FARM OF THE FUTURE: JOURNEY TO NET ZERO

Royal Agricultural Society of England

8 March 2022

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PREFACE FROM LORD DEBEN

Chairman of the UK's Climate Change Committee (CCC)

There is no way in which we can win the battle against climate change unless we recognise the central role which agriculture must play. Net Zero is not just a matter of radically reducing our emissions. There can't be human or animal life without emissions. Zero has therefore never been on the cards. However, before the Industrial revolution, the earth - through oceans, soil, and trees – sequestered enough of those emissions to maintain the climate patterns which made human life possible. That was the balance of nature with which we have interfered both by massively increasing our emissions and by reducing the earth's capacity to sequester. We have cut down our forests, polluted our oceans, and degraded our soils. No longer can the planet absorb what we emit.

The Net bit of Net Zero is therefore vitally important and crucially it's largely in the hands of farmers. Whatever we do to regenerate our seas, to stop deforestation, and to halt the march of the deserts, the most important job will be to learn how we feed the world without costing the earth. We have to regain the fertility of the soil, plant and care for many more trees, recreate the hedges we have lost and at the same time produce the food which a growing world population needs. Food production is the first of all 'public goods' that farmers offer. But it has to be done in a way which also leads to Net Zero. That is what this Report is about.

RASE has rightly recognised that farmers need help and direction if they are to shoulder this essential task. Of course, it starts with reducing their carbon footprint as much as is possible. By 2050, fossil fuels will have no place on our farms and to that end, every year serious reductions must be made. Much more careful use of inputs; an increasing concentration on regenerative cultivation; tree and hedge planting; cover crops; mixed farming replacing monoculture; effective use of gene editing; and a determination to make our soils ever more capable of sequestration – all these and more will be prerequisites in the fight against climate change.

This Report is a major contribution to enhancing farmers' ability to live up to their high vocation. And it comes at exactly the right time. The changes that are demanded are daunting. The Government's shift from production support to payment for public goods has often seemed muddled and confusing. The intervention of special interest groups from the vegans to the rewilders has discouraged and disconcerted the vast majority of farmers. This Report will come as a real encouragement to them and a reinforcement of their vital role. It will be widely welcomed.

FOREWORD FROM PHILIP GREADY

Chairman of the Royal Agricultural Society of England (RASE)

Since the creation of the first farms over 10,000 years ago, mankind has devised increasingly clever ways of harvesting sunlight and converting this into food by essentially growing carbon in sustainable farming systems. However, it is only in the last 100 years or so that we have found ways to accelerate this process, partly based on extraction of oil and gas, enabling us to produce more food for an ever-increasing population.

Our use of improved science, technology and training has been targeted at maximising production to produce cheap and plentiful food and energy supplies. This has been the strategy of governments around the globe and measured against this, the agricultural industry has been highly successful.

However, the success has come at a heavy cost to the environment through the loss of habitat for wildlife, the degradation of soils, the pollution of watercourses and, more widely, the irreversible change to climate through global warming.

The carbon that we have collectively unlocked is now posing an existential threat to mankind and there is consensus that urgent action must be taken to reduce and ultimately cease our reliance on fossil carbon and to look to alternative energy sources. The goal is to be carbon neutral by 2050.

What does this mean for our UK farmers?

Food production has to remain the key objective and responsibility of our farmers. However, the future use of rural land is one of the main solutions to stemming and potentially reversing the quantity of carbon in the atmosphere.

Future land use will also dictate the rate of recovery of wildlife in the countryside and there is growing recognition that the health and wellbeing of our population is hugely improved by having access to the regenerative power of our outstanding countryside and landscapes. Both now and in the future, we see many competing demands made of our rural landscape.

This is important for farmers and landowners as they will play a pivotal role in providing a solution to the current crisis of climate and loss of wildlife. Change will be inevitable, new skills learnt and investment required from government and the private sector in order to secure multi-layered returns from the land.

The UK can play a key role in developing sustainable land use which meets the objectives of feeding the population, sequestrating more carbon than we emit whilst improving soil health, water quality and biodiversity.

This paper (and its policy-based predecessor) has been commissioned by RASE to pull together the latest science and its potential application to land use. We aim to show what our farmers will be able to realistically achieve and the practical steps which can be taken to decarbonise our industry. This report informs our own thinking and puts us in a better position to support farmers in upskilling and making fundamental changes to their business models.

KEY MESSAGES

Each section of the 'Farm of the Future: Journey to Net Zero' report puts forward a vision of how farming across the UK might adapt to the challenges posed by climate change. It draws upon a wide spectrum of specialist knowledge and includes technical and policy insights on key topics of farm and land resource management; low carbon and renewable energy; low emission agricultural vehicles and fuels; agri-tech innovation; farm enterprises and novel crops.

The messages summarised below indicate what is required for Government, farmers, growers and land managers to respond effectively to climate change, reduce greenhouse gas emissions, and play their part in delivering the UK commitment of Net Zero by 2050:

1. It must be recognised that the **primary function of farmers is to produce food** - albeit in a low carbon regime.

2. Farmers are responsible for managing a large proportion of the UK's landmass, as guardians of the countryside, with a **vital role to play in the implementation of the country's low carbon transition plans.** Effective Government support will be essential to deliver the required 'systems change' **ensuring farm business viability throughout the transition.**

3. Greater involvement of farmers and representative organisations in the formulation ot the Government's low carbon agricultural policy and its implementation is essential. This must be **aligned across government departments** acknowledging the complex role of farmers and land managers with responsibility for managing natural resources whilst supplying a secure food supply to the nation - and remaining profitable.

4. Whilst there is evidence of commitment and activity amongst farmers already working towards a low carbon farming future, it will be challenging and high risk for many. Farmers – those well established and new to the industry - need access to **research, knowledge transfer and advisory services** aimed especially at restoring soil health, increasing biodiversity and better managing valuable land and water resources.

5. An exciting range of innovative approaches and technology solutions are becoming available to farmers. The existing **network of farm demonstration sites** should be extended to encourage uptake of nature-friendly sustainable farming practices, emerging technologies and rural renewable energy opportunities.

6. For farmers to modernise their operations and fully embrace digital and artificial intelligence (AI) technologies, urgent attention and investment must be focused on **improved rural connectivity, mobile communications and rural power networks.**

7. Agriculture is part of an extended supply chain that will be increasingly driven by **consumer awareness and choice**. Closer cooperation between farmers, processors and retailers, e.g. with food labelling and carbon accounting, will help promote the value of high quality, sustainable British food in a changing, post-Brexit global market.

8. **Sound economic valuation of natural capital** and new systems must be established to ensure farmers are sufficiently rewarded for their contribution to meeting national and local decarbonisation goals while ensuring food security.

1. INTRODUCTION

The **'Refuelling the Countryside'** report published by the Royal Agricultural Society of England (RASE) in 2014 assessed options for reducing fossil fuel use on UK farms and highlighted the potential for sustainable farm transport and on-farm renewable energy generation. It followed the Society's 2011 report **'A Review of Anaerobic Digestion Plants on UK Farms'**.

The 2014 report highlighted three on-farm fuel scenarios – electric, biogas and hydrogen – to indicate how farms might move towards a greater level of energy self-sufficiency in powering farm operations and fuelling vehicles and machinery.

Today, the role of agriculture in decarbonisation must be wider than simply a low-carbon energy and fuel transition. It should include ambitions such as:

- building and sequestering carbon in soils, improving biodiversity and managing water resources more effectively,
- maximising value from bioresources through adopting circular economy principles,
- adopting emerging business models and technologies, e.g. robotics, artificial intelligence and hands-free farming, where applicable,
- working with supply chain partners including feed suppliers, supermarkets and consumers to reduce greenhouse gas (GHG) emissions.

> "Climate change is systems change."

This "Farm of the Future: Journey to Net Zero" report (and its policy-focussed predecessor) offers stakeholders and policymakers a **vision** of change for the industry. It provides **policy insights** and background to help enable this transition, presenting current and emerging solutions in areas such as resource management, renewable energy, low emission agricultural vehicles, alternative fuels and emerging technologies, i.e. agri-tech.

The report includes contributions from industry specialists and case studies demonstrating good farming practice. These can be read as stand-alone pieces so, by definition, there may be a certain amount of repetition. It highlights current and near-term planet-friendly processes and technologies that will help implement the 'vision' for a healthier, more resilient and nature-friendly rural food supply system.

The report also examines options to decarbonise specific farm enterprises (dairy/ruminants, cereals, intensive livestock and horticulture), and suggests practical steps towards a more circular and resource efficient rural economy. The report is aimed primarily at farmers and rural stakeholders, but also includes the latest government policies for farming, with a particular focus on those issued by the Department of Environment, Food and Rural Affairs (Defra) for England (i.e. the Environmental Land Management scheme).

However, whilst some of the policy aims may differ, most of the principles discussed here apply equally to the devolved administrations. This report also provides recommendations for policymakers and takes account of deliberations and agreements reached during Glasgow COP26.

2. FARMING 2022:
TIME FOR CHANGE

LEAF's (Linking Environment And Farming) vision is a global farming and food system that delivers climate positive action, builds resilience and diversity, and enriches our food, farms, the environment and society. We see this being delivered through more integrated, regenerative, circular approaches to farming. The industry already has many of the building blocks to support such a vision, but scalability, speed and collaboration at a new level is needed.

Striving for meaningful change needs to be underpinned by science-based targets, new technology and innovation and crucially, working alongside more nature-based solutions. Peer to peer learning, through channels such as the LEAF Network of Demonstration Farms and world leading Innovation Centres, creating the market pull through LEAF Marque certification, educating and connecting young people and the wider public out on the farm, such as through 'Open Farm Sunday' - all these need to work together to help transform our farming and food systems. We need ambition, leadership, belief and a practical, 'can-do' approach to change, not only looking to achieve Net Carbon Zero, but also to enrich our environment, habitats and nature whilst ensuring profitable businesses and an actively connected society. Now is the time for change!

'Farm of the Future' – A Vision from Caroline Drummond MBE, Chief Executive LEAF


© Photo: Angela Bywater

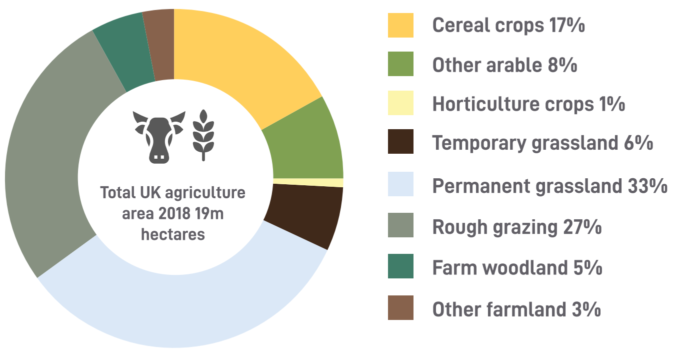
Agriculture, both in the UK and globally, faces a significant period of change over the next two decades – not least through the 'threat multiplier' effects of climate change, turning what were often regarded as 1 in 100-year risk predictions into more regular and sometimes extreme events, including flooding, drought and pest inundations. This is in addition to the other challenges that farmers have to manage – many of which lie outside of their control.

In addition to climatic uncertainties, UK farmers and land managers face other issues: a new subsidy/grant regime (largely as a result of Brexit and changing trading conditions); supply chain adjustments to meet new consumer demands; multiple policy and regulation changes; labour and skills shortages; market fluctuations - and unexpected crises such as the Covid-19 pandemic. With a reputation for resilience, farmers, land managers and rural communities tend to adopt a long term (multi-generational) view of the future.

> "Each farmer has different pains and gains."

Farming activity covers some 17.4 million hectares (ha) (43 million acres) occupying around 71% of the UK landmass (see Figure 1). As such, it constitutes a vital part of the UK's rural, agri-food and bioresource economies. Defra estimates that UK farming produced a total income of £4.1 billion in 2020. Some 219,000 UK agricultural holdings (65% of which are under 50 ha) provide 64% of the nation's food[1].

Agricultural land use in the UK, 2018



Source: *Defra (2018) Agriculture in the UK, CCC analysis*

Figure 1: Agricultural land use in the UK, 2018

Some observers might regard farming as an inconsequential contributor to the UK economy. However, linked to the food and drink industry, UK farming is an integral part of the agri-food supply chain worth over £120 billion, employing over 4 million people[2]. It has a wider impact on rural communities and the natural environment than other economic sectors.

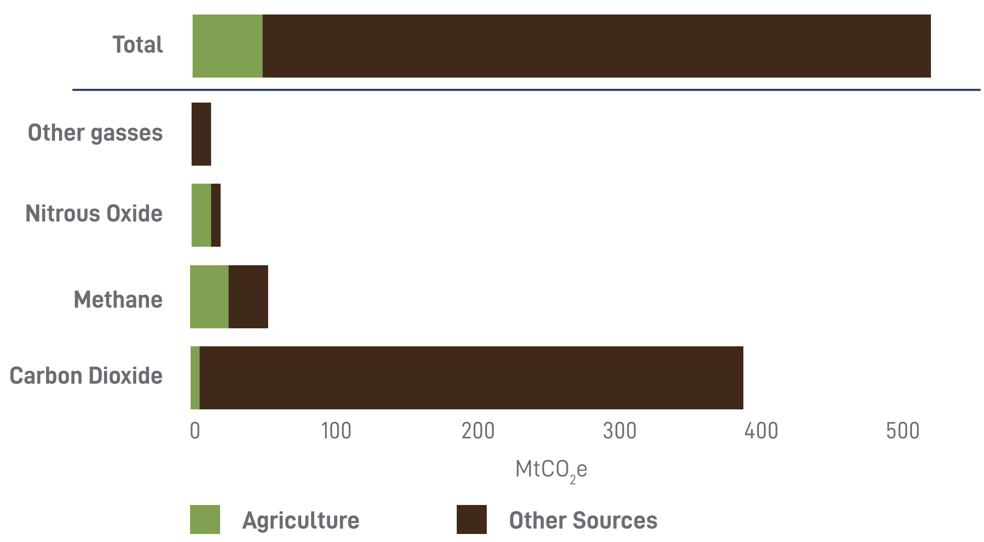
Farming activity plays an important role in sustaining rural livelihoods and managing the local environment, as well as supplying the nation's food needs. To continue to achieve this within changing economic and environmental conditions, farm businesses must remain viable, providing a living income for farming families and contributing significantly to the rural economy.

The National Farmers Union (NFU) reported in 2019[3] that greenhouse gas (GHG) emissions from UK farms amounted to 45.4 million tonnes of carbon dioxide equivalent (CO_{2e}) in 2018 – about 10% of the country's total emissions.

In contrast to other industrial sectors, only 1% of the UK's CO_2 emissions are from agriculture (mainly from fuel and energy use). However, farming is responsible for around 70% of the UK's nitrous oxide (N_2O) and 50% methane (CH_4) emissions produced from fertilisers and grazing ruminant livestock, respectively[4]. Taken together, agriculture accounts for approximately 10% of the UK's CO_{2e} emissions - see Figure 2 below.

[1] The future farming and environment evidence compendium - September 2019 edition, Defra
[2] Contributing to the economy, Countryside
[3] Achieving Net Zero, Farming's 2040 goal, NFU
[4] The future farming and environment evidence compendium - September 2019 edition, Defra

UK Greenhouse Gas Emissions (2017) in CO_2 Equivalents



Source: *Defra - The future farming and environment evidence compendium 2019*

Figure 2: UK Greenhouse Gas Emissions (2017) in CO2 Equivalents. Source: The future farming and environment evidence compendium, 2019

Although not directly a greenhouse gas, agriculture is also responsible for 88% of the UK's ammonia emissions[5], produced when organic fertilisers (e.g. slurry, manure, sewage sludge, compost, digestate) come into contact with air (wind) and warmth - and when organic and inorganic fertilisers are spread.

Ammonia emissions adversely affect the quality of air, soil, water, ecosystems and biodiversity. Whilst agriculture urgently needs to address its emissions, it has the land area to be able to curb its emissions and sequester more carbon through improved nature-friendly farming practices. Farms are also able to reduce their reliance on fossil fuels by generating various forms of renewable energy. Farming is therefore a key part of owning, framing and claiming the climate solution for rural Britain.

> "The climate, nature and our waistlines are telling us we need fundamental change now."

Following withdrawal from the European Union, UK farmers are moving away from a 40-year-old system of top-down area-based subsidy under the Common Agricultural Policy (CAP) and towards different 'post-Brexit' agricultural policies covering the devolved regions of Scotland, Wales and Northern Ireland – for example, the Environmental Land Management (ELM) scheme which now applies in England.

This policy shift is an opportunity to drive more agro-ecological, regenerative farming and nature-based solutions on diverse types of farmed land, placing carbon sequestration and carbon reduction at the heart of future plans for farming, land management and the evolving food supply chain.

Although the impact of this transition will be significant, there is as yet little clarity around what the potential income benefits for agricultural businesses might be, making future investment decisions, particularly those around decarbonisation, even more challenging.

[5] Code of good agricultural practice (CoGAP) for reducing ammonia emissions, Defra, 2018

Farm business viability is key to farming's critical functions in providing rural livelihoods, managing the environment and meeting emerging market demands. **The core economic role of farming is to harness natural resources and to do so, where possible, at a commercial profit.**

However, Defra report that between 2015 and 2018, only the top 25% of UK farm businesses made a clear profit from agricultural activity alone. Many others made little or no profit from their core agricultural activities – relying on additional income from farm or environmental diversification, along with the contribution from direct EU payment subsidies.

> "Farmers cannot be green if they are in the red."

It is estimated that 42% of UK farms will be loss-making as a result of the closure of the Basic Payment Scheme, necessitating cost cutting by 10% to compensate[6]. It is yet to be revealed what the level of support will be from the new agriculture support schemes across the UK. The nature of farm businesses is that they are 'price takers' (with limited ability to influence the value of their output) unless they sell to customers directly, e.g. on-line or at markets and fairs.

> "We are very concerned that cheap imported food post-Brexit may threaten British farming"

There is consensus that British farmers produce food to some of the highest standards of hygiene, animal welfare and environmental protection in the world[7][8]. As such, UK farms are well positioned to address the widening global demand for premium sustainably produced products.

Such opportunities are even more relevant following the UK's exit from the EU, with opportunities for farmers and processors to be innovative in meeting demands from new international markets.

It is vital to ensure that post-Brexit trade deals on food imports do not disadvantage UK agriculture in favour of cheap food produced to lesser welfare and environmental protection standards.

There is no doubt that over the next decade and beyond, farm businesses, operating within an ever-diversifying rural economy, will need to adapt to meet regulatory pressures and supply food and public goods whilst delivering against national targets on emissions reduction.

Agriculture needs to reduce emissions from production activities, and increase its potential to sequester carbon, both directly on land and indirectly, by increasing productivity and at the same time, reducing demand for land[9]. To do this and to enable better planning and on-farm investment decision making, diverse UK farming businesses need to have a clear and dynamic vision for the way forward.

There is an appetite to understand the parameters for practical change at farm and water catchment level as part of land management activities, and to develop or refine technical and operational solutions which are available now or will emerge over the next few years.

[6] Briefing Note: Food after Brexit, 15 April 2021, Rural Policy Group
[7] Animal health and welfare, Countryside Online
[8] Red Tractor
[9] Non-CO_2 abatement in the UK agricultural sector by 2050, Eory et al., SRUC, December 2020

3. SETTING THE SCENE FOR THE 'FARM OF THE FUTURE'

3.1. The need for rural decarbonisation in farming

UK farmers face a critical period of transformation which will bring new opportunities as well as significant challenges over the next 10-20 years. Such a transition will require significant changes to existing farming practices. It will also hasten adoption of emerging, innovative technologies and bring increased responsibility for managing the rural landscape as a 'public good'[10].

Successful transition across the farming sector will require a step change in terms of knowledge and technology transfer, applied research turning 'science into practice', and targeted government support to ensure farm incomes and the broader rural economy are maintained.

The core theme of this report is to investigate how farming might adjust to the challenges posed by climate change. It highlights the opportunities provided by currently available and emerging technology and system solutions that will enable UK agriculture to reduce its carbon footprint in line with the various zero emission targets being set – by global institutions, by national and local government organisations and by farm and food sector representative bodies.

Transition to a low carbon rural economy will not be easy. Meeting the national 'zero carbon' target by 2050 represents a real challenge. But the farming industry is committed and already moving into a transition phase – reflected in activities such as land use change and biodiversity, uptake of low emission transport fuels, and on-farm renewable energy generation.

[10] Public good is a commodity or service that is provided without profit to all members of a society, either by government or by private individual or organization.

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The National Farmers' Union of England and Wales surveyed farmers and growers in 2020[11] and found plans to invest in energy efficiency are at the highest level recorded, followed by plans to invest in diversification and skills and training. Specifically, farmer responses highlighted the following intentions:

- 69% of farmers plan to improve soil health or carbon content
- 51% plan to plant trees
- 38% plan to enlarge or extend hedgerows
- 35% plan to invest in more renewable energy generation
- (37% of farmers are already producing or using renewable energy)
- 35% plan to invest in low carbon agri-technology e.g. precision farming.

This signals just how important sustainability and efficient food production is for farm businesses, and how British farmers are best placed to deliver climate-friendly food both now and in the future.

NFU Deputy President Stuart Roberts said: "This survey demonstrates that farmers are eager to do more as we work towards our ambition of becoming net zero by 2040. As an industry, we have huge potential when it comes to contributing to the government's green growth ambition, whether it's boosting farms' productivity and efficiency, increasing renewable energy production, creating jobs, contributing to economic growth, and building on UK sustainability credentials at home and abroad."

At the same time as reducing emissions, the UK farming industry is adjusting to the impacts of leaving the European Union in January 2020. To many, this represents an opportunity to 'do things differently' in terms of land management and food production.

It will be vital to develop an acceptable balance between sustainable production methods and food affordability to meet home and export market demands. Whether as a response to climate change or to Brexit, farmers and food producers must react positively to these uncertainties and investigate new 'modus operandi'. These will take account of what can often be seen as competing demands for quality, sustainable yet affordable food production, environmental land management, and the other uses of finite land resource for energy generation, housing and transport.

The Royal Agricultural Society of England (RASE) is committed to supporting a sustainable and zero carbon future for farming and food. Other farm representative bodies actively promoting farm decarbonisation include Sustain, Linking Environment And Food (LEAF), Nature Friendly Farming Network (NFFN), the Country Land and Business Association (CLA), the National Farmers Union (NFU) of England and Wales, NFU Scotland and the Ulster Farmers Union.

Farmer organisations such as Innovation for Agriculture (IfA), Gentle Farming, Groundswell, Agricology, Innovative Farmers as well as events such as the Low Carbon Agriculture show and LAMMA are just some of those providing a range of excellent farm demonstration and dissemination events supporting transition to low carbon agriculture.

[11] Farmers prioritising sustainability investments, NFU survey shows, NFU, 30 March 2021

3.2. Sustainable food production – systems, standards and consumer trends

The impact of GHG emissions reduction within the off-farm sectors of the UK's food supply chain will influence and drive change in food production and processing systems. This report highlights that customer awareness in healthy food from 'field to plate' has gathered pace – issues such as source of origin, labelling and animal welfare are now influencing consumer choice. This trend is reflected by food retailers who are broadening their 'sustainability offer' and adjusting supply contracts with producers and processors to meet these changes in consumer demand.

At the same time, the cost of food must remain competitive to maintain social equity and ensure quality food for all. Maintaining this balance and indeed the reputation for quality and good value British food – supported by food standards schemes, will be increasingly important both for securing home markets and accessing global export markets[12] whilst ensuring food security for the population.

The commitment of UK farmers to achieve high standards of production based upon robust environmental and animal welfare standards, in line with changing consumer demands, is well known. Following decades of progress on production yields and efficiency, the emphasis is now shifting to a more sustainable base, with broad attention now focussing upon the impact of farming on natural, often fragile and sometimes finite resources such as soil, water and clean air.

New policies and subsidies will encourage farmers to expand their role in delivering 'public goods' such as managing the landscape, improving biodiversity and reducing harmful emissions. This raises important questions about how UK food production can become more sustainable whilst at the same time maintaining farm incomes. It is clear that future financial support and clear guidance/advice from government to the agricultural sector will be major drivers of change[13].

3.3. Reducing transport emissions within the food production supply chain

British agriculture represents around 8% of all UK transport GHG emissions, derived from on-road and off-road farm transport and other fossil fuel driven machinery. Modern agriculture is heavily reliant on mechanisation – and increasingly on automated transport systems. The study examines the industry's traditional reliance on diesel - mainly in the form of subsidised 'red' diesel - as the dominant fuel source, accounting for nearly 15% of all UK diesel sales[14].

The UK farming industry retained the benefits of the red diesel subsidy in the March 2020 budget – but clearly this issue may re-emerge as the national economy seeks to recover from the consequences of the Covid pandemic, and with the impact of increasing pressure to remove fossil-based transport fuels.

A number of industry-led initiatives are underway to investigate viable alternatives to this widespread use of diesel – and this report highlights some of those opportunities. Many of these were raised in the 'Refuelling the Countryside' report published by the RASE in 2014, which reviewed a number of emerging technical and operational options for farmers and other land-based businesses. The 2014 study was based upon three scenarios

[12] Global Britain: Exploring Global Export Opportunities, AHDB Conference October 2018
[13] Farming for the future - policy and progress update, Defra February 2020
[14] Rishi Sunak ready to end freeze on fuel duty in Budget, Financial Times, 3 March 2020

that demonstrated the prospects for green electricity, green hydrogen and bio-methane in terms of on-farm generation, storage and use of alternative and sustainable fuels.

Clearly, the transition to non-fossil transport fuels on farms and the associated availability of low emission tractors and other vehicles will not be straightforward and will take time as well as investment. A series of workshops led by the NFU in 2019 highlighted the challenges posed in terms of moving to alternative fuels and, in particular, to battery powered options. This formed the basis of a consultation response to the UK Government's proposal to bring forward the end of the sale of new petrol, diesel and hybrid vehicles from 2040 to 2030.

The NFU concluded that, 'We do not think it is currently possible to set a date for phasing out new sales of diesel tractors and other non-road agricultural machinery and [the NFU] calls upon government to encourage and accelerate the demonstration and introduction of ultra-low emission electric and hybrid tractors. In the meantime, we strongly support a continued role for high biofuel blends like E10 ethanol and B20 biodiesel.'

3.4. Stakeholder partnerships in low carbon transition

Following the UK's departure from the European Union, and 'new' levels of independence in terms of regulations, standards, funding and markets, the links and partnerships between farmers, processors, retailers and consumers take on a greater importance. UK farmers have a good story to tell – highlighted by the NFU in its report Levelling up Rural Britain. Other success stories have been published from organisations such as Countryside Online and Farming UK.

The vital contribution of farms and food producers to the rural economy is acknowledged widely – and has been well supported over recent years through the Rural Development Programme of England (RDPE). Whilst this scheme is being phased out, it is being replaced by more targeted grant schemes such as the Transforming Food Production Challenge (TFP is part of the Industrial Strategy Challenge Fund) and the Rural Community Energy Fund (RCEF). Such schemes encourage cooperation between farmers and rural communities – both are key stakeholder groups in the economy and environment in which they live and work.

A strong partnership between the UK farming industry and Government authorities - centrally and devolved - is crucial to the successful transition to a low carbon farming industry.

Farming is a 'long game' – it needs long term strategic planning and cannot operate through short term legislation. The potential benefits and consequences of replacing the Basic Payment Scheme (BPS) with the Environmental Land Management (ELM) scheme (in England) and its equivalents in the devolved regions of the UK are detailed later in this report. It is critical that policy makers fully understand the challenges of transition to a low carbon farming future.

Supply chain networks – whether these be for food, energy or other land-based products – remain vital to ensure that the right outputs are produced from the available land, meeting legislative and consumer requirements whilst protecting the environment and natural resources.

Minimisation of waste – in terms of crops, water and energy – will be encouraged by the widespread introduction of farm-scale technologies and circular operational systems. One example of this (expanded further in this study) is the potential for biowaste-to-energy on farms and in food processing units which use anaerobic digestion (AD) to extract energy for renewable power (biogas) and transport fuels (biomethane) from livestock manures, crop residues and food waste.

Collaboration between producers, processors, transport operators and food outlets and the provision of a workable legislative framework that facilitates transfer of resources between stakeholders is essential to achieve targets of zero waste and consequentially make a significant contribution to GHG emissions reduction.

Since the demise of experimental husbandry farms (EHF) and publicly funded advisory services, farmers are in need of technical and business evidence to support them through transition and help make husbandry and investment decisions. University and research organisations will make an important contribution to farm transformation – through applied research programmes, technology demonstrators and field trials.

Figure 3: Drilling a field using autonomous equipment.

One excellent example (highlighted further in this report) is the 'Hands Free Hectare Farm (HFHa)' operated by Harper Adams University, now expanded to a 35-ha field trial, aimed at demonstrating the future of autonomous farming vehicle technology.

Increasingly, farmers are meeting together to identify to exchange information, to take a close look at good on-farm practice, and 'kick the tyres' in terms of technology innovation. The success of the annual Groundswell regenerative agriculture show – referred to several times in this report and a pioneering initiative by the Cherry family on their farm in Hertfordshire – is testament to the interest farmers have in new methods of sustainable production whilst maintaining and improving the natural resource base of farms.

4. FARM AND LAND RESOURCE MANAGEMENT: SOILS, WATER AND BIODIVERSITY

Increased adoption of nature-friendly practices such as regenerative farming and agroforestry see improved soil carbon sequestration, increases in pollinator numbers, a trend in improvement in plant, fungal and animal biodiversity and reduction in fossil fertilisers (reducing agricultural emissions), herbicides and pesticides.

4.1. Background

Farm based emissions are widely reported and include methane from ruminants, loss of carbon from soils through repeated cultivations and energy use by machinery. The off-site manufacture of fertiliser, agrochemicals, farm inputs and machinery accounts for a considerable proportion of energy consumption associated with farming and land management.

However, farms can be part of the solution through harnessing the power of photosynthesis to grow and build carbon in soils and through recycling opportunities such as on farm anaerobic digestion and composting. Reducing periods when soils are bare, incorporating cover crops, minimising soil disturbance and increasing species composition and diversity of grassland can all provide part of the solution to minimising carbon loss and optimising carbon building at farm level.

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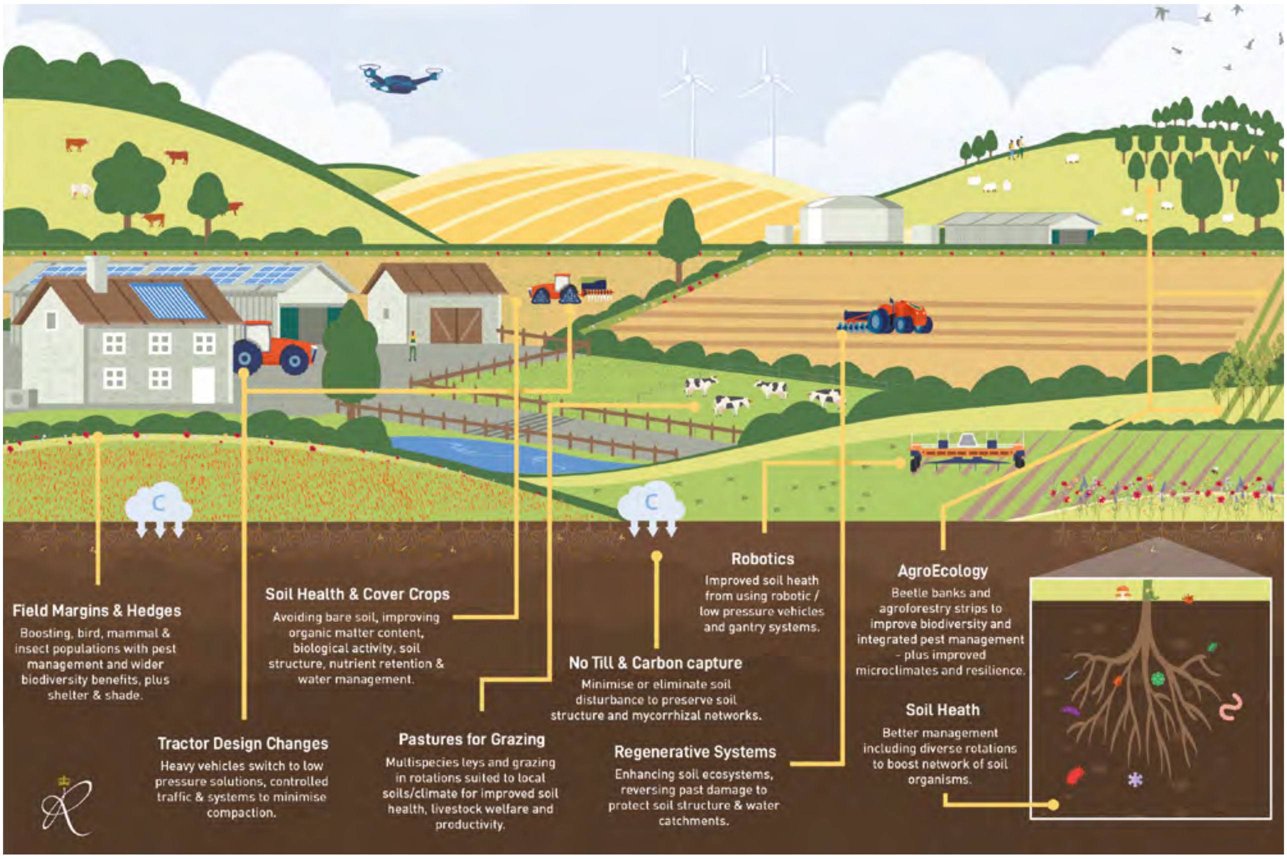

Figure 4: Managing soils, sequestering carbon and supporting biodiversity

The primary role of a farmer, a forester and land manager is essentially to harvest sunlight, mix with carbon dioxide, oxygen and water, and 'grow carbon'. The above-ground carbon is then harvested and sold or consumed as a food source by other on-farm enterprises, whilst the accumulated below-ground carbon is either sequestered as long-term stable humus or partially consumed and cycled through the soil microbial biomass as a food and energy source.

The level of sequestration versus cycling depends on land management practices including cropping, cultivations, disturbance, use of synthetic inputs, etc. Increasing soil carbon levels improves crop performance and resilience through improved soil nutrient cycling and cation exchange capacity, improved soil drainage and available water holding capacity, reduced cultivation power requirements (i.e. no-till/minimum till) and enhanced resilience to extreme weather (e.g. flooding and drought).

There is no denying that agriculture has become vastly more productive over the last 80 years. Productivity increases have resulted from improvements in breeding, genetics, mechanisation and management skill. They have also in part increased as a result of using up embedded carbon in the soil - carbon that was laid down over millennia and released through intensive farming activity to fuel productivity.

When Jethro Tull said 'ploughing is fertiliser', what he was describing is the oxidation of carbon through cultivation, which fuelled soil microbial activity and resulted in improved yields. All fine, then? Well yes, but only as long as farmers keep putting carbon into their soils.

The problem is that for many decades increasingly intensive agricultural practices have returned less carbon into the farmed soils than have been taken out. The result has been declining soil carbon (soil organic matter) and with it, a corresponding decline in long term resilience and productive potential.

> "A 1% increase in soil organic matter is approximately equal to 1.5T CO_2 sequestered/ha/yr, potentially worth £100-£200/ha/yr on C sequestration alone, disregarding other benefits."

Research undertaken by Cranfield University reported a £1.75bn (range £1.05 - £1.75bn) economic cost of soil degradation in England and Wales in 2019. 40% of these losses were associated with arable cropping, 20% with improved grassland and 25% with unimproved grassland. Associated with this, UK soil organic carbon levels have declined overall by circa 3% from c. 2.24% to c. 2.19% over the last 75 years in loam soils[15].

A 3% soil organic carbon (SOC) reduction represents soil organic matter (SOM) reduction of circa 6%. With medium soils typically having a soil organic matter content ranging between 5-12%, reducing levels by 6% has a significant impact on carbon stocks and the productive capacity and resilience of soils.

Where carbon levels are suboptimal, soil degradation from compaction, wind and water loss results in soil particulate loss into streams, rivers and oceans, with accompanying siltation and pollution problems from associated fertilisers and chemicals. In many cropped soils in Eastern England, soil organic matter levels are as low as 3%, restricting infiltration, drought resilience, nutrient cycling and long-term productive capacity .

SOC is a vital component of soil, with important effects on the functioning of terrestrial ecosystems. Storage of SOC results from interactions among the dynamic ecological processes of photosynthesis, decomposition and soil respiration. Human activity over the course of the last 150 years has led to changes in these processes and consequently to the depletion of SOC and the exacerbation of global climate change. But these human activities also now provide an opportunity for sequestering carbon back into soil.

Future warming and elevated CO_2, patterns of past land use and land management strategies, along with the physical heterogeneity of landscapes, are expected to produce complex patterns of SOC capacity in soil.

4.2. Carbon and soils - A perspective contributed by John Cherry, Weston Park Farms and co-founder of Groundswell

Much can be learned from studying soil. It is a bewilderingly complex ecosystem with millions of species of bacteria, fungi, viruses and many more microscopic organisms in a wonderful food web which ends up with earthworms, insects and beetles, etc, that can actually be seen. While there is a lot of 'nematode eats bacteria' action, there is also an extraordinary amount of symbiotic interaction where fungi and bacteria help each other and the growing plants.

[15] Initial assessment of projected trends of SOC in English arable soils, ADAS, 2003, Defra Project SP0533

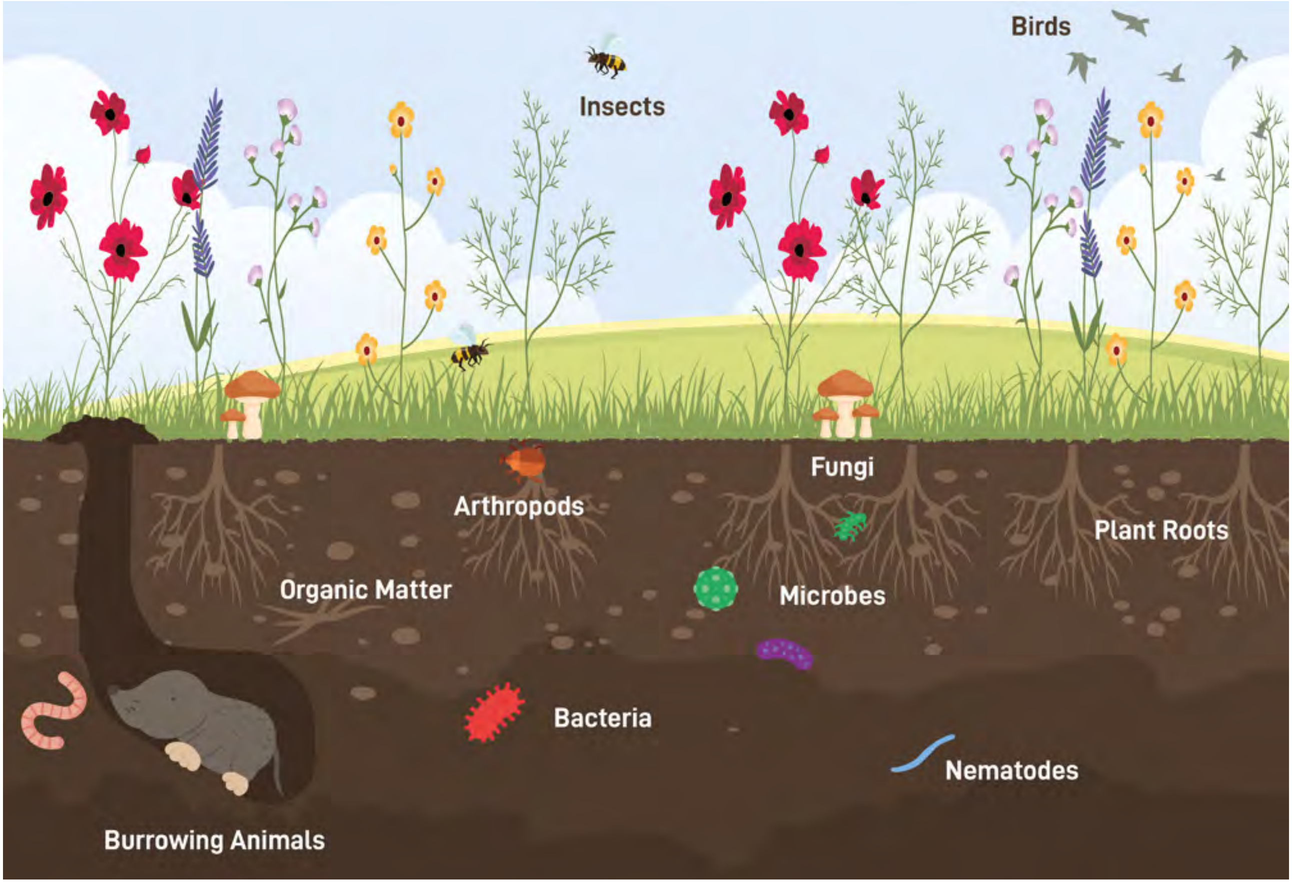

Figure 5: Soil biology and diverse landscapes

At present there is, quite rightly, a focus on limiting the release of greenhouse gases, particularly carbon dioxide (CO_2). But there is already too much CO_2 in the atmosphere and so the excess also needs to be removed. Carbon capture and storage can be done very cheaply by plants grown in soil (or very expensively by high-tech inventions) as plants remove CO_2 from the air and turn it, via photosynthesis, into sugars which are the building blocks they need to grow.

Depending on circumstances, a large proportion of these sugars (up to 70%) are exuded directly into the soil to feed bacteria and fungi which cluster around the plant root, exchanging other nutrients and water with the exuded carbohydrates. This symbiotic transaction is at the core of how farming can support the global transition.

Figure 6: From right to left: Soil sample from under the hedge bordering a field, showing good soil organic matter; re-seeded grass established by non-inversion shallow soil loosening; re-seeded grass established in the same manner, but drilled 3 weeks later showing slumped soil surface; compacted soil sample from the field margin.

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Soils vary enormously of course (for example, see Figure 6). But nearly all of them are improved by increasing carbon. Importantly, stable soil organic matter (humus) can absorb six times its own weight in water as well as supporting other microscopic soil dwellers which all help to create a sponge-like soil structure with capacity to absorb rainfall more effectively and help prevent flooding while mitigating the effects of drought.

Most agricultural soils are degraded to some extent, but they can be rapidly regenerated by sympathetic regenerative farming methods. This can take a longer time in some soils, but anecdotal evidence suggests that regeneration to a meaningful degree can be achieved in as little as 5 to 7 years.

There are five key principles at the heart of this approach:

1. **Minimise disturbance of the soil**, both physically and chemically. The micro-flora and fauna that form the soil ecosystem are harmed by cultivations, especially ploughing, which inverts the top few inches. There is often a nutrient boost from aggressive cultivating; resulting in short-term release of nutrients during a long-term decline as many underground 'workers' are killed or rendered homeless and get eaten by predators or scavenging arthropods. Similarly heavy fertiliser or pesticide use will upset the delicate balance where healthy soil is created, for instance too much nitrogen will upset the carbon-nitrogen ratio and encourage microbes to eat organic matter and thus set any improvement back.

2. **Keep the soil covered**, either with living plants (green cover crop) or a mulch of crop residue, like chopped straw. This protects the soil from rain impact, reducing the damage that high speed raindrops will do to the surface and allowing the water to percolate gently down. A good soil cover will also stop overheating by hot sun or freezing in winter, both of which are antagonistic to healthy soil.

3. **Maintain living roots in the soil** for as much of the year as possible. Living roots are the conduit that feed the soil. In conventional arable systems the soil is often left bare for months at a time, but by planting cover crops the underground ecosystem can be kept functioning.

Figure 7: Direct drilling into a cover crop

4. **Maintain as much plant diversity** as possible. Monocultures are an anathema to nature and restrict the variety of soil creatures that can be supported. A diverse population of plants can be grown in companion cropping systems, where two or more crops are grown simultaneously and are harvested together with the seeds being separated post-harvest. More conventionally, robust crop rotations ensure healthier soil and reduced weed and disease pressure. There is also potential for growing crops through a living mulch of clovers which stay close to the ground and allow the cereal to tower above and be harvested when ripe, leaving the understory to carry on feeding the soil and fixing nitrogen.

5. **Reintroduce livestock** into the system. There will already be trillions of living creatures in the soil and incorporating grazing livestock into the farming system will turbo-charge their numbers and increase the biodiversity to the benefit of the soil, as well as adding to the farm income. A diversity of farm animals (cows, sheep, chickens, pigs and goats) will further boost soil fertility and aid animal health.

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Figure 8: Agroforestry using apple trees

These principles work on any farm worldwide, as long as they are applied within the local context of soil types, climate and markets for produce, etc. From this basic framework, all sorts of ideas are being trialled on farms up and down the country. Some systems are including trees, as in agroforestry, silvopasture or full-grown permaculture. All these 'stack' systems and greater biodiversity onto each hectare, and produce more income streams for the farmer.

Agroforestry usually consists of arable crops being grown between rows of trees planted 25-40 metres apart. The trees help create a beneficial microclimate for the row crops, protecting them from wind and overheating, as well as foraging deep into the soil for nutrients which would otherwise be unavailable for the crops and spreading them on the surface in the form of leaf-litter in the autumn. Leaves also make a good mulch.

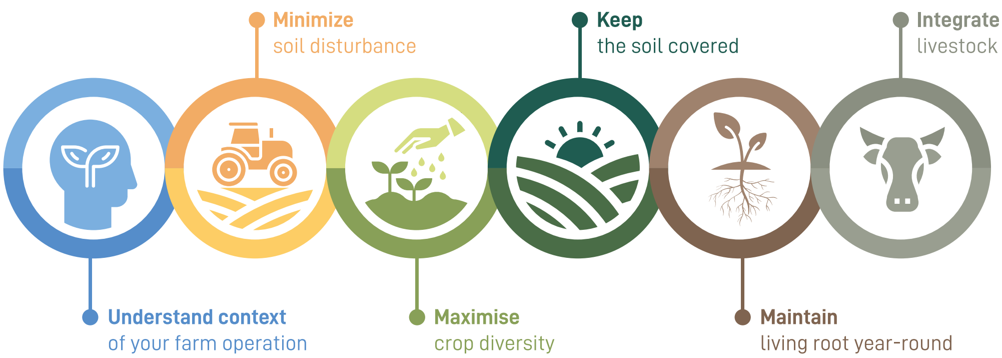
Trees recycle nutrients from deep in the soil to near the surface. Importantly, the tree roots and canopy are managed to occupy different space than the annual crop, and to use different resources of sunlight, water and nutrients in different periods of the year so as to minimise competition[16].

Silvopasture involves integrating trees within grazing landscapes. Trees provide protection from wind, sun and rain for livestock, as well as a certain amount of browsing potential (grazing of foliage) which is often very beneficial to animal health as the browsers can access minerals that might be otherwise unavailable. In both these scenarios, the trees also give extra income, either from fruit/nut harvesting or periodic timber/wood chip harvest[17].

'No-till' farming is becoming more popular as farmers see the benefits of farming in a more enlightened way, using less cultivating machinery, fewer tractors and, as their soil improves, less chemical fertilisers and sprays. On its own, no-till might be just observing the first principle above, but it won't work properly unless the first four tenets, at least, are followed. Luckily, most farmers who start down this route, soon become obsessed with their soil and want to do all in their power to nourish it.

Demonstration is the best method to effect change, i.e. by showing farmers how to make their operations more economically and environmentally resilient. Groundswell is an annual show and conference – an on-farm low carbon demonstration event designed to showcase ideas and techniques to farm more sustainably.

6 Core Principles of Regenerative Agriculture



Graphic courtesy: *Paul and John Cherry, Groundswell*

[16] See Benefits of agroforestry on a Cambridgeshire farm (YouTube), The Woodland Trust, 12 June 2014

[17] See excellent agroforestry videos (https://euraf.isa.utl.pt/resources/agroforestry_videos) and case studies (https://euraf.isa.utl.pt/resources/featured-farm) at the EURAF website.

There are emerging alternative streams of funding for regenerative systems, like carbon trading and Green Bonds which will reward farmers for locking up carbon and for flood prevention. Green Bonds[18] are new to the UK, but they will enable insurance companies to reduce their exposure to flood damage by helping landholders to prevent floods from happening. Everyone would be a winner! The Government could offload much of the expense of subsidising farming to the private sector, insurance will become cheaper and farmers and the environment will be better off.

The lessons to be learned from the interspecies cooperation in the soil food web, where a myriad of microscopic creatures work in harmony, can thus be extended to human-scale, to create food systems that produce nutrient-dense food, at the same time as looking after the other creatures and their biomes, with whom we share the planet.

4.3. Grassland and the role of ruminants in carbon management - Contributed by Tom Chapman, Farm Manager, St. Pauls Weldon Bury Estate and Mob Grazing Specialist

Grasslands are a vital ecosystem, covering over 52 million kilometres, or 40.5%, of the total terrestrial area globally (excluding Greenland and Antarctica). Historically, huge numbers of wild grazing animals roamed across these naturally occurring landscapes and they, in conjunction with climatic conditions, kept the trees at bay. In modern times, the majority of these large herds have been replaced by domesticated grazing herds, and they, and increasingly human activities, continue to maintain the open grazing areas familiar today.

A significant proportion of these grasslands worldwide are not suitable for cultivation, due to a combination of altitude, topography, geology, hydrology, geography: in other words, it may be too steep, too wet, too dry, too cold, too rocky or too remote to be viable for crop production and the raising of livestock and production of meat proteins is often the only way to exploit such areas to meet human needs.

These 'permanent' grasslands are an important ecosystem and carbon sink, as well as playing a vital role in the human food chain. However, many grasslands are more temporary in nature, and have been used as part of a crop rotation, to build soil fertility, for hundreds of years.

Figure 9: Mob grazing cattle

Typically, an area of land is sown with grasses, clovers and possibly many other species of forage plant and would be grazed over a three-to-five-year period. During this time, ruminants (typically cows and sheep in the UK) would repeatedly graze the forage plants during the growing season, converting tough cellulose to dung and urine and this, in conjunction with trampled leaves, root exudates and fungal and microbial soil organisms, would increase the fertility of the soil.

The farmer would then terminate the forage crop, either chemically or mechanically, and would grow combinable cash crops for several years until the soil fertility had been depleted. He or she would then return the land to grass and the cycle would start again.

[18] For example, UK Government Green Financing Framework, HM Treasury, June 2021

In the 20th and early part of the 21st century, the increasing availability of artificial nitrogen, manufactured using the very energy-intensive Haber-Bosch process, and the application of other agrochemicals, meant that farms could reduce and even eliminate livestock from their rotations and still grow acceptable yields of grains and plant proteins.

This allowed specialisation to occur and resulted in the investment in fewer, but much larger and heavier machines, and a corresponding reduction in the rural workforce. This, in turn, meant output per unit of labour increased dramatically over the last 60 or 70 years.

The combination of the loss of livestock in the rotation, the increased weight of machinery and the application of large amounts of artificial chemicals and fertilisers did not come without a cost, though. Artificial nitrogen oxidises and removes vast quantities of humus and other organic matter from the soil, making the soil more prone to slumping, compaction and erosion.

The ever-heavier machinery being used compounds this effect. Arable-only rotations have long periods when the soil is either bare and exposed to the elements (especially in a tillage-based system) or has senescing and dead monoculture plants awaiting harvest.

Both of these situations kill one of the most important soil organisms, arbuscular mycorrhizal fungi, and leads to long term damage of the soil. They also mean that, for a significant part of the year, little or no sunlight is being captured. Given that farmers effectively sell sunlight (in the form of meat, milk, grains, eggs, etc) and that soil biology depends on the energy from sunlight for its very survival, this is doubly detrimental to the farm business.

The reintroduction and use of livestock within arable rotations can reverse many of these problems, something that has been recognised for hundreds of years. Recently, researchers in the USA and elsewhere have developed five 'golden rules' for building and maintaining a healthy soil. These are:

1. Always keep soil covered to avoid exposure to extremes of sunlight, temperature, rainfall and wind
2. Always keep a living root in the soil
3. Avoid disturbing the soil by either physical or chemical means
4. Maintain a diversity of plants
5. Include livestock in the system.

Figure 10: Checking soil health

Very few all-arable systems manage to achieve even two or three of these, even when introducing practices such as direct drilling, under-sowing crops and using cover and break crops.

The introduction of livestock can help farmers to achieve all five of the golden rules which will lead to a dramatic improvement in soil-sequestered carbon and a significant increase in soil health. However, it is essential that the grazing animals are managed correctly to maximise the beneficial impact they have on the land.

The first aim is to graze plants at the correct stage in their lifecycle. They should be at, or nearing, maturity which means they are starting to enter the reproductive phase. At this point, root exudates, sugars and other carbon compounds arising from the photosynthetic process in the plants are at their peak, feeding the microorganisms in the soil.

This leads on to the second aim when grazing, which is to group animals together in a tight 'mob' on a patch of land and to move them regularly to fresh grazing. The regular moves ensure the animals only have to eat the best bits of the near-mature plants; they are not being forced to eat the older, more lignified parts. Keeping the animals in tight groups means that those parts of the plant that are not eaten get trampled onto the soil surface acting as a protective blanket and providing additional feed for the soil microbes.

'Herbal leys' are very fashionable at the moment, for good reason. If the 20th century was the age of chemical farming, the 21st century has to be the age of biological farming. A polyculture, or mixture of plant species, can speed this move away from a reliance on chemicals and increase the biological activities of our soils.

Figure 11: A mixed ley

There are a myriad of benefits:

- Legumes in the mix can fix nitrogen from the atmosphere, for free, without recourse to fossil fuels;
- Different plant varieties root at different depths meaning the access to nutrients, minerals and water from the whole soil profile is maximised;
- Diseases find it very difficult to spread from plant to plant within a diverse herbal ley as they are almost always species-specific;
- Livestock performance is much improved and trials have shown animals are capable of self-selecting the most nutritious diet when offered a varied platter;
- Additionally, some of the plants grown in a herbal ley – chicory or sainfoin for example – have anthelmintic properties which reduces the internal parasite burden in the grazing animal.

Scientists are split on how much carbon may be sequestered using grazing animals, with some research showing as much as 8 tonnes of carbon per hectare per year may be captured under adaptive multi-paddock, or 'mob' grazing systems. Whilst this may be at the upper end of expectations, it is not inconceivable that, under good management practices, between 1 and 3 tonnes of carbon per hectare per year should be achievable.

The 'elephant in the room', when discussing ruminant livestock and carbon sequestration, is the effect of their emissions, particularly methane, on the climate. The issue came to the forefront of the debate when the Intergovernmental Panel on Climate Change (IPCC) published methodology showing the heating effect – known as the 'Global Warming Potential' (GWP) – for various 'greenhouse gases'. The initial calculations attempted to show the impact over a one-hundred-year period of each gas (the figure being referred to as GWP100).

Recently, serious questions have been raised over the original calculations behind these figures as they take no account of, for example, the degradation of methane to carbon dioxide in just over a decade. Making the assumption that the gas persists for 100 years seriously over-estimates its effect on the climate.

Scientists are now working on a new metric, referred to as GWP* which adjusts for this degradation. However, even GWP* appears to have a major flaw in that it still only focuses on the emissions side of the equation.

Ruminants are part of the carbon cycle: for every atom of carbon they emit, whether it is as methane from enteric fermentation, or as carbon dioxide from respiration, an atom of carbon has been removed from the atmosphere by the photosynthesising plant, prior to being eaten. None of the GWP calculations account for the global cooling effect of removing this carbon from the atmosphere.

Until this issue is addressed and embraced by policy makers, figures on emissions from ruminants should be taken with a pinch of salt and should not be allowed to mask the invaluable work grazing animals can do in sequestering carbon into our soils.

4.4. Measuring farm carbon - Contributed by Becky Willson, Project Officer at Farm Carbon Cutting Toolkit

4.4.1. Why should carbon be measured?

The old adage of 'you can't manage what you can't measure' is certainly true of carbon accounting. But when it comes to agriculture, measuring carbon isn't as simple as it may first seem.

The variations in emissions and carbon stocks are due to the fact that they are based on measuring biological systems, which are impacted by climate, soil type, topography and vegetation, as well as what farmers are doing in terms of land management. Which makes the whole thing a little tricky. However, undaunted by this complexity, carbon metrics are an essential tool that farmers can use to not just identify climate solutions, but also to baseline the farm's emissions and hence, drive technological change.

Identifying the carbon footprint of a farm business is the first vital step in being able to quantify the contribution that the farm is making to climate change. A carbon footprint calculation identifies the quantity and source of carbon dioxide, methane and nitrous oxide emitted from the farm (plus carbon sequestered in soils and woodland), highlighting areas where improvements or changes can be made to reduce greenhouse gas emissions.

Greenhouse gases are much talked about, but they are inherently intangible. They can't be seen, tasted, heard or touched; and they are all gases that are released in relatively small quantities on a continuous basis. So how can a farmer fully understand what is going on with them and how can comparisons be made?

Reducing carbon emissions in a farming business makes sense on many levels. High carbon emissions tend to be linked to high use of resources, and/or wastage, so reducing emissions also tends to reduce costs. This makes the farm more efficient and should improve profitability. As well as the business opportunities that come from reducing emissions, farmers and landowners are in the unique position to be able to sequester carbon in trees, hedgerows and margins and within the soil.

Before acting to reduce emissions, it is necessary to first understand where the emissions are coming from. Are the largest emissions coming from livestock, soils, fuels, or fertilisers? It is vital to get a picture of the farm business – and this is made possible by carbon footprinting.

4.4.2. Choosing a tool to use

There are various carbon footprinting tools that have been designed for use by individual farmers (or groups of farmers) interested in understanding what is happening 'on-farm'.

Although the often-held belief is that there are many tools to use, in reality there are three main options which are available to all UK farmers and growers who are keen to start footprinting; these are the Farm Carbon Calculator, AgreCalc and the Cool Farm Tool.

There are other footprint calculators; however, these aren't universally available, and are used specifically within a supply chain (for example, within the dairy sector). The golden rule is, once a farmer has decided what tool to use, stick with it, as there are differences within the methods used in each calculator, so comparing results between calculators is meaningless.

Although the simple principle of completing a carbon footprint assessment is the same (emissions minus sequestration equals footprint), there remains some variation between the scope and boundaries that the tools use to calculate the results. Boundaries of a calculation determine what aspect of production is being assessed; for example, whether the emissions associated with one farm enterprise or the whole farm are being calculated, or whether it is assessing operations within the farm gate or taking account of what happens off farm.

A key part of selecting the tool to use centres around what the carbon footprint is used for:

As a marketing tool – if farmers are wanting to use the results for marketing purposes, it is a good idea to choose one that has a clear method attached to it, and which sets out what is included and excluded from the calculations. There are also potential commercial benefits, particularly where financial rewards for decarbonisation are involved (e.g. see 'insetting' discussion in the 'Decarbonising UK cereal production' enterprise journey). In this way, the carbon credentials are completely transparent.

As a management tool – if the results and the data are to be used as a management tool, perhaps to highlight areas to improve in the future, then the tool needs to be able to evaluate the impact of changing the management of the areas being assessed. These tools tend to need more data to be added in at the start, so that the impact can truly be seen.

For interest – if a farmer is simply interested in what might be happening in carbon terms on the farm, then again choosing one that explains clearly what is included and omitted, and shows the footprint broken down into key areas is a good starting place.

4.4.3. Carbon sequestration – in or out?

A key question to look at when footprinting is whether carbon sequestration is included in the calculation. Carbon captured within trees, hedgerows and field margins as well as the carbon held in soil is an important part of the footprint and shouldn't be overlooked.   If the tool doesn't include sequestration, then the footprint will look at the negative without assessing the positive!

One of the challenges facing carbon calculators which are working at supply chain or enterprise levels is the ability to include sequestration as part of the calculation. It is much harder for these approaches to include the opportunity that farmers have to store carbon on the farm, as they are aligned with only one aspect of production on the farm.

It is important that the agri-food sector creates or adopts systems where these tools can include sequestration so that the true picture of what is happening on-farm is produced.

4.4.4. Getting started

Once the tool has been chosen, the first step is to gather all of the input data. This includes information on fuel use, livestock numbers, fertiliser inputs, use of materials, waste produced, etc. In order to be accurate, the assessment needs to be comprehensive. The list can look daunting at first, but if the record-keeping is reasonable, then this process should be achievable in a couple of hours. Once this exercise has been completed, the next time will be quicker.

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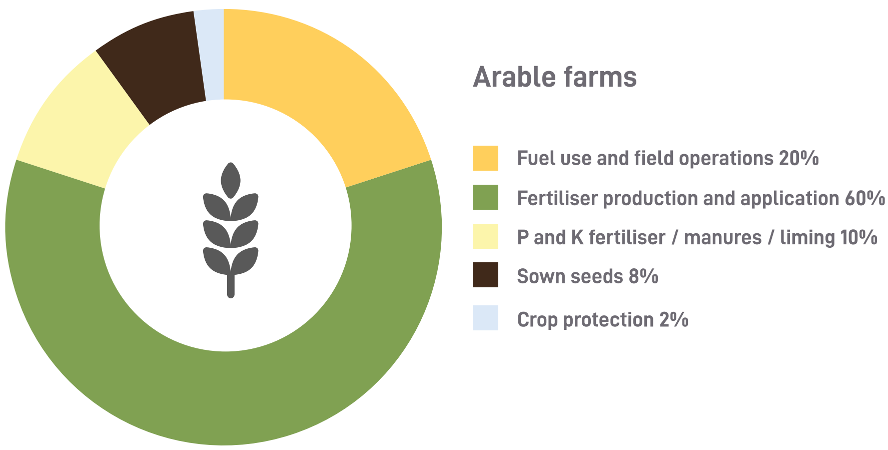
Once the data has been gathered, it's simply a case of entering it into the calculator, which shouldn't take more than an hour. The calculator should then produce a breakdown of carbon emissions by sector, both in amounts (kilograms or tonnes of CO_{2e}) and percentages of the total footprint by category. Armed with this data, it is then possible to consider how to reduce emissions and increase sequestration.

Although value can be seen from completing a carbon footprint as a one-off endeavour, the really interesting part comes when the process is repeated at regular intervals, usually annually.

When a regular assessment is made, the direction the farm is moving in starts to become clear and it is easier to see whether the actions taken are working.

4.4.5. Emissions sources

Although each farm will vary in its carbon footprint, Figure 12 below show the average breakdown of emissions across a typical livestock and arable farm.



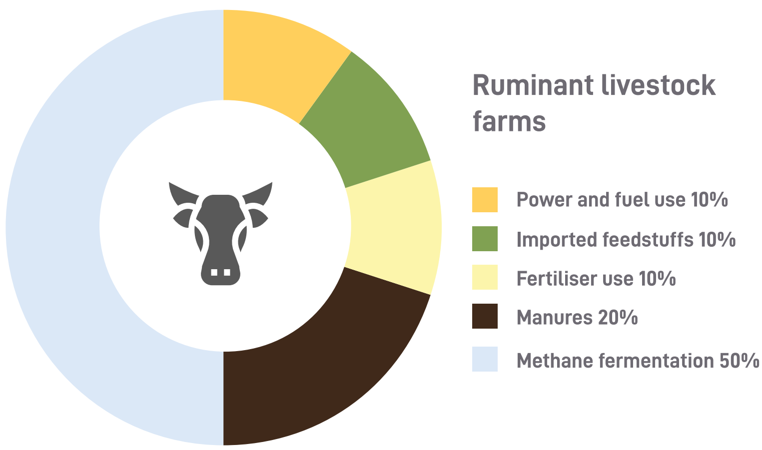


Figure 12: Average breakdown of emissions across a typical livestock and arable farm

4.4.6. Next steps

Once the carbon footprint of the farm has been ascertained, deciding what to do is the next key step. The footprint result will be reflected as a carbon dioxide equivalent but should also show where emissions of nitrous oxide and methane are produced. Key areas to focus on are the management of soils, fertilisers, manures, livestock, cropping, energy and fuel.

There are numerous opportunities to reduce both emissions and costs. This leads to improved resilience and profitability, as well as opportunities to improve carbon sequestration and soil health - the ultimate resilient business model! Absorbing more carbon than the farm emits is a goal that all farmers could work towards and understanding the farm's current carbon position by footprinting is the first key step.

The spotlight is being well and truly shone on agriculture's carbon credentials. This offers an opportunity for the sector to take the first step and understand what is happening on individual farms, and what can be done to improve profits, reduce emissions and build soil health and sequestration.

Carbon metrics offer a fresh lens through which to evaluate agricultural businesses and build resilience for the future.

4.5. Fertiliser and agrochemical manufacturing, use and resource efficiencies - Contributed by Professor Jonathan R Leake, Professor of Plant-Soil Interactions, University of Sheffield

Agrochemicals, including crop protection products, fertilisers and lime, contribute direct greenhouse gas (GHG) emissions through the use of fossil fuels in manufacture, packaging, transport and their application to fields using diesel-powered tractors[19].

Once applied to fields, nitrogen fertilisers can contribute additional GHG emissions from nitrous oxide (N_2O), as can animal manures, urine and slurries[20]. Agricultural lime (ground limestone $CaCO_3$) releases CO_2 on dissolution to neutralize soil acidity, whilst the burning of limestone to produce quicklime (CaO) and hydrated lime ($Ca(OH)_2$) has already[21] released this CO_2.

Figure 13: Artificial nitrogen fertiliser

[19] Lal R. (2004). Carbon emission from farm operations. Environment International **30**: 981-990

[20] Misselbrook TH., Cardenas LM., Camp V., Thorman RE., Williams JR., Rollett AJ., Chambers BJ. (2014). An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environmental Research Letters 9: 115006

[21] Wang Y., Yao Z., Zhan Y., Zheng X., Zhou M., Yan G., Wang L., Werner C., Butterbach-Bahl K. (2021). Potential benefits of liming to acid soils on climate change mitigation and food security. Global Change Biology 27: 2807–2821

Synthetic agrochemicals (directly and indirectly[22]) have been estimated to contribute more than 1% to UK GHG emissions[23]. However, some of these emissions may be offset by increased CO_2 fixation by crops and grasslands, carbon sequestration into soils, and reductions in N_2O fluxes, for example due to liming[21], so the net overall GHG fluxes of different inputs need to be considered.

4.5.1. Crop protection products

The combined contributions of herbicides, fungicides, insecticides, molluscicides, and growth regulators are estimated to comprise only about 3% of the total GHG emissions in arable cropping[24].

There are significant uncertainties in these estimates, but exact measurements may not be critical as these emissions are typically offset by a very large margin through better crop performance taking more CO_2 from the atmosphere[19,25]. Consequently, emissions are avoided by not having to replace lost yield with cultivating and fertilising more land[26]. For example, fungicides applied to the main UK arable crops have been estimated to decrease annual GHG emissions by over 1.5 Mt CO_{2e}[25].

However, increasing over-reliance on a small number of crop protection products is selecting for resistance genes in weeds, pests and diseases. This is undermining both their effectiveness[27] and their capacity to offset the emissions from manufacture and use.

Future approaches to pest, disease and weed management will become less reliant on chemical and technological solutions that require use of fossil fuels and be more reliant on ecological strategies to build resilience, for example, to weeds[27]. More diversified cropping and herbage production systems and longer rotations are likely to increase in importance to reduce the build-up of crop-specific pathogens and pests[28] and boost both climate and economic resilience.

4.5.2. Fertilisers

Most of the GHG emissions from chemical inputs to agriculture comes from use of nitrogen (N) because of the large quantities used (e.g. 191 kg N/ha on managed agricultural land in England[29]) and the high fossil-fuel energy intensity and greenhouse gas emissions in N fertiliser manufacture. This is typically 4-8 kg CO_{2e} per kg N for ammonium nitrate[30], but it can be reduced to about 3 kg CO_{2e} per kg N by catalytic reduction of nitrous oxide (N_2O) released during nitrate production using current technologies[30].

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[22] Direct emissions include those from manufacture, whereas indirect emissions include losses associated with application and nitrogen use efficiency

[23] Audsley E., Stacey K., Parsons D.J., Williams A.G. (2009a). Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use.

[24] Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., and Williams, A. (2009b). How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. FCRN-WWF-UK.

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[30] Brentrup F., Pallière C. (2008). Energy efficiency and greenhouse gas emissions in European nitrogen fertilizer production and use. *International Fertiliser Society Proceedings* **639**.

Further reductions in fertiliser production emissions are plausible by use of renewable energy sources to produce ammonium[31]. However, for farmers using fertilisers, the main challenge remains the problem of soil denitrification, releasing N_2O at rates that typically more than double the overall GHG release from current production and use of N fertiliser[30].

Agriculture is the main source of nitrogen pollution of air and water, and this arises mainly from low efficiency of uptake of applied N fertiliser and organic manures[29].

Although UK farming practices are becoming more efficient, 45% of applied N fertiliser (85 kg N/ha) is not taken up or retained by crops or grassland[29] and this excess is leached, mainly as nitrate, or lost by volatilization, contributing to N_2O and ammonia (NH_3) emissions.

Lifecycle analysis of the production of a loaf of bread in the UK[32] shows the importance of optimising nutrient use, as 66% of the GHG emissions arise from growing the wheat, with N fertiliser alone estimated to contribute 43%. This assumes 'best practice' in the nitrogen use efficiency of the crop of 71%, which is considerably above the 55% average efficiency across all types of managed agricultural land in England[29] in 2018.

Low efficiency of fertiliser use involves substantial avoidable costs to farmers and avoidable emissions and pollution. Hence, a key priority for reducing on farm GHG emissions is to improve N use efficiency, including that of organic sources such as manures, composts, biosolids, and anaerobic digestate, and to minimise losses, especially those leading to N_2O release[33].

In the arable sector, precision N fertilisation using soil testing and crop sensors can improve the effectiveness of timing and spatial targeting of applications, to meet crop requirements[34]. Timings of applications should be informed by medium-range weather forecasting and soil moisture assessments to minimize risks of N_2O losses from nitrate fertilisers and NH_3 losses from manure and slurry applications.

Using a combination of approaches, an approximately 20% increase to 75% nitrogen use efficiency by 2050, has been suggested as a goal for European agriculture[35].

Such efficiency gains are likely to benefit from ongoing improvements in weather forecasting, soil moisture sensing, satellite remote sensing of crops, how manure and organic wastes are deployed, and use of nitrification inhibitors[20]. However, the effectiveness of precision fertiliser application is often constrained by poor soil health, especially by depletion of organic matter.

Figure 14: Low emissions slurry injection equipment

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However, the effectiveness of precision fertiliser application is often constrained by poor soil health, especially by depletion of organic matter. This reduces soil pore space and infiltration rates, increasing susceptibility to compaction and poor drainage which restrict root growth, thereby reducing nutrient uptake efficiency and increasing losses.

To improve N fertiliser use efficiency therefore will normally require combining improvements in soil health, including structure and organic matter content, alongside more precise timing and placement of fertiliser, nitrification inhibitors, and selection of crop varieties with improved rooting traits to enhance uptake and reduce N_2O emissions.

In addition, there is a role for increased cultivation of nitrogen fixing legumes to decrease N fertiliser demand and its associated emissions, although significant amounts of N_2O may still be released, for example, on ploughing up legume-rich leys[36].

Nonetheless, the reintegration of legume-rich leys to arable rotations may confer multiple benefits from improving soil structure, organic matter content, enhancing nutrient and water use, and climate resilience by the following crop[37].

Substantial efficiency gains in N fertiliser use are achievable in the UK livestock sector, through much wider utilisation of soil testing to inform N fertiliser application rates and ensure other nutrient limitations do not constrain uptake.

Priorities for improving management and application of manures and slurries include the use of slot injectors. This reduces the volatilisation of ammonia by 70-80%, thereby increasing nutrient use efficiency, without increasing N_2O emissions to an extent that undermines these benefits[38]. However, it is important to avoid soil compaction, potentially by using umbilical systems with tankers parked on field tracks so their weight does not pass over a field.

As in arable cropping, timing of applications to match plant demands and suitable soil conditions to minimize risks of N_2O release can improve efficiency and reduce GHG emissions from pastures.

Replacing sown ryegrass pastures that require high N fertiliser inputs to maintain production, with species-rich herbal ley mixtures that include nitrogen-fixing legumes, can simultaneously improve livestock health and productivity[39] whilst reducing N fertiliser use by 45% from 163 kg/ha to 90 kg/ha. Such species mixtures grown with 150 kg N/ha have been shown to reduce N_2O emissions by 24-58% compared to ryegrass monocultures grown with 150 and 300 kg N/ha respectively[40].

4.5.3. Future directions and priorities

Reducing greenhouse gas emissions from agrochemical use involves decreasing inputs and improving efficiency, strongly aligning with other environmental and sustainability goals including reducing air and water pollution, enhancing soil quality and biodiversity, thereby delivering multiple societal benefits. The most urgent priorities are

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[37] Berdeni D., Turner A., Grayson R.P. Llanos, J., Holden J., Firbank L.G., Lappage M.G., Hunt S.P.F., Chapman P.J., Hodson M.E., Helgason T., Watt P.J., Leake J.R. (2021). Soil quality regeneration by grass-clover leys in arable rotations compared to permanent grassland: effects on wheat yield and resilience to drought and flooding. *Soil and Tillage Research* **212**: 105037
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[40] Cummins S., Finn J.A., Richards K.A., Gary J. Lanigan G.J., Grange G., Brophy C., Cardenas L.M., Misselbrook T.H., Reynolds C.K., Krol D.J. (2021). Beneficial effects of multi-species mixtures on N_2O emissions from intensively managed grassland swards. *Science of The Total Environment* **792**: 148163

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to increase N use efficiency from both fertiliser and organic nitrogen sources such as manures and slurries and reducing N_2O emissions.

Improving drainage of mineral soils prone to waterlogging can decrease N_2O emissions and is one of the most effective soil interventions for GHG reductions from agriculture, potentially saving over 1.7 Mt CO_{2e} per year[41].

Improving soil health, especially soil crumb structure, macropores and soil organic matter will be central to achieving nutrient use efficiency gains, coupled to growing crops and grasslands with deeper and more effective roots.

Correcting soil acidity using lime improves root growth and soil structure, increases yields of many crops, decreases N_2O release by about 20%, and can increase soil carbon sequestration[21]. However, the GHG benefits of lime are typically balanced by emissions generated by the mining, processing and reactions of lime in soils[21].

One promising alternative approach to increase soil alkalinity, reduce N_2O release, and sequester CO_2 is the application of calcium and magnesium rich silicate rock dust the weathering of which ultimately removes CO_2 from the atmosphere through the precipitation of soil or ocean carbonates[42]. If ground basalt is deployed, it releases a suite of plant-essential elements such as phosphorus and potassium, thereby substituting part or all of the requirements for fertilisers containing these elements[43], and the 0.5-0.7 kg CO_2/kg emissions associated with the mining and production of these fertilisers[19].

As highlighted later in this report, there are significant opportunities in arable and livestock farming to reduce GHG emissions by improving efficiency and reducing costs and environmental impacts of agrochemical inputs, through a combination of approaches that include improving soil quality, reducing N fertiliser losses, and limiting over-reliance on crop-protection products.

4.6. Nutrient recycling/management: the role of by-/co-products - Contributed by Anna Becvar, Managing Director, Earthcare Technical

The use of organic materials, by-products, and co-products as a valuable source of plant nutrients has long been practiced. Currently around 50 million tonnes (Mt) of livestock manures, 1.9 Mt compost products, 4.3 Mt digestate products (from commercial facilities) and 3.5 Mt biosolids are applied to agricultural land in England on an annual basis[44], alongside which a considerable quantity of waste materials is applied under Environmental Permitting Regulations.

[41] MacLeod M., Moran M., Eory V., Rees R.M. Barnes A., Topp C.F.E., Ball B., Hoad S., Wall E., McVittie A., Pajot G., Matthews R., Smith P., Moxey A., (2010). Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agricultural Systems* **103**: 198-209.

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[44] An assessment of the impact of Farming Rules for Water, RSK ADAS Ltd, AHDB, 7 June 2021.

The recovery of wastes, recycling of products, by-products and co-products to land provides an opportunity to reduce the environmental footprint of food production, as well as being part of a circular economy.

Applying such materials can enable the effective use of nutrients that might otherwise be lost or released to the environment in a detrimental manner. Careful application of these materials to land benefits both crops and soils and reduces reliance on manufactured fertilisers. It is of note that overall manufactured fertiliser use in England and Wales has decreased by around 30% since 1982, while significantly more for phosphate and potash-based fertilisers.

The UK Government's 25 Year Environment Plan (2018) refers specifically to soil health and sets a goal of improving our approach to soil management by 2030. A key objective is to improve soil condition and carbon storage by adding organic matter. This needs to be achieved whilst balancing the equally important objectives of reducing the impact of excessive nutrients on the wider environment, taking into consideration impacts on water and air quality, as well as reducing greenhouse gas emissions.

The UK has an increasing capability to treat a wide variety of biodegradable wastes, or feedstocks, from a range of different sectors including food production, catering waste, industrial processes, water industry residues, and amenity gardens.

Figure 15: Using low emissions spreading equipment for high readily available nitrogen (RAN) fertilisers

The resulting organic materials are enhanced in terms of the beneficial nutrients they can provide, whilst potential risk of hazards or dis-benefits are mitigated or reduced. One key process example is anaerobic digestion (AD). The AD process breaks down biodegradable materials in the absence of oxygen to produce methane-containing biogas, and digestate – a valuable source of nutrients (often termed 'biofertiliser').

The AD process changes the characteristics of the original feedstock materials, increasing pH and converting organic nitrogen (N) to ammonium N, to produce a material with more readily available N. The resulting digestate is a very good fertiliser replacement product and provides improved scope for targeted N application to meet crop need.

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However, plastic contamination within feedstock materials (e.g. from household garden and food waste) introduced to any treatment process present a potential barrier to the end use of the resultant material within agriculture. Elimination or significant reduction of plastics in feedstocks is an essential solution to this problem but presents a significant challenge to the recycling industry.

Excessive application of materials to land, especially those containing large quantities of nutrients, poor timing of application, or unsuitable application techniques contribute to losses to the wider environment.

Water quality in English rivers has generally improved over the last 20 years but in 2021 this improvement appears to be flat lining. Only 14% of rivers in England meet Good Ecological Status under the Water Framework Directive, and that figure has not changed since 2009.

More recently, the Environmental Audit Committee reported in their January 2022 report that 'It is clear, however, that rivers in England are in a mess. A 'chemical cocktail' of sewage, agricultural waste, and plastic is polluting the waters of many of the country's rivers.'

Climate change may be changing the frequency and intensity of rainfall events and droughts which could change the stability of nitrate in soils and lead to increased risk of soil erosion events.

The four main routes by which materials may be managed in the UK are as:

- discarded waste to be recovered under environmental permitting regulations,
- a non-waste product under a Quality Protocol,
- a product or by-product which has achieved 'End of waste' status,
- an exempt agricultural waste such as cattle slurry.

The application of waste materials under the Environmental Permitting regime is strongly regulated. An up-to-date laboratory analysis of the material to be spread must be assessed both in terms of its beneficial attributes and potential dis-benefits, such as additions of potentially toxic elements (e.g. copper, zinc, lead, mercury) and physical contamination levels. The waste is assessed against receiving field soil analysis and application rate is calculated to meet crop nutrient need.

Furthermore, to adherence with Good Practice Guidance[45] and Nitrate Vulnerable Zone regulations[46], attention must be given to the potential effects of the application on designated environmentally sensitive receptors. Three examples of this are:

- A site-specific risk assessment is required if the receiving land is within 500 metres of a Site of Special Scientific Interest (SSSI) that might be detrimentally affected from ammonia emissions from the waste application.
- Applications cannot be carried out in a Source Protection Zone 1 (SPZ1), designated to protect drinking water supplies, and mitigation measures must be considered if the field is within a lower risk SPZ2 area.
- The potential for odour from temporary storage of material and during application must also be considered and mitigated if deemed a risk.

[45] Code of Good Agricultural Practice (COGAP) for Reducing Ammonia Emissions, Defra, July 2018
[46] The Nitrate Pollution Prevention Regulations 2015

Figure 16: Manure leaching in field storage

The application of materials outside of Environmental Permitting has been less heavily regulated. This is perhaps changing with a recent more vigorous interpretation of the Farming Rules for Water (FrFW)[47], initially introduced in 2018, to fulfil diffuse pollution obligations under the Water Framework Directive.

Rule 1 aims to ensure that 'all reasonable precautions' are taken to prevent diffuse pollution following the application of organic manures and manufactured fertilisers. To comply with Rule 1, farmers must demonstrate they have planned nutrient applications to ensure they are applied in quantities that are sufficient to meet, and not exceed, the crop and soil requirements.

FrFW is pertinent to all types of organic materials which contain readily available nitrogen (RAN). Only applications to crops such as winter oilseed rape and grass to support late season growth in August and September are deemed acceptable.

This new approach closes the window for applications of a wide range of organic materials that have moderate, and relatively low RAN, including livestock manures, biosolids, and some by-products applied directly to land. It does enforce much better use of high RAN materials, such as digestate, which should be stored and used when nutrient uptake from them can be optimised.

However, the process of gaining planning permission for new storage facilities is currently a slow one, often exceeding two years, and is not keeping pace with need or the speed of regulatory requirements.

By forcing most applications to spring for such a wide range of materials, nitrate as a potential pollutant is prioritised, potentially at the risk of 'pollution swapping' to an elevated risk of ammonia emissions and phosphorus losses. Soil damage and erosion may increase and the potential for soil incorporation of materials to mitigate odour may be reduced.

Nutrient management planning should consider the source, pathways, and receptors model for pollution. This can sometimes make overarching national policy seem draconian and leaves little room for consideration of mitigating risk where, for example, pathways to surface water and groundwater are remote.

The European Commission has sought to encourage large scale fertiliser production from domestic organic or secondary raw materials in line with the circular economy model, by transforming waste into nutrients for crops. The EU Fertilising Products Regulations published 5 June 2019[48] seek to harmonise the requirements for fertilisers produced from phosphate minerals and from organic or secondary raw materials in the EU, opening new possibilities for their production and marketing on a large scale.

Great Britain and Northern Ireland have historically operated separate domestic regulatory regimes under the Fertilisers Regulations 1991 and the Fertilisers Regulations (Northern Ireland) 1992, respectively. A review of the UK Fertiliser Regulations presents an opportunity to streamline the categorisation of nutrients produced from the circular economy.

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[47] The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, referred to as 'Farming Rules for Water'

[48] Regulation (EU) 2019/1009 of the European Parliament and Council, 5 June 2019, laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003

Innovation in the recycling industry is flourishing. Companies are exploring the production of fertilisers and fertiliser replacement products from a wide range of individual wastes and combinations of waste streams. One example is further treatment of digestate to produce ammonium sulphate fertiliser, which can be used more efficiently and improve both the producer and farmers operational carbon footprint.

Investment in Government funded research, alongside an effective, fast and supportive dialogue with regulatory authorities is required now to maintain momentum within the recycling industry and in support of the circular economy.

4.7. The potential of recycled by-products to increase carbon sequestration and encourage beneficial microbial activity in soils - Contributed by Professor Jennifer Dungait, Soil Health Expert

Loss of soil carbon, of which soil microbes are a living part, is a primary indicator of soil degradation. Recycling carbon-rich by-products of rural, urban and industrial activities back to soil can help to rebuild soil carbon and presents an opportunity to mitigate climate change as part of a circular economy approach to sustainable waste management[49].

The benefits of increasing soil organic or inorganic carbon for soil carbon sequestration and soil microbial activity depends on the individual characteristics of the recycled by-product and the receiving soil environment. A range of waste materials are available for land spreading on farms, both organic (derived from living organisms) and inorganic (minerals derived from rocks).

4.7.1. Policy Priorities

The following points should be highlighted in determining future policy on recycling of bio-wastes and residues:

- Repurposing organic and inorganic materials from waste streams as recycled by-products for carbon-sequestering activities in farm soils, that would otherwise go to landfill, is a virtuous intention.
- Large and repeated applications of recycled by-products are generally required to create measurable increases in soil organic carbon.
- As the living part of the soil carbon pool, the soil microbial community plays a key role in carbon sequestration and is affected by the specific properties of different recycled by-products.
- Risks associated with land spreading of recycled by-products must be considered, including potential toxic and polluting effects, and include full life cycle assessments of greenhouse gas emissions.

4.7.2. Potential benefits of recycled organic by-products for soil carbon cycling

Organic recycled by-products like composts, digestates and biochars are relatively familiar soil amendments compared to inorganic recycled by-products (see below). Note: types of organic recycled by-products are described in section 4.7.5 below.

[49] What is a circular economy?, Ellen MacArthur Foundation

Applications of organic materials can help to build soil carbon, but experiments in the UK suggest that repeated applications of bulky organic by-products over several years are ne to create a measurable change in soil organic carbon contents, e.g. applications of composts at rates to provide 250 kg N/ha for 9 years[50], or large single application rates are needed to achieve short-term effects, e.g. 50 tonnes of biochar/ha[51,52]. However, if by-products contain sufficient nutrients to supplement or replace synthetic fertiliser inputs, they can further reduce the carbon footprint of farming as part of nutrient management plans[53].

Composts and digestates have their own microbial communities that can increase the size of the microbial biomass directly by inoculating the soil with live bacteria and fungi[54]. Because conditions in the soil are different from those in the compost pile or anaerobic digester, the microorganisms may die quite quickly, but their remains provide an important source of carbon (and nutrients) in the soil.

The promotion of a diverse and abundant soil microbial community, including bacteria and fungi, through better soil management is a goal for farmers moving to more sustainable approaches to agriculture.

The effect of applying organic recycled by-products on soil microbial biomass, activity and diversity is generally positive. There is a direct relationship between desirable soil structure and organic carbon content that is related to an increase in microbial activity[55,56].

The addition of bulky organic recycled by-products causes physical increases in soil volume and air space and helps to control soil moisture contents which provides suitable conditions for soil microorganisms to grow and multiply. Other benefits include the treatment of soil acidification (caused by long-term, over-application of nitrogenous fertilisers) by applying recycled by-products with a high pH, like biochar[57] and silicate-rich rocks (see below).

4.7.3. Potential benefits of recycled inorganic by-products for soil carbon cycling

Inorganic carbon sequestration by rock weathering may offer a novel solution to mitigate climate change which is fundamentally different from organic carbon sequestration[58,59].

Dust from silicate-rich rocks such as basalt, dolerite quarry fines, and industrial by-products including cement and slags from iron and steel manufacturing, can be applied to acidic farmed soils, instead of limestone to increase soil pH.

[50] Bhogal, A., Nicholson, F.A., Rollett, A., Taylor, M., Litterick, A., Whittingham, M.J. and Williams, J.R., 2018. Improvements in the quality of agricultural soils following organic material additions depend on both the quantity and quality of the materials applied. Frontiers in Sustainable Food Systems, 2, article 9, 1-13.

[51] Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H. and Murphy, D.V., 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biology and Biochemistry, 45, 113-124.

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[53] Digestate and compost in agriculture: Good practice guide, WRAP; Fertiliser Manual (Nutrient Management Guide (RB209) Section 2: Organic Materials, AHDB; SRUC Technical Note TN650: Optimising the application of bulky organic fertilisers; Environment Agency Technical Guidance Note EPR 8.01 – How to comply with your landspreading permit, Environment Agency.

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[56] Collier, S.M., Green, S.M., Inman, A., Hopkins, D.W., Kendall, H., Jahn, M.M. and Dungait, J.A.J., 2021. Effect of farm management on topsoil organic carbon and aggregate stability in water: A case study from Southwest England, UK. Soil Use and Management, 37, 49-62.

[57] Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R., 2010. A review of biochar and its use and function in soil. Advances in Agronomy, 105, 47-82.

[58] Lehmann & Possinger, 2020. Atmospheric CO¬2 removed by rock weathering. Nature, 583, 204-205.

[59] 'Rock on Soils' show potential for better carbon sequestration and soil biodiversity, The James Hutton Institute.

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The carbon dioxide (CO_2) dissolved in rainwater forms a weak acid that reacts with the base cations[60] (i.e. ammonium, calcium, magnesium, potassium and sodium) in the rock dust forming dissolved carbonates that either leach from soils into waterways ultimately ending up buried in ocean sediments, or form secondary carbonates in soils, where they can remain for many millennia[61].

A recent experiment showed that arbuscular mycorrhizal fungi (AMF) can grow in artificial soils formed from crushed dolerite and concrete, typical of urban demolition waste. As the growth of mycorrhizal fungi increases soil organic carbon, and the rock dust forms inorganic carbon, it appears that dual mechanisms for carbon sequestration can both be active in soils treated with silicate-rich rock dust[62].

Figure 17: Fungal growth in digestate fibre

4.7.4. Risks associated with applications of recycled by-products to soils

In general, carbon itself may become a pollutant if dissolved and particulate forms leach through or run off soils into watercourses, potentially causing oxygen deficiencies that affect aquatic organisms, and water quality issues including changes in taste and colour[63].

Recycled by-products may contain toxic elements including heavy metals and plastics that can cause pollution and contamination of the soil and wider environment and might pose human health risks. The pyrolysis process for biochar production may be a source of polycyclic aromatic hydrocarbons (PAHs) which are a threat to environmental and human health because they are potentially carcinogenic[64].

Despite the acknowledged and potential benefits of applying recycled organic and inorganic by-products to increase soil carbon, it is important to remember that the carbon sequestration potential depends on full accounting for emissions of all GHGs (CO_2, N_2O and CH_4) associated with their production and transport to the point of use[65], plus their effects on soil processes. However, potential emissions may be offset if crop growth both above and below ground, i.e., roots and root exudates, increases due to improvements in soil quality and fertility.

Application of plentiful soluble carbon and nutrients (nitrogen, phosphorus and potassium) in the liquid fraction of digestates to soils can cause substantial emissions of greenhouse gases CO_2 and N_2O, volatilisation of ammonia (NH^4+), and may also present a pollution risk to local waterways through leaching[66]. Whilst the porous structures of

[60] Elements which have an electrical charge are called ions; positively-charged ions are cations and negatively-charged ones are anions. Soil cations can be base or acid. Base ones are ammonium (NH4+), calcium (Ca++), magnesium (Mg++), potassium (K+) and sodium (Na+)

[61] Beerling, D.J., Leake, J.R., Long, S.P., Scholes, J.D., Ton, J., Nelson, P.N., Bird, M., Kantzas, E., Taylor, L.L., Sarkar, B. and Kelland, M., 2018. Farming with crops and rocks to address global climate, food and soil security. Nature Plants, 4, 138-147.

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[64] Quilliam, R.S., Rangecroft, S., Emmett, B.A., Deluca, T.H. and Jones, D.L., 2013. Is biochar a source or sink for polycyclic aromatic hydrocarbon (PAH) compounds in agricultural soils? Global Change Biology Bioenergy, 5, 96-103.

[65] Hopkins, D.W., Wheatley, R.E., Coakley, C.M., Daniell, T.J., Mitchell, S.M., Newton, A.C. and Neilson, R., 2017. Soil carbon and nitrogen and barley yield responses to repeated additions of compost and slurry. The Journal of Agricultural Science, 155, 141-155.

[66] Bhogal, A., Chambers, B.J., Whitmore, A.P. and Powlson, D.S., 2007. The effects of reduced tillage practices and organic material additions on the carbon content of arable soils. Defra, London.

biochars and some composts with high C:N ratios can retain nutrients which can be beneficial for preventing water and air pollution, this nutrient immobilisation has the potential to increase the carbon footprint of crop production in amended soils, if additional fertiliser application is required to support crop growth[67] .

4.7.5. Primary types of organic by-products recycled to land

Digestates (anaerobic digestate, AD) and composts are bulky organic materials considered as renewable fertilisers created from organic materials sourced on- and off-farm, whilst biochar is manufactured from various organic feedstocks specifically for the long-term storage of carbon, or as a by-product of charcoal production.

- **Digestates** are by-products of anaerobic digestion, which is the controlled biological decomposition of organic materials such as food wastes or animal manures in the absence of oxygen (i.e. anaerobic conditions). Digestate contains less organic carbon than compost (C:N ratio 4-20) but relatively large amounts of readily available nitrogen, mostly as ammonium nitrogen (NH_4^+-N), plus phosphate, potash, sulphur, magnesium. Digestate is normally produced 'whole' (a slurry with 3-10% dry matter), but it can be separated into fibre (20-40% dry matter) or liquor (1-6% dry matter) fractions. The larger dry matter content of the fibre fraction indicates a greater organic matter content[68].

- **Composts** are used as soil conditioners due to their large organic matter content (40-60% dry matter) and as a source of plant nutrients. They are produced by controlled biological decomposition in the presence of oxygen (i.e. aerobic conditions) of green wastes (e.g., lawn clippings and woody material) or from a mix of green waste and food waste. The nutrient value of compost primarily includes readily available potash (i.e., potassium), phosphate, magnesium and sulphur, but contain less readily available nitrogen compared with digestate due to losses during composting (C:N ratio >30).

- **Biochars** are produced from a range of organic materials by heating them in an oxygen-depleted atmosphere (i.e., pyrolysis) to produce a porous carbon-rich solid (C:N ratio >30-500) that is resistant to decomposition and intended for the long-term storage of carbon in the soil. Biochar from 'charcoal fines' is a by-product of charcoal production. The specific physical and chemical characteristics of each type of biochar is based on the pyrolysis conditions and feedstock, and they may contain substantial quantities of basic cations, potassium and phosphorus. Biochars are not manufactured to provide nutrients, but their porous structure can hold onto nutrients in soils that have low cation exchange capacity and low organic matter content[69].

[67] Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22, 1315-1324.
[68] Digestate and compost in agriculture: Good practice guide, WRAP
[69] Gao, S., DeLuca, T.H. and Cleveland, C.C., 2019. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. Science of the Total Environment, 654, 463-472.

4.8. Agricultural subsidy payment plans in the UK

4.8.1. England

Defra has announced details of the new ELM scheme support mechanism for farmers and landowners in England. This consists of three environmental land management schemes:

Sustainable Farming Incentive (SFI) – focuses on making agricultural activities more sustainable. To be launched in Spring 2022, SFI will include actions such as reducing inorganic fertiliser and pesticide use, better soil care and improving farmland biodiversity, water quality, air quality and carbon sequestration. Defra's target is for at least 70% of farmers, covering at least 70% of farmland, to take up Sustainable Farming Incentive agreements.

Local Nature Recovery – this is in effect a successor to the Countryside Stewardship Scheme. This fund is intended to make space for nature within the farmed landscape and support nature recovery schemes such as tree planting, peatland restoration, natural habitat creation/restoration and natural flood management.

Landscape Recovery – which will support larger landowners or land managers wishing to make long-term and large-scale changes to land use (e.g. woodland planting, extensive peatland restoration) leading to significant environmental and climate outcomes. Defra plans to deliver at least 10 Landscape Recovery projects covering over 20,000 ha by 2024.

By the end of the proposed agricultural transition in 2028, Defra expects the government's £2.4bn annual farm funding pot provided for farmers in England will be split equally among these three schemes, with some money also being invested to improve farm productivity.

4.8.2. Wales

Following Brexit, the Welsh government had planned to end direct payments and begin phasing in a new funding regime from 2021. However, in September 2021, it was announced that their 'Sustainable Farming Scheme' would not open until January 2025. A new agriculture bill (setting out a more detailed policy framework) is planned for summer 2022, with a final consultation on the new scheme and transitional measures expected in spring 2023. The current Basic Payment Scheme and the sustainable land management payments will continue until 2023. The Sustainable Farming Scheme is expected to encourage Welsh farmers and land managers to farm in a way that promotes a range of environmental benefits, including carbon storage, soil improvement and water quality. Payments will be based on the principle of 'public money for public goods'.

4.8.3. Scotland

Scotland has a much higher proportion of less favoured area land (LFA) than the rest of the UK and as such, the Scottish government has the challenge of striking a balance between providing support for hill and croft farmers, maintaining a high quality of food production, protecting the environment, and targeting net zero carbon. Farmers in Scotland will continue to receive subsidy payment under the Basic Payment Scheme – a support policy effectively inherited from the previous Common Agricultural Policy – until 2024, after which it will present new proposals for its future subsidy framework.

4.8.4. Northern Ireland

Farm subsidies form part of the Northern Ireland Protocol. Payments to farmers are roughly equivalent to previous CAP payment levels. Northern Ireland's Department of Agriculture, Environment and Rural Affairs is responsible for the administration of farm subsidy payments until 2022. From then, the Northern Ireland assembly will legislate for and develop a future agriculture policy framework.

4.9. CAP to ELMs: A new farm policy, a new era for farmers in England - A perspective contributed by Vicki Hird MSc. FRES, Head of Sustainable Farming at Sustain

This contribution explores the opportunity created by the transition from CAP to a post-Brexit agricultural policy with specific reference to the Environmental Land Management (ELM) schemes in England and the need to put emissions reduction in the whole of the UK at the heart of future plans for farming, land management and the supply chain.

One significant, possibly positive, but as yet unmeasurable, impact of Brexit was the opportunity for the four devolved nations to decide for themselves how to support farmers, make better use of the land, and regulate farming. The Agriculture Act 2020 has been several years in the making and, with considerable lobbying, has been written to provide a useful framework for the UK.

The Act moves from a support mechanism for farmers via the EU Common Agricultural Policy of around £3.2bn per year to one based on payments mainly for delivering public goods such as protected nature, critical climate mitigation, public access and clean water. The evidence is pretty clear that this policy shift must drive more agroecological, regenerative farming and nature-based solutions for climate on all farmed land, with diversity at its heart.

If the schemes, budgets and wider policy that flow from this legislation are designed well, it could be an amazing example of 'policy fit for purpose', delivering climate and biodiversity impact whilst also ensuring a healthy food supply. As these new schemes will be rolled out while the key farm income support (the basic payment scheme - BPS) is being wound down over 7 years, it is crucial that they work well as the majority of farmers rely on BPS to support farm viability and supplement farm incomes.

England has made the most progress in establishing a post-Brexit agricultural subsidy regime (see details of ELM scheme in section 4.8 above). As indicated above, the devolved nations of Scotland, Wales and Northern Ireland are engaged similarly in designing their new support regimes but with more emphasis on basic farm support.

Ideally all new schemes must provide payments for activities, capital grants, advice and a strong regulatory baseline to ensure farmers can survive and deliver vital public goods.

These should include, really for the first time, climate action through building carbon stores in soil and trees and reducing emissions from fertiliser use and soil disturbance for instance. Schemes need to align well enough to not disadvantage a particular sector or group of farmers across the UK, and to minimise the administrative and compliance burden in cross-border regions.

At the time of writing, there has been an impressive level of testing and on farm trialling of possible scheme designs. Farmer pilots of the England Sustainable Farming Incentive (SFI) are testing the various elements of the design. These include the payment methodology, land management plans and the 8 pilot standards (covering arable and horticultural land and soils, improved grassland and soils, low and no input grassland, hedgerows, on farm woodland, and waterbody buffering).

There is a push for new standards to support whole-farm agroecological systems, i.e. those that work with nature to deliver positive outcomes such as agroforestry, agro-diversity (in crops and livestock), and better coverage for horticulture, small scale/peri-urban[70] farming.

A wider Agricultural Transition Plan (ATP) is providing a larger set of tools, from farmer-led research and productivity grants to animal health and welfare pathways, new entrants and farmer exit schemes. But there remains a major publicly funded advisory scheme gap – something all the trials have indicated is vital as many of the requirements, such as those on climate, are new to farmers.

For all this to work, the farming industry requires a budget that is multiannual and which fits the significant scale of need including the reversal of the decline in the state of nature[71] on farmland; a halt to the continued harm to watercourses; and actions to tackle the 10% of UK GHG emissions from farming. **Critically there is a need for wider policy shifts to ensure the market supports the transition to climate and biodiversity-based farming.**

Without restructuring the retail supply chain – which is deeply unbalanced, with a handful of dominant buyers – the public good schemes will fail. The 2020 Agricultural Act contains useful new powers to deliver more transparency and fairness in the supply chain after considerable lobbying[72]. Such measures could help farmers to gain a better deal and more value via new, enforced statutory codes of practice for the supply chain.

There is as yet no timetable for implementation and there is insufficient action to diversify the retail sector. Nor is there much evidence of intent to provide regional and local infrastructure (such as for abattoirs, processing, milling and storage) to build better routes to market for farmers who wish to use more rotations and diversify their businesses in order to maintain a regenerative system.

And there are not yet the regulations underpinning all this to ensure basic nature and climate protections are secured via a new and long-overdue Environment Act 2021. This should ideally have been developed in tandem with the 2020 Agriculture Bill.

Trade deals are also a huge part of the shaky ground on which the UK is building a new post-Brexit food system. The global market is a poor replacement for the EU market on our doorstep. New trade deals should be about a race to the top on animal welfare, environment and public health[73] (antibiotics, pesticide residues[74]).

For those struggling to afford good food, policies should target incomes via wages, house prices and welfare support mechanisms, rather than make food ever cheaper in a 'race to the bottom' on standards via imports which the public don't want.

UK farmers see major issues in competing with imports at lower standards and this would undermine the capacity of the new farm schemes to deliver.

[70] Peri-urban farms are those on the edge of conurbations
[71] State of Nature Report 2019
[72] Fair dealing and the Groceries Code which discusses a fair and transparent supply chain
[73] Future trade deals could threaten plans to tackle child obesity, Sustain 2021, Trick or Trade: the impacts of Free Trade Agreements on food environments and child obesity
[74] UK pesticide standards could be slashed in new trade deals, threatening public health and the environment, PAN-UK/Sustain 2020 Toxic Trade

Other challenges created by Brexit include labour shortages, with over 3.9 million employed in the UK food industry (which is worth £113bn to the economy)[75], where a significant part of that workforce is or was from EU countries. Policies are needed to ensure that the food and farming sectors can invest in better wages and conditions to attract and train more UK workers. Such policies are not attractive to cheap food advocates or global traders, so political will is needed.

As a positive, there is a welcome legislative push to drive action and budgets in ways that should help farmers and the planet. However, safety nets and knowledge transfer schemes are needed along the way as the new schemes are rolled out to avoid bankruptcies, farm amalgamations, job losses and environmental damage as a result of intensification and ever larger field sizes.

With the longer-term risks of major climate change, extreme weather and land use impacts affecting food supplies both in the UK and abroad, it will be crucial for the Agricultural Transition Plan and other wider policies to build in resilience and adaptation, hard, into our food and farming systems.

4.10. Promoting biodiversity: creating a balance between livestock farming and Nature - A perspective by Chris Clark, Nethergill Associates and Martin Lines, Nature Friendly Farming Network

4.10.1. Promoting a proper balance with Nature

Nature and farming are inevitably closely related. Bad farming practices can easily adulterate the natural environment and some aspects of farming have a reputation for passing-on the costs of rectification to other parts of the economy (such as re-instatement of water quality after capture). Promoting a better balance between farming and Nature can only come when the evaluation of natural benefits can be quantified on an agreed basis and when dependence on qualitative (and widely disputed) measures can be made obsolete.

4.10.2. Natural capital

The benefits of 'Nature's bounty'

In livestock farming, energy from the sun produces grass which then feeds livestock for meat production. Grass can be seen as being supplied to farmers as a 'free-issue' commodity in return for land ownership or tenancy. This gives competitive advantage to the farmer which is manifested in unit costs of production. If substitutes for grass are used, these will involve come at some 'real' extra cost. In general, the benefits of Nature's Bounty come in the resulting profitability of the business.

Revenues can be converted into an equivalent capital sum by using an annuity factor; this equivalent capital sum is the value of the natural capital prevailing in a business at that time.

The concept of Nature as a stakeholder

A shareholder in a business typically invests capital in the expectation of a dividend as a reward. The provision of dividend income is an implied obligation of the business and will be a burden on its profits. In recent years it has

[75] Food Statistics in your pocket 2017: Food Chain, Defra

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become normal practice to recognise the importance of customers, suppliers, and employees in a business by treating such constituencies of interest (alongside shareholders) as stakeholders.

In any farming business Nature, too, must be a stakeholder but it is a stakeholder with a difference. Instead of placing a burden on profits to deliver a dividend, it provides benefits such as natural grass, on a 'free-issue' basis. The more productive Nature is, the greater the benefits will be to the business. If the adulteration of Nature reduces its productivity, this would be the equivalent of working against stakeholders' interests (and constitute a self-inflicted penalty).

Fitting in with accounting conventions

If the concept of Nature as a stakeholder is to have real validity, it must be accommodated into existing accounting conventions. In particular, it must have a role on the balance sheet.

Table 1 below sets out a typical balance-sheet and how this might be adapted to account for natural capital and for Nature as a stakeholder. The starting point is the recognition that stakeholders' interests are a liability on the balance-sheet and that as Nature behaves in a diametrically opposite fashion to a shareholder, it must rank as a 'negative liability'.

Balance Sheet Conventions (Traditional Construction)	
ASSETS	**LIABILITIES**
Fixed Assets - Land - Buildings - Plant and Machinery Current Assets - Stock and Work-in-Progress - Accounts Receivable (Debtors) - (less Accounts Payable/Creditors) Intangible Assets - Reputation - Goodwill	Shareholders' Equity - Subscribed Capital - Retained Profits Obligations to Lenders - Long-term Debt - Short-term Overdrafts
Net Assets Employed	**Net Liabilities Incurred**
Modifications to Account for Nature	
(Natural Capital Assets)	(Nature's Equity)

NOTES:
1. Intangible Assets perform the role of a balancing item
2. Natural Capital = Annuity Factor (taken to be 2.5x – see text) * Profits
3. As accumulated profits comprise Shareholders' Equity, Nature's Equity is the contribution of a single year

Table 1: Traditional Balance Sheet conventions modified to account for Nature

The modified value of the net assets employed is reduced compared to the more traditional calculation. This makes it easier for a farming business to deliver a specific ROTA (Return on Total Assets) performance. This phenomenon goes some way to justifying why the most productive farmland sells at a premium, which appears to fly-in-the-face of generally poorer returns in relation to other sectors of the economy.

The annuity factor

Setting an appropriate annuity factor to compute a natural capital equivalent of Nature's Bounty is ultimately a matter of judgment for the financial sector. It is analogous to a price/earnings ratio (P/E) and these are driven by profit expectations and an adjustment for factors affecting the quality-of-earnings prevailing in a sector.

Farming has an intrinsically low quality-of-earnings, as profits can vary enormously from one year to another (particularly as a consequence of the weather). A factor of 2.5x has been adopted and this compares with an industrial business of average performance of 5x and some fashionable internet-stocks of 20x.

4.10.3. Environmental stress as an economic indicator

The concept of environmental stress

Farming in the UK lives in a largely managed landscape. It has been progressively modified, for good and ill, for more than 400 years. This landscape was broadly in balance with Nature, however, some practices introduced since 1945 have adulterated a growing proportion of the farming landscape.

The economic role of farming is to harness natural resources and to do so at a commercial profit. When Nature supports maximum levels of profitability, the value of the natural capital employed is also maximised. This is then the long-run stable position for Nature. If Nature is adulterated or compromised, profitability will be reduced, and the value of natural capital employed will also be reduced. In such cases the physical asset (associated with Nature) can be seen to work harder for less economic benefit.

It can therefore be argued that the stress on the environment as a consequence of farming activities is minimised as profitability is maximised.

The key relationship between stress and Maximum Sustainable Output (MSO)

Profitability, which is the level of profits in relation to the value of outputs, must be differentiated from absolute profits. Profitability is maximised at the MSO point – that is the point at which Corrective Variable Costs (CVCs)[76] are eliminated. In contrast, absolute profits are maximised at the break-back point (where profitability has retreated to zero) – and this position is both unstable and more stressful to the environment.

Natural capital delivers its greatest value at the MSO point and if, as a result of the elimination of CVCs, Nature is considered to be in equilibrium with farming at this point, then the stress on the natural environment must be minimised.

The concept of an Environmental Stress Index (ESI)

Mathematically, as the value of a parameter measuring natural capital is maximised, the inverse of the parameter is being minimised. Therefore, a parameter based on the inverse of a natural capital measure would be a surrogate for levels of environmental stress.

[76] Corrective variable costs (CVC's) are additional unforeseen variable costs incurred, e.g. having to buy additional feed for animals when grazing runs out or needing to buy additional veterinary/medicinal inputs for an unforeseen health breakdown.

Such an ESI has been defined based on the model set out below:

The Environmental Stress Index (ESI)
Notional Natural Capital (NNC) = Farm profits * Annuity Factor (of 2.5x)
ESI = log(GTq/NNC)
Where G = Universal scaling factor to put ESI's into useable values T = Topographical rating = Elevation * Latitude/Acreage Q = Quality rating based on cover-type categories A log scale is used (as with the Richter scale)

Table 2: Calculation of Environmental Stress Index (ESI)

Using the model set out in Table 3, ESIs can be computed for farms operating at actual outputs, MSO levels, and zero outputs. This is shown in Table 3, where X is the ESI point at actual output, MSO is the ESI point at MSO, and Z is the ESI point at zero output. It will be seen that ESI is minimised at MSO (and profits are also maximised).

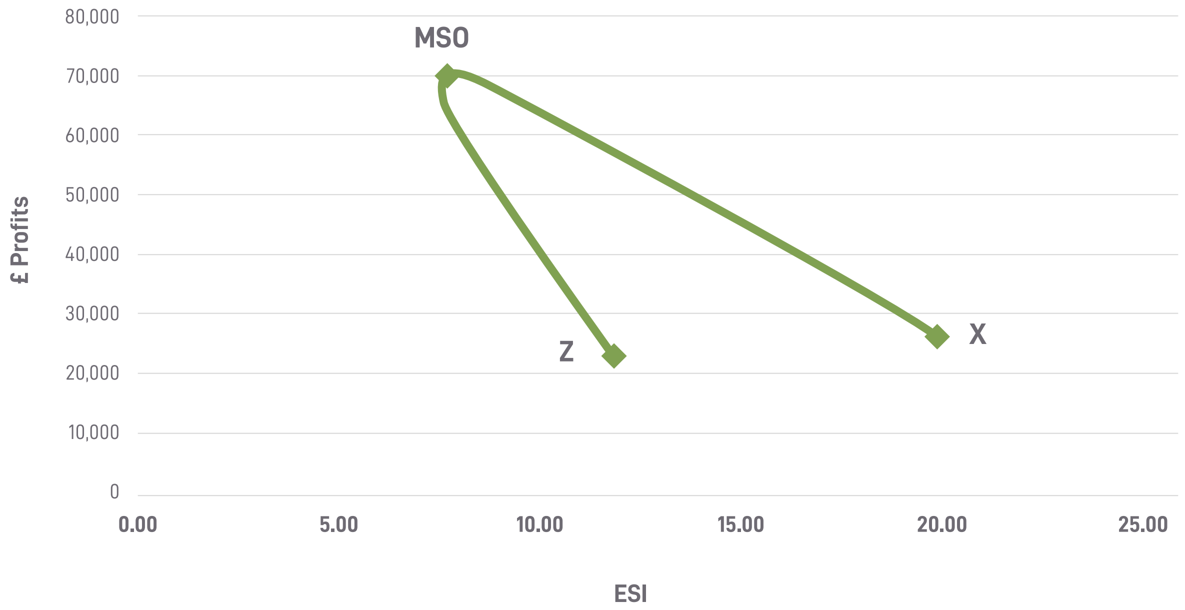

Table 3: Typical pattern of behaviour for an Environmental Stress Index (actual case)

4.10.4. Observations on de-stocking/re-wilding

The managed landscape

At the MSO point, profitability is maximised, the ESI is minimised, and the managed landscape is in a state of stable equilibrium. Small changes on either side of the MSO point will result in an increase in the ESI. This appears to be counter-intuitive in the case of downsizing from the MSO point and it has significant implications for the mechanisms of re-wilding.

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All forms of change in a system from one state of affairs to another will result in a change of 'entropy'. Entropy is essentially a measure of disorder but in a pragmatic sense it reflects inefficiencies and wasted effort. The behaviour of the ESI about the MSO point might be explained in the following way:

- Moving down from an existing level of output to the MSO point will incur an increase in entropy from the change itself. However, this is more than offset by an increase in profitability and the ESI decreases.
- Moving down from the MSO point to a lower level of output also incurs an increase in entropy from the change itself but now profitability also reduces and there will be no offsetting effect. The ESI therefore increases.

The behaviour of Nature

Nature, unlike much of the human race, does not actively seek competitive advantage from every situation. It tends to be indifferent in this regard. However, there will be some underlying objective that will determine its response to change, and it would seem to be that when faced with change, Nature chooses a path that will result in a minimum increase in entropy. This would account for the stability of its long-term equilibrium with the managed landscape and hence, the importance of the MSO concept.

When faced with a binary choice as to how to respond to change (such as adapt or ignore), Nature's responses will follow a statistically random or *normal distribution* curve. However, if it does adapt, what results will depend on the starting point (mathematically, the initial conditions) and the nature of the surrounding environment (mathematically, a feedback mechanism). This is a definition of 'chaos theory'.

It is therefore probable that Nature adapts chaotically to change. This might sound dramatic but all it signifies is that the outcome will be difficult to predict. Perhaps, surprisingly, order (in a localised form) comes out of chaotic behaviour under special conditions. This phenomenon is a form of '*resonance*'.

An example of this is the hexagonal structures to be found in the Giant's Causeway in Ulster and this effect can be demonstrated in the kitchen when a saucepan of water is boiled. As the water cools there will be a point when the surface aligns into a jigsaw of hexagonal shapes, and it so happened that the Giant's Causeway crystallised at this point.

The implications for de-stocking /re-wilding

If a farm is run-down to zero levels of output, Nature will reclaim the property. However, there is no guarantee that this would take the land back to its 'original state' (or 'status quo ante') – it will just be different and unpredictably so. What results may well satisfy some people, but the intrinsic value of the change is impossible (at this time) to quantify. All that can be said is that if the landowner is satisfied, then they will have valued the change as being greater than any net income that will have been foregone.

© Photo: Angela Bywater

The value of re-wilding strategies (at this time) can only be qualitative and, as such, will not be universal; that is, different people will assign different values and priorities to the changes.

5. RENEWABLE ENERGY/ BIOENERGY SYSTEMS

Solar PV farm installations continue to grow. Small onshore wind has regained popularity due to its ability to extend generation throughout the year with the addition of battery storage for use on-site and at peak times in an increasingly flexible grid.

As heat pumps become more price competitive, installation has increased. Small scale off-grid biomethane production from farm residues is supplying on-site heat and fuel. Adoption of slurry cover rules is also enabling smaller AD plants to supply off-grid gas or inject aggregated gas to the grid. Carbon capture, utilisation and storage is more common, with numerous plants also providing both food and non-food grade CO_2.

Many farms will supply increasing amounts of low carbon energy and potentially modify vehicle powertrains to utilise this energy.

5.1. Decarbonising energy use and farm diversification

It has been said that 'farming is the art of turning fossil fuels into food'. However, a transition to a low carbon economy requires reducing food production reliance on fossil fuels as much as possible, as well as reducing other GHG emissions.

Although agriculture contributes only 0.5% to the UK economy, farmers and land managers take care of 71% of the land area and provide half the food we eat. Agriculture is responsible for around 10% of the UK's CO_{2e} emissions (45.4 Mt CO_{2e} of 451 Mt CO_{2e} in 2018[77]).

Whilst the sector is responsible for only 1% of CO_{2e} emissions (largely from energy and fuel), it is responsible for half of the UK's total methane (CH_4) emissions and 70% of the nitrous oxide (N_2O) emissions. Grazing livestock are said to be responsible for 90% of CH_4 emissions and nitrogen fertiliser for 90% of N_2O emissions[78]. These figures do not consider any offsets at farm level, for example, from low carbon or sequestration initiatives, but much still needs to be done.

Some farmers have chosen renewable energy generation as part of farm diversification enterprises. With 68% of farms using their resources to carry out non-agricultural activities (2019/20), 22% of farm business selected solar energy as a diversification option (see section 5.6 below), with 11% choosing 'other' sources of renewable energy, typically wind power and bioenergy (biomass, biofuels and biogas)[79].

Many of the case studies in this document illustrate how the introduction of a **single renewable energy technology acts as a gateway** to further integrate complementary technologies and practices to reduce carbon emissions across the business (see Caerfai Farm, Copys Green Farm and Marsh Farm case studies).

[77] Non-CO2 abatement in the UK agricultural sector by 2050, Eory et al., SRUC, December 2020
[78] The future farming and environment evidence compendium - September 2019 edition, Defra
[79] Farm Accounts in England: Results from the Farm Business Survey 2019/20, Defra, 18 Feb 21.

The addition of **farm-level battery storage** is becoming an increasingly attractive option as battery costs fall, particularly where intermittent renewable energy (e.g. from on-site wind/solar) is available and the farm's electricity requirements justifies its use. With intermittent renewable energy production, matching energy use to energy production is essential. Energy storage of all kinds (e.g. battery; pumped storage hydropower (PSH); electrolysis) is an important part of being able to extend those hours of energy use (see section 5.8).

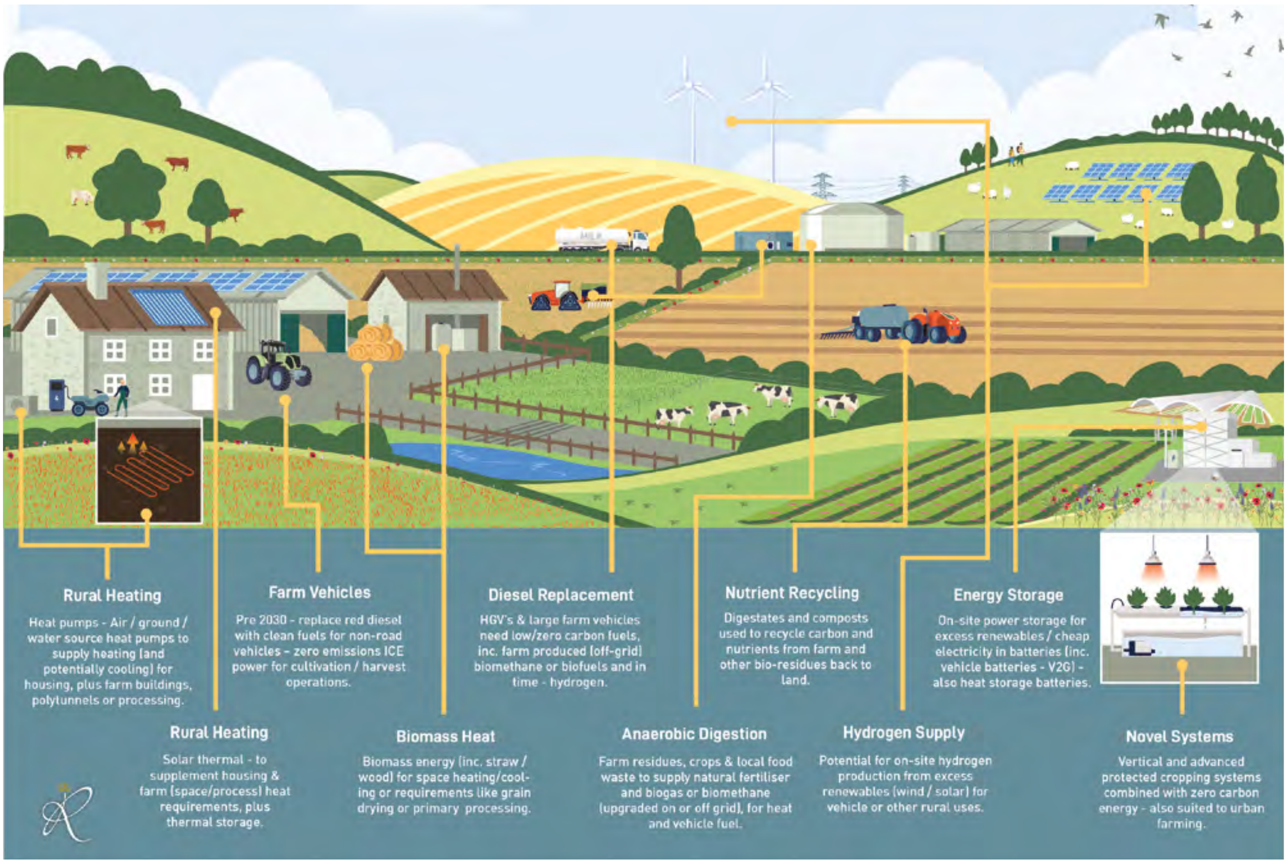


Figure 18: On-farm low and zero carbon renewable energy

Heat pumps (see section 5.5.1) are likely to be an increasingly attractive option, in particular for heating properties not on the gas grid. Such installations require a thorough assessment of the building fabric, insulation and airtightness in order to size an installation properly. It is also perfectly possible to utilise heat pumps in older buildings (after a few basic measures have been taken) or to have a hybrid system which includes an LPG boiler and a heat pump.

Farm-scale anaerobic digestion (AD) (see section 5.4) based on livestock, local food waste and crop residues, particularly at small scale, has massive potential to provide 24/7 energy production which can be used flexibly for heat, electricity and transport fuels. Unlike other renewable energy systems, AD has further important non-energy benefits including fossil fertiliser replacement, weed seed reduction and improved animal health, with treated digestate spread on grazing land, replacing raw slurry. There is still a policy gap to support smaller systems[80], particularly for their environmental benefits on livestock farms.

Where a suitable watercourse is available, **small hydropower projects** can provide farms, communities and businesses with a non-intermittent supply of renewable electricity. As a rural resource, there needs to be on-going support for such projects. A number of these have also been built by community energy initiatives, providing wider

[80] On farm and smaller scale AD is excluded from support under the Green Gas Support Scheme (GGSS).

rural benefits. The Renewable Energy Foundation FIT register shows that hydropower provides a contribution of 247.79 MW to the UK's energy supply.

Table 4 shows examples of a hydropower plant (excluding industrial), with the range of sizes shown in square brackets.

Type	England	Scotland	Wales	Total
Domestic [.3 – 100 kW]	140 (1.95 MW)	130 (2.19 MW)	111 (1.50 MW)	385 (5.79 MW)
Community [4 – 500 kW]	24 (0.85 MW)	17 (2.15 MW)	14 (0.79 MW)	56 (4.29 MW)
Commercial [3 – 2253 kW]	134 (16.21 MW)	383 (160.64 MW)	153 (14.14 MW)	736 (230.13 MW)

Table 4: Domestic, community and commercial UK hydro installations (and power) in receipt of FIT by country. Source: REF

Community energy initiatives such as those supported through the Rural Community Energy Fund (RCEF) need continued support to make important contributions in identifying and addressing specific rural community energy needs, particularly for those not connected to the mains gas grid or where housing stock is energy inefficient. Community groups facilitate much more than just energy generation: they support skilled rural jobs, provide wider social benefit, act as a knowledge hub and engage people in a collective drive to net zero.

> "The sun does not shine at night and wind does not blow every day, but renewable energy can generally be produced somewhere in Britain at any time day or night.

The **integration of on-site energy systems**, within the farm itself and as part of the grid is an exciting growth area, particularly with the development of smart devices and energy supplier tariff schemes which enables users to prioritise and automate energy use. This enables electricity from solar and small on-site wind turbines to be preferentially used on-site in a 'cascading' priority of uses (e.g. firstly for space heating, then to dairy hot water and finally to office hot water).

Electric vehicle charging systems will become a necessity as the transition to EVs progresses. Battery storage will better enable the utilisation of renewable energy for on-farm EV charging e.g. cars, vans, quad bikes and compact tractors. 'Smart charging' allows EVs to charge when grid electricity is at its cheapest, i.e. off-peak. The development of Vehicle-to-Grid technology (V2G[81]) provides the opportunity for two-way charging to and from the EV and the battery or mains grid.

Renewable electricity can also be used (either directly or stored) to heat water for space heating and other farm uses, possibly supplemented with solar thermal panels or biomass boilers. If heating or cooling is an on-site priority, further options may include heat pumps and/or a 'heat battery' which uses phase change materials to store energy (see Sunamp case study).

Heat recovery and ventilation systems offer further scope for potential energy savings. Such systems, for example, could be used to supplement the heat required to operate a small farm-scale anaerobic digester, which in turn can be used to provide heat and/or electrical energy for on-site use.

[81] V2G is a process of feeding the energy stored in an electric vehicle's battery back into the 'smart' grid.

There is a clear policy gap which prevents rural homes and businesses - especially those off the gas grid – from using their own resources (wind, solar, thermal, water and biomass) to create their own energy, either individually or at a community level. This gap particularly applies to biogas (and off-grid biomethane) production derived primarily from wasted local organic resources. However, policy should also include other biofuels such as bio-propane. All of these technologies can support rural decarbonisation, energy resilience and local jobs.

5.2. Understanding the energy landscape

In terms of fossil fuel reduction, general 'energy hierarchy' principles (see Figure 19 below) apply equally to rural businesses and landowners.

It is important for the farm business to understand where and how much energy is being used and where reductions can be made. Measuring energy use is part of the overall farm carbon accounting exercise is discussed in section 4.4 above.

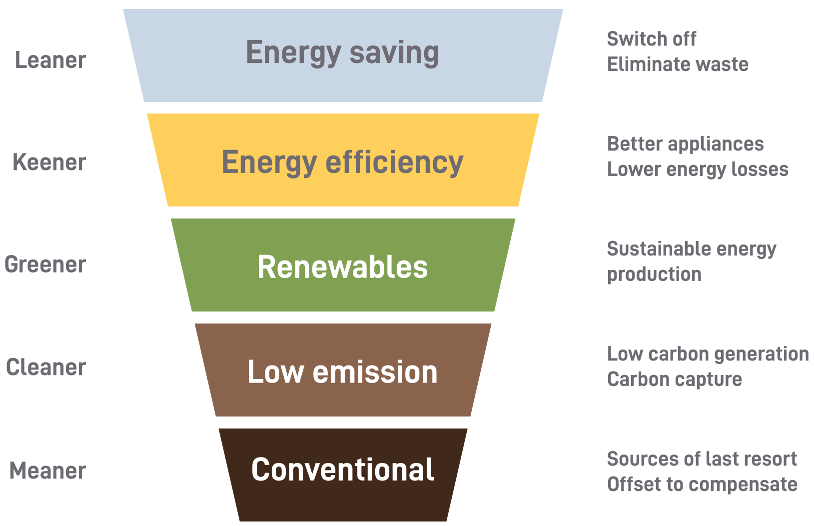


Figure 19: The Energy Hierarchy with the most favoured options at the top.
Source: Philip R Wolfe, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Energy efficiency measures include building fabric improvements (e.g. insulation, draught-proofing, double glazing), installing low energy (LED) lighting, using more energy-efficient appliances/machinery, lagging pipes and using smart devices to minimise energy use.

There are often further energy savings to be found by optimising existing gas/oil boilers, to cut hot water temperatures from 80ºC to 60ºC or by adding weather compensation[82] in order for boilers to take into account weather conditions. Useful tips for a range of energy efficiency measures based on farm type can be found on the Farm Carbon Toolkit website and the Carbon Trust have a useful guide to Energy efficiency in agriculture. Some energy companies also outline a range of energy saving tips (e.g. Octopus Energy).

[82] Weather compensation controls assist the heat source and help it to work at its optimum operation which can help lower running costs.

CASE STUDY: A World First: Wyke Farm's Carbon Neutral Cheese

In 2010, Wkye Farms, the UK's largest independent cheese producer, made a commitment to control costs and generate all of their gas and electricity from renewables, spurred on by a 'huge' energy bill received one month when the dairy's power bill jumped £70,000.

This led to the installation of an anaerobic digester system which produces 13,500 m^3 of methane daily from cow and pig slurry, saves 20 million kilograms of CO_2 yearly and creates digestate for farm use thereby offsetting fossil fertilisers. The farm business has also installed five solar arrays – and also tested the New Holland TG180 – the very first methane tractor prototype ever made for the UK.

But Wyke Farms didn't stop with energy generation. To implement its "100% Green" sustainability plan, the farm business has worked on further improvements: adjustments to farming practices (feed, land management, energy use, regenerative practices); changes to production systems (heat recovery, waste minimisation, rainwater capture and utilisation, energy reduction); and increased conservation (tree planting, wildflower corridors, bird boxes, insect habitats). A committed sustainability plan and incentive programme is now in place which guides all farm operations and also applies to Wyke Farm suppliers.

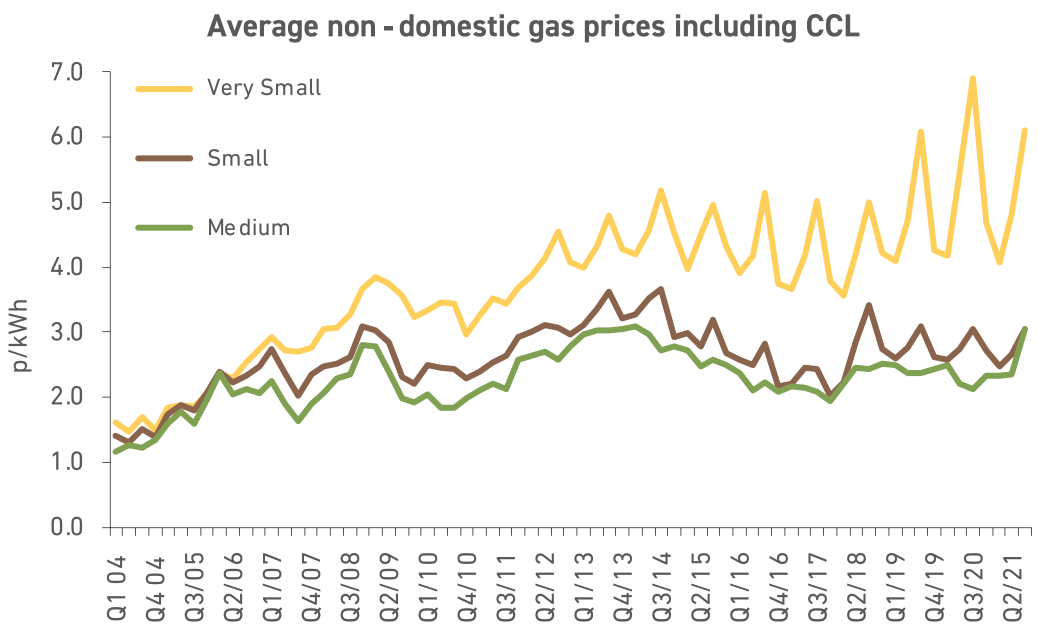
Such low carbon initiatives have resulted in the farm's prize-winning 'Ivy's Reserve Vintage Cheddar' being officially certified as 'carbon neutral' by the Carbon Trust in accordance with PAS 2060 – an internationally recognised specification for carbon neutrality. Richard Clothier, managing director, explains the family's philosophy of nurturing natural resources:

"Living in the heart of Somerset is a privilege. One we'll never take for granted. We understand this beautiful region gives us so much. So we do everything we can to take care of it. Our goal is to create a sustainable working farm, harnessing our natural resources to source our electricity and gas from both solar and biogas, generated from farm and dairy waste. It's something our ancestors would be proud of – as well as our children."

Find out more at https://wykefarms.com/green/

The high energy prices which characterised the winter of 2021-22 clearly illustrate that those who have taken energy efficiency measures ***before*** these energy market cost increases occurred are affected to a lesser extent and are therefore in a better financial position than those who have not. An energy-saving measure which may not appear to be very cost-effective in a time of low energy prices can make a big difference when prices go up, and it is worth understanding what that difference might be against a number of background energy price scenarios. A similar assessment should be made when considering a capital investment in a renewable energy installation.

In any case, the trend for energy prices has been upwards over the past 20 years, as shown in Figure 20 below[83]. From a climate change perspective, it is notable that the smallest energy users perversely pay the greatest per unit cost and have also seen the largest price rise.



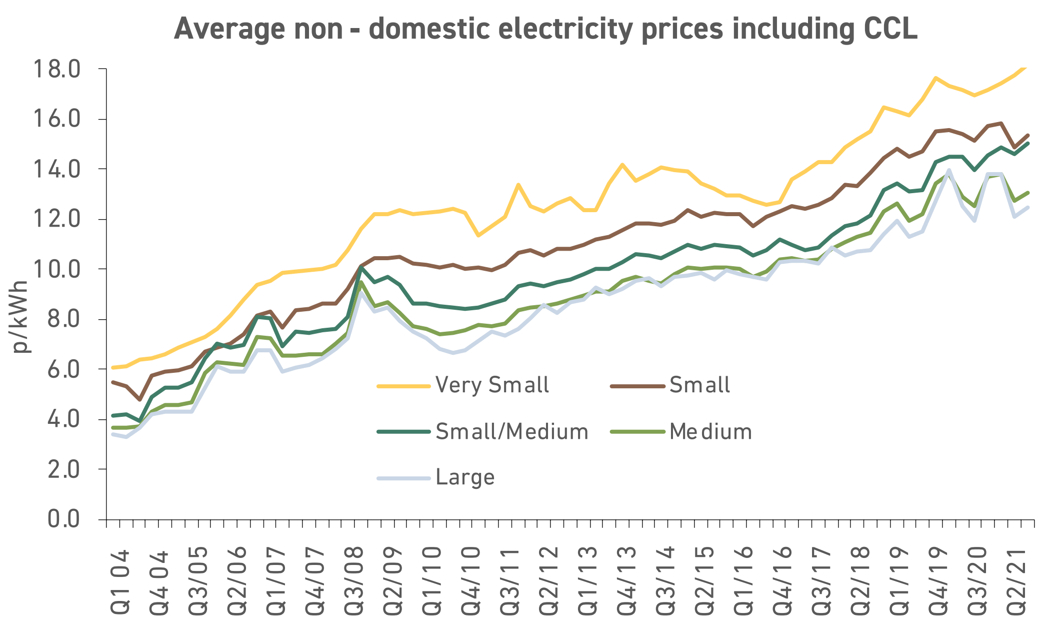


Figure 20: Average UK non-domestic gas and electricity prices (includes Climate Change Levy-CCL)

[83] Gas and electricity prices in the non-domestic sector, BEIS, updated 23 December 2021. Gas user annual consumption (MWh): Very small: <278; small: 278-2777; Medium 2,778-27,777; Large: 27,778-277,777 (large/very large removed). Electricity user annual consumption (MWh): Very small: 0-20; small: 20-499; small/medium 500-1,999; medium 2,000-19,999; large: 20,000-69,999 (large/very large/extra large removed)

It is interesting to note that the useful asset life of many renewable energy systems, which may have offset some of this cost and cushioned food production businesses from energy price fluctuations, is in excess of this time frame[84]. Such technologies, discussed below, are an important part of the range of decarbonisation tools that farm businesses can access.

There has been a general worldwide shift from coal to gas for energy production[85] to reduce emissions of CO_2 and air pollutants. It is unclear, however, whether the 2021-22 'perfect storm' of high energy prices caused by a 'Covid recovery' demand growth for gas, a lower-than-expected supply, sub-average storage inventory and cold weather will continue.

According to the International Energy Agency, 'the exceptionally high gas – and by extension electricity – prices … are likely to have a lasting negative impact beyond the current seasonal tension'[86].

Nevertheless, the energy transition is happening as generation moves from centralised to decentralised systems with a commensurate shift from analogue to digital technologies. These conditions help to enable farm businesses to actively and easily manage their energy generation, consumption, carbon footprint and their bills.

5.3. Rural energy housing challenges

Nearly four million, mainly rural, UK homes (15%) are not connected to the gas grid and therefore must use another energy source, generally oil, liquid petroleum gas (LPG), coal or electricity for heating and these have higher emissions than natural gas. Getting these homes onto low carbon heating is therefore disproportionately better than getting the same number of gas grid homes to switch[87].

The Climate Change Committee has noted that 8 out of a total 9 Mt CO_{2e} of direct emissions in off-gas homes, oil and LPG-heated homes are responsible for 8 Mt CO_{2e}. These 'off gas' homes, mainly situated in rural and peri-urban areas, make up a greater share of heating emissions (23%) due to the higher carbon intensity of oil and LPG compared to gas[88].

With nearly 20% of homes in rural areas in the lowest F and G energy efficiency bands (compared to just 2.4% in urban areas), the rural poor have to save proportionately more on their energy bill than their urban counterpart.

Figure 21: Off gas grid rural stone-built farm-house heated with wood/coal.

Defra considers that 'around 50% of houses in the rural areas are 'energy inefficient' compared to 7% in urban areas' [89].

[84] Useful Life, The National Renewable Energy Laboratory, US Department of Energy
[85] The Role of Gas in Today's Energy Transitions, World Energy Outlook special report, July 2019
[86] Gas Market Report, Q1 2022, including Gas Market Highlights 2021, IEA, January 2022
[87] Boiler bans for off grid homes – a rural design challenge?, Design@Open, 14 December 2021
[88] Annex 2. Heat in UK buildings today Climate Change Committee, October 2016
[89] Rural Proofing in England 2020, Delivering policy in a rural context, Defra, March 2021

The Energy Savings Trust expressed this 'double disadvantage' of poor housing stock coupled with expensive off-grid heating thus: 'the typical rural, fuel poor family would have to find a way to save over £600 a year on their energy bill before their energy costs become affordable. A typical fuel poor family living in town only has to achieve around £300 savings to reach an affordable level'. They add that only 40% of homes in rural areas have gas boilers (the cheapest heating option) compared to 91.1% of urban households[90].

One of the authors of this report carries out farm energy audits in preparation for renewable energy feasibility studies and has surprisingly often found that the biggest electricity use across the whole farm comes from the farmhouse itself - so its impact on the farm's overall energy cost and carbon footprint should not be ignored.

Figure 22: Rural multi-source renewable heating example

A 2011 report by the 'Future of Rural Energy England (FREE)' project found a recurring theme which suggested that people on private rented accommodation were concerned about improving their homes, for fear of being subject to rent increases. A regional study found that they were also concerned about complaining about poor building fabric and heat to landlords (e.g. on tenanted estates) for fear of losing their home and their livelihoods.

Rural areas need higher installation rates of small-scale renewable technologies (e.g. solar thermal, biomass and heat pumps) for renewable heat in rural locations, and particularly for those off the gas grid[91].

Nevertheless, there are clear policy gaps that need to be addressed to enable rural homes and businesses (particularly those excluded from the gas grid) to utilise their own resources (wind, water, sun and biomass) to create energy, either individually or at a community level.

5.4. Anaerobic digestion for heat, electricity and transport fuel

5.4.1. Introduction

Anaerobic digestion (AD) is the decomposition of organic materials (biomass) by microbial communities in the absence of oxygen. It is the process which over millennia created the natural gas which is core to the UK's electricity and gas grids.

This process occurs naturally in places such as landfill sites, rice paddies, septic tanks and in slurry storage tanks, leading to uncontrolled emissions of biogas, which primarily consists of methane (known as biomethane) and carbon dioxide. Although anaerobic digestion occurs to a lesser or greater degree at a wide range of temperatures, AD plants require heat for the microbes to operate in an optimal fashion (typically 35-40°C).

[90] Why outside the grid does not mean outside of help, Energy Savings Trust, 19 March 2019

[91] Renewing Britain: The changing landscape of homegrown energy 2008-2021, Microgeneration Certification Scheme (MCS)

An AD plant captures the biogas and can then beneficially utilise it in of a number of ways: in a specially designed boiler for heat only, in a combined heat and power plant (CHP) to create electricity and heat, as vehicle fuel or directly injected into the gas grid. CHPs are usually connected to the electricity grid but can be used off grid in 'island mode' if there is enough energy use or storage on site.

If used as a vehicle fuel or injected into the gas grid, the carbon dioxide is normally stripped from the methane in a process known as upgrading. Some European countries allow small quantities of biogas to be injected into the gas grid without being upgraded, but UK rules require the addition of propane to the biomethane in order create a consistent calorific value for customers. The requirement to add fossil propane to this renewable gas for grid injection has been questioned and should be reviewed with some urgency.

The carbon dioxide produced from the upgrading process can also be used in a number of ways to offset industrial CO_2 created by fossil fuels. These include greenhouse environment enrichment for improved plant growth, in abattoirs or, if upgraded to a high specification, for food and beverage industry use (e.g. beer, cola, crumpets). As a mainly pure carbon source (unlike air at 400 ppm), it could even be 'sequestered' (pumped underground/undersea).

Figure 23: Digestate fibre

The output from AD plants is known as digestate and it is a fertiliser high in readily available nitrogen (RAN). It can be used 'whole' or separated into a liquid fraction and a solid fraction. Its use is discussed in sections 4.6 and section 4.7 above.

When incentivised by Pollution Control Grants in the 1990's, AD plants were relatively small (with a capacity under 350 m^3 and suited to herds of ~350 dairy cows). They were installed as an advanced slurry/farm waste management and nutrient/organic carbon recycling system and, in many cases, the driver was odour control. Such digesters were regarded as another item of valuable farm equipment and not a major diversification activity. The biogas was used directly in Agas and Rayburn stoves, and robust cast iron boilers which lasted for many years.

Figure 24: Small biogas plant on mixed sheep, dairy and free-range chicken farm

With the introduction of Renewable Obligation Certificates (ROC's) and the Feed-In Tariff (FIT) which followed the German model of incentivised electricity production via CHP, digester sizes increased, as did the proportion of purpose-grown crops (e.g. maize) required to feed them.

The resultant increased quantities of digestate require a larger land base to recycle nutrients back to, with a commensurate increase in transport distance and cost. The majority of farm AD plants built recently under the Renewable Heat Incentive (RHI) were even larger in order to justify the cost of upgrading/gas-grid injection equipment and on some sites excluded farm residues.

It is predicted that AD plants built under the latest incentive, the Green Gas Support Scheme (GGSS), will be even larger due to the scheme structure and because the biomethane must be grid injected. Sustainability criteria were introduced or included in these latter schemes in order to minimise indirect land use change by limiting the amount of crop input. This offers further opportunities for minimising 'waste miles' by including local wastes (such as food waste) into farm AD, as long as appropriate biosecurity measures are followed.

It is perfectly feasible to utilise small upgrading systems to produce off (gas) grid biomethane for local use in biomethane tractors and farm delivery vehicles[92] - or for a boiler or CHP. Such systems can be used to add value to large digesters or in smaller systems, thus removing the cost of gas injection and the propane supplementation equipment. If used in transport, biomethane attracts an incentive known as Renewable Transport Fuel Certificates (RTFC's) (explained in footnote 113 below) and does not require propane addition.

An excellent resource for all aspects of biogas can be found in the IEA Task 37 brochures.

CASE STUDY: Sustainable Dairy Farming at Copys Green

More than 15 years ago, Stephen Temple began making steps to improve the sustainability of his dairy herd of dairy herd of 126 Brown Swiss dairy cows and their followers on his 230-hectare Norfolk farm.

He believes that sustainability is not just about the use of special technologies or techniques, it is about the whole approach to the farming operation, as well as attention to detail on each aspect. Quantification of the financial benefits of each measure has been difficult to quantify, but the dairy herd has moved from loss-making to being profitable.

His small 870 m^3 anaerobic digester is fed with manures, low quality silage (leaving the best for the cows) and whey, with 70% of the electricity being exported from the 140 kWe CHP. The heat from the CHP is utilised to offset fossil fuel heating: for dairy hot water, cheesemaking, grain drying, 4 houses, office, workshop and cow drinking water. With 24/7 on-site energy production, **the farm has gradually electrified:** the 6-cylinder diesel pump is now an electric one; digestate is pumped to the field by underground mains to avoid road traffic; there are 3 electric farm cars, a ride-on mower, an electric Gator for herding cows and an electric loader for scraping out slurry.

[92] See Refuelling the Countryside, RASE, 2014, page 23

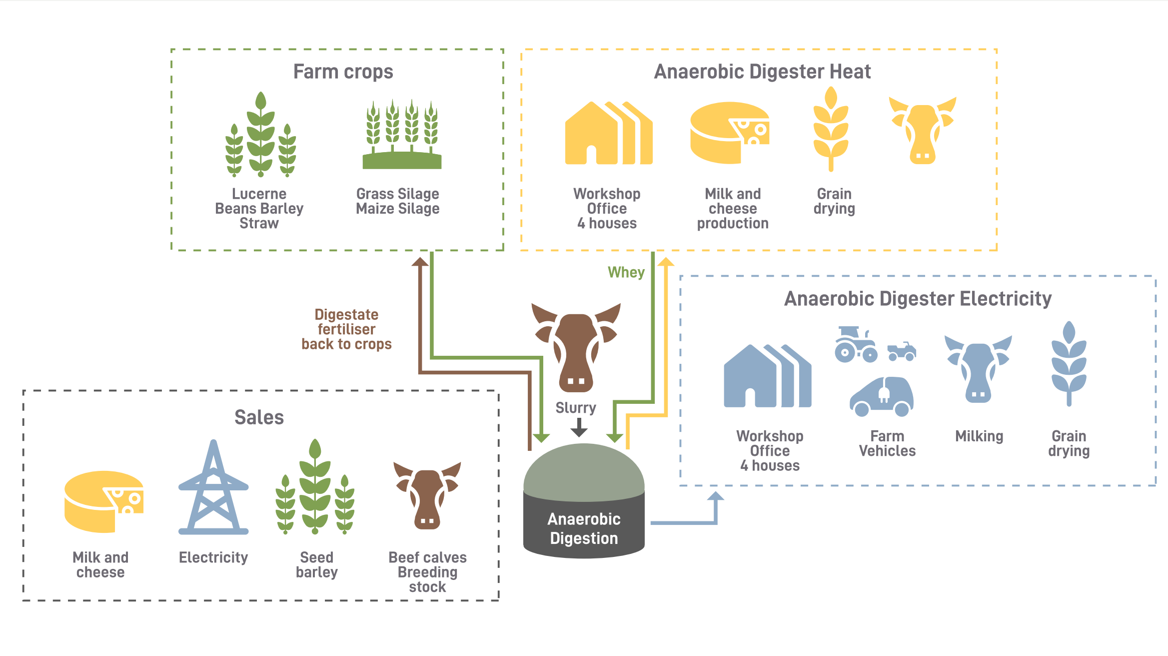


Figure 25: Integrated sustainability approach at Copys Green farm

A **focus on a healthy, productive herd** includes routine testing, vaccination where possible, reducing antibiotic use by utilising good bacteria (Pruex) in water and bedding to fight infectious bacteria, using outdoor calf hutches and, with a closed herd, breeding for longevity. Sexed semen is used on the best cows for replacement heifers and good beef semen for quality beef cross calves sold to a local rearer and fattener. As much feed as possible is grown on the farm, eliminating soya: lucerne for protein at low input levels; maize (experimentally grown with climbing beans) and grass silage, barley and beans.

The farm has worked closely with the Norfolk Rivers Trust to protect and enhance their chalk stream and with the Norfolk Wildlife Trust to **improve the environment** for wildlife, such as developing wildlife corridors between ponds.

Protection and improvement of soil structure through regenerative practices is a core principle: direct drilling and strip tillage in combination with cover crops and rotations to improve soil. Over a decade, Stephen developed a maize drilling system to strip till into cover crops. Digestate liquid is applied with trailing shoe to reduce ammonia losses and they are experimenting with acidifying the digestate to further reduce losses.

Further sustainability measures include reducing plastic by buying feed and feed supplements in bulk/1 tonne bags; eschewing wrapped bales for silage in favour of using a silage clamp; using straw bales to maximise volume stored under cover (and, unlike bale mesh, recycling the string); and washing udder cloths in an industrial washing machine instead of using disposable wipes.

There is a lot of trial and error that occurs in their sustainability journey and all at Copys Green Farm are **generous with their time and knowledge**, regularly hosting tours of farmers, schoolchildren and the general public.

5.4.2. Small scale on-farm biogas - Contributed by Michael Chesshire, Lutra Ltd

Anaerobic digestion has become a significant technology in UK for the treatment of waste materials (food waste, sewage sludge and manure) and for the processing of crops. It is currently mostly being applied at a large scale because the only game in town is the injection of biomethane to the grid, which is subsidised by the UK government. The technology for biogas upgrading and addition of propane for grid entry is only economic at large scale. In rural areas, there are limited suitable locations for grid entry.

With the UK's commitment to net zero and with increasing energy prices, the moment has come for a reassessment of the role of small-scale on-farm biogas, which can be carbon-negative. A suitable definition is where feedstocks for the farm digester are sourced locally or from the farm and where the digestate is used directly and beneficially on the farm. It is an added bonus if the bioenergy is also used on the farm.

A couple of early reports which are relevant to the discussion about the GHG mitigation credentials of the anaerobic digestion of manure include:

1. In 2015, Bangor University and REA produced a report sponsored by the BBSRC AD Network: "Evaluating cost effective greenhouse gas abatement by small scale anaerobic digestion". This concluded that each tonne of dry matter of cattle manure processed through anaerobic digestion results in the avoidance of 1449 kg CO_{2e}. This figure includes the other GHG benefits of energy production and fertiliser reduction.

2. In 2012, a brief report (by the author and not peer-reviewed): "**Greenhouse gas mitigation from anaerobic digestion**" suggested that each tonne of dry matter of cattle manure processed through anaerobic digestion results in the avoidance of 900 kg CO_{2e}.

These reports use different assumptions for the GHG mitigation credentials of the anaerobic digestion of manure, but all point to a very positive mitigation of GHG. The numbers may vary, but it is important to conclude that the production of biogas from manure results in negative emissions of GHGs. In this, biogas is unusual because most renewable energy technologies have small positive emissions of GHG.

Other significant benefits include reducing the costs of farming and sheltering the industry from energy and fertiliser price inflation. Biogas from manure was pioneered in 1970's in the wake of the Middle East oil crises and high fossil fuel prices. In 1980 the price of oil, inflation adjusted, was US $124 per barrel; during 2021 it varied between US $46 and US $66 per barrel, and has risen to circa US $100 per barrel in 2022.

Until the price of energy increases to a level which makes biogas economic, farms should be incentivised to install on-farm biogas plants, probably through capital grants or loans. This can be justified to achieve the decarbonisation and environmental benefits required from agriculture. The advantage of tariff-based subsidies is that they help encourage good performance, but they can be expensive for government to monitor.

5.4.3. Future options for biogas

Anaerobic digesters are part of the circular bioeconomy, as a tool within the carbon cycle: using engineered systems to capture and utilise fugitive emissions from bio-degradation. Therefore they are - and will always be - a low carbon system in a net zero world.

Due to multiple factors – not least the number of domestic boilers that will need replacement - the gas grid is unlikely to become close to 100% hydrogen during the asset life of current biomethane plants. However, the first plants built under the Feed-In Tariff (FiT) will lose their tariff support in 2030 (2031 for the first of the RHI plants) and some policy consideration will be needed to ensure that these do not become stranded assets.

Those sites near a gas grid may be able to raise the capital to expand their feedstocks, AD plant and land base in order to make it economic to do grid injection. Those who cannot need other options, and this includes smaller scale biomethane upgrading for fuel use.

One option may be a virtual pipeline where several plants upgrade their biogas on-site, and compress the gas into tanks which are then transported to a central gas injection point (see RASE Refuelling the Countryside report for a description of this). For small plants, researchers have explored the possibility and costs of a mobile biogas upgrading vehicle as part of a virtual pipeline. A further variation on this theme for both smaller plants and those FiT plants coming to the end of their life is described in the CNG Services case study below.

A further option is 'in-situ' biomethanisation (or 'power-to-gas'), where electrolytic hydrogen from renewables is injected into a digester and resultant biogas is produced at circa 95% methane content, as the carbon (C) in the carbon dioxide (CO_2) combines with the hydrogen (H_2) to produce methane (CH_4). The process can also be carried out biologically at larger scale in a separate reactor ('ex-situ'), using electrolytic hydrogen and a large carbon source (e.g. CO_2 from cement production)[93].

However, in-situ technology is better suited to farm-scale. Technically, this requires sufficient excess renewables and an electrolyser of a suitable size, such as those being developed by Enapter. The economics of such an undertaking are complex and will be determined by factors including carbon pricing, energy prices, hydrogen policy, grid composition, etc.

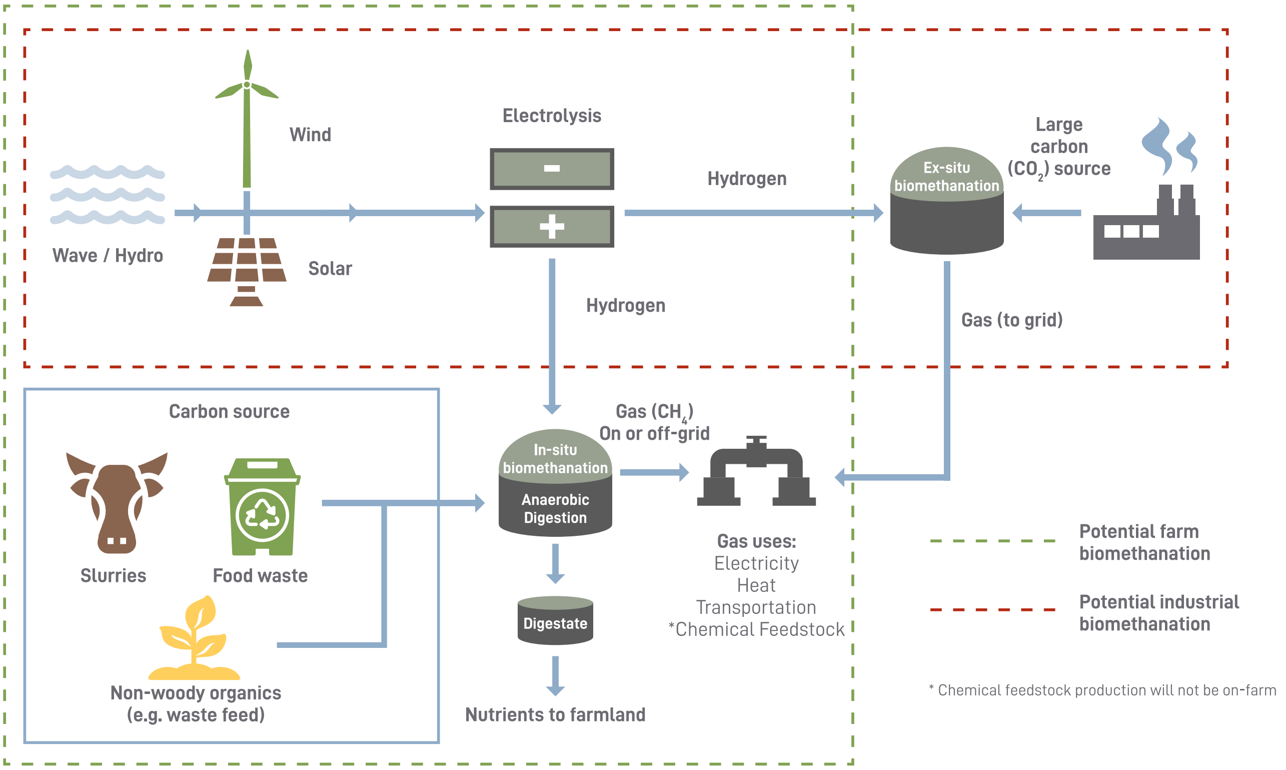


Figure 26: Power to gas

Producing local protein sources for both animals and humans is a major challenge for agriculture and it is possible to take excess waste nutrients produced from AD of food and farm waste to cultivate algal biomass, which could be used as a protein source for animal feed and other products of value (see the ALG-AD project).

[93] Companies such as Electrochaea and Microbenergy have early-stage commercial systems.

The carbon dioxide produced during the biogas upgrading process is an important product for industry and is a concentrated source which is helpful in terms of its economic usage. Companies such as Biocarbonics are seeking to utilise 'green CO_2' from a number of AD plants to provide a local continuous supply for food, beverage[94] and greenhouse use.

In another business model entirely, Future Biogas have partnered with the Northern Lights Project to build a port facility on the Humber Estuary for CO_2 from AD biomethane plants to be transported for storage under the North Sea. As this is permanent geological storage (carbon capture and storage-CCS), the company plans to sell carbon offsets to corporate buyers who wish to offset their emissions.

CASE STUDY: Integrating Renewable Technologies and AD in a Circular Economy

CNG Services is planning to construct a distributed network of anaerobic digesters in Cheshire to feed dry biogas through underground pipelines into a central upgrading hub. At the hub, biogas will be upgraded into biomethane and injected into the gas grid (National Transmission System, NTS). All CO_2 produced from the membrane-based upgrading process will be captured and taken to carbon capture and storage (CCS) facilities. Revenue will be generated from a combination of the Green Gas Support Scheme (GGSS) and Renewable Transport Fuel Certificates (RTFCs).

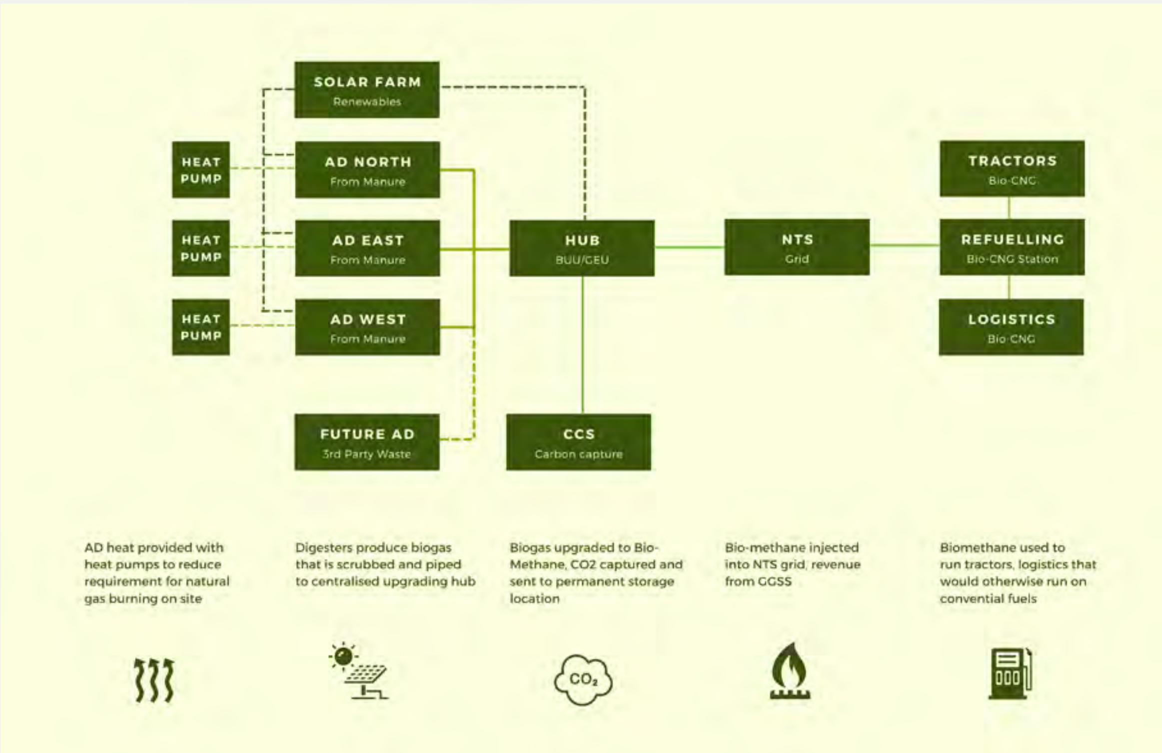


Figure 27: Integrating renewable technologies with AD for biomethane production

[94] For example, see Brewdog's plans to use AD CO_2 in their brewery

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The project will be a good example of integrating renewable energy systems, since the digester heating will be provided by ground/water source heat pumps. Electricity will be supplied using a private electricity network (SP Networks) which includes ~25 MW solar generation and batteries.

The hub will include a bio-CNG 'Mother Station' supplied from the NTS to allow farm tractors and trucks in the area to be supplied with biomethane. The aim is for no diesel vehicles on the farms from 2025. The hub, which will have no flare, will be designed with extra capacity to allow future AD's to be added to the network. There is a target of 10 AD plants by 2025, likely requiring 50 miles of dry biogas pipelines.

The initial AD plant will fund the hub upgrading, NTS injection and bio-CNG infrastructure. To join, smaller AD plants will only require dehydration and H_2S removal to condition the biogas before it is sent into the pipeline, thus making smaller mainly manure-based[95] AD plants more viable. This is further improved by eliminating the cost of a CHP and the need for a CHP.

It is envisaged that the heat pumps will be between 50 kWe and 120 kWe, depending upon the size of the digester and heat will be supplemented through digestate heat recovery. The heat pumps will provide sufficient chilling for condensate removal from the biogas and, at one site, will also be used to chill milk at the main dairy.

The British AD technology is capable of handling slurry from cows bedded on sand and it incorporates low energy mixing technology that further reduces energy demand.

In addition to biomethane injection at the Hub and use on the farm, the bio-CNG will be exported by trailer and available for use by logistics companies in the area, including those involved in food distribution.

Due to its combination of highly efficient heat pump technology, solar PV, battery storage, manure AD feedstocks, digestate production as a replacement for fossil fertiliser, biomethane tractors/heavy goods vehicles and grid use, the whole project will have an extremely low carbon footprint which will only improve as the electricity grid decarbonises even further.

[95] Under energy production incentives, small manure-based plants struggle to be viable. Dairy cattle slurry produces less biogas - ~ 25 m^3/tonne of slurry (manure ~80 m^3/tonne) - versus maize silage (and potential land use issues) in the region of 200 m^3/tonne of feedstock.

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5.5. Low carbon heat technologies

Farms require heat for a range of purposes e.g. grain and vegetable drying; produce chilling; controlled livestock environments; and - not to be forgotten – the farmhouse!).

Most, like many other rural businesses and homes, are not on the mains gas grid. Heating therefore has to be sourced through a range of fuel types – oil, bottled/tanked gas, diesel, biomass and electricity. The impact of using fossil fuels impacts notably on farm GHG emissions. Investment in renewable energy technologies, for heat and electricity, has led to significant reductions in manufacturing costs – the justification for the removal of Feed in Tariff (2019) for electricity production and the Renewable Heat Incentive (2021).

> "If we don't get heat sorted, we don't get to net zero."

Renewable heat technologies have some way to go to replace the fossil fuels used for this purpose on farms. The Climate Change Committee (CCC)/ Element Energy Report outlined a number of heating options and deployment levels in their balanced pathway in the UK's Sixth Carbon Budget (see Table 5). Some of these technologies will be more appropriate for rural areas. A discussion of all of these technologies is outside the scope of this report.

Cumulative deployment for selected technology groups k: thousands; m: millions	Balanced Pathway deployment [range across scenarios]					
Low carbon heating technology group	2022	2025	2028	2030	2040	2050
Heat pumps	70k [24k-70k]	240k [88k-260k]	1.3m [450k-1.5m]	2.7m [640k-3.2m]	10.5m [1.6m-16.1m]	16.2m [1.9m-20.2m]
Hybrid heat pumps	59k [0-59k]	210k [10k-240k]	450k [190k-800k]	570k [250k-1.4m]	3.0m [270k-6.2m]	4.8m [280k-11.0m]
Electric storage	7k [2k-8k]	23k [8k-28k]	56k [40k-150k]	110k [80k-340k]	390k [280k-1.9m]	490k [330k-3.3m]
Electric resistive	8k [2k-8k]	26k [7k-26k]	85k [45k-120k]	180k [89k-300k]	890k [310k-2.5m]	1.4m [370k-3.2m]
Hydrogen heating (boilers only)	0 [0-0]	0 [0-3k]	0 [0-12k]	0 [0-330k]	0 [0-6.6m]	0 [0-9.3m]
Hydrogen heating (boilers + hybrid H_2 heat pumps)	0 [0-0]	3k [0-75k]	12k [0-350k]	80k [0-1.1m]	2.2m [0-11.5m]	3.9m [0-18.8m]

Table 5: Cumulative deployment for selected technology groups. Source: CCC

Heating (and chilling) are energy intensive processes, and demand can be highly seasonally variable. Hence, heat storage, transfer and recovery are increasingly important, particularly where intermittent renewables are involved. Possible farm applications are discussed below, although it should be noted that uncertainty of long-term government support for heat decarbonisation makes it difficult for farm businesses to make investment decisions.

5.5.1. Heat pumps

A heat pump extracts natural heat from a medium using 'reverse-refrigeration' processes. The medium is typically air (air source heat pump - ASHP) which has a varying temperature; ground (GSHP) or water (WSHP) whose temperature varies less than air.

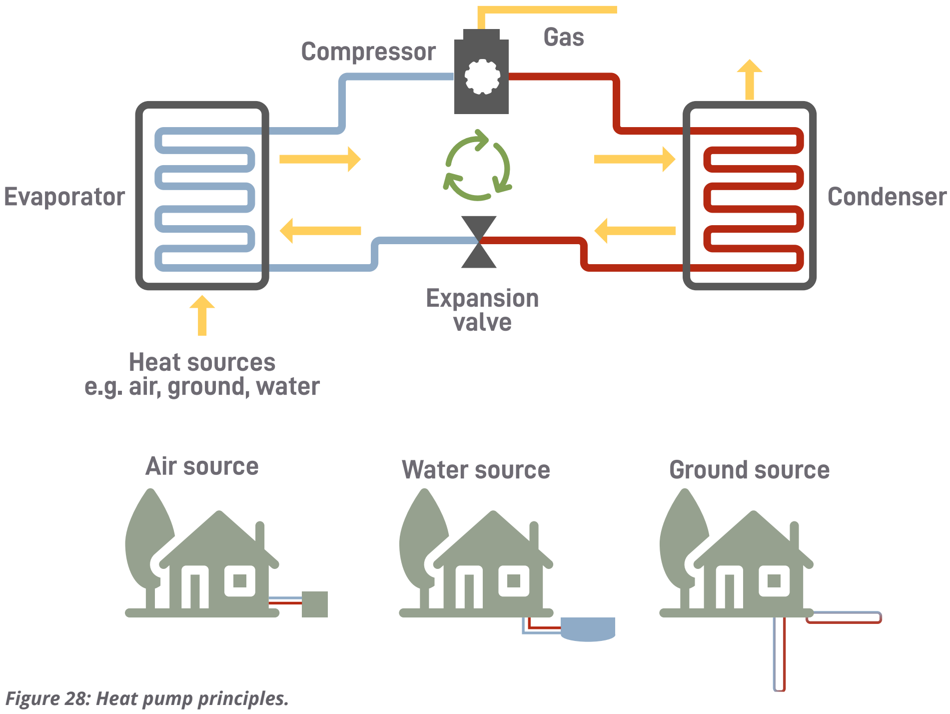


Figure 28: Heat pump principles.

A heat pump uses electricity to concentrate heat from the medium by using a vapour compression cycle. Heat pumps increase the temperature received from air/ground/water by compressing a refrigerant gas which heats up because the heat energy is concentrated into a small space. A heat exchanger transfers the heat to the heating circuit of the building. When the high-pressure gas gives up its heat, pressure is released through an expansion valve, whereupon it becomes very cold. Heat is then transferred to the cold coolant via the source.

ASHPs are typically 'air to water' (heat transferred in a hot water circuit) and less commonly 'air to air'.

All heat pumps have a 'coefficient of performance (COP)', i.e. the ratio of useful heat energy produced to the amount of electrical energy consumed. Thus, a COP of 3 means that the heat pump will supply 3 kilowatt-hours (kWh) of heat for every 1 kWh of energy that it uses.

A fossil boiler has a circuit temperature typically set at a default of 65 °C-70°C and could be sized using a set of relatively rough parameters since extra energy could be easily obtained by burning more fuel. With the low-grade heat of an ASHP which is around 35°C-50°C the design approach is different.

If an ASHP is retrofitted to a building, larger radiators may be required. Installers have to balance a number of factors to size the heat pump and optimise the installation. These include taking into account local climate, the heating circuit flow rate and temperature, the heat transfer from emitters (radiators/underfloor heating) and building losses from poor insulation and draughts.

A study of air and ground source heat pumps by Fraunhofer found that those retrofitted to buildings worked perfectly well with radiators, although systems with the highest efficiencies had the lowest flow temperatures (~35°C) and (typically) underfloor heating.

Figure 29: Air source heat pump

For an average UK dwelling, 2021 ASHP costs vary between £8000 - £18000 and are cheaper to install than GSHP or WSHP. The cost of heat pumps is still well in excess of a gas boiler. It is envisaged that costs will come down as more are installed; for example Octopus Energy has highly ambitious plans to drive the cost down to parity with boilers and have built an R&D centre to do that, as well as training installers and further optimising the technology.

The UK also ranks below the European average on gas prices and above it on electricity prices, a factor which further discourages electrification unless some self-generation is available.

The UK government has now confirmed that gas boilers will be banned from new housing in 2025, and all households will no longer be able to buy gas boilers from 2035. To encourage this transition to low carbon heating a Boiler Upgrade Scheme has been launched, which will offer UK households at least £5,000 towards the costs of installing a new air source heat pump from April 2022. It should be noted that the initial grant budget will be limited to £450m – equivalent to providing around 90,000 homes with a grant.

A ground source heat pump extracts ground heat through a system of pipes and a heat exchanger (powered by electricity) to the heat pump. It can be installed using a borehole or in shallow trenches. Because the ground acts as a large thermal store (both a heat sink and a heat source), the ground temperature varies much less than that of air and thus the COP variance is much smaller.

A ground source heat pump is very efficient: it can deliver 3 to 4 kW of heat for every 1 kW of electricity it consumes. For example, the COP of a GSHP with access to a ground temperature of 10°C (typically constant ground temperature at 10 m depth) will be significantly higher than that of an air source heat pump with access to -5°C from the ambient air.

This concept of utilising the earth as a heat sink by putting waste heat (e.g. from solar thermal, heat pump) from warm weather into the ground and retrieving it during times of cold weather works well with ground source heat pumps. It has been marketed by ICAX as 'Interseasonal Heat Transfer' and used for both heating and cooling.

A water source heat pump can extract heat from an underground aquifer or from a river or lake; again, water does not have the temperature variability of air. Professional advice is required in order to assess the geology and potential environmental considerations, as well as the heat pump design and installation.

The Wales and West 'Freedom' project converted 75 houses to use a combination of heat pump and gas boiler, coupled with a smart controller which predicted the user's needs. By switching between gas and electricity, this avoids electricity use at peak demand and can benefit from time-of-use pricing (i.e. utilising electricity at the cheapest times).

Further resources (including case studies) on heat pumps are available from many sources, including the Ground Source Heat Pump Association (GSHPA) and the Heat Pump Association, as well as from podcasts such as BetaTalk – The Renewable Energy and Low Carbon Heating Podcast. A series of case studies are available from the GSHPA and from the Element Energy report for DECC on heat pumps for district heating. This latter report is less applicable to farms, but an important option for off grid rural heating.

5.5.2. On farm heating/cooling options

A heat/chill heat pump system can be used to provide low carbon heat for a range of on-farm agricultural process, for example, grain or grass drying, space heating, daffodil drying, wood chip drying or any other type of agricultural product drying. The process can also be used 'in reverse' to chill products like potatoes or milk. The low-grade heat recovered can be supplemented and used for heat applications such as hot water and space heating.

At its Eastern AgriTech Innovation Hub, NIAB is trialling a number of renewable energy technologies and have installed an ASHP for both heating and cooling a large polytunnel. Dyson Farming's large strawberry glasshouse at Carrington, Lincolnshire is powered by renewable energy from the adjacent digester, as well as being supplied with waste heat from the site's combined heat and power (CHP) plant. It could potentially supply CO_2 in future.

Ventilation heat exchangers in livestock barns are an important way to recover heat from ventilated air. Such systems are less common in the comparatively temperate UK climate, as payback is faster in colder temperatures and with well insulated buildings. There is some excellent Canadian information on agricultural building ventilation systems which examines heating, cooling, ventilation, odour and biosecurity issues, with some general information here.

Championing the Farmed Environment (CFE) have compiled a list of free resources for UK farm building efficiency which includes information on heating. An excellent ammonia case study on heat recovery from air scrubbing[96] is available at the Pig & Poultry online forum.

Many farms take a 'whole farm' approach to reducing emissions, so their measures do not fall neatly into 'decarbonising heat', 'building soils' or 'renewable energy'. Two case studies which illustrate this are Stephen Temple's Norfolk dairy farm and that of Wyn Evans below.

[96] Heat exchange discussion starts at 28 minutes

CASE STUDY: Integrating Renewables for Farm Use on Caerfai Farm

Wyn Evans' organic farm on Caerfai Bay is a model for how integration of renewable energy on a small farm can mean that energy flows surprisingly seamlessly around the various farm enterprises.

The farm has a digester built in 1979 which uses slurry from 65 cows housed during winter and whey from the ice-cream and cheese-making operation. The farm also grows 2.5 hectares of potatoes.

Renewable energy technologies include a roof-mounted solar PV, thermal solar, a ground-source heat pump and a small 20 kW wind turbine. Biogas is used in an Aga with a back boiler, along with solar thermal and the GSHP. It is also used to heat dairy water[97].

Figure 30: Solar thermal on anaerobic digester building.

Heat is extracted from the potato store and put into a tank which is then supplemented either with solar PV or solar thermal to heat the digester. Solar thermal and solar PV are used for hot water heating for showers in the camp site.

The GSHP, solar PV, solar thermal, wind and biogas are used for ice cream and cheese making. The farm installed these renewables many years ago and the full case study was featured in the RASE Report 'A Review of Anaerobic Digestion Plants on UK Farms'.

Figure 31: Solar PV and rainwater recovery

[97] Heating water accounts for 23% of the energy costs on a typical dairy farm. Guide to water heating options for your dairy parlour, Farmers Weekly, 6 June 2019

5.6. Solar photovoltaics (PV)

Many farms have invested in solar photovoltaics (PVs) largely encouraged by the Feed in Tariff scheme introduced in 2010. Many farm barn roofs as well as ground-mounted systems are now operating and are providing a sound return on investment.

Figure 32: Roof-mounted solar on an agricultural building

Since the demise of the Feed in Tariff scheme, the number of small scale (i.e. sub 50 kWe) solar and wind installations on farms has declined significantly. However, reduced component costs (e.g. solar panels) combined with the steady increase in mains grid electricity costs and more cost-effective farm and grid scale battery storage solutions will still enable more farms to capitalise on the opportunity to supply 'home grown' or decentralised energy.

In total, solar PV capacity in the UK now sits at 14.6 GW, up 5.3% compared to 2020 levels. Solar Energy UK notes that all three solar markets - residential rooftop, commercial scale and ground-mount – are seeing stable growth without the assistance of subsidies[98].

Use of farmland for larger solar parks, occupying 25 ha or more, continues to expand – exporting to the national power grid or directly feeding into heavy electrical or transport demand hubs. Such installations will provide an increasing share of renewable energy to the national grid – along with onshore and offshore wind.

Figure 33: Solar farm used for biodiverse planting or potential under-grazing

In most cases, farms receive a negotiated payment per acre/hectare for the use of the land for between 25 – 40 years. But such sites need more emphasis on good installation practice demonstrating the balance in land use terms between technology, plant diversity and integrated livestock grazing.

Agro-photovoltaics (or Agri-PV) is a relatively new mounting technology which enables the use of agricultural land for both food production and solar power generation at the same time. Although these mounting structures are more expensive to begin with, the shading that the PV system provides can (in some areas) enable lower water use and higher crop yields, along with renewable energy generation.

Further advances in solar capture technology can be expected, as well as continuing reductions in the cost of components due to mass production or alternative, cheaper materials. Emerging innovations will include solar photovoltaic thermal hybrid panels (PVT) – with the capacity to generate both electrical and thermal energy. The installation of on-farm battery storage on a large (>1MW scale) will enable better management of grid demand and also provide an additional income source to farms.

[98] UK solar market shows strongest growth in six years, edie, 21 February 2022

Increasingly, small systems are being provided with battery storage to power increasing electrification of energy. Because of this, power inverters, which change DC to AC current, are changing, too. Solar panels modules are being increasingly integrated with micro inverters, particularly for bifacial modules, i.e., modules which can generate on both sides of the panel. Hybrid inverters for solar and storage systems are increasingly being added to PV supplier's portfolios. Panels have increased in power as well, with 500 watt modules becoming more commonplace and a 700 watt power module being unveiled at a recent technology event[99].

Since the degression (reduction in incentives) and the final demise of the Feed-In Tariff (2019), UK solar installation capacity has declined to single figures, growing in 2020 at a modest 4.6% in terms of generation[100] with installation potential predicted to be 20th in the global solar market to 2025[99].

Nevertheless, recent high energy prices have underlined the need for localised energy production; solar PV, coupled with battery storage is a critical gateway technology which enables the introduction of further farm decarbonisation measures (e.g. heating, small vehicles, pumping) through electrification.

CASE STUDY: Combining Wind, Solar and Storage Technologies to Maximise On-site Energy Use

Eocycle Technologies is a Canadian-based wind turbine manufacturer and systems integrator. Eocycle has reduced the Levelised Cost of Energy (LCOE) of smaller wind systems to below the tariffs charged for electricity in the US and Europe. As farms electrify, they are realizing that they need more capacity than the grid can supply.

Their solution is to bring together **Wind** plus **Solar** plus **Storage** (named WS2) which enables farmer generators to avoid exceeding their grid constraints. This effect is magnified as farmers strive for resilience and independence. Large agricultural corporates are eager to help their supplier farms in their decarbonisation efforts. Cost savings of around £170/tCO_{2e} can be made by farms that electrify (and this is excluding the better electricity tariffs they get from owning their own supply).

Distributed renewable energy infrastructure is a nascent, untapped investment opportunity, and an essential part of the process of decarbonizing agriculture and electrifying farms. Eocycle's WS2 solution, which consists of their patented wind turbine technology combined with solar and storage, is breaking grid parity and moving away from centralised, outdated power generation.

Electrification and decarbonisation is by no means the complete solution to reducing agriculture's GHG footprint. A diverse range of measures must be taken, from improving fertilisation practices to optimising animal feed mix. However, decarbonisation through on-farm electrification may be a cost-effective solution with immediate impact, allowing farmers to produce the world's food while protecting the planet.

Figure 34: Shropshire farm with EOS X-16 wind turbine producing 75,000 kWh/year.

[99] Global Market Outlook for Solar Power 2021-2025, Solar Power Europe, July 2021
[100] Digest of UK Energy Statistics, DUKES Chapter 6, BEIS, updated 29 July 2021

5.7. Farm-scale onshore wind

In the period 2010-2019, renewable electricity generation in the UK from wind power grew from 2.7% to 19.8%, with offshore wind exceeding onshore production towards the end of 2019.

By 2020, onshore and offshore wind together generated 75,610 GWh of clean electricity, accounting for 24% of the UK's total electricity output, with onshore wind accounting for 11%[101] – much of this located on farmed or managed land.

This technology will continue to play an important part in the UK's renewable energy mix – and provide an additional source of farm income and opportunity for business and community investment.

It can also be economic to combine solar PV, a farm-scale wind turbine (under 50 kWe) and battery storage for use on-site or for grid export. The addition of wind to solar PV systems can increase renewable generation over the year and better match the demand cycles, as many areas experience more wind in the winter months when solar PV output is minimal.

A small wind turbine makes an excellent addition to a solar PV system because the wind often blows in winter when the sun doesn't shine. Both technologies are amongst the cheapest forms of producing low-carbon electricity. The Climate Change Committee's projections require 22-29 GW of onshore wind capacity and 23-43 GW of solar by 2030 – and more by 2050 – compared to existing onshore wind and solar capacity of around 13 GW each in 2020[102].

5.8. Energy storage technologies - Contributed by Frank Gordon, Director of Policy, Renewable Energy Association

Energy storage (ES) technologies offer great potential for supporting renewable energy and the UK's energy system. In 2014 the (then) Department for Business, Innovation and Skills (BIS) named storage as one of 'eight great technologies the UK can be world leaders in'.

Good progress has been made but more research, development and commercialisation is needed to reach this potential. ES technologies are able to absorb and release energy when required and provide ancillary power services which help benefit the power system. The storage industry can therefore deliver tremendous benefits for power system stability and security of supply, as well as helping to decarbonise UK energy supplies.

Storage technologies offer flexibility during times of fluctuating energy generation e.g. from wind and solar, and demand (daily and seasonal). This makes energy storage technologies an important part of a low carbon network. In addition, there are significant economic benefits – the landmark National Infrastructure Commission Report 'Smart Power' projected a possible £8 billion saving to the UK per year by 2030 if storage and flexibility measures are introduced on a large scale. This also highlights the role of energy storage as one of a range of measures for increasing flexibility.

[101] Wind energy in the UK, June 2021, Office for National Statistics
[102] CCC welcomes Government re-commitment to onshore wind and solar, CCC, 3 March 2020

Storage can help deliver the low carbon energy the country needs and it is therefore vitally important that it is appropriately incentivised and supported.

Storage technologies can be deployed at different scales on a distributed (i.e. 'local') and/or centralised basis. The development of energy storage technologies varies across the industry. While some are quite mature, others are still in their development stages. There is significant investment in energy storage around the globe and the UK is now in something of a technology and deployment race.

For the energy storage industry to develop rapidly and the UK to gain the huge benefits possible as a result, the Government, grid operators, industry, the manufacturing supply chain and stakeholders need to work together to take action to support it.

Figure 35: On-farm battery storage

In particular on farms, battery energy storage can be installed in a range of settings from barns to standalone containerised units and can be used to store excess electricity generated renewably on site for use later – in order to avoid buying costly power at a later date – or to use directly as a source of power (e.g. produce drying, lighting, heating) and charging electric vehicles.

This may become even more important as the UK's energy system decentralises and 'Time of Use Tariffs' become more common. Such tariffs (much like sophisticated Economy 7 tariffs) will reward those able to shift when they draw electricity from the grid. This provides a commercial incentive to store electricity. It is also possible to use some (but not all) energy storage systems to provide uninterrupted power supply systems (UPS) in the event of power cuts – as frequently happens on more isolated farms and rural communities.

Energy storage costs are falling rapidly, with Bloomberg NEF finding that there has been more than a 73% fall in Li-ion battery pack costs since 2010[103]. Costs are expected to fall further over the next decade – driven to a large extent by the market growth of electric vehicles.

Future demands from heat pump installations (section 5.5.1 above) are predicted to drive demand for both electrical and thermal storage. Scottish technology company Sunamp provide such thermal storage technology using phase change material (see Sunamp case study below).

[103] Lithium ion battery costs and market, Claire Curry, Bloomberg, 5 July 2017

CASE STUDY: Sunamp thermal storage

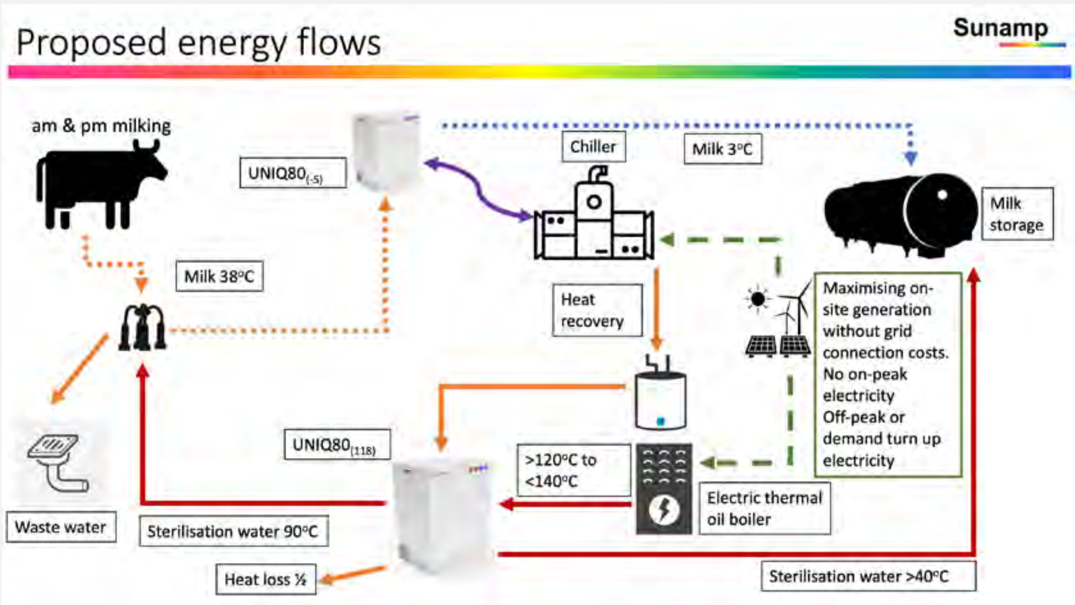
Scottish company, Sunamp use 'Phase Change Materials' in thermal stores for waste heat and cooling applications, heat and cooling networks and renewable energy applications. Their thermal storage units can operate from -30°C to 285°C and range from briefcase to shipping container size to provide heating, cooling and hot water provision on demand.

Dairy farms across the globe have a hot water and chilling requirement for milk processing. In the majority of cases, this requirement is provided from electricity via an electric hot water cylinder and electric powered chiller supplied from the grid at on-peak electricity rates.

Dairy farms can utilise Sunamp's thermal storage in conjunction with either off-peak or time of use/ flexibility tariffs and/or embedded renewable generation to provide revenue savings to the farmer and low carbon emissions, which could provide the farm business with positive branding opportunities.

Dairy farms have typically large energy demand peak requirements, inter-spaced with long periods of low energy demand consumption. This lends itself well to the use of energy storage and embedded on-site generation systems. The proposed solutions aim to provide long-life resilience and decoupling from reliance on grid electricity, thereby stabilising dairy farm energy costs for decades into the future. The technology proposed is reliable with multi-decade lifespans.

A simplified solution using Sunamp's thermal storage is set out below.



The key points of the proposed on-farm application are:

1. The storage is sized to meet the peak milking demands.
2. Any existing surplus embedded renewable electricity generation is routed to charging the UNIQ80(-5) or UNIQ80(118) battery.
3. New embedded generation is installed, but without a grid connection (thereby saving that cost) and connected directly to the electric boiler and chiller to charge the battery. A DC connection could also be explored as potentially this could offer further savings.
4. The dairy farmer is encouraged to move to a flexible off-peak/time of use tariff linked to electricity grid demand. For example, there is significant grid constraint in Scotland and shifting the site's electrical demand is valued in these circumstances.

5.9. Hydrogen

There is no 'natural' source of hydrogen, so it is produced in the UK most commonly by steam methane or auto thermal reforming (49%), partial oil oxidation (29%), gasification (18%) and electrolysis (4%)[104], although it can be produced through a number of other methods such as certain biological processes (creating 'biohydrogen').

In steam reforming, methane is first heated with steam at high temperatures, then processed further to produce hydrogen and CO_2.

This is a standard process which is known as 'grey' hydrogen. If the CO_2 is captured, some emissions are mitigated and the resultant hydrogen is known as 'blue' hydrogen, although its low carbon credentials when compared to the status quo are subject to debate[105].

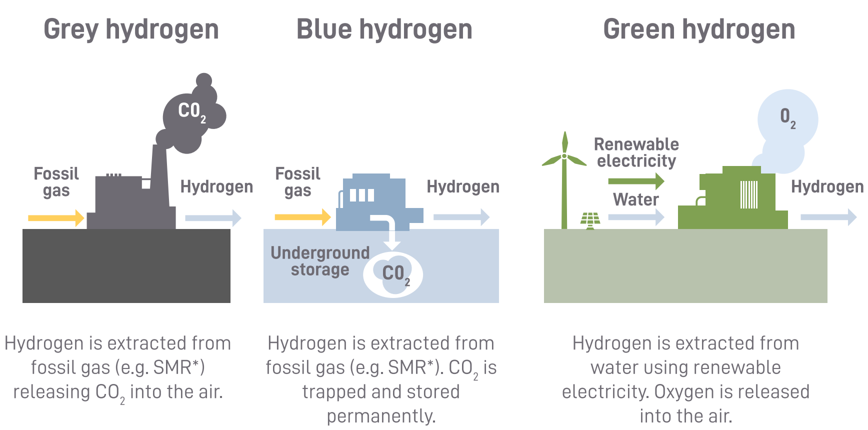
Whilst there are other colours of hydrogen (black, brown, pink, turquoise, yellow) named due to their various feedstocks and production processes[106], green hydrogen is the method with minimal greenhouse gas emissions, produced using clean electricity from renewable sources (primarily wind/solar) to electrolyse water (H_2O) to oxygen and hydrogen.

The UK government published its hydrogen strategy in August 2021, referring to 'critical decisions being made...on the potential for use of 100 per cent hydrogen in heating in the mid-2020's...potentially reaching right into people's homes', but also reiterating the 'need to be flexible in how we decarbonise heat in buildings given the diversity of heat demand across different building types and geographies'[107].

Nevertheless, government's own predictions show that by 2030, demand for low carbon hydrogen heating will be relatively low (less than 1 TWh – about 0.2% of the UK's total domestic heating/hot water demand of about 457 TWh – 39.3 Mt of oil equivalent in 2020[108]). The strategy states an expectation of 45 TWh of hydrogen for heating by 2035 or circa 10% of UK domestic demand but the majority of this will be utilised by large energy-intensive industries.

This work is of course mainly predicated on getting hydrogen to homes using the existing gas network and as noted above, many rural properties do not have access to the gas network. Even where households are connected to mains gas, work by the UK Energy Research Centre (UKERC) shows hydrogen is unlikely to play a significant role for heating homes before 2030[109] and that a combination of energy efficiency, heat pumps and district heating are likely to be the 'least cost' approaches for heat decarbonisation over the next decade.

Most hydrogen applications are not expected to have a major role in farming and rural communities as they will require large-scale



**SMR: steam methane reforming*

Figure 36: Types of hydrogen

[104] Future Energy Scenarios, pg 101, National Grid ESO, July 19
[105] Carbon from UK's blue hydrogen bid still to equal 1M petrol cars, The Guardian, 22 August 2021
[106] The hydrogen colour spectrum, National Grid
[107] UK Hydrogen Strategy, BEIS, August 2021
[108] Energy Flow Chart 2020, BEIS
[109] The pathway to net zero heating in the UK, UK Energy Research Centre (UKERC), October 2020

hydrogen production. For space heating and transport applications, hydrogen is generally not regarded as good as direct electrification alternatives, with electricity-to-useful-energy efficiencies of approximately 10% (light trucks) to 35% (boilers), translating to electricity requirements that are 2-14 times higher[110].

The CCC predict zero hydrogen boiler installations (with a range from 0-9.3 m across all decarbonisation scenarios) in their balanced pathway deployment by 2050 (see Table 5). However, vehicle power applications in fuel cells and H_2 adapted engines are potential opportunities (see JCB case study).

5.10. Digital technologies and renewable energy

Although technology is still developing, the UK is in a favourable position with its increasingly 'smart' and 'flexible' electricity grid, which uses technologies such as artificial intelligence (AI), smart devices and digital control dashboards to match demand with supply.

The nation's power is increasingly sourced from distributed electricity generated from intermittent renewables (e.g. wind and solar) and storage (e.g. batteries; pumped water storage). Such innovation enables farm businesses to adjust their electricity requirements to take advantage of on-farm generated and stored power or cheaper off-peak tariffs.

A 'time of use (TOU)' electricity tariff (such as Octopus Energy's Agile tariff) encourages electricity users to shift demand away from peak use periods (typically 4-7 pm), particularly if they have equipment which can use significant amounts of electricity, such as heat pumps, electric vehicles, battery storage, large pumps, motors, etc.

Such 'pricing encouragement' changes consumer behaviour. These tariffs can be coupled with simple electric or appliance timers, various 'Internet of Things (IoT)' devices, simple wireless smart plugs, smart vehicle chargers and more to allow access to the cheapest tariff.

If a TOU tariff is coupled with on-site generation (e.g. from PV) and/or battery storage, the business can use smart devices to optimise its energy production and usage in order to save the most money. For example, on a winter's day, a business might find it more cost effective to direct limited daytime solar PV to farm office electricity usage and heat hot water in the very early morning using an immersion heater and a low electricity tariff. This is particularly important in rural areas where many farms and some communities still lack a resilient electricity supply.

Community energy cooperatives have worked with landowners to develop renewable energy projects and are an important part of rural decarbonisation activities. Groups such as Sharenergy and the Westmill Solar and Wind Farm Cooperatives have developed projects which allow communities to have a stake in local energy production, keeping money in the communities that invest.

Technology companies such as Limejump use their technology platform to aggregate smaller renewable energy producers into a large 'virtual producer' to leverage the best returns. This is the next level from the 'farm co-operative'. Limejump both manage varied renewable energy producers (wind, solar, AD, hydro, etc) via power purchase agreements (PPA) and support the National Grid to maintain a resilient electricity grid. Such aggregation, via digital platforms, data analysis and artificial intelligence is an important part of maximising investment returns in renewable energy for farm businesses.

With electric vehicle batteries essentially acting as 'mobile electricity storage', any excess energy could be used for other applications on the farm or put back into the grid ('vehicle to grid, V2G'), conceivably being accounted for with other generation, either directly using smart systems to maximise the export tariff or even via an aggregator.

[110] Potential and risks of hydrogen-based e-fuels in climate change mitigation, Ueckerdt, F., et al., Nature Climate Change, Vol 11, May 2021, 384-393.

5.11. An introduction to financing farm energy decarbonisation - Contributed by Matthew Stamp, Investment Analyst, Leif Capital

Farms are electrifying. Agriculture is decarbonising. With roughly a quarter of the world's population employed in farming, the changes afoot affect us all. The GHG footprint of agriculture has become too large to ignore, with 27% of global GHG emissions resulting from agriculture, forestry, and land-use.

The steep increase in climate goals and net zero commitments in the private and public sectors is adding pressure across rural supply chains. Much of this pressure is falling on the shoulders of farmers. They are being told to strive for sustainability whilst their margins are being squeezed, with higher energy prices and commodity prices steadily declining.

The climate emergency has triggered a worldwide mobilisation to develop emission reduction technologies within agriculture, and the investment community is taking notice. Venture capitalists and banks alike have been investing millions in soil tech, data gathering software and electric equipment to accelerate this sustainable transition in farming.

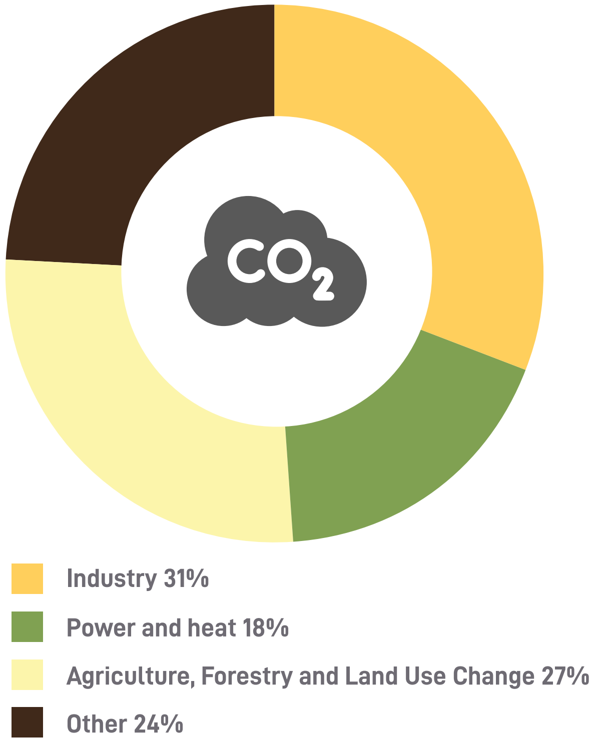
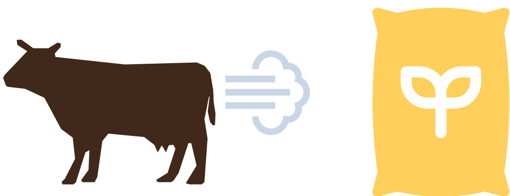


Figure 37: Total greenhouse gas emissions by sector, %

Nonetheless, sustainable progress has faced some barriers.



Firstly, there are billions of farmers to engage globally, and it is difficult for new farm practices and technologies to reach small-scale farms around the world. Secondly, the most potent GHGs like methane and nitrous oxide come from processes which are proving difficult to optimize sustainably, such as enteric fermentation and synthetic fertilisation.

Solutions often appear capex intensive. However, methane and nitrogen emissions may be distracting farmers from efficient, cost-effective solutions that can be implemented now.

A report by McKinsey Agriculture and Climate Change; Reducing emissions through improved farming practices published in April 2020 identified the top 15 measures for reducing potential emissions on farms using their own global agriculture marginal abatement cost curve (MACC).

The report stated that adopting zero-emissions on farm machinery and equipment had the largest amount of on-farm emissions abatement potential, with reductions of 537 Mt CO_{2e}, at a huge cost savings of £170/t CO_{2e}. The decarbonisation of agriculture, through the electrification of farms, is the easiest win for the farmers. But it's being overlooked.

Farms can reduce emissions and costs in one fell swoop. The US EIA's Annual Energy Outlook unsurprisingly predicts there will be more than a 30% increase in electricity demand by 2050. This trend will be accelerated by the electrification of farm equipment. So, how do farmers access cheap electricity sustainably? The answer is – distributed renewables! Distributed, 'behind-the-meter' (i.e. energy produced and used on-site) renewable energy is a new asset class which presents some attractive opportunities.

- **For owners**, such energy systems give them more control over their longer-term electricity tariffs, providing them with resilience and energy independence from the grid.
- **For investors**, the behind-the-meter tariffs could enable a higher return than a conventional windfarm or solar farm.
- **For utilities**, the systems can solve the problems of quality of electricity supply at the edge of the network and avoid expensive network upgrade costs.

This is a potential win-win-win situation, so why do investment analysts think that there is a real opportunity now? Primarily, these systems have become more cost effective. Leif Capital's report on Electrifying Farms, Decarbonizing Agriculture highlights a number of venture-backed start-ups involved in the sustainable transformation of farming, and includes Eocycle Technologies, for which a case study is presented above.

The electrification of farms through the installation of distributed energy infrastructure remains an untapped investment opportunity and is an essential part of the process of decarbonising agriculture.

6. ALTERNATIVE FARM FUELS, POWERTRAINS AND AUTOMATED VEHICLES

This section looks at the prospects for non-fossil fuel replacements for diesel as the main power source for farm vehicles and machinery. It considers the options available now and in the future – as well as the likely asset and fuel costs that may result.

As diesel tractors become more expensive to run due to recent fuel price rises as well as the eventual removal of the red diesel subsidy, alternative low emission drivetrains have started to appear either as market ready vehicles e.g. biomethane - or prototypes e.g. electricity, hydrogen.

Smaller electric farm vehicles, such as quad bikes and telehandlers are increasing in number, bringing the opportunity to maximise the use of on-farm renewable electricity generation. When hydrogen supplies become more accessible, fuel cell, hydrogen internal combustion and hydrogen/diesel hybrids will appear.

6.1. Vision for decarbonising agricultural vehicles and fuels - With input from Jonathan Wheeler - Freelance photo-journalist at Wheeler Woodhouse Limited

The rural transition away from fossil fuels needs to include the replacement of diesel as the main vehicle fuel on farms and elsewhere. If the rural economy is to play its part in the reduction of emissions of carbon dioxide, nitrous oxide and diesel particulates, it needs to develop a pathway to replace diesel, with low and zero carbon fuels. While it is unlikely that there will be a single replacement fuel, the industry needs a strategy for diesel replacement.

Click here to read the full vehicle specialist paper

This requires clarity from policy makers, including on targets for on-road and off-road farm vehicles and the transition to clean technologies that includes lower and zero emission gas fuels and radical changes in vehicle design. In some respects, the basic design of systems used on farm have changed very little since the first mass-produced tractors were sold, apart from becoming much more complex and heavier, in the past few decades.

Funding and policy support is needed with some urgency if the vision for the productive and low emissions farm of the future (efficient, sustainable, safe) is to be realised.

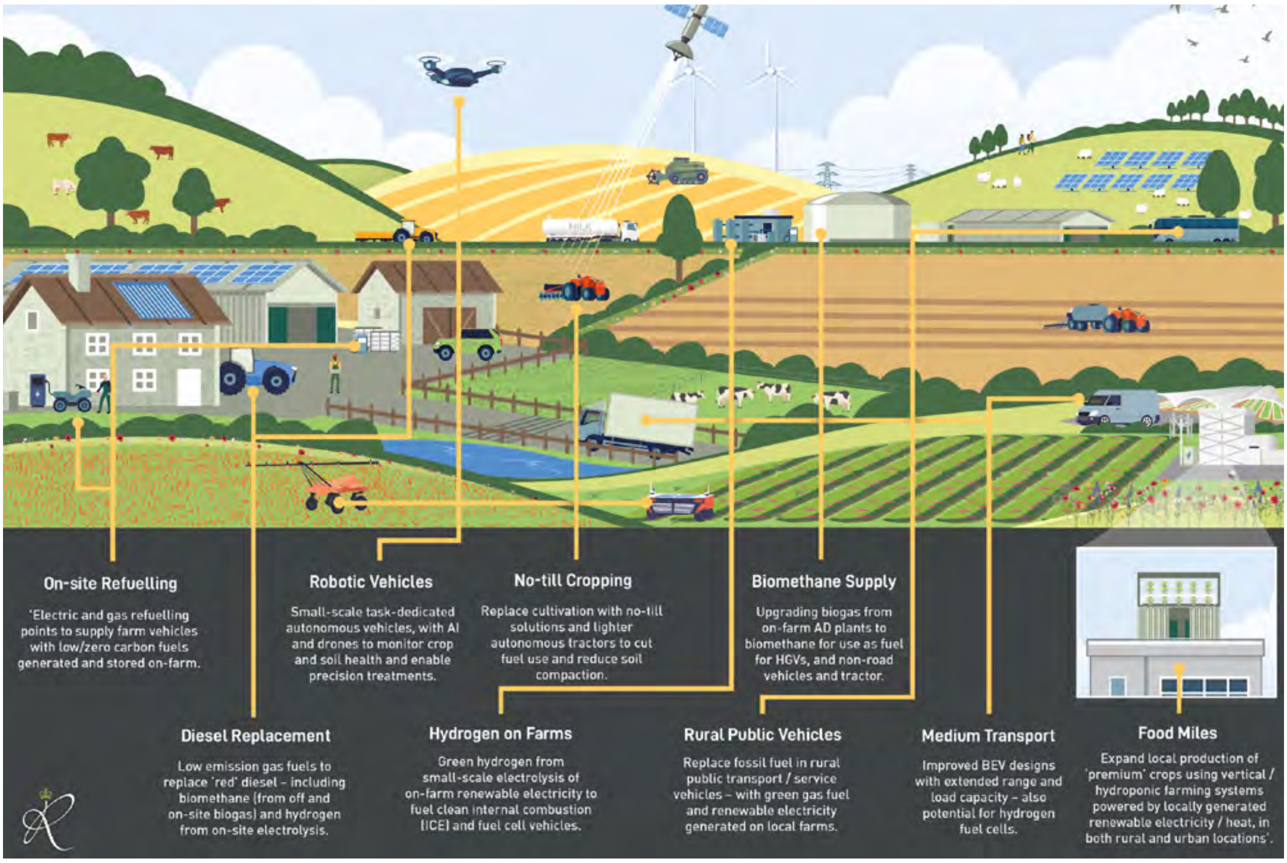


Figure 38: Low emission vehicles, fuels and powertrains

Plans for the replacement of red diesel on farms must be addressed with some urgency. Alongside the transition to smaller and low ground pressure vehicles, there are a number of options for farming's 'fuel of the future'. Electricity, biofuels (in liquid or gas form) and hydrogen are the main options. In the medium term, it is unlikely that one fuel will predominate, and a mix of gas and electric power trains will emerge.

Agriculture also has the capability to play a significant role in the supply of replacement fuels for diesel. It can be much more than just a supplier of raw materials for biofuel blends. **With a range of gas power train options being developed, farms can become green fuel providers for their own vehicles** – and there is also the potential to provide a service for rural businesses and communities.

The key points that need to be highlighted to policy makers, regulators and other stakeholders include the following:

- **Replacement of diesel as the prime fuel for the rural non-road, heavy vehicle sector should be a priority for regulators and vehicle manufacturers.** Improving how the industry can reduce its vehicle emissions (whether in livestock or cropping sectors) is dependent on commercial viability but also access to on-farm energy supplies.
- **Policy failure to include agriculture in the replacement pathway for red diesel is a major oversight.** Diesel's time is limited, and like many other industries, agriculture has to figure out what will replace it as the primary fuel for vehicles used on farms.
- The industry needs to start to move away from fossil fuels before 2030, with adoption ready solutions already in place. These include supply of biomethane (on or off-grid) from farm AD and wider deployment of other gas fuels in non-road vehicles.
- Non-fossil gas fuels offer better potential for farm transport and machinery, having a higher energy density than electricity and offer a short and long-term option for non-road vehicles. Compressed biomethane (bio-

CNG) can be produced locally on farms, is affordable and can make use of existing infrastructure with less inflationary impact than BEV solutions.

- The industry must look beyond increasing farm vehicle size to other solutions such as controlled traffic systems to prevent soil compaction. **Alongside minimum or zero tillage, the role of autonomous or robotic vehicles, along with gantry technology will increase.**
- Smaller, robotic machinery platforms can operate very efficiently with renewable electricity generated on farm (from solar panels, wind turbine or biogas combustion). For heavy traction, another option will be hybrid tractors that make use of more than one fuel source e.g. gas and electric.
- Demonstration is key to farmer adoption and delivering systems change. **Field scale trials and on-farm demonstration events for low and zero emission vehicles are an excellent way of encouraging change and should receive external funding support.**
- BEIS and DEFRA should support the further development and roll out of proven non-fossil fuel technologies already available on farms, such as biomethane. **This will require a change of policy to boost green gas production on farms.**

6.2. The net zero transition: fuels, technologies, markets and infrastructure - Contributed by Dr Nick McCarthy and Keith Budden, Cenex[111]

6.2.1. Asset and fuel choice for farm vehicles

It is essential to consider vehicle or infrastructure asset replacement cycles. Given that many farm vehicles have working lives of 15 to 20 years, capital investment decisions in the next decade will have limited opportunities for revision before 2050. Although the business case for gas fuels may seem straightforward to the end-user, fuel suppliers need to justify the capital investment over an extended period. Moving away from CO_{2e} emitting fuels on farms is reliant on investment cycles and access to low carbon power trains.

Fuel technologies – and their impact upon vehicle design and powertrains – are at various stages of their development. Diesel has had the greatest influence on farms of course – with petrol and tractor vapourising oil (TVO) also featuring in the early development of farm tractors. The need for transition away from such fossil fuels has triggered the development of alternative, low emission fuels and is leading to the redesign of powertrains for tractors.

The emergence of digitally controlled driverless (autonomous) technology and the need for more environmental and resource-sensitive field operations will lead to a revolution in vehicle design. With a move to low or no-till agriculture, lighter, smaller automated vehicles which are more suitable for electrification could become more widespread on farms and in horticultural enterprises.

The energy requirements of large farm vehicles make the use of battery electric technology unlikely in the near term as they would require huge and heavy batteries, regular high-power charging or battery swapping - all of which are impractical in a rural farm setting. (A detailed energy assessment for farm vehicle technologies and fuels can be found in the specialist paper.)

It is unlikely that the UK farm sector will be able to go through multiple transitions from fossil-fuelled internal combustion engines (ICE), to FAME (fatty acid methyl esters, i.e. biodiesel derived from renewable sources), to biomethane and eventually to hydrogen used either in ICE or fuel cell systems.

[111] Cenex, the Low Carbon and Fuel Cells Centre of Excellence, is an independent non-profit research and consultancy

More likely, due to long asset replacement cycles found on farms, only one or two transitions are likely before 2050. Coordinated planning of technology change (including by vehicle manufacturers) will help justify investment in selected technologies (such as gas fuels), help assure supply chains, and drive down unit costs for farmers and growers.

Industry bodies and the UK government can provide leadership in this area. **With the path to zero emission tailpipe vehicles still relatively unclear for non-road vehicles, biofuels and biomethane offer a short-to-medium term opportunity to reduce carbon emissions now.** These 'bridging fuels' can provide significant CO_{2e} savings in the short-term, while zero emission technologies improve, and battery and fuel cell prices fall.

Figure 39: JCB telehandler

Given the long replacement cycle for farm vehicles and the fact that under 15,000 tractor units (including compacts) are sold each year in the UK[112], there should be greater scope for retrofitting cleaner, dedicated biomethane/bio-CNG engines.

This has already a proven technology as demonstrated by the JCB hydrogen ICE engine prototype planned to be installed in new JCB diesel backhoe loaders in 2023, also suited to retrofit.

ICE retrofit design and systems should be encouraged amongst engine manufacturers, not only as a means of keeping older (and perhaps vintage) units going.

Fuel	Factor	Tractor
Biodiesel - FAME	Operational	(amber)
	Emissions	(green)
	CapEx	(red)
	OpEx	(amber)
Biodiesel - HVO	Operational	(green)
	Emissions	(green)
	CapEx	(green)
	OpEx	(amber)
Diesel/Petrol - Electric Hybrid	Operational	(grey)
	Emissions	(grey)
	CapEx	(grey)
	OpEx	(grey)
Electric	Operational	(amber)
	Emissions	(green)
	CapEx	(red)
	OpEx	(green)
Alternative hydrocarbon-based fuels	Operational	(amber)
	Emissions	(green)
	CapEx	(amber)
	OpEx	(amber)
Hydrogen	Operational	(grey)
	Emissions	(grey)
	CapEx	(grey)
	OpEx	(grey)

Table 6: Traffic light assessment of potential fuel options. Source: Cenex

The RTFO (Renewable Transport Fuel Obligation)[113] should encourage the shift to bio- and gas fuels in the next decade. Their operational similarities with fossil fuels will aid uptake as they require little change to adopt them. Renewable generation on-farm can improve the business case for battery powered tractors. It may also be possible, with dual-fuel or hydrogen ICEs plus development of better supply and refuelling infrastructure, to envisage a modest role for on-farm hydrogen over the same period.

A comparison of the potential alternative fuel options has been carried out for tractors as an example. Table 6 highlights the current situation. A red/amber/green (RAG)[114] reporting system is used.

[112] Tractor statistics, Agricultural Tractor Registrations (>50hp): Monthly 2020-2022, AEA

[113] The Renewable Transport Fuel Obligation (RTFO) applies to all fuel suppliers - to meet their obligation in they can either claim Renewable Transport Fuel Certificates (RTFCs) for supply of renewable fuels, or pay a fixed sum for each litre of fuel to 'buy-out' of the obligation

[114] RAG reporting uses a traffic light system with 'red' representing an alert, amber representing caution and green indicating that things are 'on track'.

It is anticipated that in the next five years, HVO (hydrotreated vegetable oil or 'renewable diesel') and electric hybrids will become increasingly attractive as will alternative gaseous fuels such as CNG (compressed natural gas) and bio-CNG. It is expected that electric tractors will become more available and cost effective for lighter farm or horticulture duties.

The long term zero emission option of hydrogen is still many years away, the key challenge being access to an affordable and easily accessible supply of green hydrogen (via electrolysis) at a farm level to fuel initially ICE hydrogen engines and eventually fuel cell/electric hybrid tractors.

In choosing potential low carbon vehicles, farmers need to take into account a number of considerations with regard to the fuel, vehicle size and use patterns, the capital and operating costs of the equipment and the infrastructure requirements. This is a market that is rapidly changing. Table 7 below provides an overview of the current technology options for tractors.

Table 7: Summary of tractor fuel technology maturity, emissions, costs and operational considerations

Tractor technology options (Cenex, 2022)	
Technology Maturity	• **Biodiesel (FAME / HVO)** – Currently available. • **Diesel/Petrol - Electric hybrid** – Not available. • **Electric** – Small tractor ('compact') only. • **Alternative hydrocarbon-based fuel** – Large tractor (agricultural) using CNG. • **Hydrogen** – R&D prototypes only. **Biodiesel, electric & alternative hydrocarbon-based fuels are** reviewed in more detail below.
Operational restrictions and benefits	**Biodiesel FAME** Increased maintenance regime; mineral diesel fuel and engine flush required before storage. Fuel quality requires monitoring and managing. **Biodiesel HVO** HVO is a 'drop-in' equivalent for diesel fuel. **Alternative hydrocarbon-based fuel (e.g. biomethane)** CNG/bio-CNG tractor requires a CNG/bio-CNG refuelling station, either on-site or within close driving range. Operating time is reduced significantly with on board CNG tanks. Ongoing development of LNG tanks on tractors will address this. **Electric** Reduced maintenance and operating costs resulting from the elimination of many service points compared to diesel machines. Operational time is limited (see below). Small 'compact' tractors only with c15 kW electric motor for small and light-duty work e.g. horticulture
Operating time	**Biodiesel** The same operating time as diesel. **Alternative hydrocarbon-based fuel (e.g. biomethane)** Agricultural tractor example: CNG/bio-CNG tractor requires a CNG/bio-CNG refuelling station either on site or within close driving range. **Electric** Compact example: Farmtrac FT25G with electric indicative run time of 6 hours.

Tractor technology options (Cenex, 2022)	
Refuelling/ recharging time	**Biodiesel** Same refuelling time as diesel. **Alternative hydrocarbon-based fuels (e.g. biomethane)** Same refuelling time as diesel. **Electric** For example, the Farmtrac FT25G electric 240V has a 5-hour recharging time using a standard 32-amp outlet.
Emission reduction	**Biodiesel FAME** Emission reduction variable depending on blend (circa 18% wheel-to-wheel WTW CO_2 reduction available from B25 blend). Engine design, fuel quality and operational cycles essential in assessing total emissions with biodiesel – with some authors reporting increases in emitted NOx, particulates and CO. **Biodiesel HVO (unblended)** Circa 91% WTW[115] CO_2 reduction available. **Alternative hydrocarbon-based fuels (e.g. biomethane)** CO_2 emissions reduced by 10% from CNG. Biomethane CO_2 emissions depend on production route, but typically near zero. Very significant particulate matter (PM) and NOx reduction. **Electric** Zero at tailpipe, zero TTW[116] emissions, WTW CO_2 emissions depend on energy generation, using grid rechanging the savings typically ~50-60% (based on DEFRA UK 2020 emission factors).
Additional notes	**Biodiesel – FAME** Manufacturer approaches vary depending upon emission stage e.g. all John Deere engines can use biodiesel blends. Stage V engines operated within the European Union may use blends up to 8% (B8). Concentrations up to 20% (B20) can be used for all other John Deere engines providing that the biodiesel used in the fuel blend meets EU Standard (EN) 14214. **Alternative hydrocarbon-based fuels (e.g. biomethane)** Large (agricultural) tractor e.g. New Holland T6.180 Methane Power used to illustrate. It is the only biomethane option currently available in the UK (2022). **Electric** Smaller (compact) battery powered tractors e.g. FarmTrac FT25G electric provides an illustration. It is the only compact tractor option available currently in the UK (2022).

[115] Well to wheel (WTW) emissions include all those related to fuel production, processing, distribution, and use.
[116] Tank to wheel (TTW) emissions are a subset of WTW emissions and are calculated from the point at which the vehicle's energy is absorbed (charging point; fuel pump) to the point of discharge (i.e. in motion)

Tractor technology options (Cenex, 2022)	
Cost analysis	**Diesel** In the 2020 Budget, the UK government announced that it would be removing the entitlement to use red diesel from non-agricultural non-road mobile machinery (NRMM) in April 2022. No announcements have been made for the removal of subsidised 'red' diesel for agriculture. **Biodiesel - FAME** **Plant Costs** – For high biodiesel blend use, manufacturers may require a biodiesel upgrade package to be installed, typically costing several hundred pounds. For B100 use, the vehicles require a conversion to include a simple system for warming the fuel. Various conversions are available either at factory or retrofitted. These typically cost from £6,000 - £8,500 per vehicle. These are not likely to be available for small plant such as ATVs. **Fuel Costs** – Comparable to road diesel. **Maintenance Costs** – Some vehicle manufacturers suggest modified routines such as increased fuel filter and oil changes. **Infrastructure Costs** – Biodiesel blends up to B30 can be stored in and dispensed from existing infrastructure for diesel vehicles at no extra cost. B100 however needs to be kept at an appropriate temperature to ensure it remains liquid in the colder months. This will result in some heating costs. **Bio-diesel - HVO** **Vehicle Costs** – No impact on vehicle cost. **Fuel Cost** – Cost of fuel per litre is typically higher than road diesel. **Maintenance Costs** – Identical to those of diesel vehicles. **Infrastructure Costs** – No specialist equipment is needed to store HVO. **Alternative hydrocarbon-based fuels (e.g. biomethane)** Research suggests a 10% price premium for such systems. **Fuel Costs** – New Holland suggest a 30% reduction, but this is dependent upon CNG/biomethane prices. As a reference, a price quoted (Bennamann-Corserv) is £0.60 per kg. **Electric** **Machine Costs** – Research suggests a significant price premium. As an example, a FarmTrac FT25G fully electric costs are around 100% higher than its diesel equivalent. **Fuel Costs** – Estimated running cost for operators using an industrial electricity supply will be around 50% lower than for 'red' diesel and up to 60% lower than if using 'white' diesel.

6.2.2. Biodiesel and biomethane market demands

Biofuels are limited in the amount of energy they can supply to the market. It has been suggested that biomethane can contribute 30% of the UK's 2030 legally binding carbon targets[117]. In the next decade, biofuels will be readily available for use in rural transport. This may not continue beyond 2030 as other market sectors seek to reduce their emission profiles.

However, the limited period of low competition for biofuels is not a justification for inaction in the agricultural sector. The move away from diesel use on farms needs to gain greater momentum and the industry must change but based on adaptation rather than revolution.

[117] Biomethane: The Pathway to 2030, ADBA, March 2020

While UK food supplies cannot be put at risk, farmers need solutions for the next 20 years, including those based on the existing ICE engine technology.

There is a diminishing window of opportunity for cost-effective use of biofuels, due to the adoption of increasingly strict emissions legislation and increasing competition for biofuels across all market sectors. **This has implications for low margin sectors like farming and hence there is a need to deploy farm produced biomethane as an early diesel replacement.**

Also, there is a need to reassess the benefits of continued use of the internal combustion engine (ICE) on farms. Organisations that can make the financial and operational justifications for biofuels adoption today should do so as well as highlighting the wider potential of gas fuels.

6.2.3. Battery electric vehicle (BEV) infrastructure costs

The transition to electric vehicles on farms has started – mainly on horticultural enterprises (e.g. compact tractors and with smaller farm machines such as quadbikes and small telehandlers). On-road electric cars and vans are also growing in popularity. In the near future, driverless vehicles (e.g. robots and gantries) will be powered by electricity. For this transition to succeed, accessible and reliable power supplies 24/7 – either from the grid or from on-farm renewables such as solar or wind – will be a co-requisite.

BEV charging infrastructure costs can be high and there are issues caused by the lower demand in dispersed rural areas and the weaker grid capacity often found in remoter areas. EVs can be charged either by using AC (grid) or DC (i.e. battery) electricity. There is good potential for on-farm DC microgrid systems to maximise on-site renewable electricity generation and battery storage for recharging farm vehicles and reduce the reliance upon grid electricity.

Table 8 shows the primary capital outlay (assuming <5 meters of connection cable) for commercial BEV charge-points. The need for rural electricity grid reinforcement (to meet increased energy demand) can increase these costs significantly. Farmers and installers must address the options for grid reinforcement and cable lengths on a case-by-case basis.

	AC or DC	Power / kW	Capital costs (excluding grid reinforcement)
Standard	AC	7-11	£8,200
Fast	AC	11 – 22	£9,000
Rapid	AC	43	£11,000
	DC	50	£30,000
Ultra-Rapid	DC	150+	£67,000

Table 8: Charge point capital cost estimates 2021 (Cenex)

6.2.4. Gaseous fuels (biomethane and hydrogen) infrastructure cost

Biomethane

There has been significant investment in biomethane refuelling infrastructure by the likes of CNG fuels in recent years, but the sites are gas-grid connected and more suited to haulage fleets than farms[118]. These central grid bio-CNG sites[119] have a key role in haulage, but for farm use there is a need for virtual pipeline delivery or installation of biomethane upgrade plants on-site. site Using as an example the need to operate 5 or 6 trucks and tractors, this would require circa 60 m^3 of bio-CNG per hour, using smaller modular upgrade units.

However, farm demand at a single location is unlikely to provide the year-round demand required to justify anything other than a smaller plant (perhaps 60 m^3 to 150 m^3 per hour output of bio-CNG). Biomethane uptake may therefore remain a niche option, unless installation of small biogas-to-biomethane upgraders on existing biogas sites can gain some traction. This will require some policy intervention, but **on-farm biomethane does offer the only adoption-ready solution currently for the replacement of diesel.** Demonstration sites are needed to expand this potential.

Figure 40: Small-scale biomethane on-farm refuelling station, Sweden

Small scale biomethane dispensing operations have been developed, based on the UK natural gas supply, with slow fill systems[120] that can draw methane from natural gas infrastructure and store it on site (and can be adapted for on farm bio-CNG. There are examples in Europe where farm-produced biomethane is being dispensed to service local community transport fuel needs – seen here on a Swedish farm equipped with a small-scale AD plant and bio-CNG upgrader.

Hydrogen

Hydrogen infrastructure faces similar barriers to biomethane[121]. Renewable or 'green' hydrogen production is still undergoing technology development and if produced in quantity, dispensing prices may fall significantly in time. However, there is no guarantee that green hydrogen as a vehicle fuel will become price competitive with biomethane at a grid connected scale, let alone for smaller scale on-site modular systems.

Full replacement of diesel on farms with BEVs or hydrogen fuel cells may not be achievable or indeed appropriate before 2050. There are also issues with fuel cell durability in 'dirty' locations such as those found on farms.

Clearly, hydrogen or biomethane fuelled ICE engines can provide low margin industries such as farming with an affordable heavy power train. While some OEMs[122] develop hydrogen engine technology, others are focused on biomethane as a pathway diesel replacement over the next 25 years.

Fuels and engine designs that are currently available and do not involve a 'paradigm shift' will form an important part of the transition to a zero-emission farm vehicle fleet.

[118] Transport Energy Infrastructure Roadmap to 2050, Low CVP/Element Energy, June 2015. NOTE: this does not address needs of rural areas and the ability to use existing biogas plants to supply fuel using small scale upgrading.
[119] A critical issue limiting bio-CNG uptake is the need for a high 'anchor load' of demand to justify the capital investment.
[120] Time fill CNG Fueling Station for Hardworking Fleets, CMD Alternative Energy Solutions
[121] Hydrogen Fueling Stations Cost, US Department of Energy, 11 February 2020 - data on hydrogen refuelling infrastructure indicates £1.3m to £2.25m cost to install hydrogen supply/dispensing equipment to deliver circa 1,500 kg of green hydrogen per day.
[122] Original Equipment Manufacturer

However, investment decisions on hydrogen (for ICE) production, storage, and use should factor in the risk that future net zero legislation may not allow this option, but JCB and other ICE manufacturers plan to change this. The use of hydrogen in adapted ICE's could provide the demand for hydrogen as a fuel that would help facilitate adoption of cleaner hydrogen technologies such as fuel cells in the future. For low margin business sectors, operability issues (mud, dust, water, vibration) remain a concern for fuel cell 'engines', as are the high initial costs.

Replacing red diesel on farms

Emerging technology and fuel supply chain options will impact on future availability of clean fuels. **Predicting technology innovation pathways needs vision, but it also tends to proceed in small leaps rather than large ones.**

Clearly, the pace of change will be influenced by future adjustment of the red diesel subsidy. The NFU and other farmer representative organisations have raised concerns over the impact on farm profitability should the diesel subsidy be reduced or withdrawn – leaving farms paying the full price for diesel. However, there is a view that the industry's low carbon credentials would be undermined if it is allowed to retain the subsidy beyond 2030.

> "You can't predict where we will be in several moves. This is like the energy transition. The only way to get to the end state (not that there really is one) is to make moves. Each move reveals the next set of options. One rule: reduce carbon at min cost. Next move, please"

Low-margin sectors such as farming cannot afford the inflationary impact of transport engine systems that rely on costly raw materials – often used in battery and fuel cell technologies. Farms need affordable, robust, high-torque power. Ahead of 2030, this can only be delivered at scale with biofuels (gas or liquid) using the internal combustion engine (ICE).

Biomethane offers the means to replace red diesel while facilitating the transition to other fuels like hydrogen. It is a farm and rural transport solution that can be cost comparable to diesel.

The pace of change depends on how cost-effectively fuel supply infrastructure and vehicle design change is implemented. JCB's hydrogen ICE, based on a design initiated in 2020, will be on sale in the construction sector in 2023. The expected cost will not be inflationary because it uses adapted ICE technology and readily available materials and components.

Diesel replacement for farms and rural areas requires cost-effective power trains and better supply of green gas fuels (e.g. biomethane, ammonia, hydrogen). A government commitment is needed to show support for gas fuel generation systems and modified engines as a replacement for diesel and this will encourage more low and zero carbon emission ICE[123] power trains to be developed.

[123] Hydrogen fuelled internal combustion engines (H_2 ICE) should not be regarded however as 'zero carbon emissions' – all ICE engines produce NOx which are indirect GHG's, albeit not direct ones.

CASE STUDY: JCB is Investing in a Zero-Carbon Future

Replacement of diesel in farm and non-road vehicles is closer thanks to a revolutionary hydrogen fuel internal combustion engine (ICE) developed by construction machine manufacturer JCB.

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

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

"JCB manufactures diesel engines. We are currently producing 400 a day for our own range of agricultural and construction machinery. However, with the Government's commitment to end the use of diesel, we needed to look at alternative means of powering our machines."

Development of the Hydrogen ICE

Engineers developed the H_2 ICE using established technology with readily available components. The hydrogen back-hoe loader matches its diesel equivalent's performance with an engine far less complicated than a hydrogen fuel-cell.

In July 2020, engineers at JCB Power Systems started designing the new engine. By December, the working prototype of a high-performance, zero-CO_2 hydrogen fuel power train was being tested. The four-cylinder (4.8-litre) H_2 engine provides comparable power and torque to JCB's 'Dieselmax 448' equivalent. Unlike battery powered (BEV) or fuel cell vehicles, the H_2 ICE engine and the production vehicles will not be much more expensive than diesel versions, currently being trialled.

Lord Bamford commented, "It is robust, cost-effective and it could be integrated into all forms of powertrain. Most importantly, a familiar technology and lack of complexity make hydrogen an ideal zero-carbon solution for our customers and our supply chain."

JCB is developing a telehandler for on farm and other uses, more powerful than its current electric offering.

Hydrogen ICE – a Propulsion System for the Future

JCB machines often operate well away from existing infrastructure - on farmland, in quarries or on construction sites. BEVs are impractical for equipment with high power demand in such locations.

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

JCB expect the first H_2 ICE machines to be supplied to customers in 2023. Widespread adoption requires access to green hydrogen supply from surplus renewable energy generated by solar or wind power. Lord Bamford hopes that green hydrogen power will be a key part of the solution to climate change.

6.3. Autonomous systems on farms

Flexible robotic machinery, coupled with GPS and artificial intelligence (AI) are being used in multiple applications such as precision planting, harvesting and weed/disease notification and control. Autonomous vehicles and robotics use 'service' business models, as well as outright purchase or lease.

This section covers potential transformation of farming operations based on system such as controlled traffic farming, autonomous vehicles and robotics. A wider range of options, including smaller robotic systems, gantry equipment and novel fuel sources, is enabling radical farm vehicle re-design. Robust internet connectivity is a critical element to realise the maximum potential benefits of these technologies, many of which are data-driven and utilise artificial intelligence.

6.3.1. Transforming farming operations through controlled traffic farming, autonomous vehicles and robotics - Contributed by Professor James Lowenberg-DeBoer, Elizabeth Creak Chair of Agri-Tech Economics, Harper Adams University

Technology is transforming systems and energy use in food production. Conventional crop production systems were developed assuming an abundant and relatively affordable supply of energy dense fossil fuels for mobile power. The perceived scarce resource was human labour and attention. That led to practices where fossil fuels were used to substitute labour and time, for example, planting systems that require tillage and harvesting technology using mobile power for on-the-go threshing.

Limiting greenhouse gas emissions will require everyone, including agriculture, to use less energy and it may require using it in less energy dense forms. Energy from renewable sources, especially solar and wind, is becoming more available and affordable, but with current battery technology it is less energy dense and thus less useful for the mobile power needed for crop equipment.

The comparison of energy density between batteries and fossil fuels depends on the fuel and type of battery used, but per kilogram diesel has many times more energy than the best batteries. Other energy alternatives, such as hydrogen, are more energy dense but have other challenges. This section explores how agri-tech solutions can reduce overall energy use in crop production, while simultaneously boosting crop production and improving environmental management.

Controlled Traffic Farming (CTF) is a well-established approach given a practical boost by access to reliable and affordable Global Navigation Satellite Systems (GNSS). CTF is able to operate equipment repeatedly on the same routes in the field. With random field traffic, up to 100% of the soil may be driven over in a year. With CTF, the portion of the field depends on equipment used, tyre width and operator skill, but with manual operation, it was commonly 30% to 40%.

Using GNSS, the area can be even lower – perhaps as low as 15%. Research indicates up to a 50% energy reduction with CTF, chiefly because equipment is always operating on a compacted pathway and not on loose soil, minimizing rolling resistance. Other factors contributing to energy savings are less draft force required in un-trafficked areas, less need for deep tillage to break up compaction and improved efficiency with well-planned field routes. Research and decades of farm experience indicate that in general yields increase 9%-16% in un-trafficked soils, with even greater benefits in soils prone to compaction.

The discussion of autonomous (i.e. driverless) crop equipment usually starts with the shortage of farm labour, but experience with autonomous technology suggests a wider range of practical benefits including energy saving, intensification of crop management, more timely field operations, plus much reduced soil compaction, greater precision and improved field biodiversity.

Once human drivers are removed, the incentive for larger equipment almost disappears.

Machines can therefore be smaller and lighter. Completely autonomous equipment does not need a steering system, cab, seat and other manual operation systems. Autonomous equipment can use any energy source, but because it is smaller and lighter than most conventional fossil fuel powered equipment, it can be more easily adapted to battery electric using the solar, wind and other renewable electricity that is becoming more widely available and affordable.

Making the most of battery powered electric vehicles (BEV) may require redesign of cropping systems, including development of low- or no-draft planting systems, and whole plant harvest systems[124], even for grains and oilseeds, by using centralized threshing. Smaller, lighter equipment may allow better timeliness if autonomous machines can enter the field when it is too wet for large, heavy conventional equipment.

With no driver to pay, the autonomous machine can take its time to assess the plant health, nutritional status and other needs of individual plants. Mechanical weeding and more targeted herbicide application can drastically cut agri-chemical use. Smaller, lightweight autonomous equipment can operate in small, irregular shaped fields more cost effectively and move around in-field trees and other obstacles, thus allowing for greater in-field biodiversity.

Autonomous equipment may also allow production of multiple crop species within a single field using strip cropping, intercropping individual plants or other crop geometries. Having multiple crop species in a field is common in less-intensive agriculture, but usually disappears with conventional mechanisation. Having multiple crop species within a field can benefit soil health and facilitate pest management by increasing natural competition.

Because autonomous equipment is GNSS guided and typically operates on predetermined field paths, CTF can be implemented with autonomous machines if equipment is selected to match the operational width.

[124] Everything you need to know about utilising whole crop, Farming Independent, 11 July 2018. Despite limited uptake of whole crop harvesting, it has a range of applications, in particular in ruminant livestock feeding systems

CASE STUDY: Gantry Technology Comes Into Its Own with GNSS

© Photo: Nexat GmbH

Gantry technology[125], where modular attachments are fitted to motorized wide-span vehicles has been proposed in the past[126] but with GNSS guidance it may have a brighter future. Companies such as German company Nexat GmbH could deliver new momentum to gantry technology that has been ignored for several decades. Hence CTF solutions may be capable of transforming farm mechanisation for a range of field operations and functions.

Some visionaries see autonomous battery electric crop equipment eventually powered mainly by locally produced solar, wind and other on-site electricity generation technologies but often links to the power grid will be needed to smooth out supply. The sun does not shine at night and wind does not blow every day, but renewable power can be produced somewhere in Britain anytime day or night.

Even in the best circumstances, the electricity grid in rural areas of the UK is less dense than the urban grid, and it does not reach out to most fields and pastures. If lack of BEV recharging stations is a challenge for electric cars, that challenge is even greater for farm equipment. Battery swapping technology and in-field charging will be needed to make electrical power a practical option.

Many of the benefits of autonomous crop equipment depend on some level of artificial intelligence (AI). This is particularly true of individual plant management and other knowledge intensive practices. For example, to select the right herbicide and choose the dosage for targeted herbicide application software would probably compare images of weeds in the field with an on-line library of images (for example, see the Small Robot Company case study).

Effective use of AI equipment depends on connectivity that is currently sparse in much of rural Britain. Ofcom indicates that in 2020 under 50% of rural homes or businesses could obtain 4G service from all network operators. In many fields the internet is available sporadically, if at all. This is where companies Wessex Internet, working with local rural authorities, have a role to play (see Wessex Internet case study below).

Agri-tech offers many options for improving the profitability and efficiency of agricultural production, while reducing energy use and curbing negative environmental impacts. Realising these benefits is an opportunity for businesses but also a major challenge for regulators and policy makers. **Improving the nation's rural electrical grid and broadband access are specific challenges.**

[125] Initially developed in the 1970s – the prime benefit of gantry systems is restricting soil compaction to very specific areas of fields on a permanent basis. Traffic is limited to just 5% of land area compared to up to 80% for current practices. See Machinery Focus: New chapter for gantry farming from Nexat, Agriland, 8 January 2022

[126] The history of gantry tractors, also known as wide span or wide track vehicles, CTF.org

CASE STUDY: Wessex Internet

Dorset internet provider Wessex Internet sees communications as an essential component of future farms. Their '5G RuralDorset' project is exploring how 5G can boost technology adoption.

Figure 42: Drone fitted with 5G equipment at trial farm. The 5G connection reduces image processing time from days to hours

Firstly, trials have examined the benefit remote sensors bring on-farm (e.g. measuring water quality, or soil health). Wessex estimate they will reduce energy costs by 35% and boost crop yield by 1.7%.

The main barrier to deployment is coverage and cost. Wessex Internet are partnered with Vodafone for the deployment of a 5G system called 'NB-IoT' that will reduce monthly cost to below £2/month.

Secondly, Wessex has looked at the benefits from drones and automated vehicles. New generations of light, autonomous and electric vehicles will be a key contributor to emissions reduction by 2040.

A barrier to commercial viability is the inability to transfer large data remotely. On 5G RuralDorset trial farms, Wessex has rolled out 'mid-band 5G' that can support automated vehicles (4G cannot). Costs of 5G deployments are still high and automated vehicles are yet to replace traditional systems.

Wessex suggest, within five years, refinement of 5G and these vehicles will reach a viability tipping point and private 'mid-band' 5G farm networks will support this next generation of farm vehicles.
To reduce emissions while increasing food production by 70% before 2050, farms will need to adapt to a new technology era, feeding off detailed data. Current rural communications infrastructure is not yet fit to support this. Hence, the next generation of agri-tech providers must work hand-in-hand with communications providers and farmers to ensure infrastructure can support this transition.

6.3.2. Automated field systems

Water management on farms has used laser-guided levelling since the 1990s[127]. Many critical field operations now rely on global positioning satellites (GPS), smart vision systems, and laser guidance.

Such techniques help the farmer to plant and harvest crops uniformly. Optimal planting strategies can increase yields by as much as 20%. However, most autonomous systems are currently driver supervised. A human operator on or near the vehicle ensures systems are working as intended.

In 2016, the first fully autonomous farm plots were successfully planted and harvested without human intervention in the field (see the Hands Free Hectare case study below). In addition to these, further autonomous units are now under development, including those at the UK Robotics and Autonomous Systems (RAS) Network based at the University of Lincoln. Such systems may also include larger units that operate under 'supervised autonomy' (e.g. where one tractor has a driver and additional vehicles are slaved to follow the human supervised unit).

[127] Laser guided combines for next harvest, Farmers Weekly, 13 August 1999

CASE STUDY: The Hands Free Hectare (HFH) and Farm (HFF)

Figure 43: Hands Free Hectare harvest

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

By removing the requirement of dedicated operators for each field machine, automation has the opportunity to reduce the scale of farm vehicles, reversing the trend of mechanisation to date, and critically reducing the compressive load imposed on farm soils, allowing them to regenerate.

These small machines coupled with targeted application technologies could enable ultra-precise high-resolution management with the possibility to reduce volume of farm level agronomic inputs whilst maintaining output.

The Hands Free Hectare (HFH) was a collaborative project which aimed to complete the world's first autonomous cereal cropping cycle on one hectare of land to move the industry nearer these ambitious objectives of automation.

Initially, the HFH utilised open-source unmanned aerial vehicle (UAV) systems integrated into commercially available small-scale agricultural equipment: a tractor and combine harvester fitted with a UAV control system, RTK high precision GNSS positioning[128] and safety systems. The autonomous cropping cycle of spring barley was completed in 2017 from seed establishment through to harvest. All activities in the HFH were conducted autonomously, including the use of drones and ground scout robots to monitor the crop's development.

This achievement was repeated in 2018 and was well received by the agricultural community but created further questions around a commercial output.

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

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

More information can be found on the Hands Free Hectare website.

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

6.3.3. Connected autonomous vehicles: technology examples

Connected and autonomous vehicles (CAV) prototype testing and demonstration projects are already taking place across the UK and globally, with commercially available autonomous vehicles:

- Weeding machines operate in field vegetable crops (e.g. brassicas) to eliminate weeds. Autonomous systems identify and eradicate weeds using blades (or electric shocks). These vehicles and those from the Small Robot Company operate on a pay-per-acre basis.
- Monarch electric tractors include an optional driverless mode that enables the unit to complete pre-programmed tasks, or the vehicles can be slaved to follow other vehicles.
- Harvest Croo use light detection and ranging systems (LIDR) on an automated strawberry picking device that is designed to handle fragile fruit in protected environments.
- Metomotion offer GRoW (Greenhouse Robotic Worker) for dedicated greenhouse plant management and they estimate that one GRoW robot per hectare may deliver a circa 50% reduction in labour cost for 'hi-tech' green houses in northern Europe.
- Agrobot offer bespoke automation solutions in a variety of applications, for the soft fruit sector in protected and field operations.
- AgXeed design, build and maintain autonomous agricultural field equipment solutions that are developed for a specific customer need.

Figure 44: Agxeed autonomous field equipment

These are early market solutions, with additional testing and development needed before commercial adoption within a specific setting.

6.4. Novel fuels and powertrain demonstration

The speed of replacement of fossil fuels on farms and in rural communities will be greatly enhanced by more on-farm working demonstration sites often managed by 'early adopters' of new and emerging technologies. These are essential to showcase the credentials of electric, gas and hybrid zero-carbon ICE power trains, plus autonomous vehicles using robotic technology.

Government support for such demonstration sites, as well as increased investment in robotics, artificial intelligence and rural broadband should prove beneficial, leading to faster GHG emission reduction and more sustainably sourced food production systems.

CASE STUDY: Robots Transforming Farming

Small Robot Company is a British agritech start-up looking to transform farming, to make food production sustainable. Working with farmers, it has created an entirely new model for ecologically harmonious, efficient and profitable farming, whilst protecting soil health, water quality and biodiversity.

Figure 45: Robots Tom and Dick in field trials

Its vision is for "Per Plant Farming": using robotics and artificial intelligence to reimagine agriculture, delivering the next generation of farming. Any farm, growing any crop will be able to gather intelligence on each individual plant, and take action on individual plants. This is an entirely new way of growing food.

Small Robot Company estimates it can save farmers up to 40% of their operating costs whilst producing 50% more food, worth 70% more per tonne.

Lightweight, highly accurate and precise, farming robots Tom, Dick and Harry will monitor, treat and plant crops autonomously. Guided by AI Wilma, the robots know where every plant is and understand exactly what their needs are for optimal performance. With this intelligence, farmers can act only when it's required, giving each plant only the nutrients it needs, or only targeting weeds that are a problem. The benefits include exponentially cutting chemicals, emissions and improving biodiversity. Powered by rechargeable batteries, its robots will also significantly reduce diesel emissions.

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

7. FARM ENTERPRISE DECARBONISATION

7.1. Introduction

The challenge facing farmers across the UK as they grapple with the transition away from well-established CAP support mechanisms, and at the same time deal with a changing marketplace and the obligation to decarbonise their on-farm production, is considerable.

To help illustrate the effort required to decarbonise different sectors of UK agriculture, as well as the opportunities, RASE has asked a number of farm enterprise specialists to assess how farmers are embracing change, identify the impact upon agri-food supply chains and suggest how changes to traditional farming activities can enhance carbon-saving potential.

A range of 'enterprise journeys' are summarised in this sector. For more in depth reading, full enterprise journey reports are published on the RASE website covering the following sectors:

1. Milk and dairy
2. Cereals
3. Vegetables and fruit
4. Intensive meat production

There are elements of decarbonisation that impact all elements of British farming, such as soil health, on-farm energy supply and future fuels which are addressed in the earlier sections, but there are also specific issues to be addressed and technology opportunities that relate to specific farm enterprises and husbandry systems.

For instance, the dairy sector recognises that methane and ammonia emissions are prime concerns amongst consumers, retailers and other stakeholders. Alongside changing diets[129], other issues include GHG potency and wider environmental impacts of intensive milk production.

Measures to curb ruminant methane and reduce emissions from inputs (e.g. fertiliser production) require the sector to improve management systems by adopting novel solutions such as modified diets and changes to grassland management while they reduce reliance on fossil fuels.

Based on the Global Methane Pledge confirmed at Glasgow COP26, dairy farms should consider investing in systems for on-farm methane capture (including on-site biogas plants). The dairy sector needs supply chain support to demonstrate greater ambition to curb fossil fuel use, cut energy costs and deploy bioenergy solutions (both on dairy farms and at milk processing sites).

Reducing emissions requires policy leadership but also better supply chain communication. Emissions reduction must be an integral part of the transition from CAP to ELM (in England and similar systems in the devolved nations) to ensure a positive response and minimal disruption to farm viability, where pressure to maintain yield improvement remains a priority.

[129] Change in UK consumer preferences show need for more cheese, AHDB, 6 Feb 20: "Liquid milk consumption has halved since 1974, but overall production has been maintained due to population growth and added value products like cheese."

The arable sector also needs to demonstrate an immediate ambition to curb input related emissions and fossil fuel use. Arable sector carbon reduction pledges must embrace innovation and collective action to reflect the needs of processors and their markets.

While regenerative farming systems can have positive impacts on arable farm sustainability, they are not a catch-all solution. Farmers and contractors must be encouraged to replace fossil fuel-powered vehicles and machinery – also, fossil fuel-based crop protection with novel pest and disease control systems. The scope for inter-farm collaboration should not be under-estimated.

A combined effort by growers and processors is also required if the UK horticulture sector is to reduce use of fossil fuels, cut emissions and energy costs and continue to invest in bioenergy. There are market opportunities for those businesses willing to take early action to curb emissions, with a dramatic shift in favour of plant-based diets and consumption of pulses and plant proteins.

The horticulture sector accounts for 25% of overall emissions from UK agriculture and needs to adapt available technology and process innovation to meet changing demand whilst minimising supply its emissions. In addition to cutting fossil energy use (particularly in protected environment systems), the sector needs help to improve soil health within field systems.

Farmers and growers, as well as their suppliers and customers need access to a standardised system to assess the carbon footprint of the supply chain and require support to reduce emissions.

As intensive livestock operations often lack the land base to spread slurries and manures, more consideration should be given to covered storage of, and created value from, livestock residues (including with AD) to minimise environmental impacts.

At the same time, efforts to reduce meat consumption (and from some quarters) eliminate animal protein from the national diet will harm national food security and individual farm viability. Hence, the entire livestock sector needs to find ways to encourage producers to curb their emissions.

Collaboration is needed across the ruminant and monogastric sectors (i.e. pigs and poultry) to address consumer concerns over production related GHG emissions. Carbon net-zero pledges require innovation and change at individual farm level. However, no single agricultural sector should be made responsible for targets that must be set on the basis of collective as well as on-farm actions.

The content from the four farm enterprise journey papers is summarised in the sections below. This section also looks briefly at the specific needs of pasture fed beef and sheep, hill farming, potatoes and flowers as well as new crop enterprises being promoted by changes to diets.

In addition to farm enterprise-specific issues relating to reducing fossil fuel use, challenges include the replacement of fossil fuels in the product processing and distribution chain, including processing and value addition which are undertaken on-farm or in the local area.

7.2. Milk and dairy production - John Allen, Kite Consulting

SUMMARY OF KEY POINTS

Click here to read the full dairy enterprise paper

- UK livestock farmers must endeavour to reduce energy, production and supply chain emissions, using improved husbandry practices and technologies to deliver a balance between economic viability, environmental responsibility and social acceptability.

- Milk producers and processors should address the wider environmental impacts of a complex supply chain, with the majority of emissions (including Scope 3) linked to milk production. Thus, farmers have to work closely with the dairy processing sector to reduce these emissions.

- Ruminant livestock production is recognised as being a significant contributor to GHG emissions and in particular methane. Dairy farmers must demonstrate action to reduce emissions, and where possible to sequester carbon in soils that support milk production.

- The UK dairy sector needs to work with other sectors and stakeholders to develop improved tools for GHG quantification and benchmarking. The Global Warming Potential (GWP*) model which reflects the lifetime of methane in the atmosphere more accurately measures livestock emissions.

- Based on the COP26 Global Methane Pledge, there is an urgent need for increased research into curbing bovine emissions and improved handling and storage of manures, including covered stores, low emission spreading equipment and on-site anaerobic digestion.

- If the UK dairy farming sector can reduce its GHG emissions, backed by robust data, and improve its supply chain sustainability credentials, it can create opportunities to sell more environmentally benign products in expanding home and export markets.

- Changes in dairy farming practices and management will be driven by farmers who show a desire to harness novel technologies and innovation such as methane reducing feed additives, targeted application of slurries and decarbonisation of fossil fuel derived fertilisers. Companies and farmers prepared to invest in change need reassurance that commercial benefits will justify the costs.

The dairy sector is under pressure from a number of quarters in relation to its environmental impacts. The industry needs to address its carbon footprint and reduce methane emissions while dealing with commodity price inflation, consumer concerns and dietary changes, including the rapid development of the plant-based milk sector. Concerns over diet, food intolerance or allergies and other factors are fuelling this new market.

Efforts to curb emissions across the UK dairy sector need a more integrated approach and improved collaboration between milk producers and processors. Sustained emissions reduction requires collective action across the supply chain. Emissions reduction should be part of ELM funding to encourage farmers to curb emissions without undermining farm viability.

With global milk production projected to grow by 1.7% per annum, consumers will expect much of this additional output to come from sustainable supply chains. Milk processors will need to work closely with their farmer suppliers if they are to create opportunities for the UK dairy sector to meet expanding home and global demand for sustainable dairy produce.

Emissions from UK milk production are already significantly lower than the global average, based on efficient, well-run dairy farm businesses. With early emissions reduction across the dairy supply chain, the UK could become a leader in low carbon dairy products supply. For processors this includes helping producers to cut farm level (or Scope 3) emissions.

Efforts to improve the sustainability credentials of UK dairy farms by utilising reliable and robust data is essential if the UK dairy sector is to develop premium export sales. This will add significant value for the UK dairy sector, but the milk processors need to support their farmer suppliers by giving them the confidence to invest in effective emissions reduction. Based on AHDB and FAO data, UK CO_{2e} output per litre is 1.25 kg, against a global industry standard of 2.5 kg.

Alongside changing husbandry practices and improved access to data, the development of the Global Warming Potential (GWP)* metric allows better comparison of the various GHGs and a more accurate measure of their climate impact. Systems change in ruminant livestock farming needs to reflect the COP26 commitment to reduce global methane emissions.

Dairy processors such as Arla and First Milk have made carbon pledges across their businesses and are engaging with their suppliers to deliver improvements, while investing in emissions reduction at their sites and transport of dairy products. However, as farm emissions account for the majority of Scope 3 emissions, processors need better farm level emission targets.

Sustainability transition on dairy farms needs to include changes to farming practices as well as improved livestock management systems. Benchmarking and sharing knowledge between farms should be encouraged, alongside demonstrators showing the benefits of switching to technologies, products and practices that can replace fossil fuels or curtail emissions.

Systems change at farm level will include enhanced cattle breeding to curb climate impacts: including yield per cow and improved health measures, while adopting solutions such as methane-reducing additives in feed and sequestration of carbon in soils.

CASE STUDY: Andy Welford - dairy farmer, North Yorkshire

Andy and Barbara Welford run their 125 ha dairy farm in the North Yorkshire Moors National Park along with their son Tom and his wife Wendy and their three young sons – the fifth generation at Marsh Farm. The farm is predominantly grassland with a herd of 270 cows and followers. Annual milk production is about 2.5 million litres and the farm is a member of the Arla dairy cooperative.

Andy has been concerned about the climate crisis for many years. This prompted the installation of a 10 kW wind turbine in 2008 followed by 100 kW solar PV, along with various energy saving measures. Renewable energy generated on the farm roughly matches the farm's electricity consumption. The family more recently bought an electric car.

Andy has a vision for dairy farming in the future. He says, "In truth, what we have done so far only scratches the surface. Where do we go from here? I think a sustainable, low carbon future will mean us all eating a diet of less meat and dairy produce and more plant-based food. Even so, I do believe that dairy products will continue to form a significant part of our food intake. Many areas of the UK such as here in North Yorkshire are much better suited to grass production than crop production. Dairy cows therefore as ruminants have an important role to play in getting human food from grass."

Andy recognises that improving environmental performance at Marsh Farm should be their main objective going forwards and considers there are several developments 'on the horizon' that will enable their farm business to make the transition to a low carbon, more sustainable future:

- **Genetic advances** – these offer opportunities to improve herd efficiency. Marsh Farm has started to use genomic testing of heifer calves being reared as herd replacements. This will enable the farm not only to select for production and health traits, but also in the future for improved food conversion efficiency and lower methane output.

- **Slurry Treatment** – nitrogen fertiliser is a significant contributor to farm greenhouse gas emissions. Andy sees exciting developments with slurry treatment which will enhance its fertiliser value and greatly reduce the risk of it producing damaging ammonia and methane emissions.

- **Renewable Energy** – As at Marsh Farm, many farms are benefiting from installing renewable energy technologies such as solar and wind. However, the upgrading of mains grid infrastructure is badly needed, especially in more isolated rural areas such as North Yorkshire.

- **Soils and precision techniques** – Emerging developments in monitoring soil fertility and organic matter soils and crops can only benefit farm businesses. Andy believes that increasing the level of organic matter in the soil will improve soil health, as well as acting as a carbon sink. Moreover, it will allow crop applications to be tailored to requirements more precisely using GPS controlled field equipment.

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8. Policy pathways for agricultural decarbonisation
Abbreviations
Authors

7.3. Cereal production - Dr Nigel Davies, BSc, PhD, FIFST, Dipl Brew, Hon Assoc Professor, Nottingham University/Maltdoctor Ltd

SUMMARY OF KEY POINTS

Click here to read the full cereals enterprise paper

- Arable farmers are engaged in and receptive to change leading to emissions reduction, but the supply chain must demonstrate its commitment to action across the entire range of crops and markets which also takes account of farm size and output volumes.

- The food processing sector's expectations of the arable supply chain will reflect their need to reduce emissions, driven by shareholder and customer expectations of environmental and social governance, creating added pressure back up the supply chain to farmers.

- Use of regenerative farming methods is attracting increasing interest, but there will be a range of responses from individual farming businesses to the system they select to reduce their emissions. Arable farmers will have access to a menu of land management options, but all of them will require evidence of commercial viability at a farm level.

- Arable transition needs support under the Environmental Land Management scheme in England (and associated initiatives in the devolved administrations), plus a demonstration farm network across production sectors, including public and commercial sector collaboration. More farms will be willing to become case studies to show emissions reduction leadership.

- Cereal farming has the ability to become carbon zero or even carbon negative through a range of regenerative agricultural practices (carbon farming). Farmers can play a part in halting and reversing the rise in GHG emissions on UK farms, by adopting commercially viable novel technologies and management practises.

- UK arable farmers and trade bodies need to develop benchmarking tools for emissions and carbon capture, with a standard measurement system to ensure transparency and allow effective comparison between different crops and production regimes.

- Existing arable technology and knowledge can deliver rapid improvement in resource use efficiency, but requires increased public and private funding to ensure innovations are sufficiently agile, market-ready, well demonstrated and capable of wider adoption.

- Better integration of farm data platforms is required for collecting performance metrics to enable meaningful decision making. Low carbon arable systems need to be developed and implemented with greater speed and commercial focus, in order to demonstrate clear resource use efficiency benefits backed by financial margin improvement.

Arable farmers face increasing intervention at a national policy level to change farming practices. This must include soil management, reduction of fossil-based inputs and adoption of low emission fuels. Food and beverage processors will need to see reduced embedded carbon in the crops they process and will expect an ongoing reduction in supplier emissions.

The UK cereal sector must demonstrate its desire to reduce emissions. However, the uncertainty over the extent to which future legislation will incentivise or penalise farmers may stifle the uptake of proven innovations at the scale required to deliver such ambitions at a farm level.

Arable farming's transformation is underway, albeit on a limited scale, but there are positive signs that UK cereal production can become 'carbon neutral' or even carbon negative (or nature positive), in time contributing to halting or even reversing the rise in GHG emissions from UK farms.

Change will be led by processing sectors and their customers, with their need to reduce supply chain emissions, driven by shareholder and stakeholder pressure for companies to reduce emissions more rapidly, which adds pressure up the supply chain to the farm gate.

Innovation in arable farming systems and changes in management practices need to be financially robust. But expectations of reduced supply chain emissions means that UK cereal producers must demonstrate to buyers that they are reducing their climate impact. Cutting emissions on UK arable farms may not require a revolution in farming practices but rather the evolution of emerging technologies and digital solutions with the capacity to monitor progress and aid crop management across the spectrum of farm sizes.

For several farming generations, this requires increased fixing of carbon on farms, including better soil management practices, to increase soil carbon stock. It has been suggested that a modest increase of 0.4% across the world's soils could reduce atmospheric carbon by up to 3^{o}C.

The specialist cereals enterprise journey raises the interesting debate on carbon cycling versus carbon sequestration. Most farmers tend to have less interest in total sequestration (i.e. embedding carbon permanently – 'zero carbon'). However, they can be more committed to the concept of carbon cycling (i.e. 'net zero' – resulting in an increasingly positive carbon balance). Farm systems which sequester more than they emit result in a positive build-up of carbon over time.

The shift towards incentives aimed at reducing emissions must embrace all arable farming activities – including those applicable to smaller farms that may lack the necessary technical support, as well as those larger farms (i.e. within the top productivity quartile) which are often perceived to be the main adopters of novel technologies.

Options on arable farms include replacing fossil-sourced fertiliser use with abated nitrogen products, adopting improved cropping and tillage practices ('minimum' or 'zero' tillage), the inclusion of a higher proportion of legumes in cropping systems as cash crops, companion plants and cover crops to reduce reliance on manufactured nitrogen fertiliser inputs, as well as precision techniques to better match input application to plant requirements in order to address poor current nitrogen use efficiencies of c 45%.

To assist transformational change, younger farmers will need support including specialist advice, and perhaps mentoring. This should include better access to smart farming demonstration projects that show how to combine data from soil sensors, crop software and location-based GPS and satellite data and how it can be integrated with robotics or unmanned vehicles in field operating systems.

Climate-positive farming practices should be focused on improving soil organic matter, plus fertility and water infiltration (also reducing soil erosion and flood risk) and encouraging biodiversity.

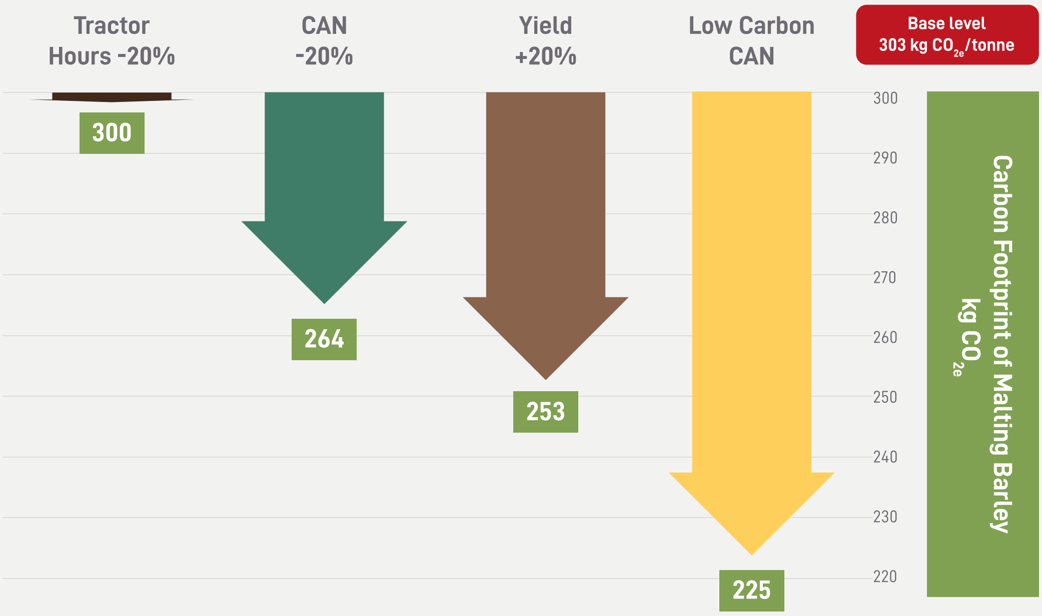
A balance also has to be struck between delivering crop yield consistency, reducing input use where possible and maintaining profitability. Policy makers will expect to see 'additionality', as a result of support funding – meaning that supported investment should have driven a reduction in emissions that would not have happened without the intervention.

CASE STUDY: The Carbon Footprint of Malt

Muntons is a manufacturer of malt and malted ingredients, selling globally to over 90 countries. Muntons has been committed for many years to using carbon tools to engage the supply chain.

The company has identified that barley is a major contributor to the total carbon footprint of malt: over 60% of embedded carbon is from malting grade barley. They have worked successfully across the supply chain to create collective opportunities for improvement and generate integration.

Based upon an analysis of options (shown below)
Muntons were the first to require their farmers to use an abated nitrogen fertiliser and used that to drive a 30% reduction in their barley carbon footprint in under 10 years.



This graph shows the reductions in carbon footprint for malting barley that could be achieved in different ways: faster tractor, 20% less Calcium Ammonium Nitrate (CAN) fertiliser, Yield improvement of 20%, Use of a lower carbon abated nitrogen fertiliser. The latter has the greatest effect and is cost neutral.

Note: A more detailed version of this case study can be found in 'Cereals Enterprise Journey'

7.4. Horticulture production - Matthew Appleby, Editor Horticulture Week, Haymarket Publishing

SUMMARY OF KEY POINTS

Click here to read the full horticulture enterprise paper

- Farmers and growers are facing increasing pressure from consumers, regulators and retailers to meet sustainability targets. At the same time they will also have to respond to decarbonisation demands from the investors in the businesses that process and manufacture their products.

- There needs to be increased focus within the horticulture sector both on delivering produce that meets diet changes of consumers and on cutting carbon emissions, with systems being deployed to avoid product waste, reduce the use of unnecessary plastics and boost production efficiency. This should encompass sustainability targets to be included in favourable loan syndication agreements.

- The most greenhouse gas (GHG) intensive elements of the UK fruit and vegetable supply chain are glasshouse heating, transport and refrigeration. Hence, food produced, but not consumed, represents unwanted production, processing and distribution emissions.

- The field and protected horticulture sectors encompass a diverse range of systems, products and processing operations from field horticulture, through to intensive production under glass and innovative systems such as 'vertical' or indoor farming operations. Boosting local production of higher value produce has to be a priority with the transition to a more plant-based diet.

- Transition leaders in the sector will tend to be the leading commercial farmers (mainly those in the top 25% of UK growers that produce 75% of the output) but efforts to increase local production should be focused on horticultural crops and products that deliver the most environmental gain.

- Growers across the horticultural sector need confidence in systems used to measure emissions and secure value from in-soil carbon capture. Greater assurance can be provided by more transparent, standardised systems, with commercial incentives to curb emissions and benchmark performance.

- Support for emissions reduction by growers ought to be combined with better engagement from regulators and planners, to avoid thwarting efforts to decarbonise existing production systems.

- For smaller farm and horticultural businesses, the scope for R&D investment is limited and it would help them to have access to an industry body able to fund research, plus delivery of best practice and innovative solutions, given that the AHDB will no longer perform this role after 2022.

The horticulture sector encompasses a wide range of fresh and preserved products and varied production systems from field horticulture, through to intensive production under plastic and glass and with more innovative, alternative systems such as 'vertical farming' (see section 7.8.1 below).

While UK farming contributes around 10% per cent of the UK's GHG emissions, one quarter are accounted for by production of fruit and vegetables. Growers need to find ways to maintain or increase output with fewer inputs and to adopt smarter methods of production.

The increased focus on diet and food choice impact on public health brings new opportunities for local production of crops like chickpeas or lentils, to exploit new demand for home grown produce and reduce seasonality impacts. Better resource use in a more circular economy will help avoid product wastage and curtail emissions, as will reducing the use of single use plastics.

The most greenhouse gas intensive elements of the UK fruit and vegetable production and supply chain are in the glasshouse or protected[130] cropping sectors. Product processing, transport and refrigeration are also key contributors and need urgent attention. The least GHG intensive fruit and vegetables are seasonal field-grown UK produce – cultivated without external heating or protection. Imported produce, produced without heat or protection and not air-freighted, can have modest greenhouse gas intensity.

Circa 19% of farm emissions are from heating buildings, including glasshouses. Improving heating, ventilation and cooling systems will reduce emissions as will capturing and re-using waste heat. Many growers have already invested in bioenergy generation systems (anaerobic digestion (AD) or biomass) to replace fossil fuels. Decarbonising heating and cooling by installing heat pumps is also an option. Biomass boilers are more evident on nurseries, but as the Renewable Heat Incentive (RHI) is no longer available, investment in bioenergy systems by farmers and growers has slowed down.

With increased interest in regenerative farming and 'minimum till' systems being applied to arable cropping, it should be noted that such methods can be less suited to production of field vegetables and therefore require the development of different precision farming techniques.

The horticulture sector in particular requires investment in novel systems to improve production and processing efficiency, capture and utilise data, and encourage precision farming systems. This also includes more innovative systems such as 'vertical farming'[131] that can base production closer to markets.

The rapid deployment of robotics and artificial intelligence (AI) will help growers to optimise the management and use of resources (water, fertilisers, chemicals and fuel). More targeted actions and crop treatments are required. A particularly exciting prospect for the sector is the ability to generate data and maps which highlight nutrient deficiencies, disease infections and pest and weed infestations.

Incentive payments for carbon farming will encourage mixed farming methods such as introduction of grazing animals to cropland aimed at improving nutrient cycling and increasing return of organic matter to the soils, whilst improving soil fungal and bacterial communities. Advances in tilling technology, drainage and irrigation monitoring and control, and a reduction in use of fertilisers and pesticides all have a contribution to make in reducing emissions and improving crop growing environments.

The on-farm generation of electricity (e.g. solar or wind), and installation of farm-scale AD plants to produce energy from bio-residues would benefit from a new incentive regime to encourage on-farm investment in renewable energy systems. In addition, UK loan provision should mirror the example of Rabobank in Holland where meeting sustainability key performance indicators can reduce finance costs.

Investing in higher-tech, low-carbon greenhouses that enable better control of energy emissions will boost productivity, using fewer inputs and resulting in less environmental damage. Increased funding support for this sector of food production will help encourage investment in technology innovation by growers. Further investment in research and development is a co-requisite.

[130] Protected' horticulture and includes a range edible crops such as tomatoes, cucumbers, peppers and baby leaf vegetables, plus soft fruit that is are grown under cover (either in permanent glasshouses or temporary systems like polytunnels.
[131] Vertical farm crops are typically grown in stack systems in a controlled environment (light, temperature, humidity, air).

CASE STUDY: Haygrove Ltd

Angus Davison, Eccentric Chairman of Haygrove, a leading international producer of soft fruit and berries and supplier of growing systems - believes private business can address the climate crisis in time as it can take decisions immediately, and that horticulture can genuinely be a leading industry in the change required.

Angus and family in the cherries

"Haygrove's journey is based upon a fundamental belief that the action required is not complex. There's a solution staring at us. We should just change the metrics by which we measure and target business, and reward its managers, to a triple bottom line of planet, people and profit.   The definition of success should be aligned to our needs, which are not just money.

We couldn't find a **carbon counting software** tool specialised enough for horticulture, so designed our own **'Hortiplanet'**. For a monthly carbon report by team and divisions, you must input waste, fertiliser and other criteria. It produces a simple environmental bottom line 'dashboard. We are sharing it as a non-profit enterprise with other growers here and abroad.

Waste is a bit of a conundrum. We are responsible for selling a lot of plastic around the world .... we're working to resolve a containerised recycling process for our customers without in-country options - a 'must do'!

Water is everything! We sell expensive water given that it is 90% of a berry! Thankfully our tunnels are very effective gatherers of today's sudden downpours, if the farm is linked to a reservoir. More and more growers in dry places are installing gutters to capture every drop.

Haygrove is focused on 'triple bottom line'[132] performance based on 'planet, people and profit' which is gradually becoming embedded into the group.

Read more at Decarbonising UK Horticultural Production

> "It is our generation's job, right now, to give an example to a new era. Horticultural businesses should logically be right in the vanguard of change."

[132] Triple bottom line is a business concept that posits firms should commit to measuring their social and environmental impact, in addition to financial performance, rather than solely focusing on generating profit, or the standard 'bottom line'.

7.5. Intensive meat production - Professor Jude L. Capper, ABP

Chair of Sustainable Beef and Sheep Production, Harper Adams University

SUMMARY OF KEY POINTS

Click here to read the full meat enterprise paper

- Improving KPIs to mitigate GHG emissions can be adopted across the pig, poultry and intensive beef sectors, providing the mechanisms employed balance environmental responsibility, economic viability and social acceptability, thus achieving a triple-win for sustainability.

- The global livestock sector needs internationally agreed tools for GHG quantification and benchmarking. The Global Warming Potential (GWP) model takes account of the contribution of grazing animals to sequestering carbon into soils. The GWP* metric accounts for variation in how short and long-lived emissions warm the atmosphere.

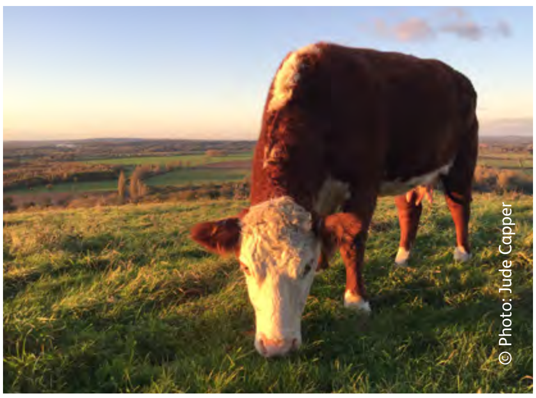
- UK livestock farmers and trade bodies need to develop ways of benchmarking GHG emissions, carbon capture and other environmental metrics (e.g. biodiversity, water use). A key and urgent issue will be choice of a standard measurement system to ensure transparency and allow comparison with other operations, sectors or markets.

- Many intensive livestock operations (e.g. pigs and poultry) lack a land base on which to spread their slurries and manures. With the requirement for transition to use of covered storage, the sector can better valorise manures as bioenergy (i.e. through anaerobic digestion) to minimise environmental impact and make better use of those nutrients.

- Improving livestock health is essential, with healthy animals performing better and having lower environmental impacts. Reducing GHG emissions based on productivity and health should not be prescriptive in terms of systems, methods or technologies.

- The industry must respond to consumer trends and stakeholder demands (including critics challenging meat production). Decarbonisation strategies can address the rhetoric around GHG emissions and improve consumer confidence in sustainability.

- The development of a clear vision and strategy for a decarbonised meat industry must be shared with policymakers, media and consumers to successfully change the rhetoric around GHG emissions and improve consumer confidence in UK agriculture.



There is an immediate need for all the UK livestock sectors to demonstrate their ambition to reduce negative environmental impacts. They must do so in an evidence-based manner that both allows progress to be benchmarked and to be better communicated to stakeholders. The choice of measurement system(s) must ensure transparency and allow comparison with other sectors and markets.

However, only using GHG emissions to differentiate between livestock systems or products ignores other important factors in the provision of sustainable food. These include, for example, consumer preferences, land use and feed sourcing. Over-simplification may also ignore important differences in the relative nutritional content of foods (e.g. meat vs. salad) or the 'opportunity cost' of producing different foods from specific resources.

Despite the Committee on Climate Change (2019) report advocating a series of changes to UK milk, meat and egg production and consumption, it is crucial to acknowledge the multiple benefits of livestock farming, including food and fibre production, soil health, biodiversity and landscape maintenance.

Livestock farming provides a range of benefits over and above food production. These include by-products (e.g. leather or pharmaceuticals), ecosystem enhancement and wider landscape management. The livestock sector forms an essential part of the circular economy in terms of converting human-inedible forages and feeds into high-quality protein (milk, meat and eggs).

Cutting direct UK emissions from food supply by eliminating livestock production or importing milk, meat and eggs from overseas is possible but is inherently unsustainable, threatening both national food security and farm economic stability, and encouraging 'emissions transfer'. It is therefore essential to identify practices and tools which will enable UK producers to mitigate emissions.

A considerable amount of media coverage is dedicated to vegetarianism and veganism, with concurrent social pressure on consumers in the Western world to reduce their consumption of animal products, despite increasing demand in low- and middle-income countries.

The increasing popularity of 'flexitarianism' (i.e. making a conscious decision to reduce meat consumption) may be a challenge to the sector, yet it may also offer opportunities if it leads to an increase in local (national) 'quality meat' consumption relative to imported products, for which the environmental or animal welfare credentials may be less transparent.

Precision livestock farming systems can help to curb inefficiencies and waste. Better data collection and its use will facilitate assessment of variations related to operations, species or breeds. Environmental monitoring and sensors can improve livestock health management, particularly in intensively stocked environments, reducing the use of antibiotics that have equivalents in human medicine.

While there is a need to curb emissions from grazed livestock, this also applies to more or less intensive monogastric livestock (pigs and poultry), including the design of feed rations, use of methane-curbing additives/techniques and installation of covered slurry stores sized for reduced spreading windows.

Improved livestock management and efficient manure/fertiliser use is key to decarbonisation. Development of on-farm bioenergy generation potential from bio-wastes (e.g. slurries) must therefore be a priority. This will reduce environmental impacts whilst providing a sustainable on-farm source of power and fuel. The failure of UK bioenergy policy to boost farm energy supply from crop and manure residues represents a major failure that needs urgent attention.

Although marginal gains can and should be achieved in terms of transport, processing, retail and consumption, the greatest opportunities for livestock sector decarbonisation occur at the farm through better husbandry and management, with underlying recognition that significant GHG mitigation is essential and achievable at all points in the production and supply chain.

7.6. Sheep and beef

There is a need to curb emissions from all grazed livestock, and not just those farmed under more intensive conditions. This includes from hill farms that are a vital part of the management of remote and upland areas. In addition to climate, commodity market prices and farm income pressures, family hill farmers are subject to a range of other challenges. These include keeping younger workers on the farm and addressing the increasing demands of countryside users wanting to access, protect and enhance upland habitats across the UK.

More than 60% of UK land is grassland, best suited to intensive and extensive livestock grazing and the supply of high-grade protein. Grazing livestock need to remain part of UK agricultural production.

Hill farming in particular needs ongoing support not only to become more profitable and resilient but also to protect biodiversity. A high percentage of a hill farm's income derives from subsidy support – and this must be at the forefront when determining the level of subsidy being planned under ELMS in England and other support schemes being developed in Scotland, Northern Ireland and Wales.

Subsidy support needs to include attention to livestock numbers as well as costs. Buying in external feed inputs increases costs, while limiting stocking densities can have environmental benefits, for example, boosting soil health to lock in carbon and enhancing the ability of upland to absorb heavy rain thereby reducing flooding risk lower in the catchment by holding back floodwaters.

CASE STUDY: Hill Farming in the Yorkshire Dales

> "A focus on margin over volume, on provenance over commodity production and on co-operation over competition"

Chris Clarke's practical experience at Nethergill Farm developed a robust model which, for them, balances food production, nature and business. On their 180 hectares in the Yorkshire Dales, they introduced a number of measures which included planting trees, restoring the moorland, halving the number of sheep, introducing hardy Whitebred Shorthorn cattle, and working with local experts to measure and understand improvements in biodiversity.

From a business point of view, this resulted in fewer vets' bills, and few input costs (e.g. fertiliser and bought-in food). He believes that the new agricultural policies for hill farmers should "ensure that it lays the foundations for hill farmers to build their businesses around maximising profit margins, rather than maximising production quantities or short-term absolute profit".

This requires knowledge sharing and experimentation to see what works on each farm[133]. Further detail on this approach is explored in a publication by the RSPB, National Trust and The Wildlife Trusts "Less is more: Improving profitability and the natural environment in hill and other marginal farming systems".

[133] The future of upland farming in the UK: a business model that works, Green Alliance, 8 June 2018

Increased collaboration in areas like catchment management[134], where farmers work in groups with external support from specialist advisers, has been shown to curb pollution and enhance water course protection. This could lead to additional cooperation aimed at lowering fixed costs through sharing machinery, collaboration on sales and sharing resources with neighbour farms. This will bring opportunities to boost margins for meat produced by adding value locally.

Upland livestock farmers (lamb and beef) will be expected and encouraged to put environmental protection and landscape enhancement at the centre of their farm management systems. This will require a combination of reward through the market (i.e. by adding value to increase meat prices), and successful applications for Government payments focused on the delivery of 'public goods'. The latter will include public access and the provision of countryside interpretation services for recreational users.

Figure 46: Sheep in the Shropshire hills

Importantly, the Global Warming Potential (GWP) model related to ruminant emissions should take account of the value that grazing animals can sequester carbon into soils. Livestock farmers and trade bodies need to develop ways of measuring and benchmarking emissions and carbon capture.

7.7. Potatoes – fulfilling their potential - Cedric Porter, Editor of World Potato Markets and Vice-Chairman of LEAF

Potatoes are a key crop for feeding a growing global population against the backdrop of a changing climate. Despite the opportunities this presents, there are challenges for UK growers.

Potatoes contain potassium, calcium and vitamin C plus fibre and protein and plenty of calories. But what really marks potatoes out is much higher yield volume than other crops. Analysis by World Potato Markets (see Table 9) shows that potatoes have the best overall ranking of seven key crops when it comes to delivering a mix of protein, calories and key minerals per hectare.

Ranking crops by how much can be produced per hectare (rather than per kilogram of crop) gives a better picture of crop productivity and wider impact. The data uses UN FAO average yield data for the seven crops – potatoes, cassava, corn (maize), sweet potatoes, lentils, wheat and rice, plus USDA nutritional data for each crop.

[134] There are an increasing number of local groups working together (such as the Catchment Based Approach) to support adoption of practices that curb soil erosion, reduce nutrient loss and pesticide pollution, while boosting habitat protection and water infiltration, with specialist advice tailored to the needs of specific catchments and farming systems.

	Protein kg/ha	Cal/ha	Potassium mg/ha	Calcium mg/ha	Vitamin C mg/ha	Ave t/ha
Potatoes	0.416	15.631	86.275	2.436	3.999	20.3
Cassava	0.151	17.76	30.081	1.776	2.287	11.1
Corn (yellow grain)	0.537	20.805	16.359	0.399	0.000	5.7
Sweet potatoes	0.492	24.6	N/A	2.46	0.000	12.3
Lentils	0.271	3.872	7.447	0.385	0.050	1.1
Wheat flour/ whole	0.336	11.62	13.79	1.155	0.000	3.5
Rice	0.124	5.98	1.61	0.46	0.000	4.6
Note: Calculated using USDA and UNFAO data. https://ndb.nal.usda.gov/ndb/search/list Highest scoring food per category in green						

Table 9: Calculated protein, calorie and mineral value of key crops by hectare (ranked by overall performance)

This productivity data needs to be evaluated alongside environmental impact. Eating a couple of small potatoes three to five times a week will add just nine kilograms of greenhouse gas emissions every year, according to the BBC's food carbon calculator developed with Oxford University[135]. Eat a similar volume of rice and the emissions jump to 69 kg, for pasta it is 25 kg, oatmeal 22 kg and bread 12 kg.

	Water use l/kg	g of CO_2/kg/l	m² of land/kg
Beef	18800	25895	146
Poultry	4805	4040	44
Cheese	6260	9250	61
Milk	1330	1255	8
Legumes	2710	1660	18
Rice	2585	3745	10
Pasta	1775	2155	12
Bread	1170	1050	7
Fruit	930	490	4
Potatoes	**555**	**1205**	**5**
Vegetables	335	775	3
Note: Barilla Center for Food & Nutrition			

Table 10: Environmental impact of key foods

Pasta company Barilla acknowledges the importance of the potato. It ranked foods according to nutritional and environmental value in a double-pyramid.

[135] Climate change food calculator: What's your diet's carbon footprint? BBC, 9 August 2019

Foods with a high nutritional value form the base of the food pyramid, while foods with a low environmental impact form the peak of the environmental pyramid. Potatoes have a high nutritional value, but a low environmental impact, making it the best performing of all the carbohydrates. When it comes to water and land use, potatoes perform well, according to the Barilla data, only surpassed by green vegetables which lack the bulk of carbohydrates.

Yield advantage

The nutritional performance of each crop can be improved by higher yields. Hence, in the UK where potato yields are double the global average, nutritional value is higher on a per hectare basis. Some UK farmers deliver wheat yields three times the world average so their nutritional impact per hectare will also be higher. However, in many developed nations more potatoes are eaten processed (high fat snacks) rather than fresh, inevitably increasing environmental impact.

The nutritional and environmental value of potatoes is being recognised by governments around the world. China plans to double its production, focusing on regions where growing rice and wheat is difficult. India is also overseeing an increase in potato area as its population grows quickly. In Europe and North America potatoes are seen as a lowland high value crop to be grown on some of the best land. That is not the case elsewhere.

The origins of the potato are high up in the Andes where the air and soil are thin. It is a crop that will grow where grains may struggle such as parts of Africa and Asia where there is increasing pressure to feed growing populations. The UN-backed and Peru-based International Potato Centre (CIP) is very active in these regions with its major breeding and agronomy programmes.

Environmental Impact

While the value of potatoes as a staple food is clear, it is also a high impact crop, agronomically, with cultivation and plant health (with the application of multiple fungicide doses in a season not unusual). Potato rotations have extended over the years and many growers now leave six or seven years between potato crops.

Potatoes are also intense users of fertilisers, fuel and energy for storing, packing and processing. Growers, packers and processors are facing much higher input bills for the 2022 season.

Figure 47: Field potatoes

The cost of growing potatoes can be as much as four times higher than wheat, with higher risks of crop failure. The environmental impact of fertilisers and agrochemicals use is significant. Hence, a third of the UK national crop is grown under the LEAF[136] Marque scheme as growers seek to limit their environmental impact.

While other nations see potatoes as a crop of the future, output has declined in the UK. In the 1960's, the crop area was nearly 300,000 ha, now it is circa 100,000 ha. Yields have increased over the years, but consumption has fallen, although retail sales lifted during the pandemic.

The UK consumes more potatoes than any other county in Western Europe and it is the second largest importer of potatoes and potato products in the world after the USA. This should be seen as an opportunity to boost home production, with lower emissions.

[136] Linking Environment and Farming (LEAF)

Meeting the Innovation Challenge

There is plenty of innovation and investment in precision planting, crop protection, fertiliser and harvesting techniques. A recent ProCam trial[137] delivered 46 tonnes/ha of potatoes by using a high-straw mulch no tillage system, which played a key part in a regenerative rotation.

Greater use of solar and wind power to help reduce carbon impact and energy bills is now widespread, while crop rejects often find their way into AD plants. In another boost to maximising the whole crop, a £6 million investment by packers Branston will take low-value potatoes and convert them into high-value powdered protein – a plant-based alternative to dairy protein.

Figure 48: Climate-controlled potato storage

The UK is also leading the breeding of more sustainable and nutritious potatoes. The James Hutton Institute in Scotland has long focused on drought and heat tolerant potatoes for growing across the world and that is now relevant to Europe. Meanwhile, blight and discolouring resistant potatoes developed by the John Innes Centre are being planted commercially in the UK. The UK's post-Brexit policy of allowing more gene-editing of crops should have an impact if consumer resistance can be avoided.

The need for investment in research and development to bring new techniques to potato growers has never been greater. Yet the UK growers have withdrawn its support for the potato functions of the AHDB. Unless its most valuable functions are replicated and funded in alternative ways, the UK could lose its leadership and experience in this sector at a time when it is globally most valuable.

The humble potato, a crop that is loved by consumers, ticks a range of nutritional and environmental boxes, with demand growing across the world. If growers can reduce its environmental footprint further, to exploit new opportunities and initiatives, greater stakeholder collaboration is needed if the potato sector is to thrive.

7.8. Other farm enterprises and novel crops

In a report of this nature that seeks to highlight the technical as well as practical implications of the emissions reduction task facing farmers and landowners, it is hard to cover all the production systems on UK farms. There will always be sections of the increasingly diverse food production and supply chain that are less well covered.

These include emerging sectors that may be harder to classify within traditional sectors, given the huge transition that is taking place in the industry. These are covered briefly below but may deserve more detailed papers in future.

[137] No-till potato trials show role in soil regeneration, Procam, 13 August 2019

7.8.1. Multifunctional land use

There are increasing opportunities for novel crops and more innovative supply systems to be set up on farms or at other locations. This applies to a range of systems from urban micro-farms to the wider opportunities for mixed farming operations that became somewhat unfashionable in the latter half of the 20th century but have real benefits as part of systems to support carbon efficiency or sequestration. Examples of novel crops and changing land use include:

- **Novel or high value crops** such as pulses[138, 139] and ancient grains (e.g. spelt, einkorn)[140], saffron[141] and hemp[142]. With some species of hemp, the entire plant can be used for plastic-free, sustainable and durable products, including fabric[143]. Other niche plants successfully grown in the UK include as chia, soybeans, quinoa, wasabi and lentils. There is a small market for herbs and medicinal plants which, like cut flowers, are often grown at 'artisan' scale. With a projected increase in field margin planting for biodiversity and integrated pest management (IPM), there may be a growing market to produce seeds for such mixes. Plants such as oats, not normally considered to be 'novel', are increasingly grown for novel uses such as dairy-free plant milk. Plant milks can also be made from a wide variety of crops suitable for growing in parts of the UK including quinoa, flax, walnuts, yellow peas, spelt, hemp and soy.

- **Energy crops** represent a specific group of non-food crops grown primarily as a source of bio-energy. They include crops such as sugar beet, wheat and oilseed rape used for producing biofuels; maize grown to feed anaerobic digesters (AD) and densely planted, high yielding perennial crop species such as miscanthus and short rotational willow coppice (SRC). Defra report that in 2019, 121,000 ha of UK agricultural land were used to grow crops for bioenergy – representing around 2% of the total arable area[144] – comprising:
  - 29,000 ha of wheat and 7,000 ha of sugar beet used for biofuels.
  - 75,000 ha of maize used for anaerobic digestion.
  - 8,000 ha of miscanthus and 2,000 ha of short rotation coppice used as biomass.

  Bioenergy crops provide farms with the opportunity to generate income from non-food crops as part of their activities. Some energy crops can fit within an arable rotation and bring added benefits of soil improvement and weed control.

  Perennial biomass crops e.g. miscanthus, SRC can generate income from poorer marginal land - and are often considered to be 'carbon neutral' as the emissions from burning is balanced by the emissions being absorbed by the growing crop.

  The potential for bioenergy crops will form an ever-increasing contribution to the UK's energy mix for electricity, heat and transport fuel – thereby replacing fossil fuels.

Figure 49: Field of miscanthus

[138] Rediscovering British Pulses, Sustainable Food Trust
[139] Hodmedods, our farmers
[140] Ancient grains deliver top prices for organic farmer, Farmers Weekly, 4 Dec 19
[141] Farmer revives lost art of saffron growing, Farmers Weekly, 13 Aug 14
[142] British Hemp Alliance
[143] The Hemp Shop (clothing section)
[144] 'Arable area' is defined by Defra as the area of arable crops, uncropped arable land and temporary grassland.

- **Mixed arable and arboriculture.** On-farm tree planting is receiving more support from incentive schemes (both from DEFRA and the devolved administrations) as part of efforts to encourage landowners to improve biodiversity, soil quality and carbon sequestration. However, with pressure on farmers to combine land use diversity with enhanced outputs, taking land entirely out of production may not always be the most desirable option. Hence, there is growing interest in including trees within arable farming systems.

  Integrating trees (and hedges) into arable systems can improve productivity, farm output diversity and resilience, while saving costs, and offering wider environmental benefits such drought mitigation and water conservation, mitigating erosion or pollution, and supporting crop pollination, biodiversity and wildlife conservation[145]. Tree planting within farm systems should extend beyond managing or planting shelterbelts, riparian strips and hedges.

- **Fruit/nut trees:** Silvo-pasture can extend to integrated production of specific premium crops including the location of fruit and nut orchards within or alongside other cropping or livestock in more mixed farming systems, plus an ability to provide additional revenue. This can include wine production as we as fruit and nut varieties that may thrive in increasingly warm UK climate[146].

- **Urban and vertical farming.** Such systems include hydroponics[147] and production in below ground tunnels as well vertical systems[148]. These present an opportunity for local production of high value crops that may currently be imported (adding to food miles). Such systems can produce premium crops 365 days a year, without the requirement for pesticides, while being unaffected by the weather. They can be located in urban sites, closer to processors, and can use zero carbon power supplies, creating new commercial opportunities and reduced emissions.

Figure 50: Vertical growing

There are plans to support the creation of woodlands with new grant schemes – e.g. the England Woodland Creation offer, where landowners and farmers will receive a grant of up to £8,500 per hectare to cover planting costs, (plus an annual maintenance payment of £200 for ten years and potential for more support if they can prove additional 'public benefit' from their tree planting)[149] this needs to include production of fruit and nut crops.

7.8.2. Novel protein sources

Alongside the impact of dietary trends, there is an increasing interest in novel and artificial forms of protein that create opportunities for farmers and the wider agribusiness sector. These include a range of methods of protein production that can have a more limited impact on the environment – but where the overall impact on emissions may need to be better assessed.

[145] The role of trees into farming systems, Practical Guidance, Agricology

[146] Growing Almonds and Apricots in the UK, Soil Association

[147] Hydroponics - Cherry Farms UK Growers in hydroponic systems, the soil is replaced by alternative substrates (vermiculite, perlite, peat moss, coconut fibre or rockwool, fed with nutrient rich water.

[148] In vertical farming systems, such as Global Vertical Farming Solutions plants are grown indoors typically using some form of stacked system in a controlled environment (light, temperature, humidity, air).

[149] Available support includes different programmes or schemes in the devolved nations (Scotland / Wales / NI – see Defra unveils new grant scheme for woodland creation, as post-Brexit green watchdog finally launches, 26 January 2022. Also the England Woodland Creation Offer and comparable plans such as the Forestry Grant Scheme in Scotland

- **Vegetable proteins.** Increased adoption of plant-based diets will impact on supply chains, with demand rising for nuts, seeds, fruit and pulses and more UK farmers should be growing these crops. Hodmedods, set up in 2012, is expanding the market for UK grown beans and pulses - which are not only nutritious but also good for the soil health and biodiversity. New crops like lentils are a low-input, fix their own nitrogen and suffer few pests and diseases and require less water than other novel crops.

- **Meat substitutes.** With a gradual policy-supported consumer shift to eating less meat, there will be increasing opportunities for growing plant-based options, at both small and large scale, that can supply the production of foods, e.g. tofu.

- **Insect proteins** offer low environmental impact protein sources for animals or people. Edible insect production can be undertaken at relatively small-scale on farms. Some models use insects as a high protein animal feed and frass (excrement) as a chitin-rich fertiliser. Companies such as InsPro utilise black soldier fly larvae to recycle food waste, with larvae providing protein for fish food. Frass can be used as a soil re-conditioner and fertiliser product. Such a process could be integrated with an anaerobic digestion plant by using heat from the AD to provide an optimal growing environment, shared permits and transport and by putting waste from the process into AD and vice versa (digestate).

- **Plant milks.** Although some plant milks are not high in protein, their popularity continues to grow, providing farmers with the opportunity to grow crops suitable for the production of these milks from crops such as oats, flax, hemp and peas. A recent survey indicated that nearly 1 in 3 people in the UK now drink plant-based milk, up from 25% in 2019, with the rate rising to 44% in those aged 25 to 44[150].

7.8.3. British cut flowers

The growth of demand for home-grown cut flowers represents a real trend from consumers – one that is making an increasing contribution towards the UK's commitment to reduce greenhouse gas emissions (GHG) and in particular CO_2.

The British ornamental horticulture sector employs over 15,000 people directly and almost 30,000 indirectly. According to the Horticultural Trades Association (HTA), the total wholesale value of the 2020 ornamental crop (flowers and bulbs, pot plants and hardy nursery stock) is estimated to be £1.4 billion. £121 million of this comes from the UK's annual flower production industry, which has seen an increase of £39 million since 2015.

Traditionally, commercial flower growing has taken place on farms producing for the wholesale market in areas such as Scilly Isles, Cornwall, Lincolnshire and East Anglia. More recently, the UK has seen a rapid expansion in small scale flower enterprises. Much of the burgeoning cut flower sector is at 'artisan scale' – with most flower farms of between 0.5ha – 5ha.

[150] Oat overtakes almond as plant-based milk sales soar in UK, Food & Beverage Insider, 20 September 2021

One of the leading small flower grower networks is Flowers from the Farm – an award-winning not-for-profit organisation which aims to promote British grown flowers. Co-chair Meg Edmonds says: "We are gaining attention for raising the 'local' focus on trade - a deliberate aim because this surely has to be the most sustainable way of providing flowers – and food. Our aim is to expand the demand for premium home-grown flowers which also represent the true production value."

There are a number of key issues which UK flower growers will have to face in the next few years – in addition to competition from imports with their much higher carbon footprint! These include transport reliability and supply chain issues, seasonal workforce, rising energy costs, and sourcing specialist seeds and bulbs. In response, growers – whether large scale or artisan – will need to review their production techniques, save home grown seed, and produce replacement stock themselves. This will require funding support to improve skills and knowledge across the industry.

Low Carbon British flowers – 'grown not flown'

In 2018, Rebecca Swinn[151] - now Innovative Farmers Manager at The Soil Association – carried out a study of the carbon footprint of imported and home-grown flowers, using Life Cycle Analysis. Her premise was that the sustainability of imported cut flowers rarely receives the media attention given to other retail produce despite their much higher carbon intensity.

Her results, shown in Table 11 below, evidenced the environmental costs of importing flowers from abroad – whether grown under intensive climate-controlled conditions such as in Holland or in warmer climates such as in Kenya. Using the functional unit of kg CO_{2e}/stem, the study concluded that an imported mixed bouquet of cut flowers produces 10 times greater carbon emissions than a British locally grown equivalent - taking account of emissions from water use, transport, heating and electricity.

Flower mix	CO_{2e} emissions
5 Kenyan roses + 3 Dutch lily + 3 Kenyan gypsophila	31.132 kg
5 Dutch roses + 3 Dutch lily + 3 Kenyan gypsophila	32.252 kg
5 outdoor grown UK snapdragons + 3 UK lily + 3 UK alstromeria	3.287 kg
15 stems mixed outdoor UK flowers, grown and sold locally	1.710 kg

Table 11: CO_2 emissions from imported and UK flowers

[151] Rebecca Swinn MSc Dissertation, The carbon footprint of flowers, Flowers from the Farm

8. POLICY PATHWAYS FOR AGRICULTURAL DECARBONISATION

"A sustainable future for UK agriculture may only be achieved by balancing economic viability, environmental responsibility and social acceptability through the adoption of new and existing management practices.

Sustainability is not a peak that can be conquered without further improvements, as the tools, technologies and systems that were sustainable in the past or present may not be so in future. For example, science relating to livestock health, welfare and environmental impacts has resulted in considerable changes to the ways that livestock are housed, fed, bred and managed over the past three decades.

A clear and immediate need exists, however, for the UK agriculture to demonstrate dedication to reducing negative environmental impacts, and to do so in an evidence-based manner that allows progress to be benchmarked and communicated. It is crucial to set appropriate targets, with greenhouse gas (GHG) emissions being the most urgent area of focus."

Prof. Judith Capper, Harper Adams University

8.1. Primary policy issues

1. **Support: ELM must include provisions to help England's farmers curb energy emissions. In the ELM Transition, there is real concern over the potential impact of change from EU CAP support.** The House of Commons Food and Rural Affairs Select Committee has issued a critical report (Oct 2021) that highlights concern over the impact of ELMS on farming livelihoods. The biggest UK agricultural policy change for 70 years, this will have a major impact on farm businesses as they navigate the transition from CAP while dealing with the climate emergency. The report finds 'failure of communication' is putting the most significant policy shake-up English farmers will have experienced at risk, at a time when they are also reducing emissions.

2. Whether it is emissions or policy reform Neil Parish MP (chairman of the Select Committee) commented, "This [ELMS] is the most fundamental change to agricultural funding in a generation and the impact of this huge change … cannot be underestimated … and must be … able to adapt to unforeseen circumstances. Government appears to be determined to plough ahead … without considering how this will impact on farmers' livelihoods and the environment."

3. **Methane:** Farmers recognise that methane and ammonia emissions are key concerns - the issues of gas potency and livestock emissions (from meat and milk production). There is a need for new measures to curb methane and ammonia output from fertilisers and ruminants and to cut overall GHG emissions. Future measures such as carbon taxation must not solely impact UK farmers. Policy should encourage better resource management and identify technical solutions, such as changing ruminant diets and methane capture to address consumer demand and the UK's 'Global Methane Pledge' commitment. Action should include more support for research into measures to reduce emissions. This can include feed preparation solutions such as straw chopping to ease digestion to curb methane output in ruminants.

4. **Subsidised Farm Diesel:** prior to 2030, replacing fossil fuels on farms must be a priority. The 'red diesel subsidy' (currently 81% discount)[152] is valued by farmers and critical to their margins - but prices have nearly doubled in 2 years. Replacing diesel is key to meeting the sector's Net Zero targets. It may undermine UK farmers' reputation if the red diesel subsidy is not phased out before 2030. Hence, farm vehicles must be included in the grant support for developing zero carbon fuels for non-road vehicles. Adoption-ready low carbon options (biomethane and HVO) will precede likely developments with hydrogen ICE power trains (e.g. JCB). **There is a policy disconnect if farmers are paid to sequester carbon on one hand, but effectively subsidised for fossil fuel use on the other.** Hence, a timetable is needed for ending the red diesel subsidy, using adoption-ready solutions.

8.2. Policy Challenges

Farmers & rural businesses should be fully consulted on wider policy change as well. They must also be fully engaged in developing solutions that optimise their ability deliver results on farms and addressing the specific challenges (highlighted in the pre-COP26 Briefing Document):

1. **Soil & Landscape:** improved soil management is needed to reverse the damage of recent decades, with changed cultivation methods and nature-friendly systems. Delivery of public benefits includes increased carbon storage in soil or trees and curbing emissions from excessive fertiliser use/soil disturbance. Farmers, individually and in groups can enhance local water course protection. **Economic valuation of natural capital will help deliver decarbonisation, restore soil health and increase biodiversity.**

2. **Livestock Husbandry:** Livestock farmers can reduce on-farm emissions and use locally produced low carbon fuels (e.g. biomethane). Support is needed for practical innovations that curb emissions from dairy production, including methane-reducing additives in feed and improved soil management, learning from practices being adopted on arable farms. **Policy on farm emissions must account for the impact of grazing livestock in sequestering carbon to soils.**

3. **Land Management:** Caring for land and nature, whilst growing food profitably is a complex task. Future policy and regulation should be co-designed with farmers to be as user-friendly as possible. Farmers responsible for 75% of the UK's landmass must be fully motivated and rewarded for efforts to transition to nature friendly systems. The UK's countryside is a living entity, and it cannot be managed from desks in Whitehall. **Change and innovation risks being stifled by excessive red tape unless farmers can input into policy, including on the delivery of public goods.**

4. **Natural Resources:** Rural transition means urgent improvement to UK soil and water quality, while boosting biodiversity. The priority for more rapid progress to rural decarbonisation is the need to correct damage to soil quality over many decades. **Farmers need supportive policy to help them deliver improved soil management and biodiversity.**

[152] Red diesel users pay a duty rate of only 11.14 pence per litre (ppl), significantly less than standard road fuel diesel (duty rate of 57.95ppl), saving nearly 47ppl). Also, red diesel is subject to a reduced 5% rate of VAT for supplies up to 2,300 litres.

5. **Farm Technology:** The low carbon transition will require systems change and a technology shift, including novel fuels and vehicle designs, to curb emissions and end soil damage. **Investment in robotics and digital technologies is needed to help drive change in farming methods.**

6. **Transition Advice:** With many novel operations and technology options, farmers and land managers need access to sound, independent, cost-effective advice and information, plus on farm (i.e. working) demonstration sites. In addition to research funding, changes must include farm level funding for professional advisors, farm clusters, and nature friendly farming groups to offer **guidance on future support mechanisms and 'systems change'.**

7. **Food vs Carbon:** Farmers will need help with mechanisms to increase production of food while being supported in efforts to reduce emissions. They can increase carbon capture in soils and trees. **This must not involve the sacrifice of the best land from food production.**

8. **Rural Communities:** There is a need to mobilise rural communities, particularly in remote and marginal areas, to allow them to play their part in the decarbonisation process. **This must include access to extra funding for development of rural infrastructure to meet specific rural needs, especially in more isolated farming areas in Scotland and Wales.**

9. **Consumer Education:** Changing consumer expectations are reflected in purchasing choices (e.g. less and/or high-quality meat) and their views on waste and recycling. Better environmental labelling on food (including carbon impact), supported by **standardised carbon accounting and farm benchmarking, is essential.**

10. **Trade Agreements:** Efforts to create new post Brexit trade agreements must not be done at the expense of farmers or rural communities. The Covid-19 pandemic has shown the importance of supply chains and risks of reliance on imported products, including food. **Agreements must not threaten the supply of quality and sustainably produced foods from UK farms.**

Agriculture faces a major challenge as it embraces decarbonisation. Farmers and land managers need the support not only of sector bodies and technology suppliers, but also the regulators and policy makers that shape how Government interacts with both farming and farmers.

ABBREVIATIONS

AHDB	Agriculture and Horticulture Development Board
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organisation of the United Nations
GHG	Greenhouse Gas
GWP	Global Warming Potential
Ha	Hectare
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
kWe	Kilowatts (electric), i.e. 1000 Watts, a measure of power
kWh	Kilowatt hour, a measure of energy, i.e. 1000 Watts running for 1 hour
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MW	Megawatt(s), i.e. 1,000,000 Watts
N_2O	Nitrous Oxide
NO	Nitric Oxide (or Nitrogen Monoxide)
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
PM	Particulate Matter
RTFO	Renewable Transport Fuel Obligation
SRUC	Scotland's Rural College
TTW	Tank-to-Wheel
WTW	Well-to-Wheel

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