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# Decarbonisation of mobile agricultural machinery in Scotland – an evidence review

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## 1. Executive summary

### 1.1 Background

Agricultural machinery is estimated to contribute around 5-10% of Scottish agriculture's greenhouse gas emissions. Agricultural land in Scotland covers 5.6 million hectares and the agriculture sector represented 19% of Scotland's emissions in 2020.

The Scottish Government's Climate Change Plan update requires a 31% reduction in agricultural emissions by 2032, from 2018 levels, a pace nearly four times faster than has been achieved up to now. Set against this, energy use from static and mobile machinery has increased 14% since 2008, according to 2022 estimates by the Climate Change Committee.

The decarbonisation of machinery could play a key role in Scotland's transition to net zero by 2045.

However, there is a lack of reliable information on emissions from mobile agricultural machinery and the options, costs and pathways to decarbonisation. This review aims to address this evidence gap to inform policy development for the fourth Climate Change Plan, due in 2024.

The use of mobile agricultural machinery varies considerably across Scotland, reflecting patterns of agricultural production. In this study we have assessed the suitability of the following low-emission technologies to power mobile machinery:

1. Biodiesel
2. Biomethane
3. Battery electric vehicles (BEV)
4. Hydrogen

These technologies were chosen after a review of market-ready and future alternative fuels for agricultural mobile machinery.

## 1.2 Key findings

- Biomethane offers the highest short-term emission reduction potential, of 77%. This is due to the availability of this technology and its suitability to current farming practices, offering a like-for-like replacement for current diesel machinery. Battery electric vehicles (BEV) and green hydrogen offer the highest emission reduction potential by 2035 (98.8% and 94.8% reductions, respectively), assuming both technologies will have matured significantly by then.
- Our research indicates that biomethane and biodiesel may be the favourable alternative fuel option in the short term. This is due to the operational similarities of these technologies with diesel and the relative maturity of each technology. However, in the long term, battery electric and hydrogen will be the preferred technologies as they mature. Emerging technologies need to be evaluated as they proliferate the market to avoid locking in potentially undesirable technologies in the short term.
- Short-term uptake of biomethane and biodiesel on dairy farms where there is the potential to generate fuel with waste materials could be prioritised. For those farms where generation of biomethane is not feasible or access to a collective source of biomethane is not possible, there could be a long-term focus on preparing infrastructure for battery electric vehicles or hydrogen.
- A rapid uptake of low-emission mobile machinery is necessary for meeting Scotland's net zero target by 2045. Depending on the intensity of use, farm operation and type of mobile machinery, machinery will be replaced between one and eight times by 2045.
- Unlike other transport sectors where the market has a clear preference for one alternative fuel type, there is not a clear preference in the agricultural sector. As with other niche transport sectors, it is likely that a mix of alternative fuels will be needed in the future.
- We found a lack of information on the number, type and age of the current mobile agricultural machinery in Scotland. There is also a lack of real-world evidence and academic literature on the financial and practical suitability of alternative fuel sources. This is combined with limited understanding of farmers' attitudes towards alternative fuels. It appears that progress in this area has been driven by market forces and manufacturers, rather than policy.

Please note that for the purposes of this report, we have estimated that mobile agricultural machinery in Scotland currently accounts to 5% of the total agricultural sector's emissions, or 0.4 million tonnes of carbon dioxide equivalent (MtCO2e) per year. This figure differs from the 2020 Greenhouse Gas Inventory, which stated emissions of 0.75 $MtCO_2e$ or 10%, and other recent assessments, reflecting different calculation methods and considerable uncertainty around the numbers of mobile agricultural machines and their use in Scotland.

| Alternative fuel | Annual operational emission saving % 2022 | Annual operational emission saving potential % in 2035 |
|---|---|---|
| Biodiesel | 4.18-16.72% | 83.58% |
| Biomethane | 77.09% | 77.09% |
| Battery Electric | 4.77% | 98.84% |
| Hydrogen (grey) - created from natural gas or methane | 10.55% | 22.68% |
| Hydrogen (blue) - produced from natural gas and supported by carbon capture and storage | 52.81% | 92.27% |
| Hydrogen (green) – generated from renewable energy or low carbon sources | 54.32% | 94.78% |

Table 1 - Summary of emission savings from alternative technologies – although these figures must be taken as indicative, due to challenges in the underlying data.

## 1.3 Conclusions

In the short term, incentivising the uptake of market-ready technologies that offer a similar level of performance to current models, such as biomethane, would reduce emissions. This could focus on farms where the generation of alternative fuels from waste materials is possible on site.

In the long term, a greater focus on adopting a mix of technologies could be preferable, with BEV and hydrogen offering significant emission reduction potential. These technologies will need time to mature and for costs to reduce. Biodiesel could play a role in offering short-term emission reductions whilst these technologies and their associated infrastructure mature.

It is likely that a mixture of alternative fuels will be needed to decarbonise agricultural mobile machinery. Farmers who can adopt market-ready technologies should be encouraged to do so. Those who are not should be supported in preparing to adopt other alternative technologies as they mature.

We found that there has been a lack of international progress in encouraging the uptake of low-emission mobile machinery in agriculture. From our research it appears that Scotland is at a similar stage of uptake as international comparators, such as countries in Europe and North America. Scotland, therefore, has the potential to set an international industry standard if the correct incentives are put in place.

We found a significant gap in the evidence base for data on machinery performance. One option could be the use of trial farms to gather and share data on low-emission mobile machinery performance. This could demonstrate that the bridging technologies have the same technical practicality as current machinery, with a short-term focus on biomethane and biodiesel.

There is potential to use current information channels, such as those from Farming for a Better Climate, Strategic Cereal Farm Scotland, machinery rings, Dairy Research Centre, the James Hutton Institute and SRUC, to promote guidance on low-emission mobile machinery. These channels could be used to disseminate new information and advice on alternative fuels, such as the potential findings from a trial farm setting.

Due to the tight operating margins in the Scottish agriculture sector, alongside increased uncertainties due to the impact of climate change, it is likely that businesses in Scotland will require financial incentives or assistance to uptake new low-emission mobile machinery. This could be a beneficial area for further research.

# 2. Contents

## 2.1 Abbreviations

| | |
|---|---|
| ATV | All-Terrain Vehicle |
| BEIS | Department for Business, Energy and Industrial Strategy |
| BEV | Battery Electric Vehicle |
| CCC | Climate Change Committee |
| CCS | Carbon Capture and Storage |
| CFT | Controlled Traffic Farming |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalent |
| FAME | Fatty Acid Methyl Ester |
| FAS | Farm Advisory Service |
| GHG | Greenhouse Gas |
| GW | Gigawatt |
| ha | Hectare |
| HGV | Heavy Goods Vehicle |
| HP | Horsepower |
| HVO | Hydrotreated Vegetable Oil |
| ICE | Internal Combustion Engine |
| LFA | Less Favourable Area |
| Mt | Million Tonnes |
| SFBS | Scottish Farm Business Survey |
| SOC | Soil Organic Carbon |
| SRUC | Scottish Rural and Agricultural College |

# 3. Introduction

## 3.1 Why the work is important

The Scottish Government has committed to reaching net zero emissions by 2045, including a reduction, from 1990 levels, of 75% by 2030. Agricultural land in Scotland covers 5.6 million hectares, approximately 73% of Scotland's total land area (CCC, 2022). Agriculture represented 18% of Scotland's emissions, or 7.4 $MtCO_2e$, in 2020. The Scottish Government's Climate Change Plan update requires the equivalent of a 31% reduction in agricultural emissions by 2032, from 2018 levels, a pace nearly four times faster than has been achieved up to now. Set against this, the Climate Change Committee (CCC) (2022) estimates that energy use from static and mobile machinery has increased by 14% since 2008.

It is therefore clear that if Scotland is to meet its ambitious climate targets, emissions from agricultural mobile machinery will need to be addressed.

Despite this, there is limited analysis on how this can be achieved in both academic and grey literature. Where the subject of mobile machinery emissions is covered, there is often a focus on improving machinery efficiency rather than moving towards alternative fuels. For example, the Evidence for the Farmer-Led Arable Climate Change Group (2019) identifies mobile machinery as the largest source of emissions in the arable farming sector yet does not suggest mitigation solutions. There is also very little data on the efficiency, such as fuel consumption, of typical agricultural machinery. This could be due to the large range of on farm activities involving machinery and the fact that recording such metrics is not a legal necessity.

This report examines how alternative fuels for agricultural mobile machinery in Scotland could aid the decarbonisation of agriculture.

## 3.2 What the report does not cover

This study focuses on mobile agricultural machinery, such as tractors, sprayers and combine harvesters. It excludes static equipment, such as generators, milking and irrigation equipment. Also excluded are vehicles in the wider agricultural supply chain, such as feed supply and animal transportation since these activities take place mostly off farm and use road transport vehicles such as heavy goods vehicles (HGVs). Conventional road vehicles operated by farm enterprises and their employees are also excluded from this study. Although these vehicles may be used off road and as part of farm operations, they face similar challenges and opportunities as passenger transport vehicles where there is already a depth of literature and real-world data in this sector.

## 3.3 Project scope and aim

The project was desk based. It included a review of relevant literature and existing research. It examined available evidence and identified gaps or areas of active debate. The research explored the following areas:

- Options for the decarbonisation of agriculture mobile machinery in Scotland. This involved an analysis of options available for implementation now and those that are likely be available by 2035. $CO_2e$ savings and operating costs were assessed for each alternative option. Potential barriers and opportunities were also identified for each alternative.

- Providing a baseline for current agricultural mobile machinery emissions in Scotland. This includes information on the current stock of vehicles and the number of replacement cycles between now and 2045, the date of Scotland's Net Zero target.
- Developing an overview of how decarbonisation of mobile agricultural machinery would fit into the wider picture of Scotland's energy transition using uptake scenarios, case studies and international comparisons. The study also looked at wider changes in the agricultural sector, such as autonomous vehicles, and how these fit into the wider context of machinery decarbonisation.

There is considerable variation within the agriculture sector in Scotland, with a range of different farm types, sizes and varying requirements for machinery. For this reason, it has been difficult to use universally applicable values in this study. Averages have been used where appropriate. Values will vary considerably in practice.

# 4. Current emissions from mobile agricultural machinery

## 4.1 Farm types and their use of mobile machinery

The use of mobile agricultural machinery varies considerably across Scotland, reflecting patterns of agricultural production.

Arable and horticultural production is concentrated along Scotland's east coast, with the main areas of production extending from the Lothians, Fife, Tayside and Aberdeenshire to Moray. Mobile machinery used by arable farms typically includes tractors which are used for a wide range of operations including spreading, ploughing, harrowing, seeding, spraying and hauling harvested crops. They are also used for general activities such as autumnal hedge flailing and verge cutting. Dedicated sprayers may be used for the application of pesticides, fungicides and other chemicals. Combine harvesters are used to harvest cereal crops and oilseeds including rape and linseed. A range of more specialist harvesting machines (self-propelled or pulled by tractors) are used to harvest root crops such as potatoes and carrots and crops such as peas, beans and sweetcorn. Balers (towed or self-propelled) are used to gather and bale straw following cereal harvesting. Telehandlers, forwarders and loaders are used to handle inputs (e.g. bags of fertiliser), harvested produce and straw bales.

Dairy and cattle farms are concentrated in Ayrshire (dairy), Dumfries and Galloway and in the north east. Again, tractors are used for a wide range of applications including hauling stock trailers, spreading slurry, cutting, turning and baling sileage, together with general operations such as maintaining hedges. Some specialist machines such as foragers (which collect cut sileage and transfer it to trailers) are also used. Telehandlers, forwarders and loaders are used to handle sileage bales and other materials. Quad bikes and ATVs provide a way of moving around a farm holding as well as gathering stock.

Sheep farming is concentrated in southern Scotland, the southern Highlands and Northern Isles, but is also found across much of the Highlands and Islands. Mobile machinery requirements are generally lower than for other farm types but can include tractors and trailers, quad bikes and ATVs and forwarders where there is a need to handle larger amounts of feed etc.

In practice, many farms comprise a mix of these different types of production, with a requirement for a mix of different types of mobile machinery or reliance on vehicles that can be used flexibly. Furthermore, it is likely that the purchase and use of mobile machinery varies within each of these categories, reflecting factors such as holding size, profitability and land manager attitudes. More extensive and profitable holdings will often use larger tractors and combines, and replace them on a more frequent basis. Smaller farms are more likely to rely on the second-hand market to source their machinery, though in some cases may be members of machinery rings (a form of cooperative providing access to specialist or less frequently used equipment). In some cases, contractors are used to harvest crops such as peas using specialist machinery. Crofters and smallholders often use much older equipment, with examples of tractors used in areas such as the Western Isles dating back to the 1950s.

We estimate that the variations in farm type and their use of mobile machinery are likely to have an influence on the pattern and speed of decarbonisation. All other things being equal, the transition to low emission machinery could be most rapid in more productive, profitable and larger holdings, with much slower take up in smaller farms and crofts where there is a reliance on second-hand machinery and replacement rates are less frequent. It is also likely to be influenced by the infrastructure requirements associated with different alternative fuels. Figure 1 below shows the geographic variation of farming in Scotland.

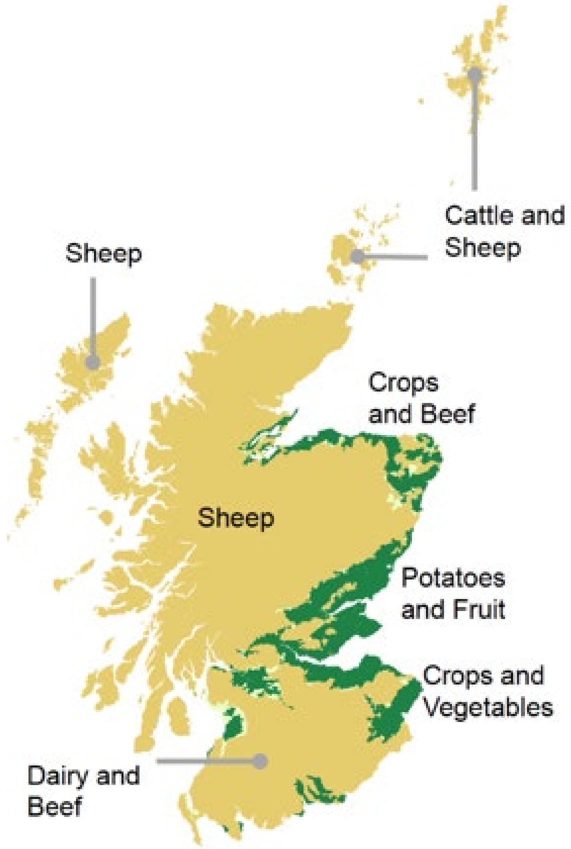


*Figure 1- Farm type by parish (RESAS, 2020)*

## 4.2 Current mobile machinery emission baseline

Agriculture contributed 7.4 $MtCO_2e$ in 2020, 16% of all Scottish emissions. Of this, 0.75 MtCO2e were from mobile machinery. The CCC (2022) estimate that energy use from static and mobile machinery has increased by 14% since 2008. This could represent the continuation of the post war trend of agricultural mechanisation, including a trend towards larger and more operationally efficient machinery. This point is further discussed in Section 1.5.

We have calculated the carbon footprint of the current mobile machinery stock in Scotland using a bottom-up approach (see Appendix A). We estimate that the current annual emissions associated with agricultural mobile machinery use in Scotland is 0.4 $MtCO_2e$. This accounts for 5% of total emissions within the agricultural sector. Our total is lower than was found by similar analysis carried out by Barnes et al (2022) and Moxey and Thompson (2021). We have calculated our total by using the mobile machinery energy inputs provided in Warwick HRI (2007) and multiplying these by the total agricultural areas in Scotland as summarised in the Agricultural Census (RASE, 2020). The total energy values were then multiplied by a diesel emission factor to provide the total footprint. This has provided us with a high level estimate of the current agricultural mobile machinery footprint. Table 2 shows mobile machinery emissions by farming type. Further detail on the methodology used to calculate this figure can be found in Appendix A.

| Farming type | Emissions ($MtCO_2e$) |
|---|---|
| Arable | 0.24 |
| Dairy and Beef | 0.14 |
| Sheep | 0.01 |

Table 2 - Current emission footprint of agricultural mobile machinery in Scotland.

Arable farming contributes the largest proportion of emissions associated with agricultural mobile machinery due to the intensive nature of this type of farming. Sheep farming emits substantially less due to the minimal use of machinery.

As noted above, our estimations differ from other previously published studies. Barnes et al (2022), in their analysis of the Scottish Farm Business Survey and Agrecalc estimate that mobile machinery is responsible for emissions of 0.68 $MtCO_2e$. Moxey and Thompson (2021), in their desegregation estimates of headline Smart Inventory figures for Scottish Agriculture came to a similar total of 0.73 $MtCO_2e$.

It is important to note that both of these studies used a top down approach, working from the 7.5 $MtCO_2e$ total for emissions from Scottish agriculture identified in the Scottish emissions inventory. The different totals estimated by this study reflect the considerable uncertainties surrounding agricultural mobile machinery in Scotland. There is a limited amount of information on the current machinery stock in Scotland, their typical duty patterns and replacement rates. This may, be in part, due to the absence of a mandatory centralised database for mobile machinery. Therefore any estimate, including this report, will rely heavily on assumptions – leading to variations depending on what calculation method is utilised.

## 4.3 Current vehicle stock and lifecycle

The most recent Scottish Agricultural Survey: December (RESAS, 2021a) includes information on tractors and machinery on farms. In this survey there were 40,386 wheeled tractors, 1,357 tracklaying tractors and 3,507 combine harvesters. A further breakdown of the mobile machinery inventory in Scotland can be found in Appendix A.

Detailed information on the age of mobile machinery and new mobile machinery purchases in Scotland is unavailable. Without this information, it is challenging to analyse current machinery stock and predict replacement rates. Despite this, indicative replacement values have been identified, drawing on the grey literature.

Warwick HRI (2007) assumes that average useful lifecycle of a tractor is 11 years and that of a combine is seven years. FAS (2021) suggest that the mobile machinery replacement rate for heavy use is three years, moderate use is five years and light use is eight years. There is also further evidence that in smaller farms and crofts the replacement rate for mobile machinery could be up to 20 years or more in some instances.

It is important to note that at the end of each cycle, machinery is likely to enter the second-hand market and the intensity of use may decrease. The replacement cycles provided in Table 3 give an indication of the possible uptake of lower carbon alternative and a basis for considering interventions that may help accelerate the uptake.

| | Heavy use | Moderate use | Light use | Small business/croft |
|---|---|---|---|---|
| Replacement cycles remaining before 2045 | 8 | 5 | 3 | 1 |

Table 3 - Replacement cycles

For larger farm holdings with heavy use, there is still a substantial number of replacement cycles before the 2045 target. For those farms with lighter use and crofts, there are between three to one replacement cycles before the 2045 target. This suggests that heavy use farms should be encouraged to adopt new alternative fuelled mobile machinery and could be more suitable for subsidised alternative machinery trials. This will increase the alternatively fuelled vehicle stock, and will increase the number of second-hand machines that lower use farms will be able to purchase at a reduced cost. It will also allow heavy use farms to adopt the latest alternatively fuelled mobile machinery that suits their situation. This will facilitate the maturity of certain technologies, such as BEV and hydrogen. Low use farms will be more cautious in choosing alternatively fuelled mobile machinery as they have longer replacement cycles and will want to ensure that they have the most suitable machinery for their needs. It may also take longer for alternative fuelled vehicles to work their way through the second-hand market while smaller enterprises may not have access to the necessary refuelling infrastructure.

It is also important to note that there has been a significant increase in the average size and power of agricultural machinery. Since 2010, there has been a 73% increase in the number of tractors with 201hp or more. Conversely, there has been a decrease in small to mid-range tractors, with a 37% decrease in the number of 55 to 80hp tractors and a 30% decrease in numbers of 80 to 108hp tractors in the same time period. This trend of increasing tractor size will add another layer of complexity, alongside opportunities, to the task of decarbonising mobile machinery in Scottish agriculture. Continued operational efficiencies could reduce emissions, whereas increased size could pose challenges to specific technologies. This is discussed in section 4.

#### 4.3.1 3.3.1 Machinery rings

Machinery rings are a mechanism for farmers to share resources (initially this was exclusively machinery, but now includes other spare resource capacity and commodities) in a low cost and efficient manner. According to the James Hutton Institute (2012) there are currently 9 rings in existence across Scotland, the largest of which has around 2,600 members. The Hutton Institute has identified three ways in which machinery rings have affected Scottish agriculture, two of which are of direct relevance to mobile machinery:

1. They provide a mechanism which allows farmers to gain access to new technologies.
2. They allow farmers to manage supply-demand relationships, generating greater efficiencies between farmers at regional level.

Machinery rings offer a potential to assimilate new alternative fuels into the farming sector by providing smaller farms with access to newer machinery, sharing the capital cost of replacing equipment and even sharing refuelling or charging infrastructure. They also have the potential to upskill workers in the sector and facilitate knowledge sharing on new technologies. Some machinery rings have special incentives with certain manufacturers. This shows the economic leverage that machinery rings possess, something that could be utilised for alternative fuels.

# 5. The potential of alternative technologies

Although there has been significant development in alternative fuels for some other transport sectors (e.g. road), there has been much less progress in the agricultural sector. This may reflect the specific challenges found within agriculture, including the range of vehicle types (e.g. tractors, combines, sprayers, specialist harvesters) applications (e.g. ploughing, hauling, spraying) and access to alternative fuel infrastructure.

There is still a high degree of uncertainty over the alternative fuels that will be the most suitable in an agricultural context in the short and long term. The main issues surround infrastructure, immaturity of alternative technology and higher upfront and fuel costs. This is particularly applicable to agriculture where the use of diesel is ingrained in operations and the challenges of small operating margins which limit technological innovation. Case studies on specific technological developments have been referenced to and can be found in Appendix B.

## 5.1 Biodiesel

- Biodiesel currently offers modest emission reductions, with this increasing significantly by 2035.
- Biodiesel provides mobile machinery users with an alternative fuel that will allow ‘business as usual’ operation.
- FAME’s corrosive and filter blocking effect on engines may dissuade users to adopt the fuel due to increased maintenance issues, whereas the current high cost of HVO could be a similar deterrent.
- There are challenges in storing and transporting the fuel, alongside considerable concerns surrounding land use competition for growing feedstock for biodiesel with food security issues

### 5.1.1. Overview

Biodiesel for agricultural use comes in two main forms fatty acid methyl ester (FAME) produced using waste vegetable oil (from sources such as oil seed rape, waste cooking oil and palm oil) blended with methanol, and hydrotreated vegetable oils (HVO).

Biodiesel is often blended with regular diesel to produce lower concentration blends, with B20 (20% biodiesel) and B5 (5% biodiesel) being the most common[1].

For use in agricultural machinery, blends up to grade B30 (30% biodiesel) are approved by most manufacturers without need for modification. Several leading manufacturers, (e.g. John Deere) use engines that are compatible with B20 (20% FAME blend) fuel, while a few others, including Deutz, can utilise higher blends. Some original equipment manufacturers (OEMs) may switch to grade B100 gasoline mixes before 2030, however public refuelling stations are unlikely to distribute this (RASE, 2022).

Biodiesel and HVO are both derived from biomass, particularly vegetable oils, but different processes are used in their manufacture[2]. As a result HVO is chemically very similar to fossil diesel and can be used as a direct substitute for diesel with little operational impact. However, production costs for HVO are higher, meaning that the fuel is likely to remain a niche alternative (RASE, 2022).

Another common liquid biofuel is bioethanol. While biodiesels can be used in current diesel-powered machinery/infrastructure with limited modification, bioethanol would require an overhaul of such technology (RASE, 2014). This is because bioethanol is only suitable to petrol machinery. As the overwhelming majority of farm mobile machinery is diesel powered, bioethanol is not considered an appropriate alternative fuel for the agricultural industry.

### 5.1.2 Advantages and Limitations

A key limitation of biodiesel is its effect on engines and parts of machinery originally intended for fossil diesel usage. While biodiesel can be utilised in such machines, the fuel itself over time can corrode metals and damage elasto-meric and rubber parts, affecting performance. This is particularly applicable to higher biodiesel blends (Milano et al., 2021). The magnitude of damage over time depends on the blend of the fuel (Trzmielak and Kochańska, 2021). As a result, using fuel blends with a higher proportion of biodiesel requires different machine parts. For example, in order to keep B100 blends from becoming waxy, unique sealing and heating apparatus are required. Biodiesel systems require more regular maintenance such as filter changes (Sasmito et al., 2022) (RASE, 2022). Farmers may be concerned that using an incorrect fuel blend could result in warranty issues. HVO does not have the same damaging effects on machine parts. However, it is much more costly to manufacture and has very limited availability at present (Helms et al., 2017) (RASE, 2022).

Biodiesel is water intolerant and thickens at temperatures below 0 degrees Celsius. It therefore tends to have a more limited ‘shelf-life’ than fossil diesel and is more complex to store. Biodiesel and high blends are ideally stored between 3 to 6 months and special additives required where temperatures fall below freezing (Trzmielak and Kochańska, 2021) (RASE, 2022).

A key advantage of biodiesel is that current diesel infrastructure can be used. On-farm technology is already established with several tractors on the market now operating on biofuel blends. As the use of biodiesel in agricultural machinery becomes more common, it becomes easier for farmers to adopt. Currently, vehicle manufacturers provide a warranty for FAME blends up to B30 (RASE, 2022). However, the supply system of biofuels base material has not yet reached commercial readiness. (Trzmielak and Kochańska, 2021).

Machinery damage, maintenance, storage and supply factors can result in additional costs and cause increases of the overall price of biofuel. Helms et al. (2017)

[1]https://afdc.energy.gov/fuels/biodiesel_blends.html#:~:text=Biodiesel%20can%20be%20blended%20and,used%20as%20a%20transportation%20fuel.
[2] biodiesel is created using the process of esterification, while HVO is created using hydrogenation (Helms et al., 2017).

demonstrates how in Germany, lower energy content (32,7 MJ/l for FAME vs. 35,6 MJ/l for diesel) and higher purchase prices (price for pure FAME from rapeseed or palm oil was about 50% higher than for diesel, January to July 2015) have resulted in a clear disadvantage for biodiesel compared with fossil diesel. This led to a significant reduction in the number of refuelling stations. Real or perceived risks of damage may also influence farmers' willingness to adopt the technology.

While biofuels are renewable, their manufacture from biomass could displace land currently used for food production (Huang et al., 2012). This could be an increasing concern given the growing emphasis on food security.

#### 5.1.3 Emission reduction potential

It is challenging to give a precise figure on the overall $CO_2e$ emission reduction potential of biodiesel. Table 4 outlines the potential $CO_2e$ emission reductions based on broad assumptions on the proportion of biodiesel allowed in each manufacturer's engine. As noted in Case Study 1, most manufacturers currently allow either 5% or 20% biodiesel blends in their engines. We have therefore assumed that if biodiesel was widely utilised with the current fleet of mobile machinery in Scotland, it would equate to either a 4.18% reduction of $CO_2e$ emissions with a B5 blend, or a 16.2% reduction with a B20 blend. By 2035, we have assumed that all new tractors will be able to run with a full biodiesel blend. This would equate to an 83.6% reduction in $CO_2e$ if all mobile machinery in Scotland were to run off B100 biodiesel.

Biodiesel therefore currently offers modest emission reductions, with this increasing significantly by 2035. Biodiesel provides mobile machinery users with an alternative fuel that will allow 'business as usual' operation. Generally, engines operating on biodiesel blends have similar fuel consumption, horsepower and torque as those running on regular diesel. Adopting biodiesel will therefore have no detrimental effect on vehicle operation. However, there are significant limitations that may prevent its widescale uptake. FAME's corrosive and filter blocking effect on engines may dissuade users to adopt the fuel due to increased maintenance issues, whereas the current high cost of HVO could be a similar deterrent. There are also challenges in storing and transporting the fuel, alongside considerable concerns surrounding land use competition for growing feedstock for biodiesel with food security issues.

## 5.2 Biomethane

| % emission reduction now (B5 blend) | % emission reduction now (B20 blend) | % emission reduction 2035 |
|---|---|---|
| 4.18% | 16.2% | 83.6% |

Table 4 - Biodiesel emission reduction potential summary

- Biomethane has the potential to significantly reduce CO2e emissions associated with mobile machinery due to its equivalent performance to current diesel machinery.
- There are some concerns with the effects of potential 'methane slips' in biomethane machinery
- If biomethane production is on-site from waste materials the process can offer near 100% CO2e emission reductions. However, if the fuel is sourced from elsewhere and a specific energy crop is grown as a feedstock, the emission reduction potential is decreased significantly (CCC, 2016).

- If there were to be widespread adoption of biomethane as an alternative fuel for agricultural mobile machinery in Scotland, there would likely be large pressures on biomethane production and availability.
- If feedstocks are specifically grown to be used in anaerobic digestion to produce biomethane for mobile machinery, similar issues surrounding land use competition for food security and emission displacement are encountered as with biodiesel.

### 5.2.1 Overview

Biogas is produced by microorganisms from organic raw materials during the methane fermentation process, where anaerobic digestion takes place. Different substrates, such as organic waste from food, industrial, or agricultural sources, as well as the biodegradable portion of municipal wastes, can be used to produce biogas. By removing unwanted gases and water, biogas can be upgraded to compressed natural gas (CNG) quality, becoming renewable biomethane (RASE, 2022). Such biomethane is made up of a large amount of CH4 (at least 90%, commonly 96% to 99%) and has few impurities. It can be pressurised and kept in storage the same manner as CNG (IRENA, 2018).

Biomethane can be used in the same manner as natural gas for the internal combustion engine (ICE) of natural gas vehicles or so-called dual fuel vehicles[3].

Compressed biomethane[4] (bioCNG) is a relatively mature technology, with road going vehicles in the UK having been run on methane for numerous years. Currently commercially available solutions for traditional engines (ICE) offer affordable power trains for non-road vehicles and the Renewable Transport Fuel Obligation supports the fuels use in heavy vehicles (RASE, 2022).

Biomethane generated from domestic/commercial waste, manure or other agricultural waste has the best $CO_2$ life cycle analysis of any currently known energy source. Biomethane produced from manure is considered to be $CO_2$-negative (CEMA, 2022) (BEIS, 2021). Biomethane produced in an agricultural setting can be used within the farm or distributed through the national gas grid.

### 5.2.2 Advantages and Limitations

Biomethane can be produced on-farm. Such a system would give farmers fuel independence, which may be highly attractive in a volatile fuel market (McKinsey & Company, 2020) (Helms et al., 2017). Biomethane produced could then be used both on site and potentially sold on, directly through a farm or rural filling station. This could also be traded as a commodity in machinery rings. As noted above, biomethane is of CNG quality and therefore falls within the Renewable Transport Fuel Obligation (RTFO) scheme. It has the advantage that it can be consumed spatially and temporally independently of its production. This helps enable demand-orientated energy production, which can increase the efficiency of fuel use and, thus, increases sustainability (RASE, 2014) (RASE, 2022).

Studies show that on-site production methods can be financially beneficial for small to medium-sized plants and achieve a methane content of 85%. However, in situ production is currently underdeveloped and mainly operates on a laboratory or microscale, with research into large scale technology lacking (Mertins and Wawer,

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[3] used as fuel to power spark ignition (SP) and self-ignition (SI) engines or added to the natural gas distribution network (Owczuk et al., 2019).

[4] Biomethane is compressed through a mechanical process when stored or transported

2022). In addition, the viability of farmers profiting from the sale of biomethane relies on the future extent of growth in uptake of gas-powered (CNG) vehicles (RASE, 2014).

Much of the technology associated with biomethane is relatively mature, with road vehicles in particular using methane as fuel in the UK for several years (RASE, 2022). In terms of agricultural machinery, there are specialised methane powered vehicles emerging into the market, such as a methane-compatible commercial version of the New Holland T6, launched in 2022[5].

Biomethane has a high potential to reduce GHG emissions and contribute to creating a more sustainable agriculture industry, as it is produced from renewable biomass and can be used to replace fossil fuels (Mertins and Wawer, 2022), for example IRENA (2018) states that "application of biomethane for transportation allows a reduction of GHG emissions in the range of 60% to 80% in comparison to gasoline". While Well-to-Wheel (WTW) emission savings can be higher for biomethane in comparison to other biofuels, this varies on the type of feedstocks used (GHG emission reduction of 73 to 82% according to the EU renewable energy directive[6] (Helms et al., 2017), for example, when waste and residues are used rather than energy crops there is a greater GHG reduction potential (IRENA, 2018). As with biodiesel, the use of land for biomass production can result in land use pressures and potentially decreased food security as such land is no longer being used for food creation.

The costs of biomethane are composed of production costs, processing costs of converting biogas into biomethane and transport/infrastructure costs (Helms et al., 2017), for production and supply for vehicle use these can also be divided into elements of capital related costs, operation-related costs and consumption-related costs (IRENA, 2018). A difficulty with biomethane is that gas ICE vehicles tend to be expensive. Biomethane also has a lower energy content than natural gas (RASE, 2014), but it is cheaper per unit of fuel, which can greatly reduce operating expenses (RASE, 2022).

It is difficult to estimate the costs associated with distribution systems as they are partially dependent on the location of supply and demand. Feedstock derived from energy crops costs more than producing biomethane from waste due to the higher price of biomass. In addition, the distance between transport hubs and customers greatly affects distribution costs. Operating costs tend to make up the highest proportion of costs and again these can vary site to site (IRENA, 2018).

In terms of biomethane production costs, large biogas plants are likely more viable than smaller plants. This is due to cost degression in investment prices, converting biogas to biomethane becomes more affordable as biogas quantities rise (Mertins and Wawer, 2022). Whilst costs are expected to reduce over time with technology improvements, because the price of biomethane is in competition with the price of natural gas, governmental regulations and subsidies will have a significant impact on how biogas upgrading technologies develop in the future (Barz et al., 2021). Furthermore, policy, including future ICE legislation, will need to change to support bioCNG prospects (RASE, 2022).

### 5.2.3 Emission reduction potential

With widespread adoption of methane powered mobile machinery in Scotland, we calculate the total $CO_2e$ reduction potential is 77.1% both now and in 2035. This figure is derived from a best-case scenario, where biomethane is produced locally or on-site with the feedstock of waste materials from farm activities. Both a biomethane tractor and combine are currently available to purchase in the market and offer similar performance

[5] https://agriculture.newholland.com/eu/en-uk/equipment/products/agricultural-tractors/t6-methane-power
[6] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

to diesel fuelled machinery. As the technology is currently market ready, the emission saving potential the same now as it will be in 2035. Table 5 summarises the emission reduction potential of biomethane.

Biomethane has the potential to significantly reduce $CO_2e$ emissions associated with mobile machinery due to its equivalent performance to current diesel machinery. Combined with the potential to generate biomethane on-site at farms, often utilising waste materials, this alternative fuel offers an attractive proposition to farmers.

There are some concerns with the effects of potential 'methane slips' in biomethane machinery (Zarrinkolah and Hosseini, 2023). There is evidence that methane can leak through the exhaust whilst machinery is in use. As methane has a global warming potential (GWP) of 25 times higher than $CO_2$, any methane slip could significantly reduce the emission savings presented below. There are also uncertainties surrounding the availability of biomethane (CCC, 2016). If there were to be widespread adoption of biomethane as an alternative fuel for agricultural mobile machinery in Scotland, there would likely be large pressures on biomethane production and availability.

It is important to note that the GHG reduction potential of biomethane varies significantly. In this study, average carbon intensity figures for biomethane production have been sourced from BEIS (2022). If production is on-site from waste materials the process can offer near 100% $CO_2e$ emission reductions. However, if the fuel is sourced from elsewhere and a specific energy crop is grown as a feedstock, the emission reduction potential is decreased significantly (CCC, 2016).

If feedstocks are specifically grown to be used in anaerobic digestion to produce biomethane for mobile machinery, similar issues surrounding land use competition for food security and emission displacement are encountered as with biodiesel.

| % emission reduction now | % emission reduction 2035 |
|---|---|
| 77.1% | 77.1% |

Table 5 - Biomethane emission reduction summary

## 5.3 Battery Electric

- Current BEV alternatives have the potential to replace diesel mobile machinery in small scale horticulture, indoor fruit growing and grounds maintenance activities
- BEV technology offers significant emission reduction potential due to the low carbon intensity of electricity generation in the UK compared to the carbon intensity of diesel.
- The main limitation of BEV technology is the inability to support all necessary farming activities at its current state of maturity. Due to lithium-ion battery technology's low energy density, to reach the same levels of power in a BEV alternative would require an unfeasibly heavy and large battery.
- Success of BEV mobile machinery rests of three main points:
  1) Improvements in lithium-ion energy density, allowing more powerful and energy dense batteries that would be suited to agricultural requirements.
  2) Advanced battery swapping systems that may negate the issue of long charging times when farm machinery is needed on an intense schedule.
  3) Extensive roll out of solar-PV, wind and micro hydro with battery storage on farms to allow generation of on-site electricity combined with the development of charging infrastructure.

### 5.3.1 Overview

Battery-electric vehicles (BEVs) use an electric motor to convert the energy stored in their batteries to mechanical energy to power the wheels. BEVs are charged using either mains power (usually at a specialised charging station) or a battery recharge system situated where it is used, such as on farms (RASE, 2022).

Though it is more challenging, there have been discussions regarding the opportunity for agricultural machinery to follow the trend in the automotive industry toward the development of hybrid electric and full-electric on-road vehicles (Scolaro et al., 2021). On-road battery vehicles are being released by original equipment manufacturers in increasing numbers. In recent years, there have been significant developments in off-road electric drives for mining loaders, excavators, heavy-duty dump trucks and some agricultural vehicles (Lagnelov et al., 2020).

Battery electric power is not yet well established in the agricultural industry, with only one BEV 'compact tractor' currently commercially available. The FarmTrac FT25G model is 18.5kW (equivalent to 25hp diesel) and was released in the UK in early 2022. The FT25G's charge cycle 0 -100% is 8 hrs for a full charge, with 5 hrs 20mins achieving 0 - 80%, and has up to 6 hours of run time (RASE, 2022).

### 5.3.2 Advantages and limitations

A key advantage of battery electric vehicles (BEVs) is that with a renewable electricity source, $CO_2$ emissions are mitigated almost entirely. If the grid is used as the electricity source there are also significant $CO_2$ savings compared to diesel. However, there are environmental issues to be considered with battery production, including the procurement of rare minerals and materials needed and the GHG emissions associated with these activities. (CEMA, 2022).

Scolaro et al. (2021) highlights that an advantage of BEVs is that there is a high Tank-to-Wheel (TtW) efficiency. In addition, (CEMA, 2022) notes that electric motors are up to three times more efficient than conventional combustion engines when employing a battery as the energy source and a fully electric drive train. Furthermore, an electric driveline gives 90% efficiency according to Frankelius and Lindah (2021).

However, a large proportion of literature indicates that battery powered agricultural vehicles are not currently a practical solution in agriculture. Batteries have a much lower energy density in comparison to diesel, with diesel possessing a 50 times higher energy density than the latest lithium-ion technologies (Scolaro et al., 2021). As a result, batteries tend to make agricultural machinery much heavier than diesel powered counterparts, with machinery requiring more power (often the case for agricultural machinery), requiring heavier batteries. This results in issues such as soil compaction and limitation of energy efficiency.

In addition, BEVs require sufficient time to charge, which is a difficulty for vehicles on a working farm as they tend to be heavy-duty requiring large amounts of power. They may operate in remote locations and are unlikely to be idle for long periods of time. Charging infrastructure therefore needs to be powerful enough to charge machinery enough for a full day, and quickly. This may be possible, however such infrastructure is much more costly (RASE, 2022).

Without such infrastructure, there may be a trade-off between a longer working day for the driver, reduced total field time, or having to recharge multiple times in a day. As a result "conventional-sized, manned BEV tractors are currently not an economically competitive option for field operations" (Lagnelov et al., 2020). However smaller more compact agricultural machinery is likely to be more viable for battery power (Lake, 2018) (RASE, 2022).

Conversely, one advantage of BEVs is that farmers can charge their machines at their own farms, as nationwide charging infrastructure is not needed (Helms et al. 2017). Many farms have large barns or sheds which could be used to mount solar panels. In addition, vehicle-to-grid (V2G) technology can result in EVs being used as decentralised electric storage resources. This could provide multiple benefits to farmers, including the creation of a new income stream (Lake, 2018) (RASE, 2022).

More potential economic benefits of using BEVs for agriculture are highlighted by Scolaro et al. (2021), who noted that there are low operating costs and opportunities for better exploitation of in-site renewable energy sources. Scolaro et al. (2021) also notes that there could be savings made regarding fuel costs.

Significant costs are associated with agricultural BEVs, particularly the high cost of batteries, including their production. For example, Ghobadpour et al. (2019) concluded that the high cost of vehicle batteries and their replacement is the reason why life cycle micro-electric tractors are so expensive (batteries account for roughly 52% of the total price). Scolaro et al. (2021) also found that the price of agricultural electricity has a significant impact on life cycle cost. As a result, more efficient and affordable batteries need to be developed before agricultural BEVs become more viable for farmers.

### 5.3.3 Emission reduction potential

Battery electric technology has the potential to reduce emissions associated with agricultural mobile machinery in Scotland. With the current stage of technology readiness, BEV machinery has the potential to reduce emissions by 4.77%. This is based on the current technology available to purchase on the market, as outlined in Case Study 4.

Current BEV alternatives have the potential to replace diesel mobile machinery in small scale horticulture, indoor fruit growing and grounds maintenance activities. Therefore, in replacing diesel mobile machinery in these limited applications, BEV technology has a limited emission reduction potential with the current technological availability. However, as BEV technology develops it will have the potential to reduce emissions by 98.8%. This is based on the assumption that by 2035 the technology will have matured significantly and will be suitable for a wide range of on farm applications. Table 6 summarises the emission reduction potential of battery electric technology.

BEV technology, although experiencing significant technological maturity in the passenger vehicle market, has yet to develop in the agricultural sector. BEV technology offers significant emission reduction potential due to the low carbon intensity of electricity generation in the UK compared to the carbon intensity of diesel. Electricity generation is also significantly more cost effective, offering reduced operating costs. If this is combined with on-site renewable generation, such as solar PV, and battery storage, operating emissions and costs could be reduced further. A further benefit of this alternative technology is the increased operator comfort due to reduction of noise associated with BEVs.

The main limitation of BEV technology is the inability to support all necessary farming activities at its current state of maturity. Mobile machinery (particularly combines and tractors) need significant power to carry out their activities. Due to lithium-ion battery technology's low energy density compared to conventional fuels, to reach the same levels of power in a BEV alternative would require an unpractical size and weight battery. Increasing machine weights could increase soil compaction, particularly during the wetter winters that are likely due to the changing climate. There are also limitations on how frequently the battery would need to be charged and accessibility to the necessary charging infrastructure.

The emission saving potential of current BEV alternatives in mobile machinery is therefore low. However, as technology develops, BEVs have the potential to offer considerable emission savings by 2035. For this potential to be realised, there will need to be substantial developments in the following areas:

- Improvements in lithium-ion energy density, allowing more powerful and energy dense batteries that would be suited to agricultural requirements.

Lithium ion energy density has increased significantly over the last decade. In 2008, lithium-ion batteries had a volumetric energy density of 55 watt-hours per litre, by 2020, that had increased to 450 watt-hours per litre (energy.gov, 2022). Even at this level, lithium-ion batteries are still around a hundred times less energy dense than diesel. There are uncertainties around how much further lithium-ion energy density can be improved. One potential solution is solid state batteries. Solid state batteries offer a higher energy density compared to lithium ion batteries, however they are not yet commercially cost competitive at scale.

- Advanced battery swapping systems may negate the issue of long charging times when farm machinery is needed on an intense schedule.

Battery swapping has been commercially deployed in China in the road transport sector. Batteries can be swapped in 10 minutes, negating the issue of charging time. It is yet to be seen if battery swapping is feasible for the agriculture industry. This is due to the large size of the batteries needed in agriculture and their associated costs. Therefore, the upfront cost of purchasing multiple batteries and the impracticality of removing heavy batteries poses a significant challenge.

- Extensive roll out of solar-PV, wind and micro hydro with battery storage on farms to allow generation of on-site electricity combined with the development of charging infrastructure.

Producing renewable energy on site will allow farmers to charge their electric mobile machinery with excess electricity that is generated by renewable sources. This could reduce the carbon emissions and operating costs associated with running mobile machinery. This may also open up further revenue generating opportunities, such as offering grid balancing services.

| % emission reduction now | % emission reduction 2035 |
|---|---|
| 4.77%[7] | 98.8% |

Table 6 - Battery Electric emission reduction potential summary

## 5.4 Hydrogen

- Hydrogen has the potential to reduce mobile agricultural machinery emissions, though the scale of reduction depends on the hydrogen production method.
- In terms of operability, hydrogen offers similar performance as current ICE mobile machinery.

[7] Current models are only suitable for small scale operations, such as greenhouse applications.

- Challenges surround the availability and production and hydrogen, alongside the associated infrastructure and storage.
- As a growing proportion of Scotland's energy production comes from renewable sources located in rural areas, there is the potential for partially decentralised hydrogen production to provide fuel to the agricultural sector.

### 5.4.1 Overview

Hydrogen can be used as a fuel, either in an internal combustion engine (ICE) or a fuel cell (FC), with 30% efficiency for ICE well-to-wheel compared to 35% for FC (CEMA, 2020). It is often framed as an alternative to BEV solutions as it is an indirect form of storage. Hydrogen can be created using various methods, with varying degrees of sustainability, these are described using various colours, with the three main colours shown in Table 7 below.

Green hydrogen (the most sustainable form when using renewable electricity), sometimes known as pure hydrogen, is used by many types of fuel cell. It is produced via electrolysis where electricity is used to split water molecules into hydrogen (H2) and oxygen (O2). The hydrogen produced can then easily be stored in tanks, while the oxygen is discharged into the atmosphere. A fuel cell can then be powered by recombining the hydrogen with oxygen from the air, which creates water and electricity (van Leeuwen, 2020).

Fuel cell technology is well-established and accessible for smaller vehicles, but commercial availability is currently limited (Hjelkrem et al., 2020). A hydrogen fuel cell tractor was launched in 2009 by New Holland (NH2) and JCB is currently developing hydrogen fuel cell engines that can be retrofitted to agricultural machinery, expecting to have the engine ready for pre-production by the end of 2022.

| Grey | Blue | Green |
|---|---|---|
| Grey hydrogen refers to hydrogen fuel that is produced through fossil fuels, with the most common created from natural gas using the process of steam methane reformation. The GHG's produced in the process are not captured. This type of production currently accounts for almost the entirety of hydrogen production globally, with 900 Mt of direct emissions in 2020 (IEA, 2021) | Blue hydrogen refers to hydrogen fuel that is produced by natural gas through steam reforming. The carbon dioxide that is produced in the process is captured by CCS. As CCS is around 90% efficient (Brandl et al., 2021), this process still creates GHG's. It is also important to note that CCS has yet to be commercially scaled. | Green hydrogen refers to hydrogen fuel that has been produced using renewable energy sources to electrolyse water. Electrolysers split water into its component parts, including hydrogen and oxygen. This process does not emit any GHGs. Green hydrogen is currently not price competitive, however the Scottish Government's Hydrogen Action Plan includes ambitions to scale up green hydrogen production in Scotland significantly. |

Table 7 - Hydrogen production methods

### 5.4.2 Advantages and limitations

When green hydrogen is used (using renewable energy to power electrolysis), hydrogen powered vehicles can be considered a 'net zero' technology. In addition blue hydrogen, while not emissions free, could also aid in the transition to full green hydrogen in the meantime and help provide affordable solutions for farmers. When used in a fuel cell, hydrogen produced from fossil fuels can reduce greenhouse gas emissions by up to 50% compared to an equivalent diesel vehicle. However, major industrial and difficult-to-decarbonise sectors are projected to be the main users of blue hydrogen (RASE, 2022). Hydrogen vehicles also produce less noise pollution and do not emit the same amount of smoke or heat as ICE vehicles (Frankelius and Lindah, 2021).

Hydrogen is potentially well suited to farmers and their operations/land (RASE, 2014). Farmers tend to own large areas of land which could provide for the on-site production (Hjelkrem et al., 2020) and storage of hydrogen. Given that fuel accounts for a sizable amount of total farm expenses, a system of this nature would also enable farmers to become independent of external energy sources and to strengthen their financial stability (Frankelius and Lindah, 2021).

Despite this, the storage of hydrogen poses a particular challenge. Due to the low density of hydrogen, significant energy is required to compress the gas to an acceptable density. Therefore, there are still concerns surrounding this storage and process efficiency of storing hydrogen in the form of pressurised gas. Hydrogen is also highly flammable in its gas form and so has associated safety issues, especially as industry standards for hydrogen compression and storage are still being developed (Scolaro et al., 2021). In addition, the high pressures required for hydrogen storage can result in significant additional costs (Hjelkrem et al., 2020).

Hydrogen, however, does have significant benefits regarding the energy efficiency, power and weight of systems. It has high energy density (39 kWh/kg) (van Leeuwen, 2020), allowing relatively light and compact infrastructure. The fuel cells are relatively powerful, with high efficiency, resulting in a capacity for relatively high workloads and driving distances (Hjelkrem et al., 2020). As a result of their light weight, soil compaction is also less of an issue.

Although refuelling hydrogen vehicles is considered fast and practical, another key issue highlighted in literature is the lack of infrastructure. There are also difficulties regarding installation and logistics for hydrogen production which further add to costs (CEMA, 2022). However, small amounts of hydrogen can be discharged from onsite fuel tanks, despite the fact that handling large hydrogen could be challenging. As a result Scolaro et al. (2021) states that the establishment of dependable and extensive infrastructures for hydrogen production, delivery, and refilling are definitely necessary for the successful deployment of hydrogen propulsion in off-road applications.

An additional issue regarding hydrogen are the current associated costs, with few scaling benefits from mass production according to RASE (2014). This includes the high cost of fuel cells themselves and the cost of producing hydrogen, especially as this process is energy intensive. However, Hjelkrem et al. (2020) states that the costs of an average fuel cell electric vehicle are predicted to converge by 2030.

### 5.4.3 Emission reduction potential

Hydrogen has the potential to reduce mobile agricultural machinery emissions, though the scale of reduction depends on the hydrogen production method. Present day emission savings are based on currently available technology, consisting of a dual fuel hydrogen/diesel tractor. Based on this vehicle, the emissions saving potential for hydrogen is 10.55% with grey hydrogen, 52.81% with blue hydrogen and 54.32% with green hydrogen. Assuming that full hydrogen mobile machinery will be available by

2035, the emissions saving potential for hydrogen would be 22.68% with grey hydrogen, 92.27% with blue hydrogen and 94.76% with green hydrogen. Table 8 summarises the emission reduction potential of Hydrogen fuel.

Currently, only one hydrogen fuelled mobile machinery vehicle is market ready. This is a dual fuel tractor, running on 50% hydrogen and 50% diesel.

It is important to note that the hydrogen production method substantially affects the emission reduction potential of using this fuel. Grey hydrogen offers modest emission savings, whereas blue and green hydrogen offer far greater potential. Currently, nearly all of the world's hydrogen production is grey. Despite this, Scotland has an ambitious hydrogen agenda, targeting 5GW of renewable and low-carbon hydrogen production by 2030 and 25GW by generation as set out in the Draft Hydrogen Action Plan (2021). As a growing proportion of Scotland's energy production comes from renewable sources located in rural areas, there is the potential for partially decentralised hydrogen production to provide fuel to the agricultural sector. Therefore, hydrogen could offer substantial emission reduction potential by 2035 as hydrogen production and technology matures.

| | Emission savings now (50/50 diesel-hydrogen technology) | Emission savings 2035 (full hydrogen technology) |
|---|---|---|
| Grey | 10.55% | 22.68% |
| Blue | 52.81%[8] | 92.27%[9] |
| Green | 54.32%[10] | 94.76%[11] |

Table 8 - Hydrogen potential emission reduction summary

## 5.5 Cost comparison

The largest component of fixed costs on farm is labour and machinery. Machinery costs therefore have a large impact on the viability and profitability of a farm business. Table 9 below shows the annualised cost difference of alternative technologies compared to their diesel equivalent over eight years. Negative figures indicate savings whereas positive indicate increased costs. Fuel costs are accurate as of the time of writing. Infrastructure costs are not included in Table 9 and have the potential to alter the results significantly.

| Fuel type | Annualised cost difference compared to diesel equivalent over eight years based on current prices |
|---|---|
| Biodiesel (HVO) | 4% |
| Biomethane | 1% |
| Electric | -23% |

[8] Includes assumption that CCS facilities are used in current hydrogen production
[9] Assumption that fuel cell tractors and CCS facilities in hydrogen production will be commercially mature by 2035
[10] Assumption that green hydrogen can be currently be produced at a competitive market rate
[11] Assumption that fuel cell tractors and green hydrogen production facilities will be commercially mature by 2035

| | |
|---|---|
| Hydrogen (Grey) | 2% |
| Hydrogen (Blue) | 2% |
| Hydrogen (Green) | 7% |

Table 9 - Cost comparison between different fuel types

Electric alternatives offer the most substantial savings due to the low cost of electricity compared to red diesel[12]. The reduction in fuel cost offsets the higher upfront cost associated with BEV machinery. All other alternative fuels have higher annualised costs due to higher upfront and fuel costs based on today's values. As farming in Scotland has a generally low profit margin, any increase in fixed costs may be enough to dissuade farmers to uptake new technologies. This highlights the need for financial support or guarantees if alternative mobile machinery technologies are to be widely adopted in Scottish agriculture.

## 5.6 Wider technological changes

The transition to lower carbon fuels for mobile farm machinery needs to be set within the context of wider trends within the agricultural sector. These may influence the types of machines that are required and the range of agricultural operations that will need to be carried out.

### 5.6.1 Reduced tillage

Soil tillage is used in 90% of cultivated land worldwide. This practice can have a negative impact on soil organic carbon (SOC) as soil disturbance destroys soil aggregates. Soil aggregates protect organic matter in the soil, and their loss prevents carbon from accumulating in tilled soil over time. There is a lack of scientific literature focused on the effects of different tillage systems on SOC over long periods (30-40 years). However, Ruis et al (2022) concluded that 'no-till' and 'reduced-till' farming systems may capture and retain more atmospheric carbon than more intensive tillage systems.

Reduced and no tillage systems require less use of machinery with consequent fuel and emission savings, reducing costs for farm businesses (SBCG, 2020). A report from Scientific American (2008) estimates that a no-till system has the potential to reduce fuel expenses by 50 to 80 percent and labour costs by 30 to 50 percent. Therefore, if no-till systems are applied in conjunction with the alternative fuels analysed in this study, further emission savings could be made.

It should be noted that no-till systems can be challenging to implement and require considerable commitment. Generally, drier and more stable structured soils are best suited to minimum tillage. This means that many areas of Scotland may not be suitable with the SRUC stating "the higher proportion of spring barley, the greater use of rotational cropping, the smaller scale of farm enterprise and the wetter climate can mitigate against the success of minimum tillage or direct drilling" (SAC, 2003).

[12] Red diesel is diesel fuel, used in off road industries, that is taxed at a lower rate and is dyed red to avoid fraud

#### 5.6.2 Controlled Traffic Farming

Controlled Traffic Farming (CTF) is a well-established practice of confining machinery traffic to narrow strips of land, often aided by satellite guidance. Studies have shown the CTF has the potential to reduce the total trafficked area on agricultural land by 30% (Smith et al., 2013). By reducing the area of agricultural land exposed to machinery traffic, CFT has the potential to increase yield and reduce SOC loss as the need to till soil is reduced to break up compacted soils. It can also reduce machinery use, equating to further carbon savings through a reduction in fuel inputs.

Operational data from Australia suggests that CFT can reduce the energy requirements for seedbed preparation, leading to an average saving of 25% in fuel. Adopting CFT therefore has the potential to increase farm productivity and resource-use efficiency in arable and grass cropping systems. CFT, alongside the adoption of alternative fuel mobile machinery, has the potential to further reduce the carbon emissions associated with mobile machinery in Scotland. Autonomous vehicles, as will be discussed in the next section, could also work in conjunction with the aforementioned process innovations.

CFT often necessitates new machinery or some modification of current machinery, due to lack of compatibility with system design of CFT; but modification risks voiding warranties and hence some farmers may be hesitant to adopt this process.

#### 5.6.3 Smart farming

Smart farming involves harnessing new technologies to improve the resource use efficiencies in farming activities. These include autonomous vehicles and robots operated through GPS systems and connected through smart applications. As with other process efficiency improvements, smart charging is anticipated to increase yields whilst reducing inputs needed, such as fuel. Challenges facing smart farming include high upfront costs, lack of reliable internet in rural areas and a lack of knowledge in the farming sector.

#### 5.6.4 Autonomous vehicles

Autonomous vehicles have long been promoted as a solution to labour shortages seen in agriculture. They can reduce labour inputs on farms and allow less skilled workers to operate machinery, with the main application in tillage, weeding and seed drilling. They have the capability to work on a 24 hour timescale in all conditions and can free up farmers time for other activities. John Deere is investing heavily in the dual autonomation and electrification of its machinery. The company recently announced that is has plans to have autonomy kit on every large tractor it ships. Automation of mobile machinery may accelerate the uptake of alternative fuels.

#### 5.6.5 Robots & drones

Drones can cover large areas in one flight whilst gathering important data related to land management, and benefits include:

- irrigation need, crop growth and livestock numbers and locations
- handling physical tasks in agriculture, such as crop spraying or livestock herding.
- scare off birds that may be damaging agricultural crops

They can give farmers a bird's eye view of their agricultural land in a short space of time, with low operational costs and they also have a short payback period, making them more attractive to farmers. However, there are regulatory issues surrounding where drones have permission to fly and there may also be privacy issues with surrounding neighbours. Both may restrict the use of drones.

## 5.7 Farmer attitudes

Key to the uptake of alternative fuels in mobile machinery will be farmers' attitudes towards implementing low carbon changes to farming activities. If alternative fuels do not carry perceived benefits, such as improved or equivalent operating efficiencies, profitability and practicality, then it cannot be guaranteed that farms will be willing to adopt new technologies.

Surveys and studies have shown that farmers are generally willing to change their practices and try new technologies (Wheeler and Lobley, 2021) (Nguyen et al., 2019). In the 2022 Farm Practices Survey (FPS) (England), 84% of farms considered it good business practice to undertake action to reduce GHGs and 74% stated that concern for the environment is also a strong positive motivator (FPS, 2022). Evidence of this attitude is provided by the over-subscribed carbon audit programme in Scotland provided by FAS in 2022.

However, this willingness is often dependent on having foresight and confidence of the benefits of doing so. Due to the emerging nature of the alternative fuel market for mobile machinery in agriculture, many farmers may perceive the risks of adopting new technologies as too high due to perceived unknowns. This is supported by FPS data which indicates that, for those farmers not taking action to reduce their GHG emissions, lack of information (30%) and lack of clarity on what to do (44%) were the main barriers (FPS, 2022). It is also interesting to note that Barnes et al (2022) found that there was little evidence between lower emissions and stronger economic performance. Earlier sections have noted concerns about the impact of some lower carbon fuels on vehicle performance, maintenance requirements and warranties. In the absence of evidence of information to contrary, such concerns are likely to discourage uptake.

### 5.7.1 Financial considerations

As with any business, financial considerations shape investment decisions and changes in business practice. Farming in Scotland is characterised by fluctuating profit margins, variations in yields and uncertainties surrounding future markets. This disincentivises high levels of investment and makes any change in practice or machinery relatively high risk. Investment decisions and management changes that are primarily focused on reducing emissions and do not have clear financial returns can be perceived as unjustifiably high risk by farmers (SBCG, 2020). This is particularly pertinent to some agriculture sectors, such as LFA farming and crofting, where margins are very low and many enterprises rely on financial support to ensure the viability of their business.

Investing in alternative fuels for mobile machinery may result in cashflow concerns for many farm enterprises in Scotland due to their higher upfront machinery costs and associated infrastructure investments needed. Indeed, the lack of ability to access financial capital to cover the costs of long-term investments in mitigation and adaptation measures is seen as a crucial barrier to increasing business resilience for many farms (Wheeler and Lobley, 2021). Scottish machinery rings have the potential to mitigate some of these issues, allowing farmers to spread risks across their network and improve access to the latest technologies.

In summary, the variable nature of the agricultural market in combination with the long pay-back period for investments in climate mitigation can disincentivise these investments. This is likely to be the case with alternative fuels for mobile machinery and underlines the need for knowledge sharing within the industry and alternative technologies that can perform to a similar capacity as current technologies (SBCG, 2020).

### 5.7.2 Business priorities

In general, farmers see GHG reduction as an important factor when making business decisions. In the FPS, 64% of farmers indicated that they thought it was important to consider GHG's when making farm business decisions. 58% suggested that they were currently taking action to reduce emissions on their farms, reflecting the priority given to immediate time pressures and the wider challenges facing the business (Wheeler and Lobley, 2021). Those not taking action may be supportive of the idea, however, feel they do not have the resources or time to consider implementing them within their business (Wheeler and Lobley, 2021).

External stakeholders often comment that farming businesses tend to focus on the short-term business planning and are often reactive to climate-related issues rather than taking a proactive position (Wheeler and Lobley, 2021). This is supported by the view that some multigenerational farms can be conservative in their approach, preferring proven methods rather than taking risks to secure the long-term viability of their business (RASE, 2021). Farming activities are also being made more challenging by the impacts of climate change. Farmers are adapting to new conditions, with a recent study exploring agricultural resilience to climate change noting that farms were replacing their machinery with larger options, allowing them to take advantage of smaller weather windows to perform essential duties (Nguyen et al., 2019).

There is a risk that farmers, in adapting to climate change, may lock in carbon intensive activities to ensure the longevity of their current business model. It also reinforces the need for alternative mobile machinery to offer equivalent performance to that offered by existing equipment. A further consideration is that some machinery, such as combines, is often shared between farms in a range of agreements and contracts. This adds another layer of complexity when considering alternative fuels as questions arise on ownership and user needs for multiple farm enterprises.

## 5.8 Application within Scottish farm types

There are a broad range of farming types in Scotland. This section reviews alternative fuel suitability for the most prominent types of agriculture, looking at the opportunities and challenges facing each. The farming types analysed are LFA, dairy and arable. The descriptions provide an analysis of the refuelling events needed by each alternative fuel for each farm type. This indicates the technological readiness of each alternative fuel and their suitability to each particular farming type. It should also be noted that there is a significant proportion of mixed holdings in Scotland and the following analysis is relevant to these types of farms also.

### 5.8.1 Hill, upland and crofting farming

The largest farmed area in Scotland is taken up by hill, upland and crofting. These areas are generally classified as Less Favoured Areas (LFAs) due to limitation on agricultural productivity due to climate, topography and soil quality (Davies et al., 1998). Most LFA farms have up to 150 livestock, with sheep being most numerous. LFA holding and crofts continue to be an integral part of rural communities in the highlands and islands. Crofts average around five hectares and number over 20,000 (RESAS, 2021). In 2018-19, the average LFA farm had an income between £11,800 and £24,000. This includes support and grants. This is below the average Scottish farm business income of £38,700 (RESAS, 2021). Without support, only 10% of LFA farms are considered to be profitable.

In terms of mobile machinery, LFA holdings are most likely to use a combination of ATVs and lower powered tractors. One farm describes ATVs as

> "must-have vehicles for farms up and down the country because they are 'vehicular Swiss army knives' for users. Their versatility and reliability make them suitable for multiple jobs and terrains. In addition, their size and power enable them to reach locations those other vehicles such as tractors or 4 x 4s may not be able to access"
>
> *(The Scottish Farmer, 2021).*

Therefore, when looking to reduce the emissions of mobile machinery in LFA holdings, alternative fuels for ATVs and small tractors should be considered.

In this area, electric vehicles are the most readily available alternative fuel that offers considerable emission and operating cost savings. Table 10 summarises the number of refuelling events per annum needed to meet the mobile machinery energy requirements for the average LFA holding based on market ready vehicles. From this table, biodiesel and hydrogen offer similar utility to current diesel models. Battery electric will require significantly more refuelling events.

Electric drones could be particularly well suited for LFA holdings as they could scope the location of livestock without the farmer having to physically check on their ATV or 4x4. They could also be used to herd sheep with a skilled operator. A recent study from Yaxley et al (2021) found that the use of drones (sky shepherding) led to lower stress sheep flocking and movement. This could save LFA farms time, fuel and increase the welfare of their flocks. Furthermore, the number of recharging events needed to meet the mobile machinery energy need on the average LFA farm is not unfeasible. The use of an electric ATV equates to approximately one recharging event every 5 days. With suitable infrastructure, this should not impact the operational capacity of LFA holdings.

The 2021 FPS found that grazing livestock farmers were the least convinced that taking action to reduce GHG emissions would improve profitability (FPS, 2022). Furthermore, LFA and lowland grazing livestock were less likely to be taking action (51% and 57% respectively) than other farm types (FPS, 2022). Due to the financial constraints faced by LFA holdings, it could therefore be a challenge to facilitate a significant change in mobile machinery use. This is compounded by the fact that alternative fuelled vehicles, including BEV ATV's have a higher upfront purchase cost. LFA holdings also generally purchase second hand mobile machinery and run the machinery beyond its typical lifecycle.

Isolation of crofting farming and communities could also mean that it is difficult to disseminate knowledge and learnings to help them adapt and adopt low carbon machinery. Power supplies and networks to rural areas may not be suitable for charging the number of vehicles needed on a larger rural farm or a remote crofting community. It should also be noted that reducing the emissions of LFA farms offers a small percentage of overall emission saving potential. Sheep farms in particular are only responsible for 3% of the total emissions associated with mobile machinery.

Reducing the emissions associated with agricultural mobile machinery in LFA farms in Scotland will most likely focus on electrification and process improvements (using drones). However, the costs associated with this transition present a significant barrier, alongside farmer knowledge and information availability.

| **Diesel** | **Biodiesel** | **Battery Electric** |
|---:|---:|---:|
| 20 | 20 | 77 |

Table 10 - Number of refuelling events per annum for the average size sheep LFA farm by technology

### 5.8.2 Dairy Farming

Beef farming accounts for 26% of total agricultural output in Scotland (RESAS, 2021). It often falls into LFA farming, whereas dairy farming often occupies better agricultural land in the lowlands, particularly in the south and west of the country. This analysis will focus on dairy farms, as the previous section on LFA farming is more relevant to beef farming.

In Scotland in 2019 there were 265,000 female dairy cattle (aged one year or older) and 56,000 female dairy calves. Dumfries and Galloway has nearly half of all dairy cows in Scotland. On average, specialist dairy farms had a farm business income of £66,000 including income from support payments and diversification, rising to £241,000 for the better performing 25% of associated farms (RESAS, 2021). Over 50% are profitable after subsidies, the most of any livestock sector. Dairy farms generally have higher profitability than any other type of farm in Scotland and rely the least on support payments.

Most of the mobile machinery use in dairy involves preparing and harvesting feedstock for cattle. This is usually either grass silage, cereals or maize, fodder beet and potatoes. Therefore, the predominant mobile machinery use in dairy and beef farming is mid power range tractors that perform a wide range of tasks on farms. Table 11 shows that Biodiesel, biomethane and hydrogen offer a similar or improved rate of refuelling based on the average dairy farm size. By 2035 BEV technology may also offer a similar refuelling profile, however current models are unsuitable to the size of the average dairy farm. Hydrogen offers similar usage as diesel but there are questions over fuel and infrastructure costs. It is likely that biomethane is an appropriate technology choice for dairy farms with anaerobic digestion on site. This is due to the accessibility of waste manure to feed the digester, with the resulting refined biomethane used to supply mobile machinery on farm. This has the further benefit of supplying fertiliser for feedstock, reducing the need for additional nitrogen inputs to soils. Anaerobic digestion using waste manure has the potential to be considered negative emissions. This is due to the capture of biogas that would usually be released into the atmosphere and the subsequent use of the upgraded biomethane in farm vehicles.

The dairy sector is most likely the most suitable to adopt new alternative technologies due to the higher profitability of the sector, availability of waste to produce biomethane and moderate mobile machinery energy input needed. This is most likely applicable to intensive processes, where animals are kept inside for a significant part of the year. This will allow waste collection, whereas grazing animals pose more of a challenge in this regard.

| Diesel | Biodiesel | Biomethane | Battery Electric (now) | Battery Electric (2035) | Hydrogen (dual fuel) |
|---|---|---|---|---|---|
| 33.4 | 33.4 | 19.5 | 622.2 | 24.9 | 30.2 |

Table 11 - Number of refuelling events per annum for the average dairy farm by technology type

### 5.8.3 Arable Farming

Arable farming is concentrated in the east of the country. Cereal crops are classified as either winter or spring, referring to simply when they were planted. Around 10% of Scotland's total agricultural area in 2019 was arable land, with farm types split between 'specialist cereal', 'general cropping' and 'horticulture' farms.

In 2018-19, the average farm business income (incl. support payments) was around £38,700. On average, general cropping and cereal farms show significantly higher profitability at £132,000 and £64,000 respectively. When support payments are excluded, over 60% of cereal farms and just under 80% of general cropping farms remain profitable, compared to 28% of farms across the agricultural sector as a whole (RESAS, 2021). Crop returns are often very sensitive to yield and market price. Differences in fixed costs, such as machinery, were traditionally the largest factor on profitability whereas input costs were relative stable across the industry (FAS, 2021). This, however, has changed in recent months at the time of writing as the industry faces soaring input costs.

Arable farms in Scotland are the most reliant on mobile machinery use, accounting for 61% of emissions associated with mobile machinery in Scottish agriculture. Mobile machinery, particularly tractors and combines, are used throughout the arable farming process. This involves ploughing, cultivating, fertilising, drilling, sowing, spraying and harvesting. There is a tendency for higher turnover of vehicles in cereal farming due to the intensive use that the vehicles undertake. Vehicles may be replaced after five years.

As mobile machinery is integral to the operations of arable farms, it is important that alternative fuel technologies offer similar operational functions as their diesel counterparts. The two most important characteristics of arable mobile machinery are:

- Possessing enough power to tow heavy loads and fit attachments to fulfil the wide range of activities needed on arable farms (ploughing for example)
- The ability to refuel quickly and efficiently to meet the often time sensitive and time pressured activities on farm (harvesting for example)

Given these requirements, alongside the refuelling events summarised in Table 12, it is clear that BEV technology is not currently feasible for arable use. This is due to the low power rating of available models, alongside the high number of refuelling events needed for the average farm size. When charging times are factored in also, this further decreases the practicality of BEV mobile machinery. Biodiesel, biomethane, and hydrogen are more suitable for arable applications. However, the availability of each of these fuels, alongside the cost of the technology and its associated infrastructure is a significant barrier.

The availability of waste material on some arable farms makes the generation of on-site biomethane feasible. With this possibility, biomethane may offer the most suitable alternative technology on arable farms due to its operational suitability and technology maturity. Furthermore, as BEV technology matures, arable farms may also be well placed to take advantage of this technology due to the opportunity to generate renewable electricity on site. Arable farms often have high renewable potential, either through solar panels installed on buildings or through use of wind turbines. The higher average profitability of arable farms could mean that these farmers are able to afford the higher upfront costs of alternative technology and to invest in anaerobic or renewable energy generation.

| | **Diesel** | **Biodiesel** | **Biomethane** | **Battery Electric (now)** | **Battery Electric (2035)** | **Hydrogen (dual fuel)** |
|---|---|---|---|---|---|---|
| **100hp tractor** | 36.4 | 36.4 | 21.2 | 679 | 27.2 | 32.9 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Combine harvester** | 8.6 | 8.6 | 5.3 | - | 27.2 | - |

*Table 12 – Number of refuelling events per annum for the average arable farm by fuel type and machinery type*

## 5.9 Summary table

Table 13 below provides a summary of each alternative fuels compared to diesel alternatives. This can be used to gain a rapid perspective on the unique opportunities and challenges with each alternative fuel technology.

| | Biodiesel | Biomethane | Hydrogen | Battery Electric |
|---|---|---|---|---|
| Carbon savings | +/- | + | + | + |
| Technology cost | + | +/- | - | - |
| Fuel cost | +/- | +/- | - | + |
| Ability to carry out necessary tasks | + | + | + | - |
| Technology readiness (now) | +/- | +/- | +/- | - |
| Technology readiness (2035) | + | + | +/- | +/- |
| Infrastructure viability | +/- | +/- | - | +/- |
| Infrastructure cost | +/- | - | - | - |
| Potential for on-site fuel production | - | + | +/- | + |
| Competition with food production | - | - | + | + |

Table 13 - Alternative technology summary. + (positive), +/- (mixed), - (negative)

# 6. Uptake scenarios

We have used a qualitative model to analyse the potential uptake scenarios of alternatively fuelled mobile machinery in Scottish agriculture. As we did not have access to any market data, only an inventory, this was the most suitable method available.

We have presented three scenarios, high uptake, medium uptake and low uptake. The results of our analysis are shown in Figure 2 on the following page. Under current policy, technological maturity and cost of fuels we would likely see the low uptake scenario realised. To achieve the medium and high scenarios, significant investment and demonstration of practicality is needed to encourage the uptake of alternatively fuelled mobile machinery.

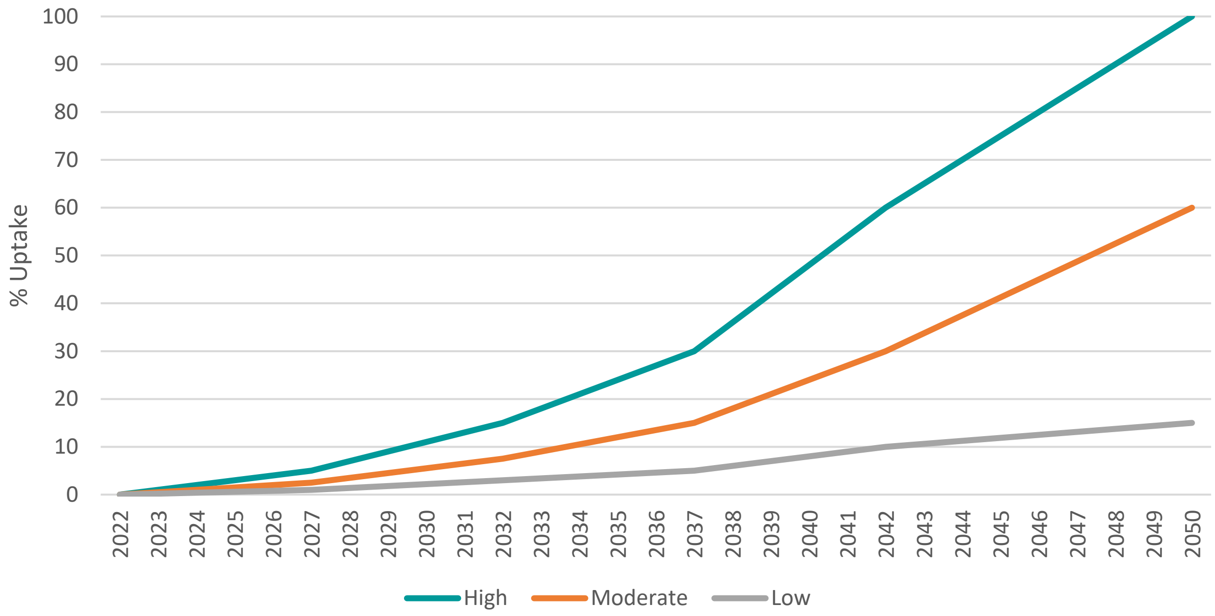



*Figure 2 - Uptake scenarios*

The key factors influencing uptake are as follows:

- Awareness and attitudes of land managers
- Purchase cost, including any subsidy, compared to conventional machinery
- Operating cost compared to conventional machinery
- Practicality compared to conventional machinery

Within each factor, there are actions that could be taken to increase the take up rate of alternatively fuelled mobile machinery. Awareness and attitude of land managers can be directly influenced by the demonstration of new technologies and the dissemination of this information throughout the industry. This can be achieved through working with industry organisation, such as the NFU, and manufacturers. Cost issues can be addressed by funding mechanisms that mitigate the impact of higher upfront or running costs. These can come in many forms and there have been similar schemes deployed in road transport and other industries. This can also be extended to include alternative fuel production and infrastructure development. Key to this is the engagement of the wider industry and manufacturers.

The assumptions used in each uptake scenario can be found in Appendix A 2.26.

## 6.1 International comparisons, incentives and policy interventions

Decarbonising the agricultural industry is an international challenge, particularly in those areas where modern farming techniques have led to a reliance on mobile machinery to complete on-farm tasks. We examined wider literature, although limited to English language only sources, for evidence of progress in other countries along with incentive programmes that could be applied in a Scottish context.

We found a lack of development in this area, with very few examples of international progress on alternative fuels for mobile machinery. For example, the European Agricultural Machinery Association (CEMA) recently released a report on "The role of agricultural machinery in decarbonising agriculture" (CEMA, 2022). This study found many of the same barriers identified in the Scottish context.

We identified only one global incentive programme. This would suggest that international progress in this area has not yet developed substantially, with other areas facing many similar contextual issues and opportunities as in Scotland.

### 6.1.1 Clean Off-Road Equipment Voucher Incentive Project (CORE) – California[13]

The CORE project is $125 million project, part of the California Climate Investments initiative[14], that encourages California off-road equipment users to purchase or lease currently commercialised, zero-emission, off-road equipment. This includes mobile agricultural machinery. This works as a point-of-sale discount, mitigating the higher upfront costs of alternatively fuelled machinery. There is no scrappage requirement and additional funding is available for charging and fuelling infrastructure and equipment deployed in disadvantaged communities. Current agricultural vehicles that are eligible for the scheme are the Monarch MK-V electric tractor and the Soletrac E25GT electric tractor. As of the 19th of August 2022, $11,647,895 of funding has been requested for agricultural vehicles to date (CORE, 2022).

### 6.1.2 Incentives

To the authors' knowledge, this is the only global incentive directly attempting to stimulate the uptake of alternatively fuelled mobile machinery in agriculture. This would suggest that policy in this area is significantly underdeveloped. Insights can be gained from observing policy development in parallel areas, such as road transport and agri-environment schemes. A recent scoping review on incentives for adoption of sustainable agriculture practices from Pineiro et al (2020) offers insights into how incentives for alternative mobile machinery adoption could be shaped.

In Pinerio et al (2020), the authors identify that economic benefits, such as increased productivity or profitability, are an essential condition for the adoption of new practices in the short term. However, in the long term, the perceived positive outcomes of new practices for their farm or the environment is a stronger incentive. Therefore, spreading awareness of the long term benefits of alternatively fuelled mobile machinery, such as GHG mitigation, should be a priority to encourage uptake. The study also notes that financial incentive levels are crucial. If payment levels compensate for operational and income losses, farmers are generally more receptive to changing practices.

Pineiro et al (2020) suggest a range of key cornerstones to base future agricultural incentive policies on:

[13] https://californiacore.org/
[14] https://www.caclimateinvestments.ca.gov/

- Balance the incentives and outcomes
  - Incentives must be high enough to encourage farmers to change processes. Incentives should ensure that farmers do not
- Know your farmers
  - Incentive programmes should be tailored to the unique situation of agriculture in Scotland, taking into account personal, political, institutional and biophysical factors.
- Keep it simple
  - Incentive programmes should be easy to understand and implement. Complex and time consuming programmes are a significant disincentive to farmers.
- Complement
  - A combination of complementary incentives is more likely to succeed. Financial as well as knowledge sharing and training incentives are an effective combination.
- Be prepared for a long time horizon
  - The opportunity cost of time has to be considered to ensure that cash flow problems are not an issue. This is particularly true with mobile machinery, where alternative technologies carry a higher upfront cost.

# 7. Conclusions

Emissions from agricultural mobile machinery contribute 0.4 MtCO2e per year in Scotland. Despite this, the technology for alternatively fuelled mobile machinery that will mitigate these emissions is still not mature. Alternative technology in agriculture has not seen the same development rate as other sectors have due to the unique use of machinery in the industry, lack of information and knowledge sharing and the high risk of adopting new practices and technologies.

Our total emissions estimate is lower than was found by similar analysis carried out by Barnes et al (2022) and Moxey and Thompson (2021). We have calculated our total by using the mobile machinery energy inputs provided in Warwick HRI (2007) and multiplying these by the total agricultural areas in Scotland as summarised in the Agricultural Census (RASE, 2020). The different totals estimated by this study reflect the considerable uncertainties surrounding agricultural mobile machinery in Scotland. There is a limited amount of information on the current machinery stock in Scotland, their typical duty patterns and replacement rates. This may, be in part, due to the absence of a mandatory centralised database for mobile machinery. Therefore any estimate, including this report, will rely heavily on assumptions – leading to variations depending on what calculation method is utilised.

We found that biomethane offers the highest potential emission reduction in the short term. This can help address the fact that in some farming sectors, such as crofting, there is likely to only be one replacement cycle before Scotland's 2045 net zero target. In the long term, we estimate that BEV and hydrogen have the potential to offer the largest emission savings. However, these technologies face significant barriers that will need to be addressed if their potential is to be realised.

Arable and dairy farmers are the most reliant on mobile machinery to undertake their farming activities. In both of these sectors, there is the potential to combine on-site fuel generation (either biomethane, renewable electricity or hydrogen) to power mobile machinery. This would provide the greatest emission savings, however these sources could be supplemented with external supplies as the associated infrastructure with these technologies develops. LFA farms are less reliant on mobile machinery. However, there are opportunities to electrify smaller machinery, such as ATVs, and use new technologies to reduce LFA farms reliance on mobile machinery.

Further research into the uptake of biomethane production, renewable energy and hydrogen production on farms would be beneficial. Future research should focus on how these assets can be utilised by mobile machinery.

We found that there is a significant lack of data, both in the scientific and grey literature, on the topic of alternative fuels for agricultural mobile machinery. Where the topic of mobile machinery is highlighted, mitigation conclusions focus on improving the efficiency of vehicle usage rather than transitioning to alternative fuels. Although this will reduce emissions to an extent, this alone will not be far reaching enough to meet emission reduction targets for the sector. We also found that there is a lack of information on the current mobile machinery stock in Scotland and their fuel efficiency values for a wide range of activities. To calculate an accurate baseline, more information is needed on the average fuel consumption of mobile machinery. We acknowledge that this is challenging due to the varied nature of on farm mobile machinery use. This study relies on Warwick HRI (2007) data for key assumptions. A new database based on real world data would allow more accurate calculations and estimates.

We conclude that the establishment of trial farms to gather and share data on alternatively fuelled mobile machinery performance would be beneficial. This could demonstrate that bridging technologies have similar technical feasibility as current machinery, with a focus on biomethane and biodiesel. This would also focus on developing insights into BEV and hydrogen technologies as they mature. This would provide the industry with specific performance and financial figures to allow businesses to forecast accurately the impact of adopting alternatively fuelled mobile machinery. Without certainty of the payback period, other financial aspects and performance of adopting alternative mobile machinery, the uptake could be low.

Due to the tight operating margins in the Scottish agriculture sector, alongside increased uncertainties due to the influence of climate change, it is likely that businesses in Scotland will require financial incentive or assistance to uptake new alternative fuelled mobile machinery. We conclude that similar financial incentives could be employed to those in the surface transport sector. This could include interest free loans to farm businesses to cover the difference between a conventional mobile machinery and alternative fuel mobile machinery. Incentives could be targeted at farms that have a higher machinery turnover, as this would facilitate the dilution of alternatively fuelled mobile machinery into the second-hand market.

It would be beneficial if detailed information on agricultural mobile machinery stock and typical usage were included in the upcoming Farm Business Survey. This could inform a more robust baseline and inform future policy decisions.

There could be an increased focus on mobile machinery in publicly funded carbon audits delivered through the FAS. This would include specialist mobile machinery consultancy advice as part of the standard package.

# 8. Appendix A

## 8.1 Energy & carbon calculations

Firstly, total kWh energy inputs for mobile machinery in a wide range of agricultural outputs were identified from Warwick HRI (2007) in a report to DEFRA. In this study the author determine how direct energy input is required from mobile machinery for a range of farming activities in the UK. Key figures used in the study are shown in Tables A1 to A4.

| Crop type | Mobile machinery Input (kWh/ha) |
|---|---|
| Edible crops | 1700 |
| Ornamental crops | 1700 |
| | |
| Horticultural field crops | |
| Leafy salad | 1100 |
| Onions | 1600 |
| Other vegetables | 1600 |
| Fruit | 300 |
| Hops | 300 |
| Flower bulbs | 800 |
| | |
| Arable crops | |
| Wheat | 1078 |
| Barley | 942 |
| Oats | 1078 |
| Other Cereals | 1078 |
| Potatoes | 3230 |
| Other arable | 1074 |
| | |
| Dairy cows | 548.7 |
| Beef cows | 453.1 |
| Ewes/shearlings | 18.9 |

Table A 1 - Energy inputs from mobile machinery by crop type

Using the total number of hectares of each different farming activity, sourced from the 2020 Scottish Agricultural Census, these were multiplied by the mobile machinery energy inputs sourced from Warwick HRI (2007). For beef & sheep, as hectare values were not available, the total number of animals were divided by the average stocking densities for dairy cows, beef cows and sheep sourced from the Farm Advisory Service's "Farm Performance in Scotland" report (FAS, 2019) [17]. Multiplying the total hectare for each farming activity type by its mobile machinery energy inputs provided a total kWh value for each farming activity. This kWh value was then multiplied by the diesel, under the assumption that almost all current mobile machinery is using red or white diesel, emission factor per kWh sourced from BEIS datasets (BEIS, 2022). This provided the total kg$CO_2$e per farming activity in Scotland, which was then used as the annual baseline emissions for this study. Table A2 below shows the summary for each type of activity.

| | Total kWh of mobile machinery input | Mt $CO_2$e |
|---|---|---|
| Arable | 998,024,099.00 | 0.2407 |
| Cattle & Dairy | 598,116,209.19 | 0.1442 |
| Sheep | 50,809,368.96 | 0.0123 |
| Total | 1,646,949,677.15 | 0.3972 |

Table A 2 – Total emissions from mobile machinery

In the Warwick (2007) study, the mobile machinery inputs into pig and poultry farming are adjudged to be minimal. For this reason, pig and poultry farming has been omitted from this study.

## 8.2 Emission Savings

The emission savings for each alternative fuel were calculated by multiplying the total kWh of mobile machinery input for each alternative by the emission factor specified in the table below. This was then compared to the diesel baseline to provide a potential emission reduction potential percentage.

| **Fuel** | **Unit** | **Total kg $CO_2$e per unit** |
|---|---|---|
| Diesel (average biofuel blend) | tonnes | 3032.89 |
| | litres | 2.55784 |
| | kWh (Net CV) | 0.25631 |
| | kWh (Gross CV) | 0.24115 |
| Biodiesel ME | litres | 0.16751 |
| | GJ | 5.05961 |
| | kg | 0.18822 |
| Biomethane (compressed) | litres | - |
| | GJ | 0.10625 |
| | kg | 0.00521 |
| Biodiesel ME (from used cooking oil) | litres | 0.16751 |
| | GJ | 5.05961 |
| | kg | 0.18822 |
| Biodiesel ME (from tallow) | litres | 0.16751 |
| | GJ | 5.05961 |
| | kg | 0.18822 |
| Biodiesel HVO | litres | 0.03558 |
| | GJ | 1.03677 |
| | kg | 0.04562 |
| Electricity generated (2022) | kWh | 0.19338 |
| Electricity generated (2035) | kWh | 0.023 |
| Hydrogen - electrolysis (grid) | kWh | 0.29065 |
| Hydrogen - fossil fuels (gas) | kWh | 0.26638 |
| Hydrogen - fossil fuels (coal) | kWh | 0.56515 |
| Hydrogen - fossil fuels (gas) with CCS | kWh | 0.02664 |
| Hydrogen - green | kWh | 0.01804 |

Table A 3 - Emission factors for fuel types

## 8.3 Refuelling events

To directly compare usability between current ICE mobile machinery and alternative fuel options, the number of refuelling events for year for a typical range of farms was calculated. Average farm sizes were calculated using data from the Scottish Agricultural Census (Scottish Gov, 2022) and are shown in table.

| Farm type | Average ha |
|---|---|
| Specialist cereals | 103.00 |
| Specialist horticulture & permanent crops | 34.00 |
| Cattle (dairy) | 162.00 |
| Sheep | 216.00 |

Table A 4 - Average farm size

The average hectare value for each typical farm was then multiplied by the closest matching mobile machinery energy input value to give the total mobile machinery energy requirements for each farm type. This value was then multiplied by the energy efficiencies of alternative fuel engines, as shown in Table A 5.

| Fuel | Efficiency |
|---|---|
| Biodiesel (FAME/HVO) | 100% |
| Methane | -30% |
| Battery Electric (BEV) | 73% |
| Hydrogen | 22% |

Table A 5 - Efficiency values for each fuel type

| Fuel type | Arable | Specialist horticulture & permanent crops | Dairy | LFA sheep |
|---|---|---|---|---|
| Diesel | 97,026 | 54,400 | 88,889 | 4,082 |
| Biodiesel (FAME/HVO) | 97,026 | 54,400 | 88,889 | 4,082 |
| Biomethane | 130,985 | 73,440 | 120,000 | 5,511 |
| Battery Electric | 27,167 | 15,232 | 24,889 | 1,143 |
| Hydrogen | 67,918 | 38,080 | 62,222 | 2,857 |
| Hydrogen/Diesel (Currently available dual-fuel technology) | 82,472 | 46,240 | 75,555 | 3,470 |

Table A 6 - Energy requirements by fuel type

The number of refuelling events for each average farm type was calculated using the energy required per year compared to the engine capabilities of each fuel type. Manufacturers specifications were used to assess the current and alternative fuel technologies. The same energy input values were used to determine the carbon savings of each alternative fuel by multiplying the energy requirements by their associated emission factor. The table below outlines the key assumptions used in the calculation of each alternative fuel.

| Fuel | Assumptions |
|---|---|
| Biodiesel (HVO/FAME) | Based on manufacturer specifications, it was assumed that current tractor ICE engines will either be able to accept a 5%, 20% or 100% biodiesel blend.<br><br>Average biodiesel (HVO) figures, supplied by the DFT (2021), have been used in this study as HVO is currently the largest source of biodiesel in the UK, with 96% of biodiesel used in the UK in 2021 coming from used cooking oil (DFT, 2021). |
| Biomethane | Refuelling events for biomethane were calculated by using manufactures specifications to estimate the total kWh per tank of biomethane in the two models that are available in the market now. This is then divided by the total energy inputs needed by mobile machinery to<br><br>This study has used the average biomethane carbon emissions per mJ to calculate the carbon savings of this technology. The carbon emissions associated with the production of biomethane varies considerable based on the type of input used in anaerobic digestion. |
| Battery Electric | The average grid carbon intensity (BEIS, 2022) was used to calculate the carbon emissions of the BEV option. Lower emissions could be achieved if renewable energy is generated on-site. |
| Hydrogen | The $kgCO_2e/kgH2$ associated with the production of grey, blue and green hydrogen were sourced from a range of academic and grey literature. The energy density of hydrogen was assumed at 33.6 kWh per kg. The average kWh of energy required to produce 1kg of hydrogen was assumed at 50.5 kWh. |
| Diesel | To calculate the baseline diesel scenario, the specifications of a typical 103hp tractor were used for comparison. |

Table A 7 - Key assumptions

## 8.4 Costs

The FAS (2021) guidebook was used to perform a cost analysis of each fuel option. The method used is outlined on p.378 of the handbook. This was based on accurate prices as of the time of writing of this report. The key assumptions can be found below.

| Input | Value | Metric |
|---|---:|---|
| Area Harvested | 103 | ha |
| Work rate | 2.75 | ha/hr |
| Annual hours worked | 812 | hours |
| Machine life | 8 | yrs |
| Depreciation rate | 10.00% | Per/yr |
| Interest rate | 5% | Per/yr |
| Insurance | 15 | £/1000 in vehicle value |

| | | |
|---|---|---|
| Spares and repairs | 4.5% | Per/yr |
| Labour | 12.5 | £/hr |
| Red diesel | 114 | Pence/litre |
| Hydrogen (Grey) | 140 | Pence/kg |
| Hydrogen (Green) | 164 | Pence/kg |
| Hydrogen (Blue) | 657 | Pence/kg |
| Biomethane (Local production) | 75 | Pence/m3 |
| FAME | 168 | Pence/litre |
| Electricity | 0.28 | Pence/kWh |

Table A 8 - Cost calculation inputs

## 8.5 Uptake scenarios

In assessing uptake scenarios, LUC used a qualitative grid matrix to determine the likely uptake rates of alternatively fuelled mobile machinery.

| Awareness and attitudes of land managers | Purchase cost Including any subsidy compared to conventional machinery | Operating cost compared to conventional | Practicality compared to conventional |
|---|---|---|---|
| Positive | Significantly higher | Higher | More practical |
| Mixed | Higher | Equivalent | Equivalent |
| Negative | Equivalent | Lower | Less practical |

Table A 9 - Uptake scenario criteria

| Area | Main factors influencing uptake rate |
|---|---|
| Awareness and attitudes of land managers | Dissemination of information, including working examples of mobile machinery on trial farms and knowledge sharing platforms. |
| Purchase cost including any subsidy compared to conventional machinery | The purchase cost for alternatively fuelled mobile machinery is currently higher. To what extent this reaches price parity with conventional vehicles will affect uptake scenarios significantly.<br><br>Subsidies and other financial incentives could support the uptake of alternative machinery. |
| Operating cost compared to conventional machinery | With the exception of battery electric technology, the fuel costs of alternative technologies are currently higher than diesel.<br><br>The amount of fuel generated on site will have a large influence over the cost of alternative fuels, and therefore the viability of alternative machinery. |

| | |
|---|---|
| Practicality compared to conventional machinery | Farmers, especially arable and dairy, need high powered and torqued machines that can operate for long periods with a wide range of attachments during certain periods of intense activity.<br><br>If alternative technologies do not offer the same levels of practicality, such as power or refuelling times, this will disincentivise the uptake of alternatively fuelled mobile machinery. |

Table A 10 - Key factors influencing uptake scenarios

### 8.5.1 High uptake scenario

| **Awareness and attitudes of land managers** | **Purchase cost Including any subsidy compared to conventional** | **Operating cost compared to conventional** | **Practicality compared to conventional** |
|---|---|---|---|
| Positive | Significantly higher | Higher | More practical |
| Mixed | Higher | Equivalent | Equivalent |
| Negative | Equivalent | Lower | Less practical |

### 8.5.2 Medium uptake scenario

| **Awareness and attitudes of land managers** | **Purchase cost Including any subsidy compared to conventional** | **Operating cost compared to conventional** | **Practicality compared to conventional** |
|---|---|---|---|
| Positive | Significantly higher | Higher | More practical |
| Mixed | Higher | Equivalent | Equivalent |
| Negative | Equivalent | Lower | Less practical |

### 8.5.3 Low uptake scenario

| **Awareness and attitudes of land managers** | **Purchase cost Including any subsidy compared to conventional** | **Operating cost compared to conventional** | **Practicality compared to conventional** |
|---|---|---|---|
| Positive | Significantly higher | Higher | More practical |
| Mixed | Higher | Equivalent | Equivalent |
| Negative | Equivalent | Lower | Less practical |

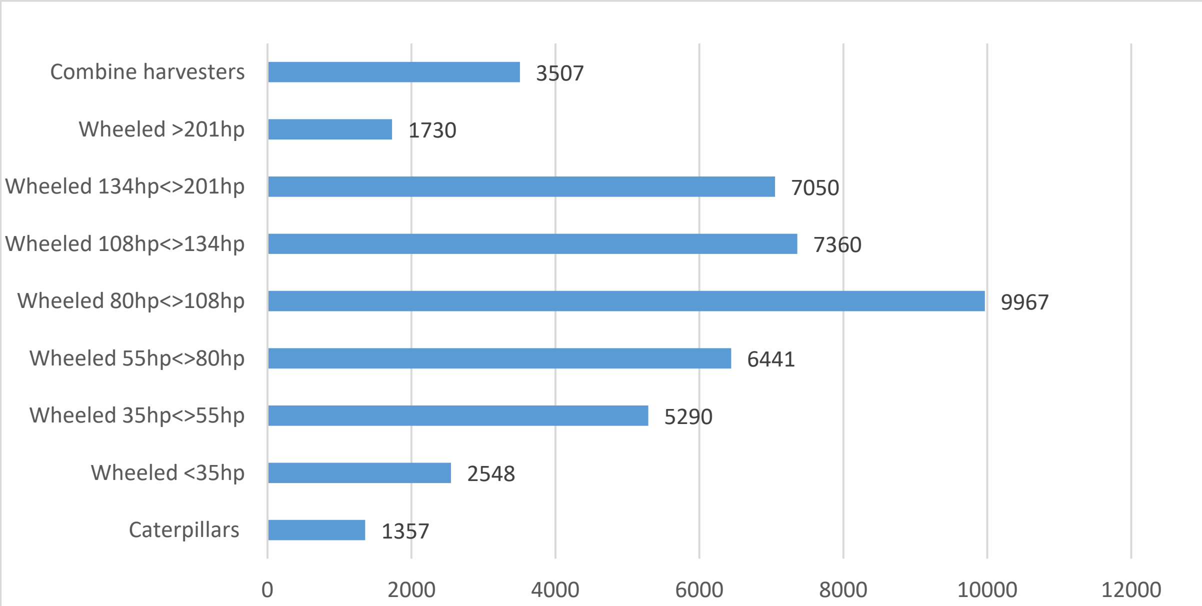
# 9. Appendix B

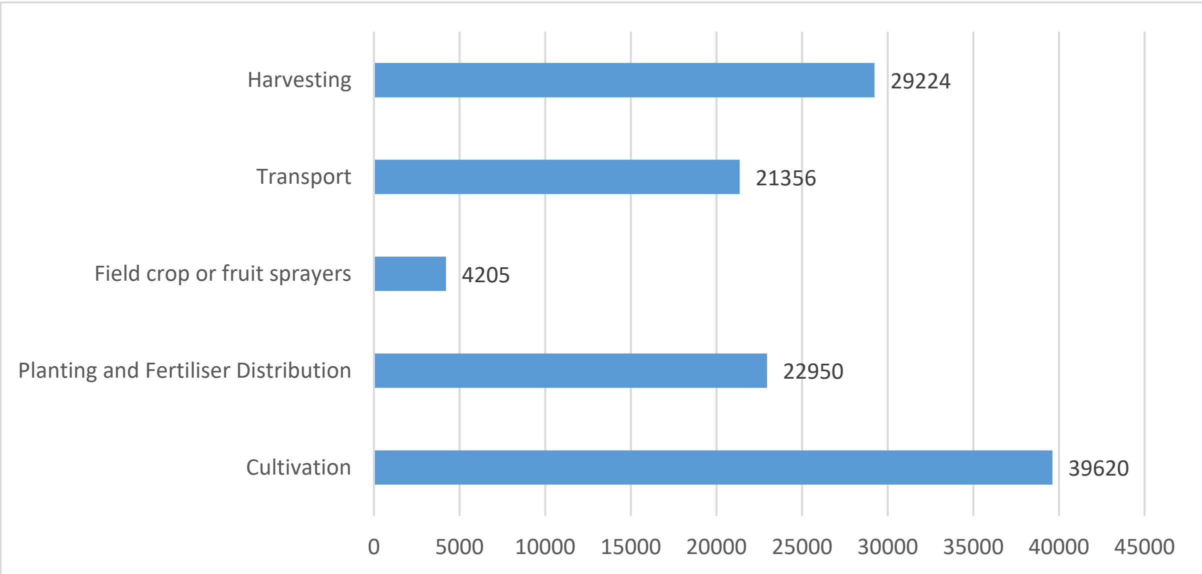
Case studies that are referenced throughout the text can be found in the following section. Further details can be found below.

### 9.1.1 Case Study 1 - Biodiesel manufacturer specifications

| Manufacturer | Biodiesel blend | Notes |
|---|---|---|
| John Deere | 5% | All tractors produced since 1989 and before 2002 can run on pure biodiesel with minor modifications. All models fitted with a common-rail engine can run on a 5% blend. |
| New Holland | 20% | New Holland approves the use of biodiesel blends up to 20%. |
| Massey Ferguson | 100% | Sisu Diesel engines fitted to most Massey Ferguson tractors can run on 100% biodiesel. Tier III engines can run on 20%. |
| Case IH | 5% | Case approves the use of 5% biodiesel for common-rail engines. Non-common-rail engines are approved to 20%. |
| Fendt | 100% | All Fendt tractors built after 1995 can run off 100% biodiesel. |

### 9.1.2 Case Study 2 - Current mobile machinery stock in Scotland



### 9.1.3 Case Study 3 - Biomethane production on farm[15][16]

**Barfoot Farms**

Barfoot farms is a family owned business based in West Sussex, specializing in producing, processing and packing a range of semi-exotic vegetables at farms and facilities around the world.

In 2010, Barfoots started operating an anaerobic digester on site. This is fed from 25,000 tonnes of waste product from the farm, mostly sweetcorn husks. The resulting biogas is used to power onsite generators, with a maximum output of 2.3mWh. One third of this resulting energy is used to power on-site processes, with the remained exported to the national grid. A further by-product is natural fertilizer, with enough produced to fertilise over 800 acres of farmland.


**Arla Farms**


Arla farms is a European dairy co-operative consisting of 11,200 farmers in seven countries.

Arla farms has started a trial on two Arla dairy farms, where waste manure from dairy cows is converted into biomethane. Arla sends its waste manure to an nearby off-site anaerobic digester, where the component parts are broken down, with biomethane produced. Arla claims that a herd of around 500 cows can produce 190 tonnes of manure a week, which can be converted to 27,000kg of biofuel through anaerobic digestion. A further by-product of this process is a rich, natural fertilizer that farms can utilize in other processes.

[15] https://www.barfoots.com/sustainability/
[16] https://www.arlafoods.co.uk/food-for-thought/poo-power/

### 9.1.4 Case Study 4 - Biomethane mobile machinery[17][18]

**New Holland T6.180**

The New Holland T6.180 methane tractor is based on the same diesel equivalent T6 model with a methane engine. The manufacturer claims that the performance is the same as its diesel equivalent and that it produces 99% less particulate matter and reduces overall emissions by 80%.

Engine category – NEF 6.7L

Engine capacity (gas) – 6728cm3

Rated power – 150hp

Max lift capacity – 7864kg

**Gomselmash Palesse GS 4118 K**

The Palesse GS 4118 is a conventional combine that runs on a Cummins 8 cylinder methane engine.


Rated power – 350hp

Engine capacity – 450 m3

Threshing-separating unit – 1500mm

[17] https://agriculture.newholland.com/eu/en-uk/equipment/products/agricultural-tractors/t6-methane-power
[18] https://eng.gomselmash.by/produktsiya/grain-harvesters/grain-harvesting-combine-palesse-gs4118k/

### 9.1.5 Case Study 5 - Battery electric mobile machinery[19] [20]

**Farmtrac FT25G**

Farmtrac have release an all-electric compact tractor that is designed for greenhouse work, groundskeeping, equestrian centres and other applications. Mower and rotary attachments can be connected to the Cat 1 rear linkage. The Farmtrac FT25G is available to purchase now.

Battery size – 21 kWh (equivalent to 25hp)

Operational hours – up to 6 hours under continuous use

Lift capacity – 450kg

Weight – 1.2 tonnes

**John Deere – Sesam**

The manufacturer John Deere has taken the view that electrification is the future fuel source for agricultural vehicles. The company is developing their electric offering and has recently released the concept tractor SESAM2. The SESAM2 can be run manually or automatically – with or without the removable cab.

Battery size – 1000 kWh (equivalent to 134hp)

Running time – 10 hours at 80% engine load

Weight – 18 tonnes

[19] https://www.reesinkagriculture.co.uk/portfolio/farmtrac-ft25g/
[20] https://www.deere.co.uk/en/agriculture/future-of-farming/

### 9.1.6 Case Study 6 - Hydrogen mobile machinery[21][22]

**Nether Aden Farm – Aberdeenshire**

Nether Aden farm in Aberdeenshire is a 203 hectare mixed use farm with 130-cow sucklers and arable land. Nether Farm took part in the Farming for a Better Climate project, looking for ways to reduce the farms carbon footprint. One of the practical solutions adopted by the farm has been retrofitting mobile machinery with hydrogen electrolysers.

Although there are questions surrounding the practical benefits of small scale electrolysers - data collected over a 15 month period showed a fuel saving of 20% on the telehandler equipped with the electrolyser, equating to 1,083 litres of fuel per year.

In a recent interview, David Barron of Nether Aden farm suggested that the price of each hydrogen electrolyser has come down to £1000 per unit, compared to £6000 per unit for his first unit. David has gone on to install an electrolyser on his tractor and on his farm vehicle.

David also claims that the vehicles fitted with the electrolysers have more torque and emit noticeably less tailpipe emissions than pure diesel alternatives.

**New Holland T5.140 H2**

New Holland and Blue Fuel Solutions have produced a dual fuel hydrogen tractor based off their existing T5.140 Auto Command tractor, a model developed for a wide range of agricultural applications. Hydrogen is directly mixed with diesel in the engine.

Tank capacity (50/50 hydrogen/diesel) – 115kg

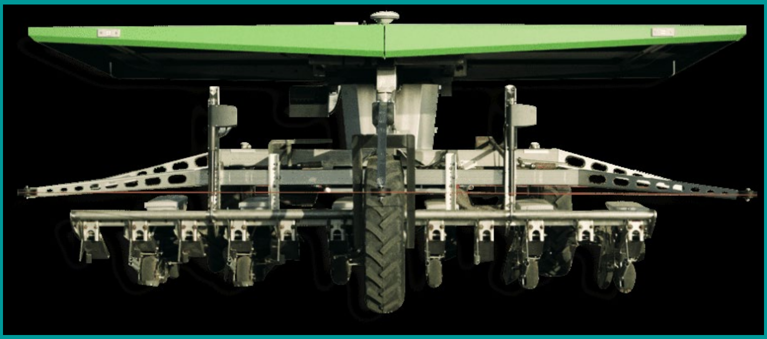
Power – 103/140

Max lift capacity – 5500

### 9.1.7 Case Study 7 - Alternative techonologies [23]

**Farmdroid**

FarmDroid FD20 is a solar panel driven field robot, by using GPS, that performs mechanical sowing and weed control.



The manufacturers claim that the four solar panels mounted on top of the machine produce power for the battery pack that can supply up to 24 hours of daily carbon neutral operation. This can ensure constant work throughout the entire season. The machine has also been designed to be as light as possible to prevent soil compaction.

[21] https://www.farmingforabetterclimate.org/climate_change_focus_farms/nether-aden-farm-aberdeenshire-beef-sheep-arable/
[22] https://h2dualpower.com/en
[23] https://farmdroid.dk/en/welcome/

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