural biogas plants could install upgrading and biomethane re-fuelling stations immediately and offers a ready-for-use diesel replacement, in advance of development of viable BEV or hydrogen ($H_2$) power trains.

*BioCNG can replace red diesel while facilitating the transition to green hydrogen fuels. Gas fuels used in ICE engines can provide lower-cost rural transport solutions for low margin sectors like farming.*

There are vehicle design issues to be overcome to increase adoption of gas fuels - initially biomethane, then hydrogen. Gas fuels are pressurised, which requires circular tanks plus a suitable chassis on which to mount them, a contrast with the ease of installation of diesel tanks. Open the engine compartment of most tractors – and it is evident how design engineers have shoe-horned diesel tanks into the design after other elements have been installed in logical positions.

An initial concern was that farm-produced biogas was of insufficient quality and needed refining (i.e. removal of $CO_2$) before use in a truck or tractor. But upgrading technology exists for grid injection is under continuous development. Smaller, off-grid modular units for on-farm use are available.


Figure 6: Biogas-to biomethane upgrader

[19] There is an increasing debate about the future of the internal combustion engine, e.g. The Future of Internal Combustion Engines as seen by Rolls-Royce Power Systems. With multiple investment in novel systems, many commentators consider that the ICE will be required in heavy vehicles beyond 2050.

Biomethane (supplied off and on grid)[20] may offer the best option for more rapid decarbonisation of farm transport. Government support is needed to 'de-risk' the transition to gas fuels and to bridge the supply gap. With more support, the UK could be a leading player in the transition to gas fuelled tractors.

Development of gas-powered tractors by Case New Holland (CNH) in Basildon has been supported by a UK Research and Innovation grant (see the CNH case study). New Holland produced the initial prototype methane tractor in 2013. Commercial supply of the T6 180 Methane Power tractor (140 hp to 180 hp) is due to start in 2022. Its power/torque is comparable to a diesel tractor, but it has lower running costs, as well as RTFO support[21].

Mark Howell, Global Product Manager for Alternative Fuels at Case New Holland (CNH) Agriculture, says that the company looked at hydrogen for a time, but decided that methane is a better option at present. That decision was partly driven by the infrastructure costs associated with hydrogen production and supply, but also because methane produced from farm sources was already available and potentially plentiful.

He says, "Hydrogen [in fuel cells] has potential, but I still think it is limited. It can have zero emissions, which will count in its favour when authorities demand that. Our gas-powered engines will make some emissions, but we are using an agricultural by-product, so the overall carbon balance can be negative".

Other farm vehicle manufacturers are developing gas, electric and hybrid fuel low or zero emission ICE power trains. An advantage of bioCNG over electricity is speed of re-fuelling. For a farm with a gas fuel dispensing point, a complete fill need only take a few minutes - comparable to diesel re-fuelling.

BioCNG produced on existing farm AD plants and upgraded cost-effectively in smaller modular units could supply major volumes of gas fuel, as 400 existing mainly rural AD sites lose their Feed-In Tariff (FIT) incentive for power generation over the next decade.

## 4.2. Hydrogen

***Hydrogen fuel cells may have major emission reduction advantages. However, if combusted in an ICE, there is potential for lower NOx emissions than diesel, plus other benefits.***

Fuel cells were used in public transport (taxis and buses) at the 2012 Olympics and are part of bus fleet plans in some cities. They have yet to make serious inroads in commercial transport, let alone in the farm environment. An alternative option already under development (see JCB case study) is the adaption of internal combustion engine (ICE) technology to run on hydrogen.

Although the situation is changing rapidly, ensuring sufficient supply and use of hydrogen for rural on-road and off-road transport will have challenges. According to companies engaged with hydrogen fuel, these are not insurmountable and small volumes can already be dispensed from modular units.

Figure 7: Hydrogen telehandler

[20] Biomethane is already being provided from grid connected fuelling stations, mainly used by hauliers with gas trucks (see CNG Fuels) but it can also be upgraded at biogas sites to supply local off-grid supply.
[21] Under the Renewable Transport Fuel Obligation (RTFO) suppliers of transport fuels meet their obligation to supply a certain amount of renewable fuel by claiming Renewable Transport Fuel Certificates (RTFCs) or by paying a fixed sum for each litre of fuel to 'buy-out' of the obligation

More widespread re-fuelling of gas fuels including hydrogen vehicles at public filling stations may take time to become mainstream. This lack of supply and refuelling infrastructure could hold back adoption of hydrogen fuel for road use and for off-road vehicles such as on farms. This could be addressed by the development of viable hydrogen generation systems using on-farm electrolysis.

## 4.3. Gas fuel policy requirements

Gas fuelled ICE engines can provide low margin industries such as agriculture with an affordable heavy power train. While some OEMs develop hydrogen technology, others will focus upon biomethane as a pathway to zero emissions diesel replacement over the next 25 years. Fuels and engine designs that are currently available and do not involve a 'paradigm shift' will form an important part of the transition to a zero-emission farm vehicle fleet.

However, the long-term access to hydrogen as a vehicle fuel will be in part dependent on its wider use as a natural gas replacement energy source for fuel-hungry heavy industry (such as glass, fertiliser and steel manufacture - all key components for the agri-food supply chain). A recent Climate Change Committee (CCC) report Hydrogen in a low-carbon economy expects applications will expand pre-2030.

The CCC also expects that after 2040, 'the rates of electricity demand growth will slow, enabling more rapid scaling-up of electrolytic hydrogen supply with further deployment of zero-carbon generation.' Up to 2050, they feel it is likely that 'costs of hydrogen supply will remain well above that of fossil gas before any carbon price'.

Rural deployment of hydrogen fuel power trains needs a network of demonstration farms to show the potential of hydrogen in an ICE.

***It must be evident to policy makers that low margin sectors such as farming cannot afford the inflationary impact of emerging engine technologies such as heavy BEV's or hydrogen fuel cells. They need affordable, robust engines with high torque that currently can only be delivered by adapting the ICE power train for gas fuels.***

The farming sector also needs to push the case for off-grid, on-farm, smaller-scale AD installations with the Department for Business, Energy & Industrial Strategy (BEIS) and the Department for Environment, Food & Rural Affairs (DEFRA). In light of decisions at COP26, this aligns with the Global Methane Pledge and the fact that AD can help mitigate methane emissions from housed livestock.

Farm use of gas fuels has the transitional capability not only to pave the way for hydrogen as part of the farm energy mix, but also the use of biomethane provides an adoption-ready solution for red diesel replacement.

# 5. FUTURE CHOICE AND THE VEHICLE DESIGN REVOLUTION

The opportunity to re-engineer farm machinery platforms is attracting interest from mould-breaking engineers and start-up companies. It is widely expected that not all future on-farm applications will require heavy vehicles where weight impacts on soil performance and productivity. This helps crystallise the question of whether switching to other fuels can enable a radical re-design of some farm vehicles.

## Viewpoint: Delivering Innovation

The pressure for more sustainable food products and for the need to reduce GHG emissions is being led by the leading brands, processors (including breweries and creameries), customers and major retailers. This is driving the push for alternative low emission fuels. Innovation consultant Dr Robert Merrell suggests farmers' reliance on a mix of different fuels to replace fossil sources, with biomethane and electricity as readily available parts of the mix.

Dr Merrell states, "Food producers are always seeking ways to distinguish themselves from their competitors. Using innovative technology can help secure a producer's position with customers and enable them to be seen as responding to public pressure."

He has been working with Case New Holland (CNH) on options for alternative-fuelled tractors, including increasing use of biofuels and biomethane, and researching both electrification and hydrogen fuels. He considers that gas offers better potential than electricity due to its energy density. For road haulage, BEVs lack the required density for long-distance or heavy work.

He said, "Haulage industry feeling is that long haul and heavy-duty applications will be better served by low carbon-producing fuels like biomethane. Battery power is likely to be more successfully applied for lighter duty tasks."

While progress is being made in reducing battery weight, Robert considers they are not yet viable as the sole energy source for heavier tractors. But he suggests gas power is not without its design challenges, "By their nature gas tanks need to be cylindrical to handle the pressure (200 bar) and cannot be fitted and moulded around other elements as diesel tanks can."

For all options, the design challenge is to maximise fuel capacity within the existing envelope of the machine. New formats are already emerging, with autonomous (driverless) vehicles from sector leading companies like AgXeed (see case study 3) with prototypes in use in Dutch field trials, and novel concepts such as the family of robotic vehicles from the Small Robot Company (see case study 2). Removing the driver eliminates the driver comfort components (cab, steps, sprung seat, air conditioning and fridge, etc).



***Figure 8: Robotic vehicles from Small Robot Company (left) and AgXeed's AgBot autonomous tractor (right).***

Discussion of driverless arable farming equipment often starts with the shortage of farm labour, but experience with autonomous technology suggests that benefits including energy saving, intensification of crop management, more timely field operations, less soil compaction and greater precision.

Autonomous vehicles are smaller and lighter and more easily adapted to battery electric – provided by solar, wind and other renewable electricity. They may require the redesign of cropping systems, even the adoption of whole plant harvest systems for grains and oilseeds that rely on centralised threshing.

Smaller, lighter equipment may allow for better timeliness if they can be in the field when it is too wet for large, heavy conventional equipment. Mechanical weeding and targeted herbicide application can drastically reduce chemical use. Autonomous equipment can deal with small, irregularly shaped fields more cost effectively (also in-field trees and other obstacles) and allow for more in-field biodiversity.

However, at present, robotic vehicles still require some human supervision and, while they may reduce soil damage, the impact on labour demand and costs is as yet unclear.

It is not just power trains that offer opportunities for innovation. Companies have developed electric weeding systems that send a charge down the plant's stem to disrupt the cells that enable growth. The first patents for this technology were taken out in the late 19th century. So why did the technology not catch on? Maybe because the safety record of early electric weeders was not great.

Farmers were also told that the emerging chemicals controls did the job much better and were, their promotors promised, completely safe to the operator and the environment! The lesson is that for whatever technology is being adopted, there should be continuous assessment of its effectiveness, wider impact and safety, combined with a willingness to change if serious problems are encountered.

Avoiding the impact of heavy machinery on soil quality and productive capacity needs to take account of the ever-increasing size of farm tractors and other machines. Options will include use of drones for monitoring crops and livestock plus development of machinery platforms that dramatically reduce soil compaction.

In addition to robots, this includes controlled traffic and gantry technology, where modular attachments are fitted to motorized wide-span vehicles (see case study 4).

German company, Nexat GmbH could deliver momentum to on-farm gantry technology that has been under-exploited for decades[22]. Splitting arable land into traffic and cropping zones limits compaction to just the tracks.

[22] Initially developed in the 1970s – see Machinery Focus: New chapter for gantry farming from Nexat - the prime benefit of gantry systems is restricting soil compaction to very specific areas of fields on a permanent basis. Traffic is limited to just 5% of land area compared to up to 80% for current practices.


***Figure 9: Nexat Gantry system (left) and the AgXeed driverless system (right).***

This protects soil structure, improves water infiltration and moisture capacity, and can limit erosion. Precise satellite-based guidance systems help improve soil health and increase yield.

**Another option is the hybrid tractor - able to utilise more than one fuel source.** This could do more than just relieve reliance on diesel. A tractor that uses a combination of biofuel and battery electricity, for example, could reduce noise and pollution impacts - with potential for using farm-generated fuels.

## Viewpoint: Future farm vehicles – silent and adaptable

The hybrid farm power train could also help maintain good relations with rural neighbours and avoid emitting fumes inside farm buildings. This is the future vision of Christian Huber, Vice President Global Tractor Product Management for Case IH and STEYR.

He envisages a scenario on a busy summer evening with grain being harvested late on one side of the village and being transported to the grain store at the farmstead on the other side.

In the field and on the road, the tractor would run on biofuel, but as it enters the built-up area of the village, it would switch to electric power (with a silent motor) and glide through the houses. Nobody would be disturbed and the only person wide awake would (should!) be the driver.

Once out of the village, it could resume using biofuel until reaching the farm. At this point, it could switch to electric power again to avoid emitting fumes in or near buildings. While electricity is an essential component in this scenario, it is not yet the answer on its own and we can expect hybrid tractors available on the UK market in the next few years.

Christian Huber states, “We believe that, for the next 10 years, there won’t be a fully electric tractor available in the power range that large-scale farmers require. If you want 200 hp and higher, our experience has shown that hybrid power is the only viable solution.”

Another key issue for farmers with margins and subsidy revenue under pressure are the purchase costs and on-going operational costs. If electric platforms and hybrid tractors have fewer moving parts (e.g. gears and clutch) will less lubrication mean lower servicing and maintenance costs?

Christian Huber adds, “Most farmers we have talked to say it sounds interesting, but then immediately ask about price. If this can be offset by lower ownership costs, many would be interested. There is a clear requirement for a tractor that runs eight to ten hours a day without needing to stop to re-charge.”

This evolution will depend on how quickly and cost-effectively the infrastructure can be established and the availability of small-scale 'on farm' gas upgrade plants, the potential for small scale electrolysis to produce hydrogen, changes in fuel distribution logistics and the expansion of rural re-fuelling systems.

***There is no single diesel replacement for farms and rural areas at present, and more effort is needed to reduce the cost and boost supply of off-grid green gas fuels (including biomethane and hydrogen).***

Other gas power trains will be developed. But an immediate Government-led commitment is needed to support gas fuel diesel replacement.  To stimulate rural fuel transition, the industry requires rural trial sites for smaller fuel upgrade plants and use of electric and hybrid power systems, alongside the integration of robotics, artificial intelligence and rural broadband and wi-fi (see Wessex Internet case study for further broadband discussion).

# 6. TOWARDS 2030: FUTURE VISION AND EXPECTATIONS

Although there has been no formal policy statement[23], it seems unlikely that the red diesel subsidy for on-farm use will remain in place by 2030. The need to replace diesel is matched by the scope for farms to supply decentralized renewable energy, including fuels for farm machinery.

A critical issue in policy debates on decarbonisation of rural transport and non-road vehicles is that low margin sectors such as farming not only require robust, high-torque power, but also cannot afford to implement technologies being proposed, including BEVs and hydrogen fuel cells.

Confirmation of the Global Methane Pledge at COP26 will require BEIS and DEFRA to work together on rural deployment of biomethane before a possible switch to hydrogen and other gas fuels.  Deployment of more on-farm biogas plants will help mitigate methane emissions from housed livestock.  Supply of gas fuels for rural areas will be boosted by converting existing on-farm biogas plants to fuel production.

Rural gas fuel use has the capability to pave the way for hydrogen in the rural energy mix, but this must be based on acceptance that modified ICEs and hybrid solutions that are able to deliver close to or zero emissions must be part of rural decarbonisation in the medium to long term, alongside BEV solutions.

The industry must make the case for increased biomethane use in ICEs to enable time for deployment of alternative gas engine technologies that also have a non-inflationary impact. Replacing diesel on farms with BEV or hydrogen fuel cell power trains may not be achievable or appropriate before 2050.


Expanded use of gas and biofuels, plus deployment of BEV's and robotics for a range of farm tasks that require lighter, versatile tool platforms will be a feature of the next decade.  This transition requires the agri-food sector to work with Government to fund farm demonstration sites for the alternative fuels and novel vehicles that will facilitate removal of red diesel subsidy and transform farming after 2030.

[23] See a summary of intentions in Govt Policy Paper: Reform of red diesel and other rebated fuels entitlement, HMRC, 29 November 2021

# 7. DECARBONISING FARM TRANSPORT – CASE STUDIES

## 7.1. CASE STUDY 1: JCB – Hydrogen ICE pioneers

Replacement of diesel in farm and non-road vehicles is closer thanks to a revolutionary hydrogen fuel internal combustion engine (ICE) developed by UK construction machine manufacturer JCB, who have adapted their standard diesel engine by re-engineering the pistons, the cylinder head and fuel system.

JCB manufactures their own diesel engines, producing 400 units daily for agricultural and construction machinery, have recognised the need to look at alternative means of powering its machines.


Figure 10: JCB Hydrogen ICE back-hoe loader

In two years, the company has developed a new combustion engine, using proven technology based on their conventional diesel power train.  It is fuelled by compressed hydrogen gas ($H_2$), eliminating carbon emissions while keeping performance for non-road machines like its ubiquitous back-hoe loader.

Chairman Lord Bamford challenged his engineers to develop the hydrogen engine in 2020. He said at the launch in 2021, “My hope is that hydrogen power will be seen as a genuinely viable alternative to electric or battery-powered machinery within the construction sector. JCB is investing £100 million to produce super-efficient hydrogen engines.”

## Development of the hydrogen ICE

In July 2020, JCB Power Systems started designing the new engine. By December, the working prototype hydrogen power train was being tested.  Engineers developed this using established technology with readily available components. The new hydrogen back-hoe loader matches its diesel equivalent's performance with an engine that is far less complicated than a hydrogen fuel cell (FC).

The four-cylinder (4.8-litre) hydrogen engine provides comparable power and torque to their 'Dieselmax 448' equivalent. Unlike battery powered (BEV) or fuel cell vehicles, the $H_2$ ICE engine and the production vehicles will not be much more expensive than diesel versions.Lord Bamford commented, "It is robust, cost-effective and it could be integrated into all forms of powertrain. Most importantly, a familiar technology and lack of complexity make hydrogen an ideal zero-carbon solution for our customers and our supply chain."

## Propulsion system for the future

JCB is developing a telehandler for on farm and other uses, more powerful than its current electric offering. Their machines often operate well away from existing infrastructure - on farmland, in quarries or on construction sites. BEVs are impractical for equipment with high power demand in such locations.

For such heavy-duty vehicles, batteries would weigh too much and cost too much.  There would be insufficient time to charge them, even if on-site charging infrastructure was in place. With its cost comparable to a traditional engine, unlike battery or hydrogen powered vehicles, the ICE is not inflationary.

Lord Bamford says, "In addition, for an engineer who is used to petrol or diesel motors, to re-train on electric models means dispensing with much of what they know and effectively starting from scratch. The logistical problems would be colossal, especially in the developing world."

JCB expect the first H2 ICE machines to be supplied to customers in 2023. Widespread adoption requires access to green hydrogen supply from surplus renewable energy generated by solar or wind power. Lord Bamford hopes that green hydrogen power will be a key part of the solution to climate change.

## 7.2. CASE STUDY 2: Small Robot Company – robots transforming farming

The Small Robot Company (SRC) is a British agritech start-up looking to transform farming and to make food production more sustainable. It has created an entirely new model for ecologically harmonious, efficient and profitable farming that can also protect soil health, water quality and biodiversity.

SRC's vision is "Per Plant Farming" using robotics and artificial intelligence (AI) to re-imagine agriculture, delivering the next generation of farming. With this approach, any farm, growing any crop, anywhere in the world, will be able to gather intelligence on individual plants and take action on optimising growth of each individual plant.

With this entirely new way of growing food, the Small Robot Company estimates it can save farmers up to 40% of their operating costs whilst producing 50% more food, worth 70% more per tonne.

Lightweight, highly accurate and precise, battery powered farming robots 'Tom', 'Dick' and 'Harry' will respectively monitor, treat and plant crops autonomously. Guided by AI platform 'Wilma', the robots will know where every plant is and understand exactly what their needs are for optimal performance.



*Figure 11: Images of Tom and Dick and the concept for Harry*

With this intelligence, farmersneed act only when required, giving each plant the nutrients it needs or only targeting weeds that are a problem. Benefits include exponentially cutting chemicals, emissions and improving biodiversity. Battery powered robots will significantly reduce diesel emissions.

Founded in 2017, the Wiltshire-based company now has 50 employees. It has developed proof-of-concept prototypes for all three robots, with trials on three farms through 2021. It is now moving to deliver commercial service on thirty farms for 2022-2023.

In its Net Zero mission, one SRC focus area is on fertiliser use - a major contributor to agriculture's emissions. Robotics provides huge scope to close the gap: delivering nutrient applications by exception. Another priority is working to optimise existing sprayer equipment for herbicide and fertiliser applications.

Robotic monitoring data identifies the problem areas so that sprayers only spray the plants that need it. This alone can provide immediate value, delivering savings of circa 20-50%. The next step will then be robotic precision application.

SRC's longer term vision is to deliver what it calls 'Carbon Positive' farming - storing more carbon in the soil than is used to produce the crop. Net capture and storage of between 1.42 and 5 tonnes $CO_2$/ha per year (based on an internal scientific report from 2017) is possible with a regenerative farming approach, rising to circa 9 tonnes by adopting robotic systems.

Ben Scott-Robinson, co-founder and CEO of Small Robot Company, comments, "Robotics and artificial intelligence will be game-changing for agriculture. It could also be the key to unlocking agriculture as one of the biggest contributors, reducing $CO_2$ emissions globally. We could cycle tens of millions of tonnes of carbon a year in the UK alone."

# 7.3. CASE STUDY 3: The AgXeed autonomous tractor

Dutch start-up AgXeed B.V., set up in 2018, is a leading player in development and commercialisation of autonomous agricultural machines. European tractor and farm machinery manufacture, the Claas Group, has taken a minority stake in the business.

The agricultural industry faces the challenges of reducing GHG emissions and increasing productivity - doing this with an ever-decreasing labour force. Machinery supplier solutions include development of precision farming technologies and the deployment of autonomous or 'driverless' farm machines.

AgXeed is one of Europe's major companies in this sector. Its operations portal allows users to plan and set out field activities to allow driverless operation for an extended and unsupervised period.

Figure 12: Agbot field robot

AgXeed's 'AgBot' is a field robot with diesel-electric drive, on wheels or crawler tracks. Its Deutz diesel engine (Stage 5 – 115 kW/156 hp, with a 350-litre diesel tank) powers the electric motors that operate the Agbot. The electrically driven tracks provide a speed capability of up to 13 km/h.

AgXeed offers an adjustable track width, load-sensing hydraulics and a standard three-point linkage with a lift capacity of up to 8 tonnes. The electric power take-off (PTO) is independent of engine speed. The remote-control system includes automated steering plus hazard and obstacle detection.

With the ability to undertake a wide range of tasks, the Agbot is in an advanced stage of development and will soon offer farmers and contractors a field-ready solution. A narrower three-wheel version is being developed for use in the horticultural sector.

The AgBot will undertake a range of field tasks using automated, optimised route planning and machine settings. A maximum weight of 7 tonnes (without ballast) means that the AgBot is more soil-friendly than comparable conventional tractors.

The intention is that an Agbot will be able to replace a tractor twice its weight, thus limiting potential to cause soil compaction. With smaller and lighter cultivation machinery, it can operate for at least 24 hours unmanned, doing twice the work of larger human-operated tractors. Whilst saving on fuel and equipment costs, it can also free up farmers to undertake other tasks rather than spend time in tractor cabs.

Autonomous equipment may also allow production of multiple crop species in a single field, using strip cropping or intercropping. Having multiple crop species within a field offers a benefit for soil health and will facilitate pest management by increasing natural competition.

The AgBot, and associated software platform, is expected to be launched commercially in 2022, with an initial 20 units to be trialled on farms in a number of countries including the UK.

## 7.4. CASE STUDY 4: Controlled Traffic and Gantry Farming Systems

The benefits of controlled traffic systems are highlighted in the main Farm of the Future Report and include reduced fuel consumption (and reduced power need), plus reduced tillage costs, more timely operations, less compaction of harvested areas, greater precision and increased yields.

Controlled traffic farming (CTF) has been boosted by access to affordable Global Navigation Satellite Systems (GNSS). With CTF, the portion of the field that is driven should be reduced from up to 80% down to 30% with conventional equipment. By adding GNSS, the area can be reduced to circa 15%.

This approach can include gantry technology[24], where modular attachments are fitted to motorised wide-span vehicles.  This has been proposed in the past, but adding GNSS guidance could deliver new momentum to a system that has been ignored for several decades.  Companies such as Nexat GmbH may have the solution to transform farm mechanisation for a range of field operations.

Nexat GmbH (founded in Germany in 2017 by Kalverkamp Innovation) is focused on development, manufacture and sale of innovative farm machinery. Its ground-breaking gantry system has been awarded the 2022 gold medal at Agritechnica.

Nexat[25]  has developed a versatile system for multiple on-field operations that currently require a range of agricultural machinery.  The wide-span system uses fixed tramlines for all arable farming operations.

In the 1980s, development work took place at the Silsoe Research Institute (SRI – formerly the National Institute of Agricultural Engineering) - on the concept developed by Cotswold farmer David Dowler.  Removing traffic from the cropped area resulted in sustained benefits, but the SRI did not survive the restructuring of agricultural research in the 1990s and a significant engineering resource was lost. More info on the evolution of the Dowler system can be seen here: Silsoe Arable Gantry.

Figure 13: Dowler gantry system at Silsoe

Wide-span cultivation can reduce the traffic area compared to the normal practice of Random Traffic Farming (RTF).  Using the wide-span controlled traffic method, 95% of farmland remains permanently untouched by vehicles, which can reduce the number of cultivation passes and contribute towards reducing emissions.

[24] The prime benefit of gantry systems is restricting soil compaction. Traffic is limited to just 5% of land area compared to up to 80% for current practices. Machinery Focus: New chapter for gantry farming from Nexat, Agriland, 8 January 2022
[25] The system was developed in collaboration with leading manufacturers inc. Swedish cultivation equipment manufacturer Väderstad plus the Osnabrück University of Applied Sciences and the Optimal Control Group at University of Bremen.

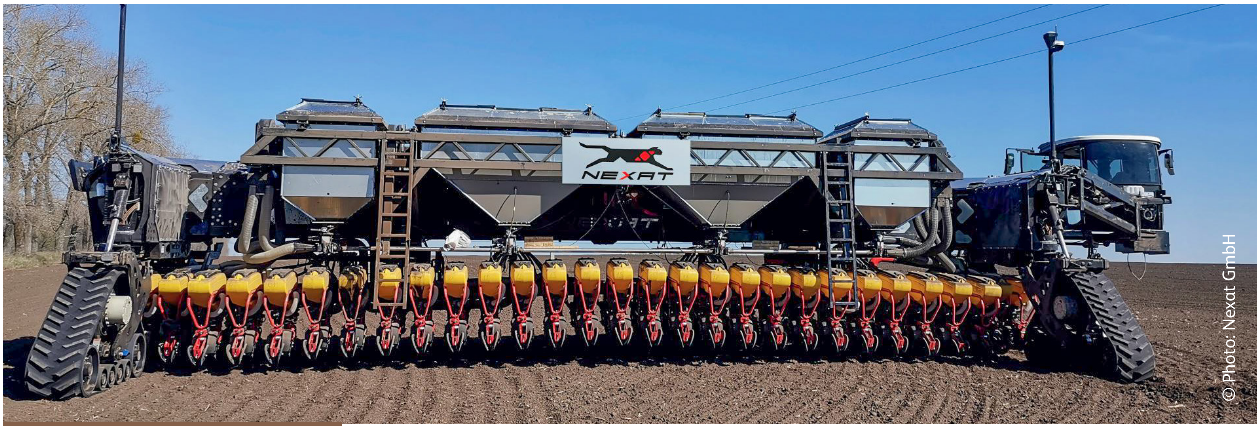



Figure 14: Wide span field gantry

A diagrammatic comparison between the RTF approach and a gantry-based CTF system is shown below.


Figure 15: Gantry-based Controlled Traffic Farming system

The 2022 Nexat system is based on a wide-span carrier platform that takes interchangeable, modular implements that perform tillage, sowing, crop protection and harvest tasks. It is 'AI compatible', with potential for autonomous (driverless) operation, electric drive and the potential for adaptation to hydrogen fuel options.

CTF systems, including the evolution of the gantry system, can help reverse soil damage from heavy cultivation systems, enabling greater precision and increased flexibility of field operation.

# 7.5 CASE STUDY 5: The Hands Free Hectare and Farm, Harper Adams University

A future of autonomous farming has been long discussed, with the earliest references going back to the early 1960s. Many of the hypothesised benefits of automation in agriculture are around improving the overall sustainability of the farm sector: economic, social and, critically, environmental.

Research has found that 90% of the effort farmers put into soil cultivations is required to correct damage done to the soil by tractors[26]. By removing the requirement of dedicated human operators for each field machine, automation has the opportunity to reduce the scale of farm vehicles, reversing the trend of mechanisation to date, and critically reducing the compressive load imposed on farm soils allowing them to regenerate.

These small machines coupled with targeted application technologies could enable ultra-precise high-resolution field management systems, able to reduce the volume of farm level agronomic inputs whilst maintaining output. The Hands Free Hectare (HFH) was a collaborative project which aimed to complete the world's first autonomous cereal cropping cycle to move the industry nearer to full automation.

Initially, the HFH utilised open source unmanned aerial vehicle (UAV) systems integrated into commercially available small-scale agricultural equipment (including a tractor and combine harvester) plus real time kinetic (RTK) high precision GNSS positioning[27].

The autonomous cropping of spring barley was completed in 2017 from seed establishment through to harvest. All activities in the HFH were conducted autonomously including the use of drones and ground scout robots to monitor the crop's development. The achievement was repeated in 2018 but created further questions around a commercial output.

In 2019, the Hands Free Farm (HFF) was established to develop and showcase autonomous farming at farm-scale. The collaboration of academic and commercial partners has developed systems required to farm 35 ha of land made up five typical UK fields, which pose all the challenges of a commercial farm including abnormal shapes, trees, power lines and footpaths.



***Figure 16: Autonomous field operations on Hands Free Farm.***

Economic analysis of the HFH and HFF automation shows potential benefits in terms of reduced cost of production to the order of £20 - £30 per tonne of wheat, alongside possible gains made through soil regeneration and input reduction. Small-scale autonomous farm machinery and improving soil health will open the opportunity for lower in-field power requirements and moves to battery electrification.

[26] Farming with robots 2050, Prof. Simon Blackmore, Harper Adams University

[27] Real time kinematic (RTK) positioning is a technique used to improve the accuracy of a standalone global navigation satellite system (GNSS)

# 7.6 CASE STUDY 6: Wessex Internet – connectivity pioneers

In Dorset, rural internet provider Wessex Internet is highlighting the importance of communications as an essential component of future farming activities. As part of the 5G RuralDorset project, the company is exploring how 5G[28] can be designed to support greater efficiency in agriculture.

According to McKinsey, successfully implementing communications into agriculture will add $500 bn in value worldwide by 2030. Two key examples, as trialled by Wessex Internet, showcase how better communications infrastructure will launch technology adoption.

Firstly, trials have examined the benefit remote sensors bring on-farm, by measuring water quality, soil health, grain temperature, while alerting farmers to leaks and so much more. It is estimated that they will reduce energy costs by 35%, water use by 8% and boost crop yield by 1.7%[29].


Figure 17: Drone fitted with 5G equipment flying at the trial farm. The 5G connection reduces image processing time from days to hours

The main barrier to deployment is coverage and cost. Wessex Internet are partnered with Vodafone for deployment of one type of 5G called Narrowband Internet of Things (NB-IoT) which uses low-power wide-area networks to tackle this. This will increase coverage to 98% of UK land mass (from 4G's 77%)[30] and monthly device costs could be reduced to below £2/ month.

It is hoped that NB-IoT will ignite the remote sensing ecosystem in agriculture. By 2024, 2.5 million devices could be in use on UK farms[31], with a large proportion connected to NB-IoT networks.

Secondly, Wessex has looked at the benefits from drones and automated vehicles. With inputs (such as fossil fertiliser) and farm machinery making up 43% of total farm emissions[32], a new generation of light, autonomous and electric vehicles will be making a significant contribution to lowering these emissions by 2040.

A major barrier to commercial viability is the lack of ability to transfer large amounts of data remotely. Some robots need to transfer over 6 terabytes of data each day. On the 5G RuralDorset trial farms, where Wessex has rolled out 'mid-band 5G', it has found that this can support automated vehicles (where 4G cannot) but that multiple radio masts are required per farm to provide sufficient coverage.

[28] What is 5G?
[29] Smart Farming – Advantages & Interesting Facts, Emorphis Technologies, 4 September 2019
[30] Vodafone expands IoT coverage to 98% as customer demands continue to grow, Vodafone, 21 July 2021
[31] Review of latest developments in the Internet of Things, Cambridge Consultants for Ofcom, 27 March 2017
[32] Towards Net Zero in UK Agriculture, A practical approach, HSBC/UCL, 13 April 2021

Autonomous vehicles are not yet replacing traditional systems and costs for 5G deployments are high. Wessex suggest that within five years, refinement of 5G and the vehicles will reach a viability tipping point and private 'mid-band' 5G farm networks will support this next generation of farm vehicles.

To reduce emissions whilst increasing food production by 70% before 2050, farms will need to adapt to a new technology era, feeding off detailed data. Current rural communications infrastructure is not yet fit to support this.

***Hence, the next generation of agri-tech providers must work hand-in-hand with communications providers and farmers to ensure infrastructure can support this transition.***


Figure 18: A 5G (NB-IoT) smart weather station. Although widely available, 4G coverage is limited and monthly costs are high. 5G (NB-IoT) will increase coverage and reduce costs

# 7.7 CASE STUDY 7: New Holland – Biomethane Tractor

One of the key challenges facing the farming sector is the need to find an alternative to diesel as the main fuel for internal combustion engines (ICE) used to power cultivation and other farm tasks.

The New Holland T6 Methane Power is the world's first 100% methane powered production tractor. Built at their UK factory at Basildon, it will be launched on the UK and other markets in 2022.

With comparable power output to its diesel equivalent, the T6 delivers up to 30% lower running costs. The high torque gas engine produces 99% less particulate matter, reducing $CO_2$ emissions by circa 10% when using natural gas (CNG). Overall emissions can be reduced by 80%, if using farm supplied biomethane. Near-zero $CO_2$ emissions would be possible if the gas comes from carbon negative biogas sites.


Figure 19: New Holland T6 bioCNG Tractor

The T6 runs on compressed biomethane (bioCNG), a ready-to-use renewable fuel that can be supplied from gas network fuelling stations and locally (off-grid) from existing or new farm biogas plants. Key challenges included tuning the engine for farm use, plus installation of compressed gas storage capacity to meet operational needs, while complying with safety and visibility requirements.

## Development of the T6

Diesel replacement requires a robust platform, with high power and torque. Since the first prototype was announced in 2013, New Holland has been developing its engine and testing tractor prototypes. They were supported in this project by UK Research and Innovation and the UK's Advanced Propulsion Centre (APC).

The Low Carbon Tractor (LoCT) project was set up to develop commercially viable gas tractors that conformed to European and U.S. emissions standards. Integral to CNH's Energy Independent Farm project , New Holland's T6 features a new NEF 6.7L engine developed for farm use by FPT Industrial, a leader in natural gas powertrains.

In 2019, Engineering Project Manager, Alistair Walshaw said, "The company's commercial vehicle brand IVECO is the market leader in on-highway gas commercial vehicles, and CNH Industrial's New Holland Agriculture and CASE Construction Equipment brands are pioneering off-road applications."

Marc Haggart, Head of New Holland Methane Tractor Sales, commented, "Our T6.180 Methane powered tractor is already gaining a lot of interest from many sectors. We are already in the field demonstrating to potential customers who operate across a wide variety of industries such as agriculture, local authority councils and whisky distilleries."

Biogas upgraded to fuel grade bioCNG is the only affordable diesel replacement for heavy haulage or farm vehicles in advance of development of alternative high-torque power trains, including heavier battery electric (BEV) or green hydrogen solutions (e.g. $H_2$ ICEs or fuel cells).

[33] The Energy Independent Farm℠ concept is part of CNHs Clean Energy Leader® strategy, set up a decade ago. The T6 tractor is integral to the Energy Independent Farm℠ concept, with a $CO_2$-neutral cycle - from field to energy back to field.

### Vision of the Future

Case New Holland (CNH) have invested in a solution based on biomethane - a clean fuel that can be produced on farms across the country and the 180 horsepower T6 offers an adoption ready diesel replacement. New Holland hopes to build sales in the UK and other markets over the next few years.

Methane powered T6.180 tractors are already rolling off the Basildon tractor plant line, destined for use around the world. CNH see this as the beginning of a very exciting journey for New Holland, where alternative fuels will play a big part and are already developing other gas fuelled models.

This includes the TK methane power crawler tractor (using the award winning F28 engine that runs on gas), part of an Italian project to create 'carbon-free' vineyards with $CO_2$-free production in 2022.

CNH have also developed the concept for electrification of orchard and vineyard implements, powered by the E-Source external generator (with rear and front PTO connection), to operate tools like the new e-Sprayer (see below) and e-Mulcher, cutting emissions and reducing fuel use by 30%.

Images below of the TK Methane power crawler tractor and the T4 110V tractor with E-Source power.

## 7.8 CASE STUDY 8: COSWORTH AND THE 'CAT GEN'

The 'Cat Gen' is an ultra-low emissions microturbine that can charge batteries in vehicles, or for portable power generation. Its ability to run at a steady state enables precise control of the fuel reaction process, minimising emissions.

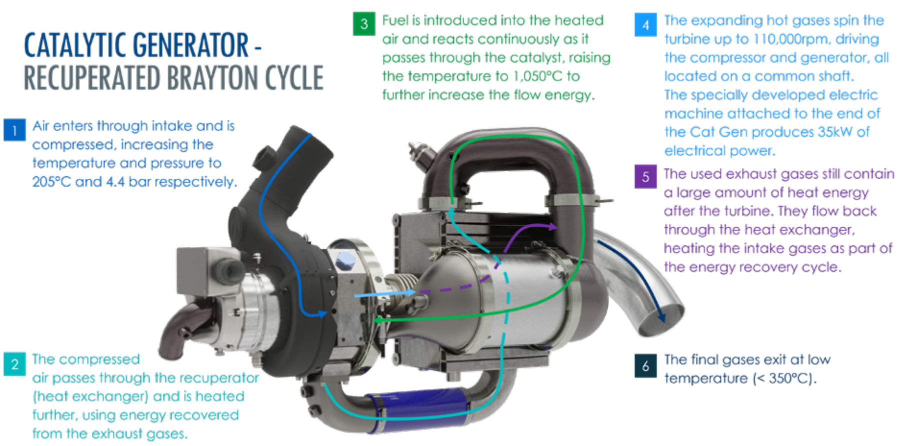



Figure 20: Cosworth Cat Gen Overview

Cosworth has been innovating in the propulsion industry for over 60 years and offer a range of products, including electronics for the automotive sector, aerospace and marine industries. In March 2021, Cosworth acquired Delta, the alternative propulsion solutions and vehicle development specialist based at Silverstone, securing access to the Cat Gen technology.

While electrification and hybridisation are the two most common solutions for curbing vehicle emissions, neither are ready to replace fossil fuel power entirely. Cosworth's objective with Cat Gen is to fill this gap with a versatile solution to aid transition to carbon neutral power generation and propulsion.

### Challenges and results

To be successful, the Cat Gen has to be cheap, simple, and reliable, making it usable across a wide array of applications. It needs to be economically viable for use in cars and heavier vehicles, such as agricultural equipment. Simplicity is key to reliability and enables the technology to be highly versatile. Being fuel agnostic is another key feature of the Cat Gen that increases both its versatility and zero emissions capabilities.

Fuels such as bioCNG are usable in the Cat Gen enabling decarbonisation of industries and services like the agricultural sector and rural transportation. The Cat Gen extends the range of vehicles when the battery charge is low. The vehicles run on battery power for the majority of their use. The device only powers up to recharge the battery 'on the go' and if required, or when there aren't any charging points within reach - for example, in remote rural areas.

Cosworth have produced two demonstrator PHEV Ford Transit prototype vans, with the Cat Gen in place of engine and generator. One also received an upgraded Delta battery, which has significantly increased daily range over the original Ford battery, making it perfect for rural use. The combination of the Cat Gen and batteries offers zero emission capabilities and additional benefits such as mass saving, enabling an increased payload.

### The future

Development of the Cat Gen is ongoing to increase its efficiency, reliability and versatility. The team are currently testing the technology with hydrogen and other zero emission, carbon neutral fuels.

Cosworth are looking for partners to develop demonstrator projects for the agri-food sector and other industries where this technology can be applied. They are open to licencing opportunities for larger manufacturer partnerships.

# APPENDIX

## Alternative fuels, powertrains and automated vehicles:
an energy assessment analysis

### A technical paper produced by Dr Nick McCarthy and Keith Budden, Cenex

As part of the RASE 'Farm of the Future: Journey to Net Zero' Report and the specialist paper on Low Carbon Fuels and Vehicles, Cenex undertook a review of the fuel options and an analysis of the wide range of emerging technologies possible now and in the future for farm vehicles featuring on-road and off-road machines.

## A1. Energy assessment for farm vehicle technologies

Detailed fuel energy assessment is challenging because of the wide variety of vehicles in use on farms, including agricultural and compact tractors, mowers, quad bikes, and excavators. Vehicle fuel demand will also be affected by site specific characteristics such as topography, soil type, and moisture content.

Cenex's analysis focussed upon three types of core agricultural field operations:

- **Tilling:** including primary activities and secondary activities to refine soil beds
- **Planting (& plant management):** sowing and other activities plus spraying crops
- **Harvest:** harvesting and transport plus removal of crop residue post-harvest.

Cenex developed an indicative high and low energy use scenarios to reflect variables listed above that can impact vehicle energy consumption. Energy use values shown in Figure 21 are an average of reported values from several sources [34, 35, 36, 37 & 38]. Cenex used UK-specific data on agricultural holding size to estimate requirement per holding[39].

In carrying out this analysis, the following facts and assumptions have been made:

- Based upon Defra data, an average UK farm holding cropped[40] area in the UK in 2019 was 64 ha.
- Cattle, sheep, poultry and pig farming field activities (including hay/silage cropping) require low energy inputs.
- Root crop field activities typically require high energy inputs.

[34] Khambalkar, V. Pohare, J. Katkhede, S. Bunde, D. and Dahatonde, S. (2010). Energy and economic evaluation of farm operations in crop production. Journal of Agricultural Science (1916-9752) 2.4: 191-200
[35] Canakci, M. Topakci, M. Akinci, I. and Ozmerzi, A. (2005). Energy use pattern of some field crops and vegetable production: Case study for Antalya region, Turkey. Energy Conversion & Management 46.4. 655-66.
[36] Downs, H. and Hansen, R. (1998) Estimating farm fuel requirements. Farm and Ranch Series. Equipment. Colorado State University Extension. Fact Sheet No 5.006. Retrieved, May 5, 2013
[37] Stubs, B.J. (2013). Energy usage of agricultural machinery for corn and soybean production in Brazil, India, USA and Zambia: Masters thesis: Science in Agricultural and Applied Economics: University of Illinois at Urbana-Champaign
[38] The John Nix Farm Management Pocketbook 2014: Agro Business Consultants Ltd: ISBN 0957693907
[39] Agriculture in the United Kingdom 2019, Defra et al., 2020, page 20
[40] Croppable area is defined as *'land under crops, temporary grass under five years old and uncropped arable land'*.

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| Diesel | 6,742 | 52,603 | 3,108 | 4,988 | 6,377 | 26,181 |

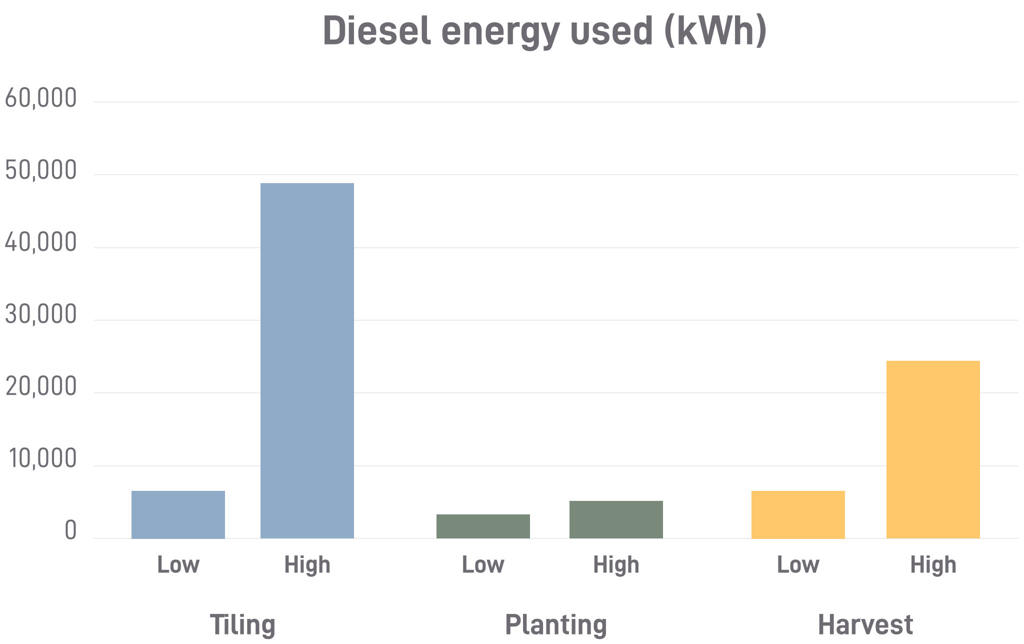



*Figure 21: Diesel energy content in kWh for farm activities (low/high energy demand scenarios) – using 64 ha area of cropped land for field operations*

When considering alternatives to diesel, energy efficiency of the various fuel solutions is a crucial consideration. These could include biodiesels (HVO[41] or FAME[42]), electricity (battery BEV), biomethane and hydrogen (fuel cell, FC). In future, range extending capacity (FC REEV) using hydrogen may provide a high energy fuel alternative.

Electric power trains are inherently more efficient than the internal combustion engine (ICE), as there is no need to convert the stored chemical energy into another form to drive a mechanical system, even if energy intensity is not as great. Table 4 shows the values used in this analysis, based on road vehicles (verified by Cenex in real-world trials) normalised with a relative figure of 100% for diesel[43].

| Diesel | 100% |
|---|---|
| FAME/HVO | 100% |
| Methane | -35% |
| Battery EV (BEV) | 72% |
| Fuel Cell (REEV) | 30% |
| Fuel Cell (FC) | 30% |

*Table 4: Relative energy conversion efficiencies*

[41] Hydrotreated Vegetable Oil
[42] Fatty Acid Methyl Ester – the generic chemical term for biodiesel derived from renewable sources
[43] Typical ICE tank-to-wheel efficiency is 17%, Well to wheel analysis of advanced fuel systems, Brinkman, Wang, et al., May 2005

Applying efficiency values in Table 4 to diesel energy use on field activities using data from Figure 21, a projected energy requirement for an average 64 hectare (ha) plot for each powertrain is generated in Table 5 below. Diesel values are shown for comparison.

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 6,742 | 52,603 | 3,108 | 4,988 | 6,377 | 26,181 |
| **FAME/HVO** | 6,742 | 52,603 | 3,108 | 4,988 | 6,377 | 26,181 |
| **Methane** | 9,102 | 71,014 | 4,195 | 6,734 | 8,609 | 35,344 |
| **BEV** | 1,888 | 14,729 | 870 | 1,397 | 1,786 | 7,331 |
| **FC REEV** | 4,719 | 36,822 | 2,175 | 3,492 | 4,464 | 18,326 |
| **FC** | 4,719 | 36,822 | 2,175 | 3,492 | 4,464 | 18,326 |

***Table 5: Energy content in kWh for farm activities (low / high energy scenarios) – 64 ha***

To be able to tailor the estimated energy demand to a specific crop area, an energy content figure in kWh for one hectare (1 ha) is also presented below. Readers can simply multiply values in Table 6 by the size of their area of worked land.

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 105 | 822 | 49 | 78 | 100 | 409 |
| **FAME/HVO** | 105 | 822 | 49 | 78 | 100 | 409 |
| **Methane** | 142 | 1,110 | 66 | 105 | 135 | 552 |
| **BEV** | 29 | 230 | 14 | 22 | 28 | 115 |
| **FC REEV** | 74 | 575 | 34 | 55 | 70 | 286 |
| **FC** | 74 | 575 | 34 | 55 | 70 | 286 |

***Table 6: Energy content in kWh for agricultural activities (low/high energy scenarios) per hectare***

## A2. Energy scenarios and refuelling events

The Cenex analysis used engine manufacturers' data for energy storage capacity (converted to kWh) to determine the number of times a tractor would need to be refuelled (or recharged for BEVs) to complete a particular activity.

This assumes all technologies are capable of completing all activities. However, BEV tractors available in the UK have low power output to preserve battery demand and limit weight. With developments in battery technology, BEV tractors may be able to provide more power for longer duration, to complete more field tasks. It remains to be seen whether higher power BEV tractors will be available by 2030.

The analysis examined the number of times a single tractor would have to refuel (or recharge) to complete each of the three core activities (tilling, planting, harvest) for low and high energy scenarios (shown below using 64 ha in Table 7 and one hectare in Table 8 as croppable area examples:

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 2.6 | 20.6 | 1.2 | 1.9 | 2.5 | 10.2 |
| **FAME/HVO** | 2.6 | 20.6 | 1.2 | 1.9 | 2.5 | 10.2 |
| **Methane** | 11.8 | 91.7 | 5.4 | 8.7 | 11.1 | 45.7 |
| **BEV** | 45.5 | 354.9 | 21.0 | 33.7 | 43.0 | 176.6 |
| **FC REEV** | 6.7 | 52.1 | 3.1 | 4.9 | 6.3 | 25.9 |
| **FC** | 16.4 | 128.1 | 7.6 | 12.1 | 15.5 | 63.7 |

***Table 7: 'Refuelling events' for farm activities (low/high energy scenarios) – 64 ha area***

To be able to tailor the estimated energy demand to a specific crop area, a 1 ha kWh energy content figure is also presented in Table 8 below. Readers can simply multiply the values in Table 8 by their actual area of worked land (ha).

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.2 |
| **FAME/HVO** | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.2 |
| **Methane** | 0.2 | 1.4 | 0.1 | 0.1 | 0.2 | 0.7 |
| **BEV** | 0.7 | 5.5 | 0.3 | 0.5 | 0.7 | 2.8 |
| **FC REEV** | 0.1 | 0.8 | 0.0 | 0.1 | 0.1 | 0.4 |
| **FC** | 0.3 | 2.0 | 0.1 | 0.2 | 0.2 | 1.0 |

***Table 8: 'Refuelling events' for farm activities (low/high energy scenarios) per hectare***

Given that the whole area of cropped land would not be worked at the same time, Table 9 below assumes that an area of land equivalent to 25% (i.e. 16 ha) is the maximum area requiring machine work at any one time. If the average tractor operational speed is 8 km/hr, then working 16 ha broadly equates to three days of continuous tractor activity (including set up and travel times.)

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 0.7 | 5.1 | 0.3 | 0.5 | 0.6 | 2.6 |
| **FAME/HVO** | 0.7 | 5.1 | 0.3 | 0.5 | 0.6 | 2.6 |
| **Methane** | 2.9 | 22.9 | 1.4 | 2.2 | 2.8 | 11.4 |
| **BEV** | 11.4 | 88.7 | 5.2 | 8.4 | 10.8 | 44.2 |
| **FC REEV** | 1.7 | 13.0 | 0.8 | 1.2 | 1.6 | 6.5 |
| **FC** | 4.1 | 32.0 | 1.9 | 3.0 | 3.9 | 15.9 |

***Table 9: 'Refuelling events' for farm activities (low / high energy scenarios) – 16 ha***

Table 9 also suggests that FAME and HVO biodiesel can be considered as like-for-like replacements for fossil-derived diesel, assuming changes to service times and for fuelling are acceptable. Methane based systems (including bioCNG) have a slightly lower energy density requiring a few additional refuelling stops. However, daily refuelling should be sufficient for low energy scenarios and the high energy planting and plant management scenario. BioCNG systems have refuelling times equivalent to diesel ICE vehicles. Lower pressure 'slow fill' systems are available to reduce the cost and enable overnight refuelling.

| | Tilling | | Planting | | Harvest | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| **Diesel** | 0.7 | 5.1 | 0.3 | 0.5 | 0.6 | 2.6 |
| **FAME** | 0.7 | 5.1 | 0.3 | 0.5 | 0.6 | 2.6 |
| **CNG** | 2.9 | 22.9 | 1.4 | 2.2 | 2.8 | 11.4 |
| **BEV** | **6.8** | **53.2** | **3.1** | **5.0** | **6.5** | **26.5** |
| **FC REEV** | 1.7 | 13.0 | 0.8 | 1.2 | 1.6 | 6.5 |
| **FC** | 4.1 | 32.0 | 1.9 | 3.0 | 3.9 | 15.9 |

***Table 10: 'Refuelling events' required for farm activities (low / high energy scenarios) – 16 ha (2030 BEV prediction highlighted)***

BEV systems do not fare well in this initial analysis. Table 10 entries above are based on manufacturers' data for current vehicles. Given that BEV technology has shown major improvements over the last decade, if advances in battery pack energy density continue at a similar rate (as technology experts in the field predict[44,45]), then performance of BEV tractors may have improved significantly by 2030.

As stated earlier, if an average tractor working speed in the field is taken as 8km/hr, then 16 ha covered broadly equates to 3 days of continuous work (including set up / travel times,). The low energy demand scenario is in reasonable agreement with the suitability of BEVs to replace high energy density fossil fuels. The McKinsey report[46] identifies zero emission farm equipment as 'the single most cost-effective method of reducing agricultural sector emissions'.

[44] Roadmaps & Foresights, Advanced Propulsion Centre
[45] Lobberding et al (2020) World Electr. Veh. J. 2020, 11(4), 77; https://doi.org/10.3390/wevj11040077
[46] Agriculture and Climate Change: Reducing emissions through improved farming practices, McKinsey & Company, April 2020

Returning to Table 10 above, the Fuel Cell REEV data (based on manufacture specifications) indicate this may offer a future viable alternative to diesel in the majority, if not all, scenarios. However, hydrogen ($H_2$) fuel cell technology, including refuelling infrastructure, is still under development. There is some expectation that $H_2$ fuel technologies will become more widely available in heavy road transport from 2030 onwards. If this proves to be the case, then increased scale of production and supply infrastructure could mean that fuel cell powertrains for farm vehicles may become viable in the longer term.

# A3. Charging requirements for battery electric vehicles (BEVs)

If the energy demand for a 16 ha cropped area is averaged across all low energy scenarios, this equates to 379 kWh power requirement. Adding in a suitable safety factor, and the standardisation of battery packs, this broadly equates to a 400 kWh battery requirement over a three-day period. Therefore, potential BEV adopters must also consider the charging infrastructure costs for such 400 kWh systems.

The table below outlines the likely charging times for various specifications of charge points for the low energy demand 400 kWh estimate. The 400 kWh demand is likely to spread over three days, so prolonged charging of two or more battery packs may be viable (disregarding cost of charge point infrastructure and additional battery packs).

| | | | | 400 kWh recharge time (hrs) per battery pack | | |
|---|---|---|---|---|---|---|
| | AC or DC | Power / kW | Charge transfer rate (kw/h) | one battery pack | two battery packs | three battery packs |
| **Standard** | AC | 7-11 | 7.65 | 49.5 | 24.7 | 16.5 |
| **Fast** | AC | 11 – 22 | 14.025 | 27.0 | 13.5 | 9.0 |
| **Rapid** | AC | 43 | 36.55 | 10.4 | 5.2 | 3.5 |
| | DC | 50 | 42.5 | 8.9 | 4.5 | 3.0 |
| **Ultra-Rapid** | DC | 150+ | 127.5 | 3.0 | 1.5 | 1.0 |

***Table 11: Estimated charge time for 400 kWh battery packs -16 ha low energy scenario***

Based on the estimates used in this document, 16 ha of arable land has been used as the likely maximum working size for day-to-day operations using BEV tractors. It is important to note that the high-power continuous operation of battery charger units requires careful consideration. High power chargers must specify active and robust thermal management systems for safe operation during prolonged operation.

The increased thermal management specification may increase charge point cost estimates. Smaller farms (47% of UK farms have 20 ha or less of arable land) with activities requiring less power may be better suited to BEV tractor solutions.

# A4. Technology assessment

Technology maturity is a key consideration in the transition to net zero emissions. The current and forecast maturity of a range of technologies is presented in this section, which also highlights critical decision factors for plant and infrastructure replacement policy.

**If typical tractor lifetimes are estimated at around 20 years, then 2030 would be the last year when traditional diesel tractors should be sold in order to meet net zero targets in 2050. However, it is not yet clear which technologies will power tractors and farm equipment beyond 2030.**

## A4.1. Technology readiness levels (TRL)

Technology Readiness Levels (TRLs) can be used to define research and development stages - before a new technology becomes commercially available. In this analysis, the scale shown in Table 12 is used to illustrate agri-sector fuel supply and power train TRLs (Table 13 and Table 14):

| TRL | 1-3 | 4-7 | 8-9 |
|---|---|---|---|
| **Fuel creation, supply, dispensing** | Small amounts of fuel available for proof of concept | Niche commercial applications | Widely available |
| **Powertrain use in commercial vehicles** | Prototype and pre-production equipment development | Demonstration phase, limited vehicles available | Commercially exploited |

*Table 12: Technology readiness level – definitions*

| | Biofuels (HVO and FAME) | | Biomethane | | Electricity | | Hydrogen (green) | |
|---|---|---|---|---|---|---|---|---|
| | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 |
| **Tillage** | 8 | 9 | 6 | 7 | 9 | 9 | 3 | 6 |
| **Planting** | 8 | 9 | 6 | 7 | 9 | 9 | 3 | 6 |
| **Harvest** | 8 | 9 | 6 | 7 | 9 | 9 | 3 | 6 |
| **Transport** | 9 | 9 | 6 | 7 | 9 | 9 | 3 (UK) | 6 (UK) |

*Table 13: Technology readiness level assessment – fuel supply*

| | Biofuels (HVO and FAME) | | Biomethane | | Electricity | | Hydrogen (FC-REEV) | |
|---|---|---|---|---|---|---|---|---|
| | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 | TRL 2021 | TRL 2030 |
| Tillage | 8 | 9 | 7 | 9 | 3 | 3 | 2 | 6 |
| Planting | 8 | 9 | 7 | 9 | 6 | 8 | 2 | 6 |
| Harvest | 8 | 9 | 7 | 9 | 3 | 3 | 2 | 6 |
| Transport | 9 | 9 | 8 | 9 | 7 | 8 | 4 (UK)[47] | 6(UK) |

*Table 14: Technology readiness level assessment – power trains*

The UK has pioneered deployment of hydrogen bus technology. However, this has not yet been translated into the use of hydrogen fuel in other transport sectors. The UK government announced its hydrogen strategy[48] ahead of COP 26 in October 2021 but there is still greater clarification required. Emerging engine technologies such as the JCB hydrogen-fuelled ($H_2$ICE) were understated, as were concerns about fuel cell viability at least in the short to medium term.

The UK hydrogen strategy and its deployment will have a significant impact on hydrogen TRL predictions made in this document, assuming it is based on meaningful commercial criteria for potential users. To put the deployment of the UK strategy in context, the German government plans to spend €8 billion on its strategy to develop hydrogen supply chains and infrastructure.

## A4.2. Technology emissions and operations

Table 15 defines the likely emission profile and operational suitability of the available powertrains and Table 16 provides an assessment of each fuel technology for operational suitability and total emissions for the 16 ha field activity area used in this study (Note: a Red/Amber/Green (RAG)[49] reporting system is used).

| TRL | Red | Amber | Green |
|---|---|---|---|
| Emissions | The same or worse the existing diesel NRMM-V engines | Reduced emissions compared to diesel NRMM-V[50] engines (well to wheel) | Zero emissions possible (well to wheel) if renewable energy available |
| Operational suitability | Does not perform as well as diesel NRMM-V on a power output or longevity basis | Equals diesel NRMM-V power output and performance | Exceeds NRMM-V power output and performance |

*Table 15: Technology RAG assessment – emission and operations*

[47] The UK lags behind the EU in larger FC vehicles. Increased uptake in the EU may accelerate developments in the UK
[48] New committee launched to help UK government avoid hydrogen policy pitfalls, edie, 31 January 2022
[49] RAG reporting uses a traffic light system with 'red' representing an alert, amber representing caution and green indicating that things are 'on track'.

| | Biofuels (HVO and FAME) | | Biomethane | | Electricity | | Hydrogen (FC-REEV) | |
|---|---|---|---|---|---|---|---|---|
| | emissions | operability | emissions | operability | emissions | operability* | emissions | operability* |
| **Tillage** | | | | | | | | |
| **Planting** | | | | | | | | |
| **Harvest** | | | | | | | | |
| **Transport** | | | | | | | | |

***Table 16: Emissions and operational assessment – 16 ha using red, amber, green (RAG) traffic light appraisal***

Table 16 does not consider the increased torque range for electric propulsion. Electric power trains also offer reduced noise, vibration, and harshness (NVH). Zero-emission electric propulsion vehicles will provide an improved working environment for vehicle operators. NVH will is reported in Table 18 below.

## A4.3. Combined RAG assessment of all tables

Table 17 shows the colour coding for the low emission vehicle technologies appraisal, undertaken as a qualitative assessment again using red, amber, green status. An additional grey category is used for neutral/conditional metrics (e.g. vehicle cost for 'drop-in' fuels).

| Key | Cost and Emissions | Maturity and Availability | All Others |
|---|---|---|---|
| | Better than diesel | OEM product | Advantage |
| | Same as diesel | Conditional | Neutral |
| | Slightly worse than diesel | Low volume | Minor disadvantage |
| | Worse than diesel | Demonstration phase | Disadvantage |

***Table 17: Technology Options Review Criteria***

[47] Non-Road Mobile Machinery Stage 5 engine

Table 18 shows a summary of low emission fuel technology against key metrics, presented in order of ascending vehicle cost (left to right). By ranking critical metrics, for a high-level assessment of relative performance is shown in a single table.

***Table 18: Summary of Low Emission Vehicle Fuel Technology Options***

| | HVO | FAME | Methane | Hydrogen Dual Fuel | Battery Electric | Fuel Cell Electric |
|---|---|---|---|---|---|---|
| **GHG Emissions** | | Blend | | SR[1] limited | | $H_2$ |
| **AQ Emissions** | Non-Road Mobile Machinery (NRMM) Emission Level 5 | | | | Zero Emission Vehicle (ZEV) | |
| **Noise Pollution** | | | SI[1] Only | | | |
| **Maturity** | | Partial OEM | | | Niche supply | |
| **Availability (2021)** | | | | | | |
| **Availability (2030)** | | | Could be phased out | Somewhat uncertain | | Availability uncertain |
| **Typical Operation** | | Fuel Use / Storage | | | | |
| **Intensive Operation** | | Fuel Use / Storage | | | Energy Storage | |
| **Vehicle Weight** | | | Gas tanks | Gas tanks | Batteries | Batteries / gas tanks |
| **Vehicle Costs** | | | | | | |
| **Fuel Costs** | | | | | | |
| **Maintenance Costs** | | | | | Expected | Expected |
| **Existing Infrastructure** | | | | | Depot Power | |
| **Infrastructure Cost** | | | Varies by site | Varies by site | Varies by site | Varies by site |
| **Infrastructure Viability** | | | Varies by site | Varies by site | Varies by site | Varies by site |

[1] SR = substitution ratio (by energy), SI = spark ignition engine (similar to a petrol engine)

## A4.4. Technology roadmaps

Technology roadmaps are a planning tool that can help to determine technology choices needed for future products. A wide variety of experts have completed a significant body of work to prepare for net zero 2050. Roadmaps have enabled the motor industry to focus research and development funding and also offer a valuable tool for policy makers. A roadmap can help show developmental needs and regulatory requirements, for example, with EU $CO_{2e}$ regulations.

For the policymaker, availability means market introduction and the opportunity to offer incentives or other policy measures to assist market uptake. Agriculture plant can expect to follow the same overall trends as rigid HGVs and anticipate the proliferation of vehicles and refuelling infrastructure for HGVs as per the following road maps.

Transition from low to zero emission road transport represents major market disruption and requires adoption of new technology. Roadmaps assist in considering technology development trends in a specific sector and visualising how net zero might be achieved.

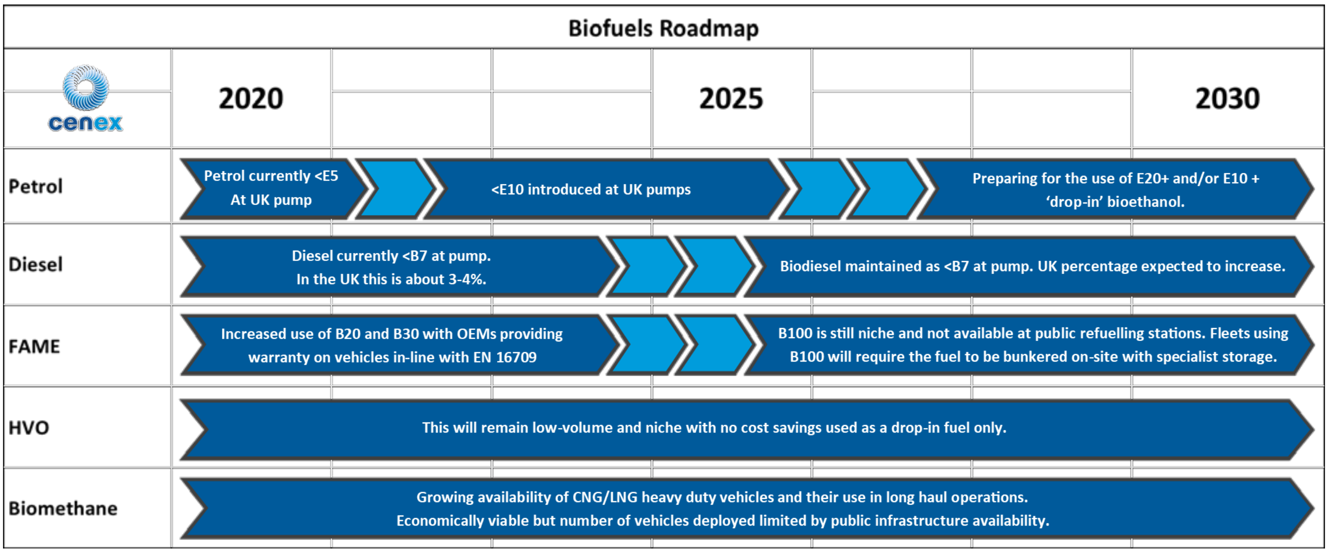
**No clear roadmaps for alternative fuels for agri-sector equipment exist yet**. But as an example of progress in other sectors, Cenex has produced several roadmaps relevant to the road transport section of the supply chain. The future fuel mix on UK roads will significantly impact the 'first mile' of the supply chain i.e. from the farm gate to the factory.

The roadmaps below relate to biofuels, electricity and hydrogen powered vehicles for development of power train technologies across six vehicle types: cars, motorbikes, small vans, large vans, heavy goods vehicles (HGVs), and buses. While it is impossible to predict the future, the roadmaps to 2025 are reasonably accurate because models in this timeframe are already at advanced stages of development.

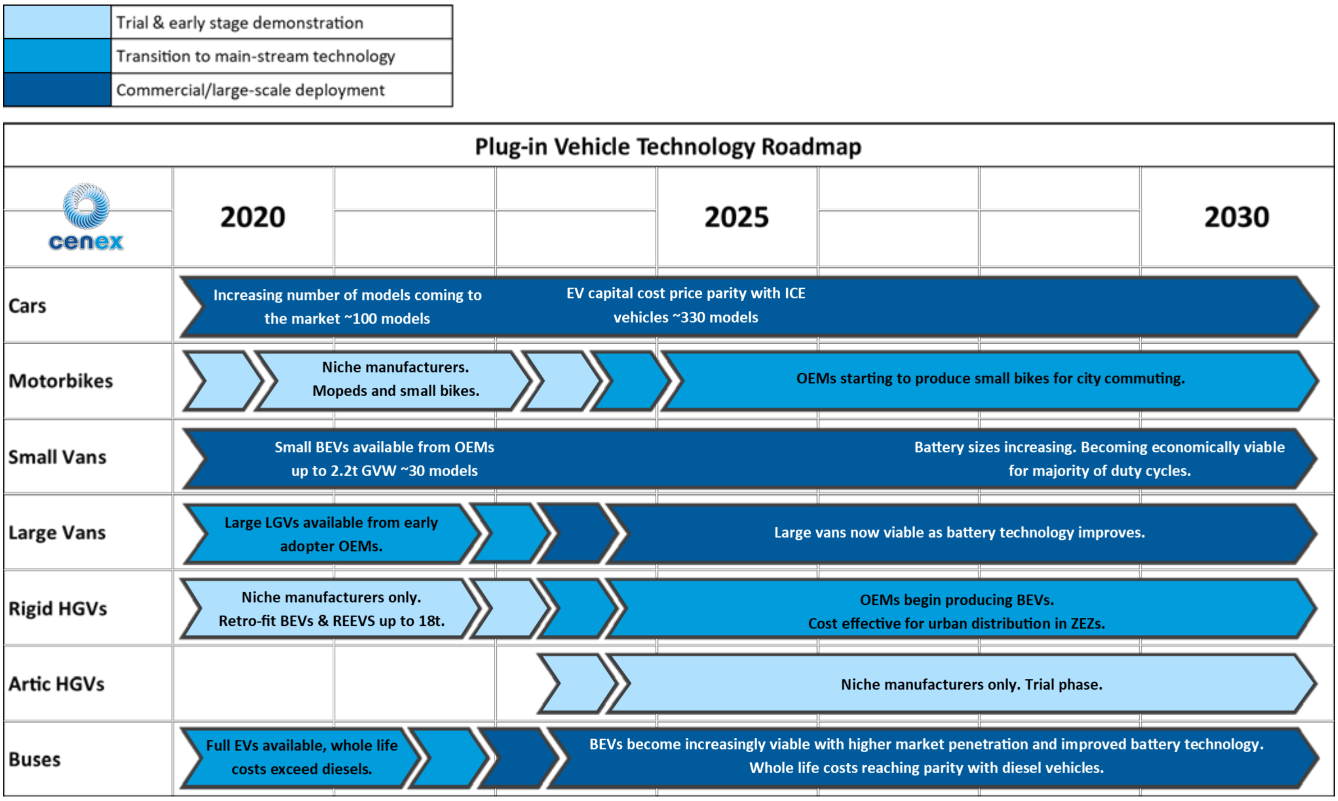
For the 2025-2030 timeframe, there is less certainty. However, key trends and disruptive alternatives would be identified within vehicle industry technology roadmaps for this period. The uncertainty relates more to the phasing and rate of uptake and not the overall direction of travel. The roadmaps below indicate when Cenex expect each technology to reach operational and commercial maturity.

***Roadmaps Note:*** *The light blue colour shown in the roadmaps below represent trial and early-stage demonstration. The dark blue colour represents commercial or large-scale deployment. Arrows on the roadmaps represent a transition phase to the subsequent development. The transition within this region is uncertain. A single arrow shows that there is a high degree of confidence in the likely time period in which this transition will happen. Two short arrows together represent increased uncertainty around the timing of a transition.*

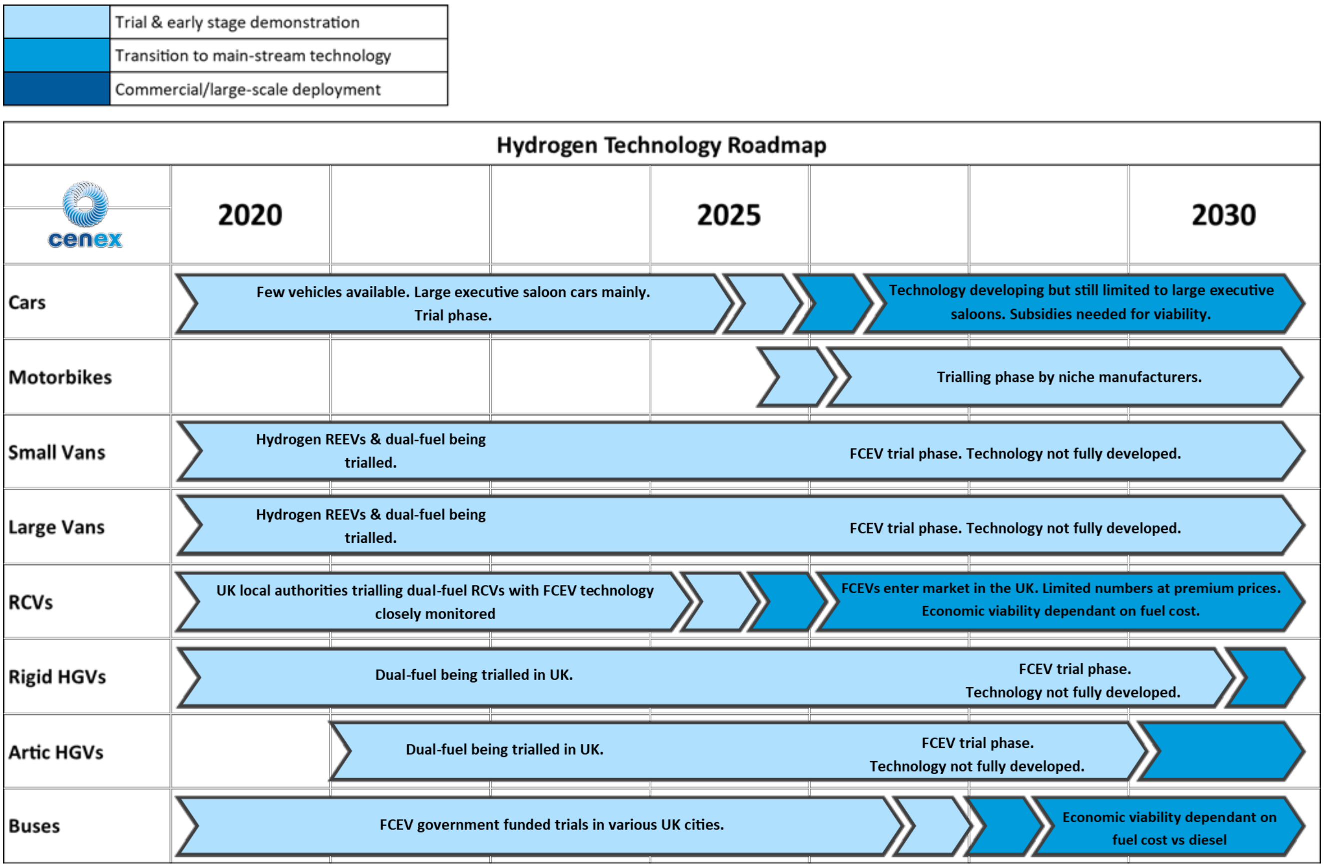
*Roadmap 1: Cenex HGV biofuels roadmap 2020 to 2030*




*Roadmap 2: Cenex plug-in roadmap for EVs 2020 to 2030*



*Roadmap 3: Cenex hydrogen roadmap 2020 to 2030*




## Additional notes:

**The biofuels roadmap** shows eventual introduction of 100% FAME biofuels after 2025 but ongoing niche use of HVO - with no cost saving over diesel but expanding use of bioCNG as supply infrastructure constraints are addressed (including rural supply).

**The EV roadmap** shows deployment of rigid BEV HGVs and larger vans after 2024 but with limited opportunities for articulated. HGVs and larger non-road vehicles (e.g. tractors).

**The hydrogen roadmap** shows some deployment across the vehicle range after 2025 - but requiring subsidy support. Scope in the commercial van and truck sectors will be limited to trials and specific uses, with low expectations in rural applications.  The analysis has not been extended to $H_2$ ICE applications.

***There is a need for stakeholders to develop a roadmap for the development of low and zero carbon fuels and vehicles for the agri-food and non-road sectors which includes a mix of BEV variants, robotic/driverless units, and heavier gas-powered vehicles.***

# ABBREVIATIONS

| | |
|---|---|
| BEV | Battery Electric Vehicle |
| $CH_4$ | Methane |
| CI | Compression Ignition |
| CNG | Compressed Natural Gas |
| $CO_2$ | Carbon Dioxide |
| $CO_{2e}$ | Carbon Dioxide Equivalent |
| DF | Dual Fuel |
| FAME | Fatty Acid Methyl Ester |
| FC REEV | Fuel Cell Range Extended Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicle |
| GHG | Greenhouse Gas |
| Ha/ha | Hectare |
| HGV | Heavy Goods Vehicle |
| HRS | Hydrogen Refuelling Station |
| HVO | Hydrotreated Vegetable Oil |
| ICE | Internal Combustion Engine |
| $H_2$ICE | Internal Combustion Engine powered by hydrogen |
| kWe | Kilowatts (electric), i.e. 1000 Watts, a measure of power |
| kWh | Kilowatt hour, a measure of energy, i.e. 1000 Watts running for 1 hour |
| LCV | Light Commercial Vehicle |
| LEV | Low Emission Vehicle |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MPV | Multi-Purpose Vehicle |
| MW | Megawatt(s), i.e. 1,000,000 Watts |
| $N_2O$ | Nitrous Oxide |
| NO | Nitric Oxide (or Nitrogen Monoxide) |
| $NO_2$ | Nitrogen Dioxide |
| NOx | Oxides of Nitrogen |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PM | Particulate Matter |
| PTO | Power Take-Off |
| REEV | Range Extended Electric Vehicle |
| RTFO | Renewable Transport Fuel Obligation |
| SI/Si | Spark Ignition |
| TTW | Tank-to-Wheel |
| ULEV | Ultra-Low Emission Vehicle |
| WTW | Well-to-Wheel |
| ZEV | Zero Tailpipe Emission Vehicle |