Hockerton Agrivoltaics' feasibility study

January 2025

Version 3

Stephen Briggs

AbacusAgri

Whitehall Farm Ramsey Road Farcet

Peterborough

PE73DR

Contents

Aim of this feasibility study

The aim of this feasibility study is to provide a coherent, useful, independent and convincing source material for farmers, land owners and Solar Farm managers, to move beyond the binary land use choices of energy vs food and to adopt multi-functional land use approaches such as agrivoltaics where multiple, integrated land use systems deliver multiple benefits (energy, food, biodiversity etc) whilst simultaneously progressing towards a low carbon economy which is more resilient to challenges of climate change.

Executive Summary

The Hockerton Housing Project, a not-for-profit sustainable living organisation near Newark, Nottinghamshire working in conjunction with Sustainable Hockerton, has access to farm land and in partnership with a solar developer is seeking to install a 50 kW ground-mounted solar array integrated with agricultural production to create a functional, agrivoltaic system where multiple, integrated land use benefits are delivered (energy, food, biodiversity etc) whilst simultaneously progressing towards a low carbon economy which is more resilient to challenges of climate change.

This report sets out the principles and defining characteristics of agrovoltaic systems and provides example of commercial and research agrovoltacs in the UK, EU and Globally.

The site characteristics for agrovoltaics at Hockerton are examined along with the opportunities to optimise and unlock yield potential by employing innovative agrolvoltaic design which uses a greater percentage of the land area for production and harness the positive impacts of locally modified microclimate whilst optimising unused solar radiation on land between solar PV panels. Recommendations on enhanced water capture and use are also made.

The practical and economic viability of a range of agricultural crops are evaluated for suitability to the agrovoltaic system. Consideration is given to food self sufficiency and resilience at a local scale, something that is an important priority for the Hockerton community, perhaps even more so that profitability. There is also the potential for localised employment and economic development through integrated land use from food/biomas production and energy production.

Different routes to market set out for different agricultural production option along with resource efficiency considerations, including the use of on-site electricity supply to power machinery and value added processes like crop drying, distillation etc so as to add vale to primary production. The opportunities for producing for niche organic and vegan markets are explored.

Recommendations for the most promising crops/cropping systems and design suggestions for the field trial at the 50kW site in Hockerton (including Hockerton infrastructure adaptation for agrivoltaics) are set out, together with a normalised business model. The recommended crops are lettuce salad crops, raspberry & strawberry soft fruits and viticulture. These have the greatest potential for integration into the proposed agrovoltaic system, to provide foods through local short supply chains, to generate income through value added (processing) activities.

It is recommended that the pilot adopts across one third of the available crop area for each option (1/3 salad, 1/3 Soft fruit, 1/3 viticulture) at the Hockerton agrivoltaics project, so as to demonstrate agronomic, economic and management viability from the pilot.

Recommendations for working with local farmers and solar developers to highlight the potential of agrivoltaics are made and include : understanding the aspirations, aims and objectives of stakeholders, provision of clear economic models, clarity on design, infrastructure, access and maintenance requirements , demonstrating market opportunities and routes to market for agricultural produce from agrovoltaic systems.

Recommendations are made for where the wider adoption of agrivoltaics is desired, setting out factors for success and barriers such as legislation and tax considerations. For wider adoption and scaling up agrivoltaics, recommendations are made on stakeholder engagement, site & crop choice, adaptations required etc. The report also sets out current funding opportunities from public and private funding and financial institutions including banks.

Introduction

The Hockerton Housing Project, a not-for-profit sustainable living organisation near Newark, Nottinghamshire. The project started in the 1990's with construction of five earth sheltered houses, and helped set up Sustainable Hockerton which owns a 225 kW wind turbine installed in 2009, plus three rooftop solar arrays.

Sustainable Hockerton is now hoping to install a 50 kW ground-mounted solar array, to use as a demonstration site showing the potential of agrovoltaic systems, with a mixed /stacked land use for horticultural cropping between rows of solar panels. The aim is to build the array in a standard layout and spacing to show cropping could be "retrofitted" around existing solar developments. This is particularly important in the context of localised and community food security, self sufficiency and resilience. There is also the potential for localised employment and economic development through integrated land use from food/biomas production and energy production, as is the case in agrovoltaic systems.

Agrivoltaics systems have been developed, installed and are working well elsewhere in Europe, but with a different maritime climate in the UK, the project will evaluate which crops suit best from an agronomic, management and stacked system basis, so as to get the most from agrivoltaic systems.

The project will also seek to work with local farmers and solar developers to highlight the potential of agrivoltaics, looking at options at smaller-scale allotment scale, at whole farm regenerative farming-type systems retrofitted into existing solar sites, and larger-scale purpose built PV models designed and built to allow broad acre arable cropping between panel rows.

Inevitably there are many different stacked land use options, from livestock grazing, horticultural crops, arable crops and permanent crops. Choice will depend on the answers to a series of foundation questions; the initial the relative importance placed on land option food vs energy production, local agroclimatic conditions, soil types, management systems, land tenure and intended markets for agricultural/horticultural produce (local vs wholesale).

All options can be explored, with the foundation questions helping funnel the viable options into a shortlist to which model will work best in certain situations.

Developers seem receptive to incorporating these ideas, as they tick a lot of boxes in terms of sustainability, so we want to influence them to change their approach, to move beyond the binary land use choices of energy vs food and to adopt multi-functional land agrivoltaic approaches which deliver multiple benefits simultaneously.

Land use in the UK

The debate over land use for food versus energy in the UK involves complex considerations of sustainability, food security, renewable energy targets, and environmental impacts. Here's an overview of the key aspects involved:

Current Land Use Landscape

- **Agricultural Land**: The majority of the UK's land (70%) is used for agriculture, primarily for food production. This includes arable land for crops and pastureland for livestock.
- **Renewable Energy**: The UK has been increasing its investment in renewable energy sources, including solar farms, wind farms, and bioenergy, to meet its carbon reduction targets.

Key Considerations

1. **Food Security self sufficiency & productivity**
    - **Self-Sufficiency**: Maintaining a high level of self-sufficiency in food production is important for national security and reducing dependency on imports.
    - At a **local scale** food self sufficiency and resilience is an important priority for the Hockerton community. There is also the potential for localised employment and economic development through integrated land use from food/biomas production and energy production
    - **Agricultural Productivity**: Maximizing agricultural productivity on existing farmland is crucial to ensure that the UK can feed its population.
2. **Renewable Energy Goals**
    - **Climate Targets**: The UK has ambitious targets to reduce greenhouse gas emissions, necessitating significant investment in renewable energy sources.
    - **Energy Security**: Increasing domestic renewable energy production can reduce dependency on fossil fuels and enhance energy security.

Balancing Food and Energy Production

1. **Agrovoltaics**
    - **Dual-Use Land**: Agrovoltaics allows for the simultaneous production of food and solar energy on the same land, optimizing land use and potentially providing financial benefits to farmers.

- **Examples**: Projects like the Westmill Solar Park in Oxfordshire, which integrates sheep grazing with solar energy production, demonstrate how dual-use land can be successfully managed.

2. **Marginal Land Use**

   - **Utilizing Non-Arable Land**: Solar and wind farms can be placed on marginal or less fertile lands that are not suitable for high-yield agriculture, preserving prime agricultural land for food production.

3. **Efficiency Improvements**

   - **Agricultural Practices**: Enhancing agricultural practices through precision farming, sustainable techniques, and technological innovations can increase food production efficiency.

   - **Renewable Energy Efficiency**: Advancements in solar panel technology, such as bifacial panels, can increase energy yield without additional land use.

Policy and Economic Instruments

1. **Incentives and Subsidies**

   - **Government Support**: Policies and subsidies that support dual-use land practices, renewable energy investments, and sustainable agriculture can help balance food and energy production needs.

2. **Land Use Planning**

   - **Strategic Planning**: Integrated land use planning that considers the long-term needs for both food and energy production can help optimize land allocation.

- **Environmental Impact Assessments**: Conducting thorough assessments to evaluate the environmental impacts of land use changes is crucial for sustainable development.

Environmental and Social Impacts

1. **Biodiversity**
    - **Habitat Preservation**: Renewable energy projects should be designed to minimize habitat disruption and support biodiversity, for instance, by creating pollinator habitats around solar farms.
2. **Community Benefits**
    - **Local Involvement**: Engaging local communities in land use decisions and ensuring that they benefit from renewable energy projects can enhance social acceptance and support.

Balancing land use for food and energy in the UK requires innovative solutions and integrated planning. Agrovoltaic systems, marginal land use, urban agriculture, and improved efficiency in both food and energy production are key strategies. Policymakers, farmers, and energy developers must collaborate to create sustainable practices that ensure both food security and renewable energy targets are met.

Opportunities and benefits of solar

Solar power offers several opportunities and benefits. It is consistently ranked as one of the most popular forms of energy generation, receiving overwhelming support from the public. A recent survey found that 94% of those living near an existing, proposed, or under-construction solar farm had either a supportive or neutral view of solar (Copper Consultancy, 2023).

One of the key advantages of solar power is its cost-effectiveness. In recent years, the price of solar technology has significantly decreased, making it cheaper than gas and many other alternatives. Solar installations can also be deployed relatively quickly, typically between 12-36 months depending on planning and grid connectivity.

Solar power also offers job creation and investment opportunities. The UK solar industry currently employs more than 6,500 people, which could increase to over 42,000 if the UK commits to 40GW of solar power by 2030 (Solar Energy UK).

Energy security vs food security: We can have both!

Solar farms currently take up less than 0.1% of UK land. Even with a five-fold increase in deployment – in line with the UK Government's energy strategy – solar farms would occupy 0.29% of the UK's total land area (Solar Energy UK). As the technology in a solar farm becomes even more efficient, this figure has been reducing over time, as fewer panels are needed to generate the same amount of energy.

The Department for Environment, Food and Rural Affairs say climate change is the biggest threat to UK food security. It could reduce the UK's stock of high- grade agricultural land by nearly three-quarters by 2050.

Costs have increased in recent years for agricultural businesses. Farmers have been exploring how to diversify their income to continue being able to farm. Solar can provide a direct and long-term revenue stream for farmers, allowing them to reinvest in the food production side of their business.

All types of solar are needed

To realise the benefits of solar and to power our homes solely on clean energy, we need to focus on developing both of the different forms of solar – rooftop, ground mount and agrovoltaic. Pursuing just one or the other will not be sufficient.

Solar power is a game-changer for the UK's energy landscape. As the country aims to reduce its dependence on fossil fuels and meet climate change mitigation goals, solar power offers a renewable and low-carbon solution.

Overall, solar power has the potential to revolutionise the way the UK powers its homes and businesses, providing a sustainable and cost-effective energy solution while reducing carbon emissions and supporting local communities

land use efficiency UK solar farms

Maximizing land use efficiency in UK solar farms involves optimizing the space for both energy production and agricultural activities. Here are strategies and considerations to enhance land use efficiency:

1. Agrovoltaic Systems

- **Dual-Use Design**: Integrate crops or livestock farming with solar panels. Suitable crops include those that thrive in partial shade, such as leafy greens, root vegetables, and berries. Livestock, such as sheep, can graze under and around solar panels.
- **Adjustable Panels**: Use solar panels that can be tilted or moved to optimize sunlight for both crops and energy production. This flexibility can enhance both agricultural yields and solar efficiency.

2. Optimizing Solar Panel Layout

- **Panel Height and Spacing**: Elevate panels to allow sufficient space for agricultural machinery and crop growth underneath. Adequate spacing can also reduce shading on crops and improve airflow.
- **Row Orientation**: Align rows of panels to minimize shading on crops and maximize sunlight capture for solar panels. An east-west orientation can be effective in certain scenarios.

3. Crop and Livestock Integration

- **Crop Rotation**: Implement crop rotation strategies to maintain soil health and reduce pest and disease pressures.
- **Livestock Grazing**: Integrate livestock, such as sheep, for grazing under solar panels. This reduces the need for mechanical mowing and enhances land use efficiency through dual production of energy and animal products.

4. Soil and Water Management

- **Soil Health**: Use cover crops, organic amendments, and other soil management practices to maintain and improve soil fertility and structure.
- **Water Use Efficiency**: Implement efficient irrigation systems, such as drip irrigation, to optimize water use. The microclimate created by solar panels can affect soil moisture, so irrigation practices may need to be adjusted.

5. Biodiversity Enhancement

- **Pollinator Habitats**: Create habitats for pollinators by planting wildflowers or maintaining hedgerows around and within the solar farm. This supports biodiversity and can improve crop yields.
- **Wildlife Corridors**: Designate areas within the solar farm as wildlife corridors to support local fauna and enhance ecological health.

6. Technological Innovations

- **Bifacial Panels**: Utilize bifacial solar panels that can capture sunlight from both sides, increasing overall energy efficiency without additional land.
- **Smart Monitoring Systems**: Implement smart monitoring systems to optimize both agricultural and energy production. These systems can provide real-time data on crop health, soil moisture, and solar panel performance.

7. Economic and Policy Support

- **Subsidies and Incentives**: Leverage government subsidies and incentives for renewable energy and sustainable agriculture to offset initial costs and improve economic viability.
- **Policy Alignment**: Advocate for policies that support dual land use and provide clear guidelines for integrating agriculture with solar energy production.

Improving land use efficiency in UK solar farms involves a multi-faceted approach that combines advanced technology, innovative farming practices, and supportive policies. By integrating agriculture with solar energy production, solar farms can enhance sustainability, economic viability, and ecological health

The potential for agrovoltaic's in UK

Agrovoltaics, the integration of solar power generation with agricultural activities, holds considerable potential in the UK due to several factors:

Climate and Geographic Suitability

1. **Moderate Climate**: The UK's temperate climate is beneficial for both solar panels and crops. Solar panels can provide shade and reduce heat stress on crops during hot periods, while the cooler climate can prevent the panels from overheating, which can reduce their efficiency.
2. **Land Availability**: The UK has significant agricultural land that can be dual-purposed for energy production. This is particularly valuable in regions where space is at a premium.
3. **Sunlight Variability**: The UK's relatively high latitude results in lower solar irradiance compared to more equatorial regions. Seasonal variations can also significantly affect solar energy production, with shorter days and less intense sunlight in the winter months.
4. **Weather Conditions**: Frequent cloud cover and rain can reduce the efficiency of solar panels. Persistent overcast conditions can limit the amount of electricity generated

Energy Demand and Policy Support

1. **Renewable Energy Targets**: The UK government has ambitious renewable energy targets and policies that support solar energy. Agrovoltaics can help meet these targets by combining agricultural productivity with renewable energy generation.

2. **Subsidies and Incentives**: Various subsidies and incentives are available for renewable energy projects in the UK. Farmers and landowners can benefit financially from these schemes, making agrovoltaics an attractive option.

Regulatory and Planning Barriers

1. **Planning Permissions**: Obtaining the necessary planning permissions for agrovoltaic installations can be a lengthy and complex process, with strict regulations that can vary by region.
2. **Regulatory Uncertainty**: Changes in government policies, subsidies, and regulations can create uncertainty, making long-term planning and investment in agrovoltaic systems more challenging.

Economic and Environmental Benefits

1. **High Initial Costs**: The capital expenditure for installing agrovoltaic systems can be substantial. This includes the cost of solar panels, mounting structures, and integration with existing agricultural practices.
2. **Financial Risks**: There is a financial risk involved, particularly for small-scale farmers. The return on investment can be uncertain due to fluctuations in energy prices and potential changes in subsidy schemes
3. **Additional Revenue Streams**: Farmers can generate additional income from solar energy production while continuing to cultivate their land. This dual use can increase the economic resilience of farms.
4. **Biodiversity Impact**: While agrovoltaics can enhance biodiversity in some cases, poorly planned installations might have negative impacts on local ecosystems, disrupting habitats and affecting wildlife.
5. **Soil Health**: The shading from panels can alter microclimates in ways that might not always be beneficial for soil health and crop growth, potentially leading to issues such as reduced soil fertility or increased susceptibility to pests. The shade provided by solar panels can help maintain soil moisture and reduce evaporation, benefiting crop health and reducing irrigation needs. Moreover, agrovoltaic systems can contribute to biodiversity by providing habitats for various species.

Social and Community Acceptance

1. **Aesthetic Concerns**: The visual impact of solar panels on agricultural landscapes can be a concern for local communities. There may be resistance to changing traditional farming landscapes.
2. **Land Ownership and Tenure**: In cases where farmers do not own the land but lease it, negotiating the implementation of agrovoltaic systems can be complicated. Landowners may have different priorities or concerns.

Technological and Practical Considerations

1. **Solar Panel Technology**: Advances in solar panel technology, including bifacial panels that capture light from both sides, can increase the efficiency of agrovoltaic systems. The development of adjustable and movable panels can also optimize both crop growth and energy production.
2. **Research and Pilot Projects**: Ongoing research and pilot projects in the UK and Europe demonstrate the feasibility and benefits of agrovoltaics. These projects provide valuable data and best practices for large-scale implementation.
3. **System Integration**: Integrating solar panels with existing agricultural machinery and practices can be complex. For example, the height and spacing of panels must be carefully designed to avoid interfering with crop management and harvesting activities.
4. **Maintenance**: Solar panels require regular maintenance, including cleaning and repairs. This can be challenging in an agricultural setting where accessibility may be limited and where additional labour might be needed.

Agricultural Impact

1. **Crop Compatibility**: Not all crops are suitable for growing under solar panels. Some may require more sunlight than what is available under the shaded conditions created by the panels. Finding the right crop-panel combination is crucial.
2. **Land Use Efficiency**: There might be concerns about the effective use of land. While agrovoltaics aims to optimize dual use, some argue that it might not be the most efficient way to use agricultural land, particularly if the primary focus is on maximizing crop yields

Research and Knowledge Gaps

1. **Limited Local Research**: While there is growing interest, there may still be a lack of comprehensive, UK-specific research on the best practices for agrovoltaic

systems, including optimal crop types, panel configurations, and economic models.

2. **Technology Adaptation**: The technology and practices developed in other countries with different climates and agricultural systems might not be directly transferable to the UK, requiring adaptation and innovation.

Challenges and Considerations

1. **Initial Investment**: The setup cost for agrovoltaic systems can be high, requiring significant initial investment. However, the long-term benefits and potential subsidies can offset these costs.
2. **Land Use Conflicts**: Balancing the dual use of land for agriculture and energy production requires careful planning and management to avoid conflicts and ensure that both activities are optimized.
3. **Regulatory and Planning Hurdles**: Navigating the regulatory landscape and securing planning permissions can be complex and time-consuming.

Despite some limitations, agrovoltaics can still offer significant benefits if these challenges are addressed through targeted research, supportive policies, technological innovation, and stakeholder engagement. By understanding and mitigating these constraints, the UK can better harness the potential of agrovoltaic systems. Agrovoltaics presents a promising opportunity for the UK to enhance its renewable energy capacity while supporting agricultural productivity and sustainability. With the right policies, incentives, and technological advancements, agrovoltaics could play a significant role in the UK's energy and agricultural future

1 Defining agrovoltaic systems

Agrivoltaic's, also known as *agrophotovoltaics* or *agri-PV*, is a method that combines solar energy production and agriculture on the same land. This is done by installing solar panels on agricultural land, which can have several benefits:

Increased land use efficiency
Agrivoltaics allows solar farms and agriculture to share land, rather than competing for it.

Multiple revenue streams
Farmers can add clean energy production to their core activities, which can provide additional revenue.

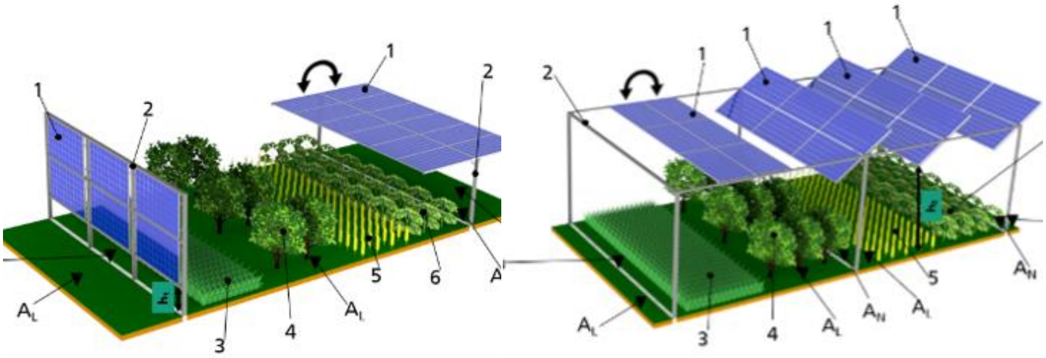
Improved crop growth
The microclimate created by the solar panels can be beneficial to crops, sheltering them from the elements.

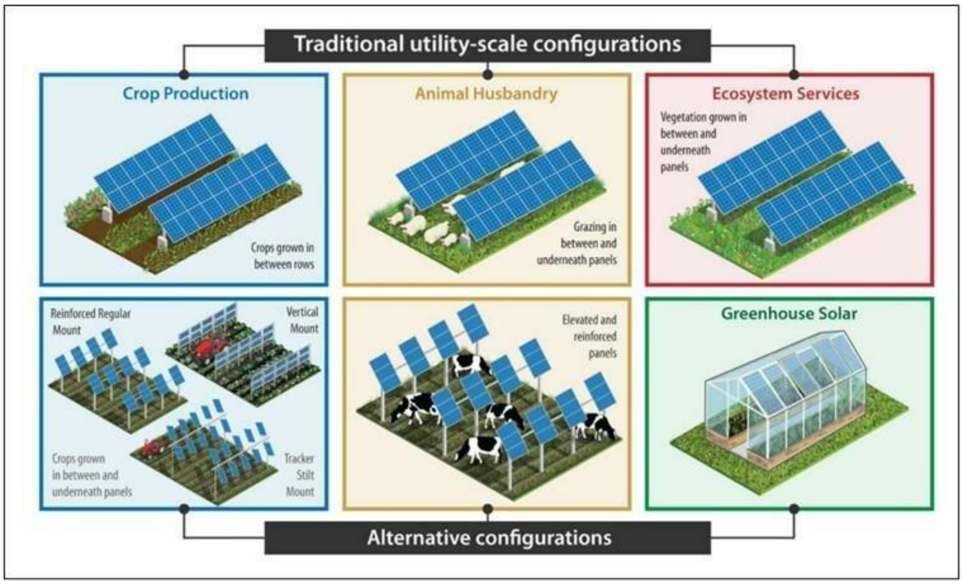
Protection from extreme weather
PV arrays can protect crops from wind, heat, cold, storms etc and provide shade for grazing animals.

Sustainable development
Agrivoltaics is a sustainable solution that helps to mitigate climate change and drive forward the energy transition

Open agrivoltaic systems are divided into highly elevated (management UNDER modules) and ground-level systems (management BETWEEN modules)
Below is an example of a typical ground mounted agrovoltaic system with horticultural crops being integrated with solar PV energy production.

Many different Solar PV layouts are possible, including horizontal and angled panels raised on structures so as to provide access for cropping/mechanisation beneath; tilting/tracking panel systems; bifacial vertical systems etc. Some of these are depicted below.





From an agricultural perspective, module technologies that let the light spectra necessary for plant growth pass are of particular interest.

While some solar farms do feature sheep grazing around panels, the integration of cropping is pretty much non-existent in the UK, however the concept of agrivoltaics has been around for decades.

The concept was introduced in 1981 by Prof. Dr. Adolf Goetzberger, founder of the Fraunhofer Institute for Solar Energy Systems ISE, and Dr. Armin Zastrow. They realized that dual land use could bring great benefits. They investigated how conventional PV systems can be adapted to allow homogeneous plant growth in parallel with solar power generation

From conception by German physicists in the 80’s, it has now become reality in many European countries, including Germany, France, Italy, Spain, the Netherlands, and further afield in China, Japan, and South Korea

With ambitious UK government targets to generate 70 GW of electricity from solar by 2035, and ongoing concerns about using productive farmland for such purposes, there could be considerable scope to adopt agrovoltaic systems.

Agrovoltaic systems use the principle of multilayered systems to capture our primary resource, solar radiation. Simplistically, by ‘stacking’ multiple production systems (energy, food, biodiversity etc) three-dimensionally.

For example, a typical wheat crop only uses around 60% of the total solar radiation available, so there’s a fair amount of light we could capture for other purposes such as energy generation through Solar PV. Furthermore, once combinable crops start to senesce pre-harvest, the solar radiation is effectively not being used for a quarter of the year from July to September. At the point where there’s nearly maximum solar radiation available, we’re not using the biggest free input to the farming system. Installing solar panels alongside either arable, horticulture or grazing systems could be a really effective way of capturing some of that energy.

2 Agrovoltaic/Solar - agricultural land use and policy

Solar farms usually require planning permission. The size of a solar farm will determine which body decides the application. For example, in England: Solar farms with a generating capacity below 50 megawatts (MW) need planning permission from the local planning authority (LPA).

Solar farms with a generating capacity above 50 MW need development consent from the Secretary of State for Energy Security and Net Zero, because they are nationally significant infrastructure projects' (NSIPs)

Planning is a devolved matter. In the devolved administrations, the size of a solar farm will also determine whether the LPA or the government decide an application. However, thresholds differ across the UK.

Policies for small-scale solar farms (below 50 MW)

LPAs in England will decide applications for smaller-scale solar farms in line with their local plan and the national planning policies. Government guidance advises LPAs to approve renewable energy developments whose "impacts are (or can be made) acceptable".

Government guidance states that there "are no hard and fast rules about how suitable areas for renewable energy [developments] should be identified". It advises LPAs to consider their potential impacts on the local environment and the views of local communities when identifying suitable sites. However, government guidance generally guides development away from the '*best and most versatile' agricultural land* and states that renewable energy developments are not usually "appropriate" development for green belt land.

Policies for large-scale solar farms (above 50 MW)

The Secretary of State will decide applications for large-scale solar farms in line with energy national policy statements. These were updated in January 2024. They now state that the development of low-carbon infrastructure, such as solar farms, is a 'critical national priority'. This means that the Secretary of State should generally grant consent to low-carbon infrastructure.

The updated national policy statement for renewable energy infrastructure advises that solar farms should be sited on previously developed and *non-agricultural land*. *However, it does not prohibit the siting of solar farms on agricultural land*.

Land use for solar farms

Solar farms are not evenly distributed across the UK. 43% of ground-mounted installations (that have a capacity of at least one megawatt) that are already operational or are awaiting/under construction are located in the South East and South West of England. It is not possible to calculate how much land is used for solar farms and how much of different types of land are used.

Some organisations, such as the countryside charity CPRE, have expressed concern that "valuable farmland" is often "the location of choice for solar developments". CPRE has said it is "essential" to preserve agricultural land for food production.

Renewable energy groups, such as Solar Energy UK, have argued that "solar farms pose no threat to the UK's food security" (PDF). They also point to the multi-functional use of land, for example, grazing sheep on solar farms, to highlight that solar power and farming are not always mutually exclusive, as with agrovoltaic systems.

Biodiversity Net Gain

The principle of biodiversity net gain (BNG) leaves the land in a measurably better state than before development.

Under Part 6 of the Environment Act (2021) all new developments**, including solar farms**, now need to be designed to deliver a minimum of 10% BNG from November 2023. Solar farms considered to be of national significance (NSIP/DNS) will need to deliver the requirement from November 2025.

Barriers to the deployment of solar power

As of May 2024, the cumulative installed capacity of solar power in the UK was 15.8 GW. The government aims to achieve 70 GW of solar power by 2035.

The Environmental Audit Committee, a Commons Select Committee, said meeting this target would be "challenging given existing barriers and current rates of deployment" (PDF). The government's advisory Climate Change Committee also said current deployment rates were "*significantly off track*".

Two of the main barriers to the expansion of solar power they identified were (i) grid capacity, and (ii) delays in securing grid connections. The Environmental Audit Committee said "upgrading the electricity grid is a crucial prerequisite to the achievement of net zero"

Agrovoltaics and planning consent

A major criticism of solar farms is that they can take large swathes of agricultural land out of production, so why not design systems that do both – agrovoltaic systems.

Agrivoltaics systems combine energy (Solar PV) and food production (crops or animals). However, currently agrovoltaic systems still require planning permission from the local planning authority (LPA) for agrovoltaic systems with a generating capacity below 50 megawatts (MW) and where agrovoltaic systems have a generating capacity above 50 MW, development consent is currently still required from the Secretary of State for Energy Security and Net Zero, because they are still deemed nationally significant infrastructure projects' (NSIPs)

Given the pressure on land-use in the UK and ongoing food vs fuel conflicts, new schemes should integrate solar alongside food production, and doing so could even help meet planning requirements going forward. Some European countries have now introduced legislation governing panel density, allowing for land-use between the rows. France has led the way in this regard with the ADEME decree of April 8, 2024 relating to agrivoltaics.

Legislation in other EU states allow for both 'fixed' stationary panels, located above crops/animals (with an inclination of around 30-35° relative to the ground to optimize electricity production) or in the middle of fields (perpendicular to the ground), or 'mobile' systems which employ electrical motors which allow the modules to be tilted at +/-90° or move across the land as modular 'tractors'.

Fixed panels are cheaper and easier to maintain, but the permanent and heterogeneous shading they generate can harm agricultural yields (particularly in orchards, vineyards and market gardens). Mobile panels, on the other hand, allow more precise control of light and shade, but involve higher costs.

Land reversibility

The reversible nature of an agrivoltaic installation is a fundamental criterion. In France, according to the APER law, an installation can only be described as agrivoltaic if it is reversible i.e the land can at some point be returned to agricultural use. This principle guarantees that the land remains dedicated to agriculture in the long term. The regulatory framework thus provides:

- an operating permit limited to 40 years, with the possibility of an extension of 10 additional years.
- an obligation to dismantle and restore the site within one year following the end of the operating permit.
- financial guarantees imposed on the investor, deposited with the Caisse des Dépôts et Consignations, in order to ensure these operations.
- This reversibility ensures that agriculture remains the primary vocation of the land
- Reform of the planning systems in the UK to recognise the multifunctional benefits of agrovoltaic systems is required, recognising that it need not be a

binary land use choice of energy or food, that with the correct design and operational frameworks, there is potential for both onto operate on the same land areas.

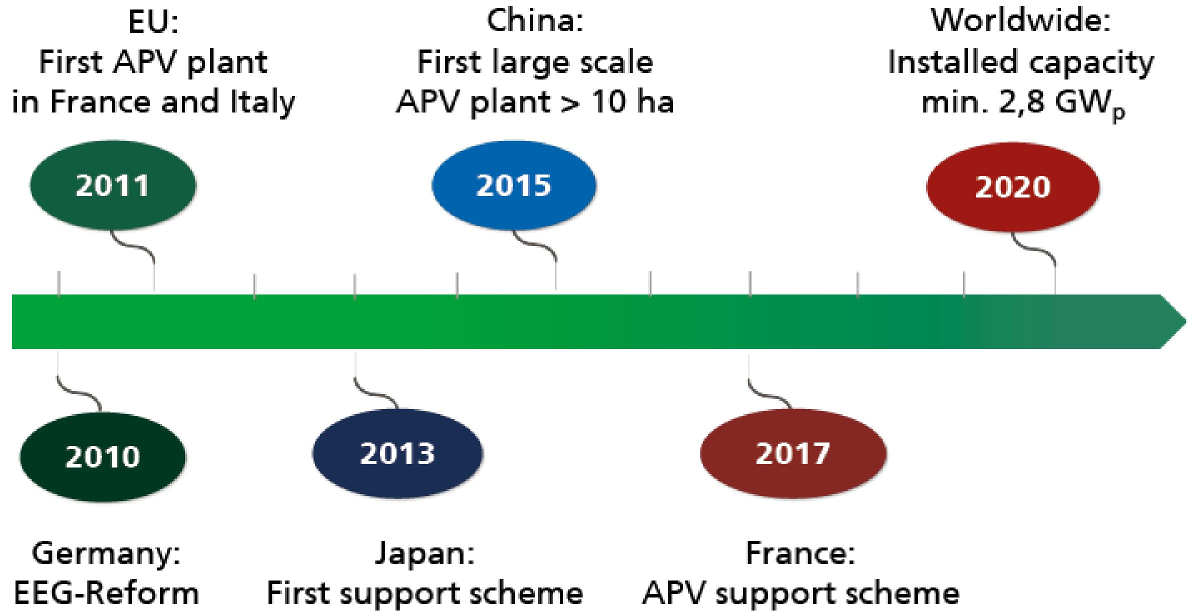
3 Case study examples of agrivoltaic systems UK and international

Agrivoltaics refers to a practice for the simultaneous use of land for agricultural food production and PV electricity production.

In this way, agrivoltaics increases land efficiency and enables the expansion of PV while preserving arable land for agriculture

In the 2000s, the first agrivoltaic pilot systems were built and researched first in Japan and then in Germany and France. Japan introduced the first government support program in 2013 and recorded more than 1,900 agrivoltaic systems in 2018.

Japan was followed by China, France, the U.S., and Korea with government subsidies for agrivoltaics, increasing the global average capacity of plants from 5 MW in 2012 to more than 14 GW in 2022.



The largest agrivoltaic systems to date, growing goji berries, was implemented in China on the edge of the Gobi Desert and is currently being scaled up to 1 GWp. The Chinese internet information services provider Baofeng Group is expanding the capacity of a 640 MW solar park in the Binhe New District on the eastern banks of the Yellow River in the Ningxia Province to 1 GW. In this giant project, the company is combining PV power generation with the production of goji berries, which are an ingredient in traditional Chinese, Korean, Vietnamese and Japanese medicine.

Baofeng Group began managing 107 square kilometers of desertified land in the area 2014, and that it initially planted alfalfa to improve the soil. The perennial flowering plant was then removed to enable the construction of the solar plants and, upon its completion, goji berries were planted underneath the panels. This helped resume goji farming in the region, which in turn revived an otherwise dead expanse of desert.

The first 640 MW section of the project, which relies on 13,000 Huawei smart string inverters, was grid-connected under China's feed-in program for solar energy in 2016. According to Huawei, the facility was built in a sustainable way. The ecosystem in this region has improved, the number of small wild animals has increased significantly, like sparrows, hares and pheasants. The agrovoltaic system reduces land moisture evaporation by between 30 and 40%. The vegetation coverage has purportedly increased by 85% while significantly improving the regional climate.

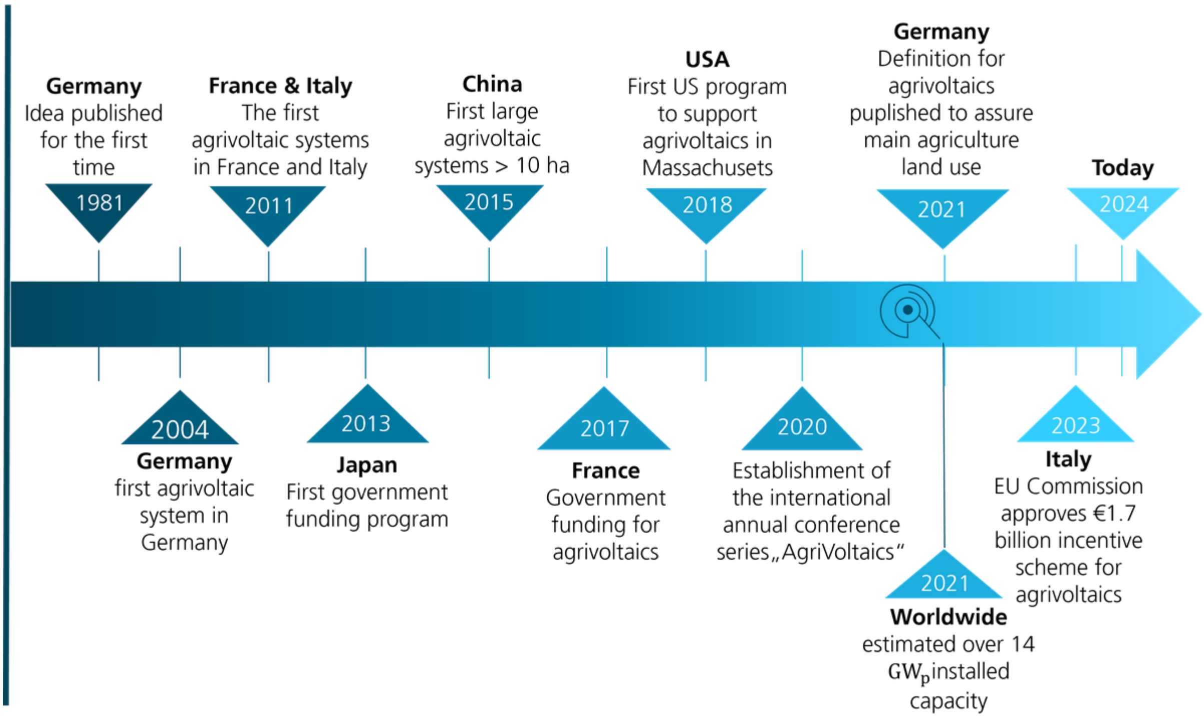
The panels were installed at a height of 2.9 m, which not only offers enough room for the cultivation of goji berries, but also ensures optimal operation and maintenance

According to a recent study from the United States, PV projects linked to agriculture have thus far shown the highest potential when combined with leafy greens such as lettuce and spinach, as well as with root crops such as potatoes, radishes, beets and carrots. The authors of the paper, however, also believe that a combination such as strawberries, blueberries, raspberries and lingonberries could also provide for strong power and crop yields. https://www.ise.fraunhofer.de/de/forschungsprojekte/apv-obstbau.html

Crops not as well suited are tall crops that may interfere more with the panels like corn or orchard crops.

Another study from the University of Arizona stated that the shade from solar panels growing crops can help produce to two or three times more fruit and vegetables than conventional agriculture setups. The group presented the results of a multi-year research project investigating how chiltepin peppers, jalapenos and cherry tomato plants grew in the shade of PV panels in a dry location.
https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?referer=https://scholar.google.de/scholar?hl=de&as_sdt=0%2C5&q=Barron+%26+Gafford+2017+Agrivoltaics&btnG=&httpsredir=1&article=1475&context=star

German renewable energy company BayWa r.e. and its Dutch subsidiary, GroenLeven, are building five pilot agrivoltaic power projects in the Netherlands, where they are testing five different types of crops: blueberries, red currants, raspberries, strawberries and blackberries



Germany

The Fraunhofer Institute for Solar Energy Systems
https://www.ise.fraunhofer.de/en.html is the largest solar research institute in Europe and has been at the forefront of agrivoltaic technology. This includes a 1 ha agrivoltaics research facility where different PV modules and orientations are being investigated to assess the impact on growth and yield of crops grown underneath.

As the costs of ground-mounted PV systems continue to fall. Research forecast that in about five to eight years, such PV installations will become cost-effective even without the financial support of the Renewable Energy incentive/subsidies. Decreasing costs spurn on new types of business models for land use and as a result new challenges arise. Increased competition for land use, for example, can cause the rental price for land to rise. The innovation group APV-RESOLA https://agri-pv.org/en/ is therefore developing and investigating a new type of PV system that ensures the coexistence of agriculture use and electricity production on the same piece of land

In central Germany Next2Sun https://next2sun.com/en/agripv/ is offering Agri-PV systems tailored to the needs of farmers and investors, including lease arrangements where the landowner just provides the land, through to joint venture agreements.

A core part of its system is the installation of '*bifacial'* vertical solar panels featuring solar cells on both sides, which when aligned east-west, aim to generate electricity mainly in the morning and afternoon or early evening. Crucially, they have a smaller footprint than standard angled panels, so take up only around 10% of the field area and allow farming to continue on 90% of the land in between.

Next2Sun recently announced plans to work with US solar company iSun https://isunenergy.com/ to construct the first agrivoltaics plant in America. The 3.7-acre site will feature 69 vertical bifacial solar modules installed in rows 30 feet apart, allowing crops such as carrots, beetroot, and saffron to be grown between the rows https://isunenergy.com/news/next2sun-and-isun-build-first-vertical-agrivoltaics-system-in-the-usa

Bavarian State Research Center for Agriculture (LfL)

- Location: Bavaria
- Project: The LfL has established an agrovoltaic pilot project to study the effects of solar panels on various crops, including potatoes, wheat, and clover.
- Details: The project aims to optimize the design and layout of agrovoltaic systems to maximize both energy production and agricultural yields.

Fraunhofer ISE Agrovoltaic Pilot

- Location: Heggelbach
- Project: Fraunhofer Institute for Solar Energy Systems (ISE) has implemented a large-scale agrovoltaic pilot project on an organic farm.
- Details: Solar panels are installed over crops such as potatoes, celery, and wheat. The project studies the microclimatic effects of the panels and their impact on crop yields and quality.

France

In 2009, the National Research Institute for Agriculture, Food and the Environment (INRAE) began a joint project with French energy company Sun’R to develop agrivoltaic systems for a range of farming situations (arable crops, market gardening, arboriculture, viticulture). https://sunagri.fr/resultats-viticulture/

(**a**) Structure 4 m above the ground (**b**) Mono-crystalline PV arrays (**c**) Single-axis sun tracking system

The research focuses on optimizing panel arrangements to balance shading and sunlight, enhancing both agricultural productivity and solar energy output.

In 2017, this included a world-first for viticulture, when 4.5 ha of vines were planted underneath controllable tracking solar panels at a demonstration site in southern France.

Sun'Agri Projects

- Location: Various locations
- Project: Sun'Agri, a pioneer in dynamic agrivoltaics, has multiple projects across France, integrating solar panels with vineyards, fruit orchards, and vegetable farms.
- Details: These projects use adjustable solar panels that can be tilted to optimize sunlight for both crops and energy production, protecting plants from extreme weather conditions like hail and frost

Italy

Agrivoltaico Project

- Location: Tuscany
- Project: The Agrivoltaico project integrates solar panels with traditional farming in Tuscany, focusing on crops like tomatoes and olives.
- Details: The aim is to study the impact of solar panels on crop microclimates, water usage, and overall yield, while also producing renewable energy.

ENEA Agrovoltaic Systems

- Location: Various locations
- Project: The Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) has multiple agrovoltaic projects aimed at combining solar energy with agriculture, including with arable production.

- Details: These projects explore the use of semi-transparent panels and different mounting structures to optimize light distribution for crops like lettuce, spinach, and strawberries.

Netherlands

Wageningen University Research (WUR)

- Location: Wageningen
- Project: WUR is conducting agrovoltaic research focusing on integrating solar panels with horticultural crops and greenhouses.

- Details: The research aims to develop innovative designs that maximize light penetration and energy efficiency, ensuring that both crops and solar panels perform optimally.

GroenLeven Agrovoltaic Project

- Location: Friesland
- Project: GroenLeven, a leading solar developer, has initiated an agrovoltaic project combining solar panels with blueberry cultivation.
- Details: The project uses elevated solar panels to provide partial shading, which benefits the blueberries by reducing heat stress and water evaporation

H2arvester

A consortium of companies and researchers has developed a large mobile solar array called the H2arvester that can travel autonomously across fields. Each 12×6 m solar “car” moves slowly (10 meters per hour) in a pre-defined direction. It is claimed that 2 MW could be generated from a 10 ha field without impacting crop production

Spain

Almería Agrovoltaic Research

- Location: Almería
- Project: Researchers at the University of Almería are exploring the integration of solar panels with greenhouse farming, a major agricultural practice in the region.
- Details: The research focuses on optimizing the placement of solar panels to balance energy production and light requirements for greenhouse crops like tomatoes and cucumbers.

Tamera Solar Test Field

- Location: Tamera, Portugal (near Spain)
- Project: Although in Portugal, the Tamera project near the Spanish border serves as a collaborative agrovoltaic research site focusing on permaculture and solar energy integration.
- Details: The project uses solar panels to provide shade and reduce water usage for various crops, aiming to create sustainable farming models that can be replicated in semi-arid regions.

Ireland

In Waterford, Ireland, a farming business has installed a 29.6 kWp Next2Sun agrovoltaic ‘solar fence’. Cows graze between the three east-west aligned rows of fencing. As the production peaks of the solar fence coincide with milking times, the dairy farm can use around 65% of the electricity produced to cover its own needs.

- Using a highly efficient module backing, the system produces 1,123 kWh per kWp per year
- It protects animals, provides shade and serves as a permanent privacy screen.
- Uses sunlight from both sides of the ‘bi-facial’ fence to increase electricity production
- Grazing areas can be optimally used for fencing and power generation at the same time.
- Easy installation and maintenance due to ground level arrangement.
- Electricity production on demand: electricity produced in the morning and evening and more in winter than in summer. It therefore exceeds the output of conventional systems.
- An ideal solution for snowy areas: remains snow-free and generates up to 8 % more electricity in snowy conditions.
- Large livestock can be prevented from touching the solar fence by using electrical wires as ‘stand-off’ fence strands

UK systems

Agrovoltaic systems are gaining attention in the UK, with several examples and pilot projects demonstrating their potential. Here are some notable examples:

1. Sutton Bridge Crop Storage Research Facility

- **Location**: Lincolnshire
- **Project**: In collaboration with the University of Lincoln, this facility has implemented a research project to explore the benefits of combining solar panels with crop storage.
- **Details**: The project involves installing solar panels above crops to study their effects on both energy generation and crop yields, particularly focusing on potatoes and other root vegetables.

2. Warwickshire Farm Agrovoltaic Project

- **Location**: Warwickshire
- **Project**: A private farm in Warwickshire has integrated solar panels with their agricultural practices to assess the viability of agrovoltaics in the UK.
- **Details**: The project aims to investigate the impact of solar panels on crop growth and energy production. Crops such as leafy greens and root vegetables are grown under the panels to measure yield differences.

3. Sheffield University's Agrovoltaic Research

- **Location**: Sheffield
- **Project**: Researchers at the University of Sheffield are conducting studies to optimize the design and layout of agrovoltaic systems for UK conditions.
- **Details**: The research includes testing different panel configurations and crop types to identify the best practices for combining solar energy generation with agriculture. The focus is on creating models that can be scaled up for commercial use.

4. James Hutton Institute's Agrovoltaic Trials

- **Location**: Dundee, Scotland
- **Project**: The James Hutton Institute is exploring the potential of agrovoltaics through experimental setups on their research farms.
- **Details**: Trials involve various crops, including barley and other cereals, to determine the impacts of shading and microclimate changes on crop

productivity. The institute is also investigating the potential benefits for soil health and biodiversity.

5. Westmill Solar Park

- **Location**: Oxfordshire
- **Project**: Although primarily a solar park, Westmill Solar Park has integrated agrovoltaic principles by incorporating sheep grazing under the solar panels.
- **Details**: This approach combines renewable energy production with livestock farming, demonstrating a practical example of dual land use. The project showcases how solar installations can coexist with agricultural activities.

6. ADAS Agrovoltaic Research

- **Location**: Various sites across the UK
- **Project**: ADAS, an agricultural and environmental consultancy, is conducting research on the feasibility of agrovoltaics in the UK.
- **Details**: The research involves pilot projects on different farms, testing the effects of solar panels on crop yields, soil moisture, and overall farm productivity. The goal is to develop guidelines and best practices for farmers interested in adopting agrovoltaic systems.

7. Agri-EPI Centre and Innovate UK Projects

- **Location**: Various locations
- **Project**: Agri-EPI Centre, in collaboration with Innovate UK, is working on multiple agrovoltaic projects aimed at promoting sustainable agriculture.
- **Details**: These projects include field trials and demonstrations to evaluate the economic and environmental benefits of agrovoltaic systems. They focus on diverse crop types and different geographical locations to gather comprehensive data.

8. University of Sheffield: Research from the University of Sheffield has highlighted the potential of agrovoltaics in the UK, emphasizing benefits like improved land use efficiency and enhanced sustainability

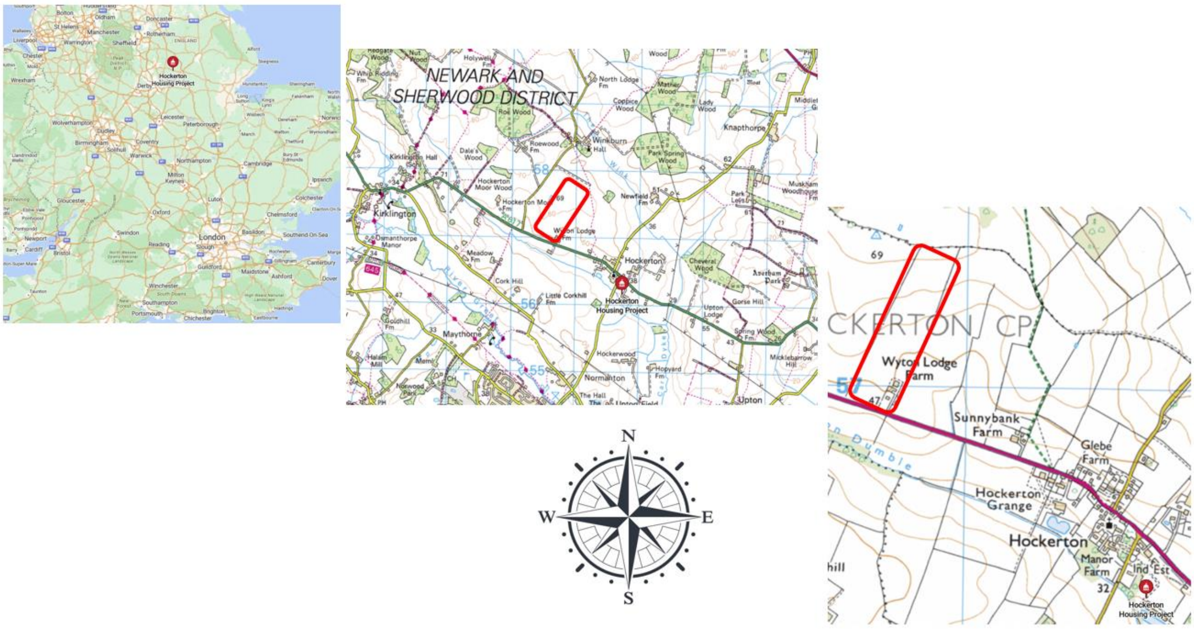
9. National Farmers Union (NFU): The NFU has been exploring agrovoltaics as part of its broader strategy to achieve net-zero carbon emissions by 2040. This includes working with farmers to integrate renewable energy systems into their operations.

These examples from across Europe highlight the diverse applications and benefits of agrovoltaic systems, from improving crop resilience and water efficiency to generating renewable energy. As research and technology advance, these projects provide valuable insights and models for broader adoption of agrovoltaics, contributing to sustainable agriculture and energy production in Europe.

These UK examples illustrate the growing interest and experimentation with domestic agrovoltaic systems. While still in the research and pilot phase, these projects provide valuable insights into the potential benefits and challenges of integrating solar energy with agricultural practices. As these projects progress, they are likely to inform larger-scale implementations and contribute to the development of sustainable farming and energy solutions in the UK

4 Hockerton site evaluation

Hockerton lies in Nottinghamshire in the East Midlands, located in the Newark & Sherwood District. The agrovoltaic site is located NW of Hockerton village at Wyton Lodge Farm, where there is an existing community owned and operated wind turbine producing renewable energy.



The original Agrovoltiac trial site sits at the northern end of the Wyton Lodge Farm field (in red) adjacent to the wind turbine, as depicted by the yellow demarked area in pictures below

A revised Agrovoltiac trial now sited in the field east of the track to the wind turbine at the northern end of the Wyton Lodge Farm field (in red) as depicted by the green and red demarked area in figures below

Hockerton revised Agrovoltaic site

Hockerton Agrovoltaic site access – looking North

Hockerton Agrovoltaic site access – looking South

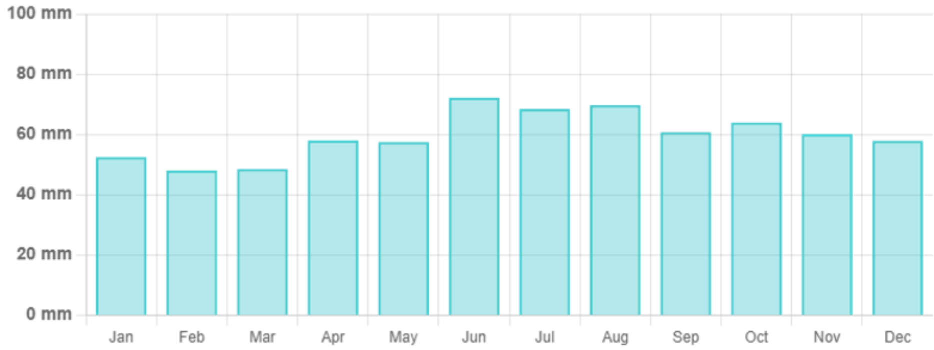
Hockerton Agrovoltaic site – looking North from the main road

Climate

Annual rainfall is 719mm/yr (30yr av.) (fig x), with average number of rainy days between 11-16 pcm over the year.

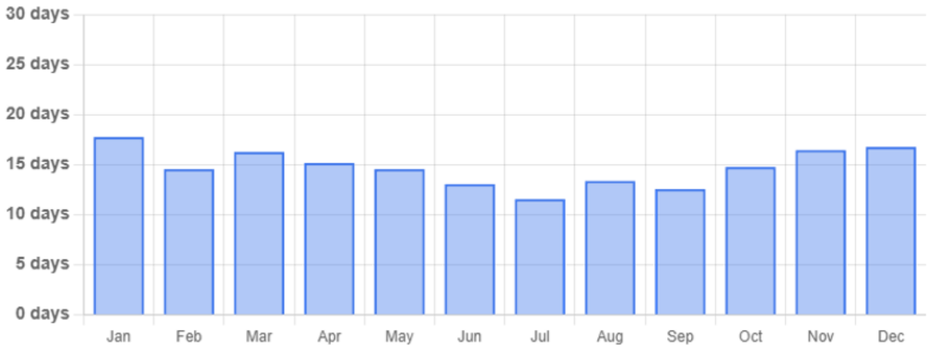
Monthly precipitation

The mean monthly precipitation over the year, including rain, snow, hail etc.



Monthly rainy days

The average number of days each month with rain, snow, hail etc.

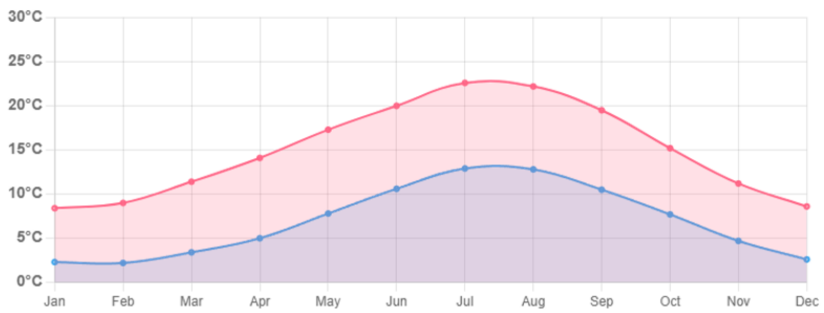


Mean min-max temperatures range from 2-7 Deg C mid winter to 12-24 Deg C mid summer.

Newark upon Trent (Nottinghamshire), averages of weather conditions over a 30-year period

Average day and night temperature

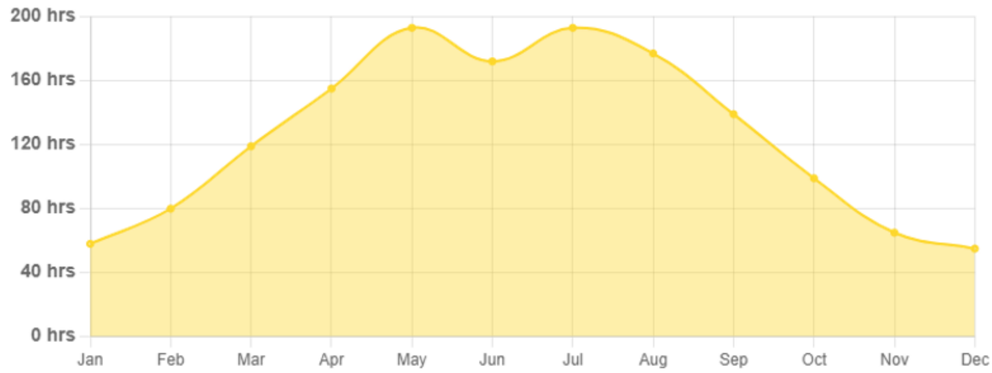
The mean minimum and maximum temperatures over the year



Monthly sunshine hours range from c50hrs pcm in winter to c200hrs pcm in summer

Monthly hours of sunshine

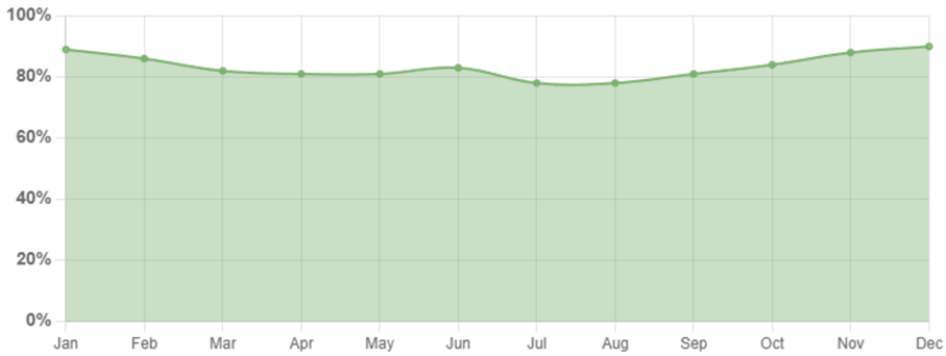
The average monthly total hours of sunshine over the year



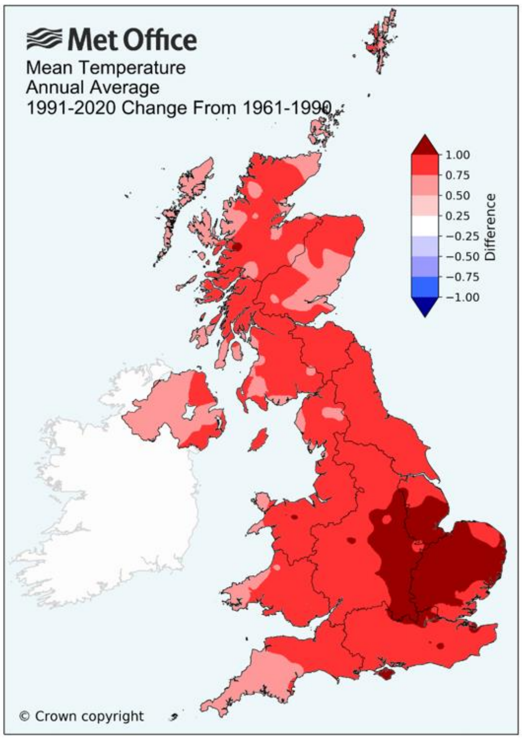
Humidity at the site is relatively stable ranging from 78-90% throughout the year.

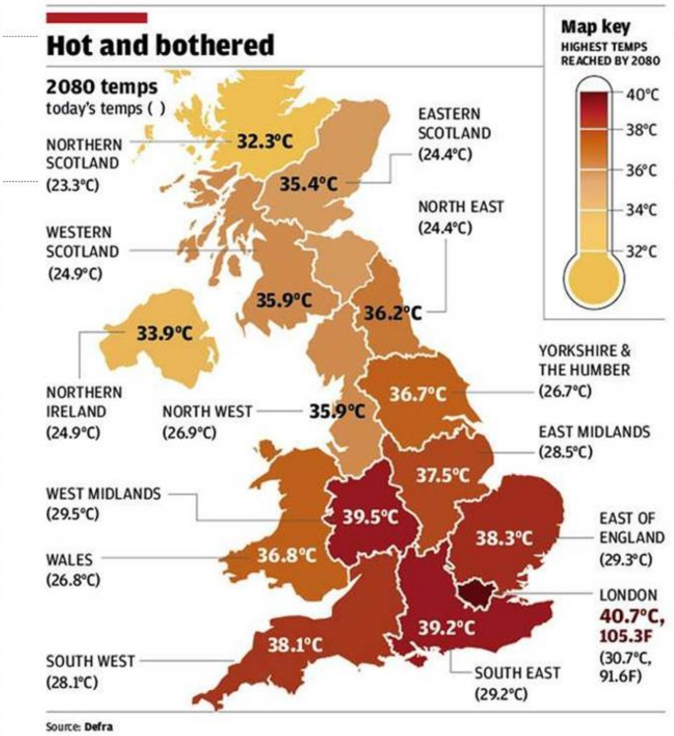
Average humidity

The mean monthly relative humidity over the year



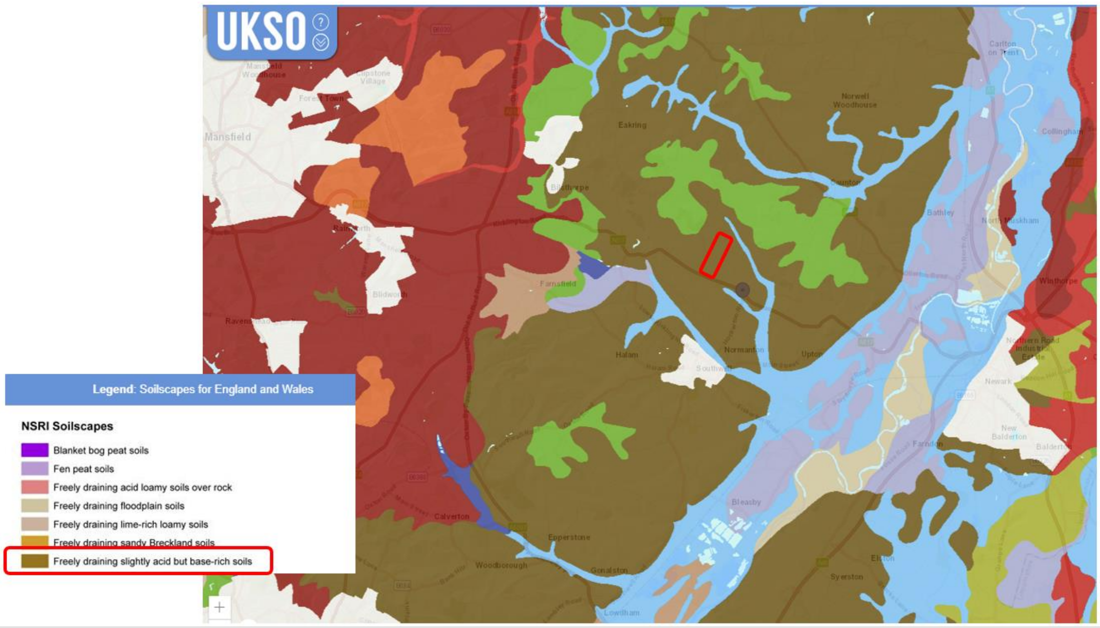
Predictions by the Met Office and DEFRA indicate an upward shift in mean annual temperature ranges, with maximum temperatures increasing from 28.5 Deg C to 37.5 Deg C in the East Midlands.

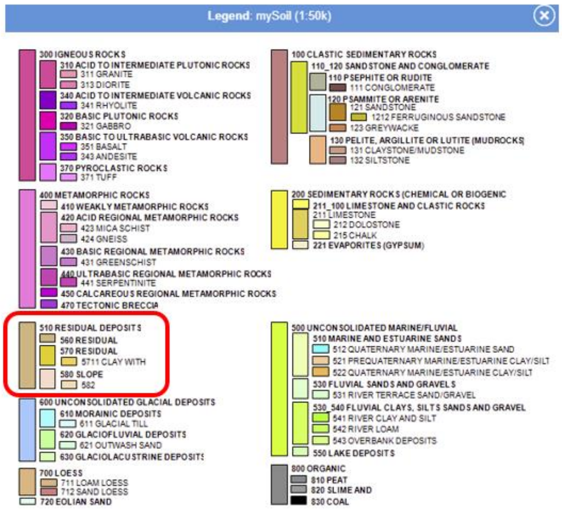


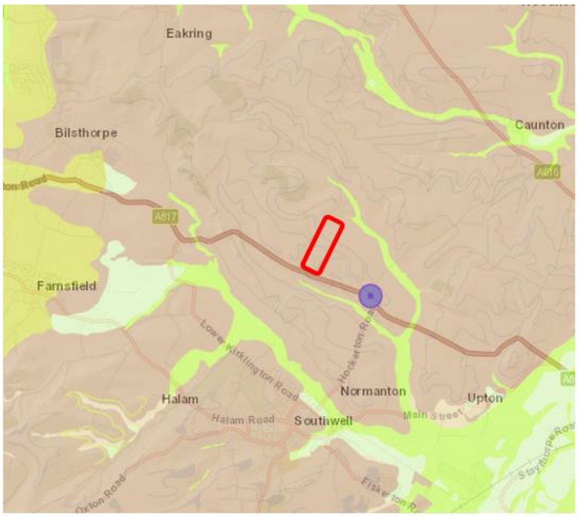


Land classification and soils

Soils are classified as ‘freely draining slightly acidic base rich soils’ under the Soil Survey of England and Wales/UK Soil Observatory. Parent material is residual magnesium limestone mineral deposits. Soils are classified as Clay loam soils.

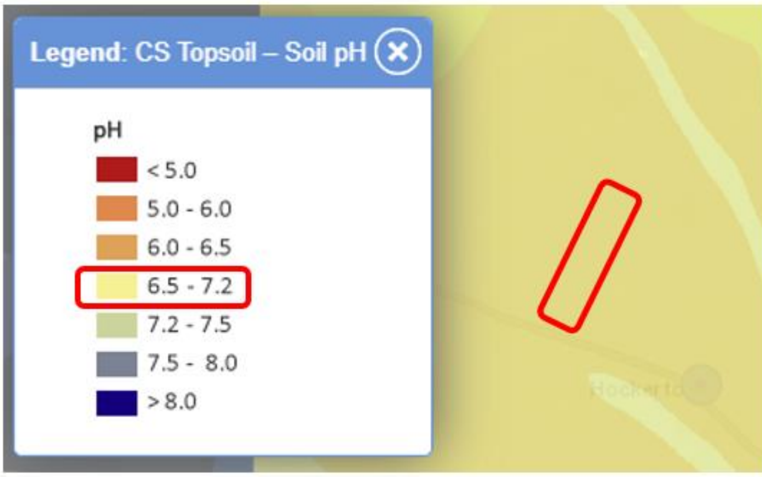






Source : https://mapapps2.bgs.ac.uk/ukso/home.html

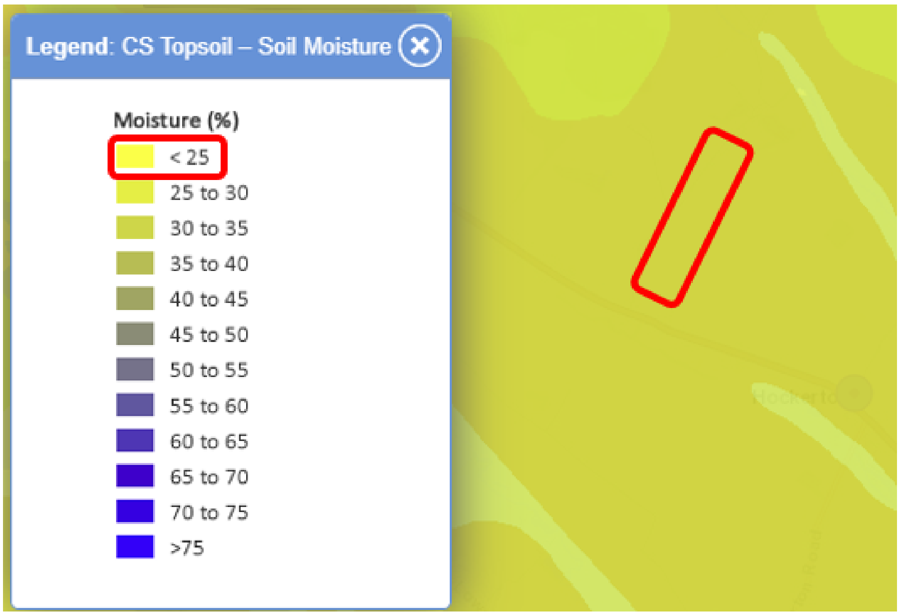
Classified **pH** levels are typically 6.5 – 7.2, confirm by soil analysis showing pH 7.2 - 7.7.



Soil carbon levels are classified at 0-10% with analysis showing soil organic matter contents using Loss on ignition between 5.1- 5.6% and Dumas of 1.8 – 2.0% - and total carbon stocks of between 27.3t/ha – 36.2t/ha

Bulk density is relatively high at 0.98 - 1.10 g/cm3 indicating structural porosity is quite cemented with suboptimal aggregation. This will limit crop development and soil water movement.

Topsoil **Soil Moisture content** levels are typically 25% - 30% of field capacity throughout the year.



Major soil minerals

Soils are dominated by high levels of calcium from the parent material. This limits some mineral availability. Phosphorous levels are generally lowish (10-34ppm) regulated by the presence of calcium.

Potassium levels (300-774ppm) are high as a function of the mineralogy and clay soils

Magnesium levels 358 - 415 ppm are very high (function of the parent material) with magnesium tending to 'consolidating' clay soils together and working against friable structure.

The **Cation Exchange Capacity** (CEC) of the soil is generally good and ranges from 19.1-21.9, with an ideal range usually between 15 to 25 milli-equivalents/100 g soil.

CEC is a measure of the total negative charges within the soil that adsorb plant nutrient cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^{+}). As such, the CEC is a property of a soil that describes its capacity to supply nutrient cations to the soil solution for plant uptake. CEC is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients: calcium, magnesium and potassium.

Full details of Soil analysis from the site can be seen in Annex 2

Trace soil minerals

Copper, Zinc, Boron, sulphur levels are generally optimal and well balanced

Iron levels in the soil are very high 382 - 424ppm, indicating poor drainage and seasonal waterlogging of soils

Manganese levels are high 90 -106ppm . Manganese is needed by crops throughout the growing seeing for essential functions in the plant like photosynthesis. Manganese acts as an activator for enzymes in growth processes and supports the conversion of nitrate (a form of nitrogen) that can be readily utilized by the crop. Levels are high but not excessive.

There are no levels of contaminants, Cadmium, Nickel etc that are of concern.

Full details of Soil analysis from the site can be seen in Annex 2

Soil Biology

As is common with soils that have been farmed under arable rotations for prolonged periods, the soils are bacteria dominated (Total and active), with low levels of soil fungi, and where present – small fungal hyphal levels, showing that soil fungi are young and have not developed strongly. The presence of beneficial soil mycorrhizae was not recorded in the analysis.

Nematode levels are low and where present are predominantly predatory bacteria feeders rather than plant feeding.

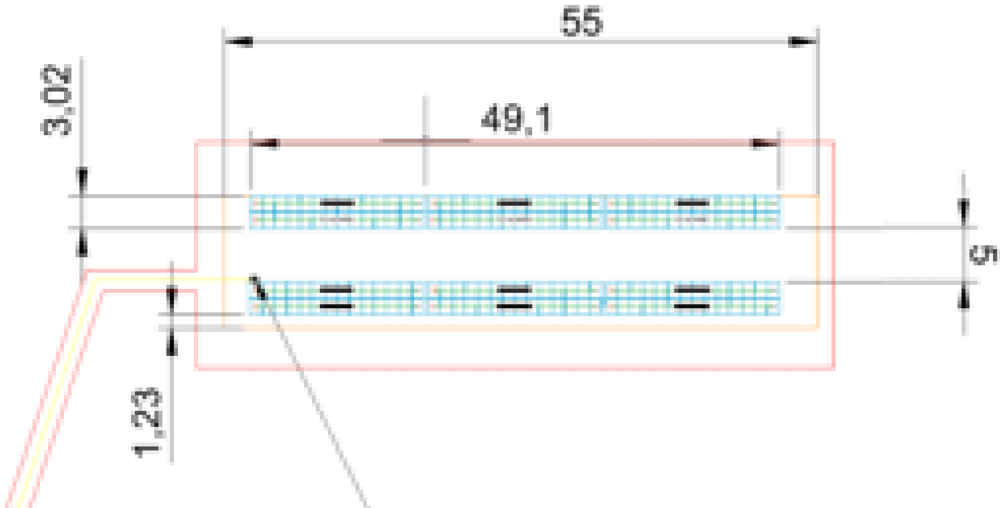
Looking at soil protozoa, ciliates numbers are higher than flagellates, indicating poor structure, aeration and prolonged waterlogging

From the analysis, in general, the lower part of the site has slightly better soils, mineral availability and soil structure than the highest part of the site near the top of the slope.

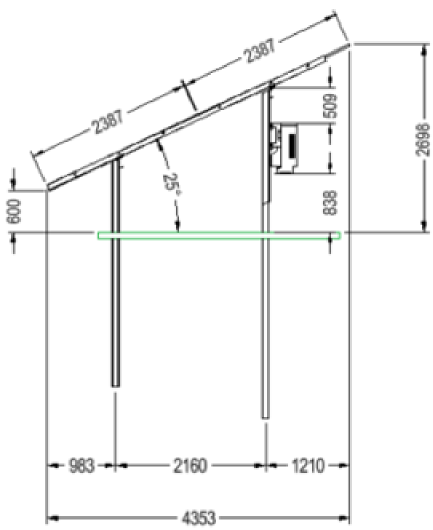
Full details of Soil analysis from the site can be seen in Annex 2

Photovoltaic (PV) layout and crop integration for agrovoltaic production

Th Photovoltaic (PV) layout at Hockerton will be based on a standard design. The working area (in m) between the panels for growing is approximately 49.1m x 5m = 245.5m2 per panel row as per the schematic below.



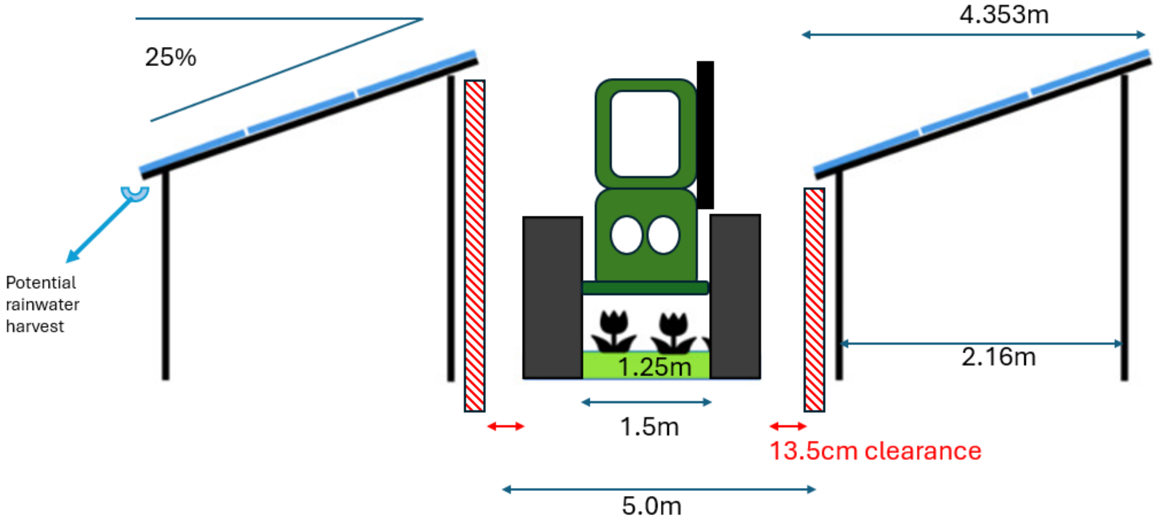
The PV panel support structure dimensions are shown below



Standard PV layout

Machinery access considerations

The distance between the panels and support structures is 5.0m

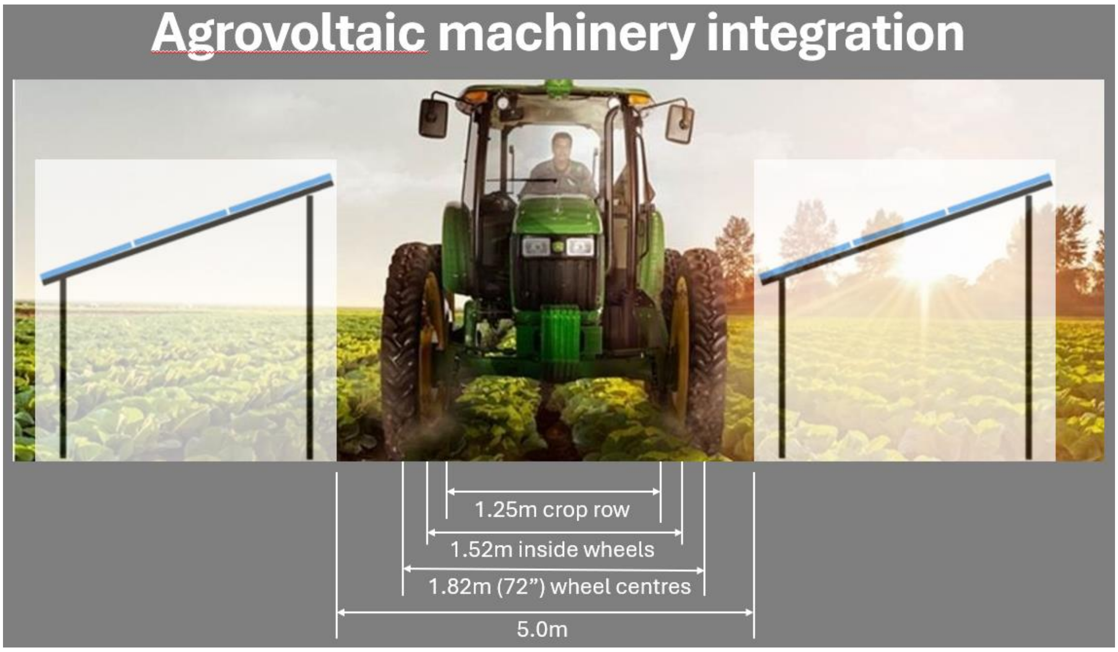


Standard tractors (medium size 100hp) operate on 1.82m (72 inch) wheel centre dimensions. Assuming 13.5cm outboard clearance each side between wheels and PV infrastructure and also 13.5cm inboard clearance between tractor tyres and crop area, results in a crop strip / bed of 1.25m width x 49.1m long = 61.375m2 (0.006ha) per panel run.

There are no particular limits on machinery Height & Width and side clearance between panels as long as the machinery does not touch the panels.

The crop area and taller crops can be grown and accommodated by utilising high clearance machinery as depicted below

The use of high clearance tractors and 'row crop' wheels/tyres will provide greater side clearance between PV infrastructure and for crop areas between tractor wheels, as depicted below.



Vegetation under panels

The vegetation cover deployed under most PV arrays is typically dwarf grass species for ease of maintenance as shown below

There is significant potential to establish legume and wild flowers under and alongside PV panels in combination with grasses. This would facilitate beekeeping applications and provide habitat for beneficial predatory insects (i.e ladybirds), important for crop integrated pest management (IPM) approaches i.e aphid control. Wildflowers integrated with PV panels is depicted below.

Bee-keeping integrated with Solar PV arrays

There is also potential to utilise livestock to manage grasses and wildflowers via appropriate grazing with sheep

PV panel maintenance and access

In the UK, it is usually enough to clean the panels 1x or 2x per year. Frequent rain is usually enough to keep the panels clean. Since the plant size is small, manual or semi-manual operation is probably the most cost-efficient.

Where cleaning and maintenance of PV panels is required, there are various options, all have different access i.e the ground clearance needed in relation to crop heights.

Pressure washing by hand may require personnel access and water access

Some panel cleaning machinery is semi-autonomous, with little access requirements

Mounted autonomous panel cleaning machinery can be used and operated automatically without the need for supervision or additional machinery.

Tractor mounted cleaning machinery is used on some sites. However, with agrivoltaic systems where crops are present between PV rows, it is likely that there would access difficulties around crops making this approach non viable.

With advances in robotics, Some PV sites are now exploring the use of drones for cleaning. This approach would not require any access between PV panels and would not interfere with crops, provided any cleaning agents do not damage crops.

5 Evaluation of potential cropping systems in Agrovoltaic systems

Generally, all crops can be cultivated in an agrivoltaic system. However, some crops are better suited than others. This depends, among other things, on how much light the crop needs to grow optimally, shade tolerance and wind/microclimate impacts.

Crops with a higher light demand or "*sun plants*" react strongly to light and growth saturation only occurs at high illuminance. "Shade plants" are not as sensitive to light and are therefore better suited for growing in a partially shaded agrivoltaic-system

Agrivoltaic system casts some shade on crops growing between or underneath panels, and crops vary in their tolerance to shade, with C4 plants such as maize, being least tolerant.

Some research suggests cereal yields can be reduced by shading, but this could be mitigated through the system design and layout - rows of vertical panels might be preferable, for example. Varieties may also differ in their responsiveness to shading.

Some crops such as onions, lettuce, potatoes, strawberries, and raspberries might suit shadier conditions better, while in sun-intense regions (beyond the UK), partial shade can increase output of vines, olives, blueberries for example.

As the climate becomes more extreme, integrated systems could help improve resilience on farms, both economically by providing additional income, and agronomically. Shade, for example, could reduce crop stress or soil moisture losses during very hot periods, while panels might shelter crops during windy periods. Equally, the cooling effect of growing crops in and around solar panels can improve panel efficiency.

Arable farming

Results from the German APV RESOLA project https://link.springer.com/article/10.1007/s13593-019-0581-3 showed that in a climatically "average" trial year, shading by the Agri-PV system led to yield reductions of between 10-20% (potato, celery and winter wheat) compared to an unshaded reference. However, in a hot and dry trial year, the Agri-PV system achieved positive effects on crop yield. Potato yield was increased by 10% and winter wheat yield by 3%.

Viticulture

The increasing temperature and solar radiation due to climate change can strongly influence the sugar and alcohol contents in wine.

This has an immense impact on the quality of the wines. To counteract this, the cultivation of wine in combination with a wide variety of agrivoltaic-systems is already being tested in France.

Fruit and vegetable growing

Fruit and vegetable cultivation is characterized by a high value added per hectare of cultivated land.

Since crops such as berries or apples are also often very susceptible to external influences, expensive protective structures such as hail nets or films are often used in fruit and vegetable cultivation to protect against weathering.

These protective structures could easily be replaced by agrivoltaic-systems. It is not only the expected increase in social acceptance that leads to agrivoltaics being seen as a great potential

Crops that can be grown in agrovoltaic systems

In the UK, agrovoltaic systems can support a variety of crops that can thrive under partial shading provided by solar panels. These crops are typically those that do not require full, direct sunlight and can benefit from the microclimatic conditions created by the panels. Here are some examples of crops suitable for agrovoltaic systems in the UK:

Vegetables

Leafy Greens:

- Lettuce
- Spinach
- Kale
- Swiss Chard

These crops thrive in cooler, shaded conditions and can benefit from the reduced heat stress under solar panels.

Root Vegetables:

- Carrots
- Beets
- Radishes
- Turnips

Root vegetables can tolerate partial shade and may benefit from the moderated soil temperature.

Brassicas:

- Broccoli
- Cauliflower
- Cabbage
- Brussels Sprouts

Brassicas generally perform well in cooler conditions and can handle some shading.

Alliums:

- Onions
- Leeks
- Garlic

These crops can grow well with partial sunlight and are less sensitive to shading.

Fruits

Berries:

- Strawberries
- Raspberries
- Blackberries
- Blueberries

Berry crops often benefit from partial shade, which can reduce heat stress and improve fruit quality.

Orchard Fruits:

- Apples
- Pears
- Plums
- Cherries

Agrovoltaic systems can be integrated with fruit orchards, providing some shade and protection from extreme weather.

Viticulture

- Wine grapes (red, white, rose, sparkling)
- Table grapes

Herbs

Culinary Herbs:

- Parsley
- Cilantro (Coriander)
- Mint
- Basil (although it prefers slightly more sun)

Many herbs can thrive in partial shade and benefit from the microclimate created by solar panels.

Grains and Legumes

Legumes:

- Peas
- Beans (Picking beans / French beans)

Legumes can adapt well to varying light conditions and can improve soil health by fixing nitrogen.

Cereals:

- Barley
- Oats

Some cereals, particularly those grown for forage or cover crops, can be suitable for agrovoltaic systems.

Specialty Crops

Mushrooms:

- Mushrooms can be cultivated in the shaded areas beneath solar panels, taking advantage of the reduced light and controlled environment.

Flowers:

- Certain shade-tolerant flowers can be grown for ornamental purposes or for cutting, such as pansies and marigolds.
- Flowers can be grown for fresh cut & sale, drying and sale as pressed flowers, or as edible flowers to augment culinary dishes.

Wildflowers & Honey production

There is significant potential to create wildflower sites and integrate commercial honey production in agrovoltaic systems, as a component part of an integrated diverse land use system. From the soil surveys completed, the clay soils are good for the following wildflowers;

- Yarrow
- Oxeye Daisy
- Musk Mallow
- Cowslip
- Birdsfoot Trefoil
- Red Clover
- Alsike clover
- White Clover
- Sanfoin
- Ragged Robin
- White Campion
- Teasel
- Common Knapweed
- Meadow buttercup
- Wild carrot
- Wild clary
- Lady’s bedstraw

Considerations for Crop Selection

1. **Shade Tolerance**: Crops must be able to grow well with partial shading. This is crucial for ensuring good yields and quality.
2. **Water Requirements**: The presence of solar panels can affect soil moisture levels. Crops with moderate water needs might be more suitable.
3. **Soil Health**: Regular monitoring of soil conditions and appropriate soil management practices are necessary to ensure the health of both the crops and the underlying land.
4. **Adjacent land** – where immediately adjacent land (ie access areas and or under solar PV panels) has other land cover such as grass, there is potential for this cover to host pests such as aphids *Aphidoidea spp* (above ground) or wireworm *Agrypnus spp*. & leather jackets *Tipula spp* (below ground) which may limit crop production choices.
5. **Seasonal Variations**: Different crops might be better suited for different seasons. Cool-season crops might perform better in shaded conditions during the summer, while warm-season crops might need more light.

By carefully selecting and managing these crops, UK farmers can optimize the benefits of agrovoltaic systems, balancing energy production with sustainable agricultural practices

Pick your own

There is potential with agrovoltaic systems to create areas where the public can pick their own produce. The produce could alternate throughout the seasons i.e

- Summer: strawberries, raspberries, blackberries, vegetables/salads
- Autumn: pumpkins, squash, vegetables/salads

However, compared to open field sites, there are complexities regarding **health and safety associated with the PV infrastructure** and any site would need to ensure this was safe to do in between panels.

Organic Production

There is potential with any of the crop (or livestock) production systems to add additional value via organic certification. This limits some operations (use of synthetic fertalisers, pesticides etc) but can capture additional market value through higher product premiums.

Pros	*Cons*
Receive premium prices for products *People trust the organic farming label and would be a selling point* *Would assist in increasing biodiversity* *Conserve energy* *Contribute to soil health* *Improve water quality* *There is funding available to convert the land to organic*	*Costs to even apply to become certified as organic – dependent on how large the land area is* *Application fee, renewal fee, assessment on annual production or sales, and inspector fees* *Takes approximately two years to convert land to organic farming*

6 potential cropping systems including adapted gross profit analysis

Profitability

The capital costs of agrivoltaic systems vary and depend, among other things, on the installed capacity and the agricultural management.

Impacts on costs as well as revenues of agriculture are also highly dependent on location and system design.

Economy

General statements about the economic viability of agrivoltaics can hardly be made due to the diversity of its application.

The investment costs of agrivoltaic systems tend to be higher than those of ground-mounted PV systems. This is mainly due to the more complex substructure, the use of special modules and the soil-conserving installation. Operating costs, on the other hand, can decrease because lease costs are shared and land maintenance is taken care of by the farmer.

Agri-PV systems are economically particularly suitable in areas of agriculture where there are high costs for protection devices, which can be replaced by an agrivoltaic system

Food security/self sufficiency

At a **local scale** food self sufficiency and resilience is an important priority for the Hockerton community, perhaps more-so than economic viability and profitability.

However, with the right structures, routes to market and marketing, there is also the potential for localised employment and economic development through integrated land use from food/biomass production and energy production

Business models

In an agrivoltaics business model, usually more actors are involved than in a ground-mounted photovoltaic system.

Involved actors have different functions:

1) Provision of the land (ownership)

2) Agricultural management of the area

3) Provision of the PV system (ownership / investment)

4) Operation of the PV system

In the simplest business model, all four functions can be performed by one party, typically a farm. This is often expected for smaller and farm-scale agrivoltaic systems.

If the land is not owned by the farm, long-term contracts, typically 30 years, for land lease and usage are required.

Field scale cereals, pulses and root vegetables, brassicas and alliums, whilst suited to the partial shade and soil types, have been discounted as they are principal commodity crops with lower values and require greater mechanisation for production. Where space and access for mechanisation is limited, these crops are not viewed as viable.

Similarly whilst orchard fruits (bush and tree forms) could be integrated in to the agrivoltaic site, they have also been discounted as size of tree/bush to achieve viable production is likely to impact of PV performance (where standard PV layouts are employed) and mechanisation for production would be challenging.

Root crops

Most root crops have been discounted due to the significant soil disturbance for planting and harvesting and the restrictions on access for larger mechanisation. However, beetroot as a root crop could be grown. The crop is more surface grown than other root crops and less soil disturbance us undertaken at harvest. There is also potential for generating vale add income streams through direct sales and processing (pickling, juicing etc).

Leafy Green vegetables & salad crops

There is potential to grow higher value leafy green vegetables and salad crops on a bed system between the rows of solar PV in an agrovoltaic system. With the access limitations, small cale high value row crop production, with minimal mechanisation and direct retail (or local box scheme) is best suited. The heavy clay soils limit choice, but with adequate compost addition to the soil there is potential for crops including;

- Lettuce
- Spinach
- Kale
- Swiss Chard

These crops thrive in cooler, shaded conditions and can benefit from the reduced heat stress under / alongside solar panels in an agrovoltaic system. The costings for field grown crops on small scale are hugely variable depending on location and level of mechanisation vs labour and the route to market employed. Below are summary costings for a range of small field scale (local box scheme scale) production with mechanisation.

Typical	outdoor	small scale		sale £/kg or head	
		yield			
		head/m2		direct sale	wholesale
crop		kg/m2			
Brussels		1.5		3	1.6
cabbage		2.4		1	0.6
calabrese		0.9		5	2.5
swede		3.5		1.1	0.6
cauli (per head)		1.65		1.5	0.85
leek		2		2.5	1.6
onion		2		1.3	0.8
beetroot		2.3		1.2	0.7
carrot		1.9		1.1	0.6
parsnip		2.2		1.7	0.9
squash		1.7		1.8	1
sweetcorn (per cob)		5.5		0.65	0.4
broad beans		1.4		2	1.1
tomato		3.4		3.25	2.2
french beans		1.4		6.5	3.5
kale		1.46		2.7	1.5
salad leaves		1.76		20	14
courgette		3		2.95	1.5
	1kg/m2 = 10 tonnes per ha				

Source : Organic Farm management Handbook 2017

Outdoor	Field scale production Typical yields, costs and margins															
				Carrots	**Parsnips**	**Beetroot**	**Sweede**	**Leeks**	**Onions**	**cauli**	**calabrese**	**cabbage**	**lettuce**	**courgette**	**sweetcorn**	**Av.**
																per ha
Yield		t/ha or	head/ha	25	18	25	25	12	25	1150	5	28000	3350	10	30000	
Price		£/t		£390.00	£605.00	£250.00	£400.00	£1,100.00	£400.00	£7.80	£1,300.00	£0.50	£4.80	£900.00	£0.30	
Output				**£9,750.00**	**£10,890.00**	**£6,250.00**	**£10,000.00**	**£13,200.00**	**£10,000.00**	**£8,970.00**	**£6,500.00**	**£14,000.00**	**£16,080.00**	**£9,000.00**	**£9,000.00**	**£10,303.33**
Variable costs		**£/ha**		**£6,143.00**	**£4,898.00**	£4,849.00	**£3,569.00**	**£12,267.00**	**£6,307.00**	**£5,538.00**	**£3,435.00**	**£9,122.00**	**£9,330.00**	**£8,679.00**	**£2,895.00**	**£6,419.33**
Gross Margin		**£/ha**		**£3,607.00**	**£5,992.00**	**£1,401.00**	**£6,431.00**	**£933.00**	**£3,693.00**	**£3,432.00**	**£3,065.00**	**£4,878.00**	**£6,750.00**	**£321.00**	**£6,105.00**	**£3,884.00**

In more detail below are costings for small field scale lettuce production

Lettuce		£/ha		£/ha	£/m2
Marketable yield	3350 doz per ha @ £/ doz		4.8	16080	1.608
88% gross yield 12% grade out					
TOTAL OUTPUT				**16080**	**1.608**
Variable Costs					
Transplants	80,000 per ha @ £38/000			3040	0.304
Irrigation	75mm per ha @ £2.5/mm			188	0.019
fertalisers				54	0.005
Crop protection				30	0.003
weeding	2 pass with inter row weeder			203	0.020
Labour - planting	40 hrs per ha @ 15.00/hr			600	0.060
Labour - weeding	60 hrs per ha @ 15.00/hr			900	0.090
Labour harvesting	3807 doz/ha @ 0.05h/doz @ £15/hr			2856	0.286
Transport/packaging	3807 doz/ha @ £0.37/doz			1409	0.141
Comissions/levies				50	0.005
TOTAL VARAIBLE COSTS				**9330**	**0.933**
GROSS MARGIN per ha				**6750**	**0.675**

Above figures based on small field scale production for local box scheme
Source : Organic Farm management Handbook 2017

Small field scale production figures suggest a gross margin of c £0.67p/m2 (wholesale). Experience from Hockerton (pers comm.) would suggest potential for c. £3-4 m2 retail prices from box scheme's or direct sales.

Lettuce production

Price is highly variable depending on type (Gem, Cos, Batavia, iceberg etc) and time of season. Continuity of supply is essential for stable markets.

Marketable yield will depend on level of trimming – approx. 12% gradeouts assumed

Planting assumes cultivation and mechanical bed preparation with planting using a 2 row planter. Irrigation is essential 10-15mm every 4 days – this could employ drip systems with water harvested from solar PV panels. Lettuce has a high Potassium demand, which the sols should be able to provide, plus additions of compost.

Cold storage at harvest is essential to maintain product quality. Energy from the agrovoltaic PV systems will help offset costs.

Soft' berry' fruit

UK soft fruit exports are worth £14 million a year, having increased 137% in the last 10 years. Soft fruit accounts for 60% of UK fruit production. Domestic consumption has also been growing steadily for many years, and modern methods enable the season to be extended beyond the traditional soft fruit season, meeting more of all-year-round consumer demand, strengthened by growing consumer interest and awareness of food provenance. Nevertheless, the EU still provides the majority market for UK- soft fruit exports, with the Netherlands, Spain and Ireland as main buyers.

EU tariffs of 11.2% on strawberries, and 8.8% on raspberries, blackberries and currants will now eat into margins of British soft fruit exporters following Brexit.

While there is potential for soft fruit market expansion, new producers will want to consider competitive advantage of production, both with current British producers and with European markets, as well as challenges closer-to-home such as uncertainty around labour availability post-Brexit, and establishment of new lines for sales and distribution. At small to medium scale direct retail to capture value is the preferred option.

Berry crops often benefit from partial shade, which can reduce heat stress and improve fruit quality. Shortlisted for agrovoltaic systems are Strawberries, Raspberries, Blueberries. Blueberries dislike soils with a pH greater than 5.5, and prefer peaty, acidic and lighter soils, as opposed to heavy clays, making the Hockerton site less suitable for blueberry production. The costings therefore focus on Strawberries & Raspberries.

Strawberries

35,000 plants per ha. 60 day cropping in yr1, with 2 further full production year cycles. Harvesting including supervision NI and holidays ranges from £900 to £1500 per tonne with an average of £975/t used in the costings. Grading/packing £375/t, packaging £475/t, transport £250/t

Strawberries produce marketable yield in year 1 and would not require trellis support systems. Strawberry productivity would benefit from the microclimate resulting from the PV arrays, with partial frost protection, reduced heat stress and reduced evapotranspiration (water loss reduced irrigation volumes).

Ground grown strawberries may come under high pest pressure from pests (Slugs, beetles, wireworm, leatherjackets etc) residing in the immediately adjacent grass strips and from birds perching on solar infrastructure. Pest pressure may be mitigated by eliminating grass from sown mixtures and planting legumes and wildflowers which may help lessen this risk as grasses are major host and growing through plastic/mesh. This is expanded on in section 8.

The 'DevOated' drinks factory based on site is using strawberries to flavour one of their products, so there is a ready market on site for the fruit if the technical challenges can be overcome.

Strawberries			
	£/ha	**£/ha**	**£/m2**
Production level	Low	High	
Yield - Tonnes per ha	18	23	0.00
Price £/tonne	2958	3825	0.38
OUTPUT	**53244**	**87975**	**8.80**
Variable Costs			
Plants/planting	4492	4492	0.45
Structures	6520	6520	0.65
Fertalisation / predators	2163	3863	0.39
Fieldwork	2487	5715	0.57
Harvesting	17550	22425	2.24
Grading/packing	6750	8625	0.86
Packaging	8730	11155	1.12
Transport	4500	5750	0.58
Commissions	4790	7920	0.79
TOTAL VARIABLE COSTS	**57982**	**76464**	**7.65**
GROSS MARGIN per ha	**-4738**	**11511**	**1.15**

Source : John Nix Farm management 55th ed 2025

Raspberries

Consideration would need to be given to support structures (posts/wires/trellis) and the pruning management of raspberries (and other berry fruit) to manage crop height so as to minimise and overshading of solar PV and to allow access with machinery. One mitigation is that full berry production would be in mid summer when the sun is high in sky, thus minimising any shading PV panels. In contract during autumn, winter and early spring, when the sun is lower in aspect and more shading occurs, the fruit bushes would be dormant and this not competing for light.

Raspberries				
		£/ha	£/ha	£/m2
Production level		Low	High	
Yield - Tonnes per ha		8	15	0.00
Price £/tonne		6018	7956	0.80
OUTPUT		**48144**	**119340**	**11.93**
Variable Costs				
Plants/planting		1216	1216	0.12
Structures		6520	6520	0.65
Fertalisation / predators		2704	5408	0.54
Fieldwork		1866	7338	0.73
Harvesting		21200	39750	3.98
Grading/packing		4800	9000	0.90
Packaging		4800	9000	0.90
Transport		2480	4650	0.47
Commissions		4335	10740	1.07
TOTAL VARIABLE COSTS		**49920**	**93621**	**9.36**
GROSS MARGIN per ha		**-1776**	**25719**	**2.57**

Source : John Nix Farm management 55th ed 2025

8000/ha at a cost of £0.55 per plant and £0.21 per plant planting costs
Land preparation and irrigation at £750- to £1500/ha
Harvesting including supervision NI and holidays ranges from £1750 to £3000 per tonne with an average of £2650/t (£2.65/t) used in the costings
Grading/packing £600/t, packaging £600/t, transport £310/t

Processing

Labour requirements for picking and packaging of soft fruit it significant, estimated at £27,000 per hectare for strawberries, or £900 per tonne of fruit. This will vary between soft fruits. Packing and storage facilities should be located on-farm, to maximise the quality of fruit from picking to distribution; the fruit should be cooled as soon as possible after picking.

The ‘DevOated’ drinks factory based on site is using soft fruit to flavour one of their products, so there is a ready market on site for the fruit.

Land and climate suitability

Strawberries, raspberries, blueberries and cloudberries will grow well both indoors and outdoors in temperate climates, although protected systems optimise growing conditions and ability for fruits to ripen further north. Strawberries can tolerate temperatures of as low as to -5°C during the growing season.

Soil suitability

Some soft fruits are particular about soil pH which may limit areas of production, as well as terrain of land for polytunnels. Blueberries dislike soils with a pH greater than 5.5, and prefer peaty, acidic and lighter soils, as opposed to heavy clays, making the Hockerton site less suitable for blueberry production.

Strawberries can be grown in beds in areas of well-drained soil, or raised in beds or trays of substrate otherwise. Otherwise they have no specific requirements in terms of soil type however they are very sensitive to salinity so irrigation and fertigation needs to be carefully managed (Yara). Raspberries thrive in well-drained but moisture-retentive, fertile and slightly acidic soils.

Inputs

Propagated material for soft fruit bushes (e.g. blueberries, raspberries) is bought 2 years in advance of production as it will take 2-3 years for the plant to reach full production. It is therefore important to plan ahead for ordering propagated materials, and factor in an unproductive phase for newly planted areas. Strawberry plants can produce in the year of planting if crowns are of sufficient size and in suitable condition (cold stored). Strawberry plants will last 4 years before they need to be replaced but in commercial situation usually just kept for 2 years as yield and quality decline sharply in year 3.

Integrating fertigation systems with harvested and recycled water from solar PV panels would work well.

Cropping systems

Most commercial soft fruit production in the UK is produced in protected systems, to optimise the growing environment, protect against severe weather, minimise pests such as birds that might eat the fruit, and help to bring forward harvest by around 1 month and also to extend the season. Pollinators must be purchased and introduced – bumble bees – to ensure adequate pollination during the spring.

Strawberries can be grown in beds of bagged soil, or raised in table-top systems or trays for greater control of water and nutrients. Bedding materials and substrates such as coir are also required. Raspberries may need support.

If grown directly into the ground, rotations are needed for strawberries to minimise disease build-up in the soil, particularly in rotations with tomatoes and potatoes due to verticillium wilt. For blueberries, where grass has been grown, a nematode test should be undertaken to assess populations of root feeding nematode species, and a break crop considered.

Machinery and equipment
Drip irrigation and plastic mulches commonly used. Irrigation costs – rainwater harvesting can reduce irrigation costs on the long term. Strawberries are particularly water-hungry. Harvesting water from solar panels in agrovoltaic systems could be well aligned to meet this demand.

Soft fruit picking is labour intensive, and as of now mechanisation technology is still in Research and Development. Fruit should be stored between 1 and 4 C within 45 minutes of picking to preserve quality, before and after sorting and packing. On-farm sorting, packing and cold storage should also be factored in.

Flower production

The value of UK-grown flowers and bulbs has increased by over £50 million between 2019 to 2024. UK Production of Flowers and Bulbs was £179m in 2023 (DEFRA). British production is now 21.4% of the total retail sales.

UK Export of Flowers and Bulbs in 2023 was £28.8m whereas the import Total for Flowers and Bulbs was £761.8m (DEFRA), so the Total UK Value of Flowers and Bulbs in 2023 was £912m.
In 2023, fewer flowers were imported and exported due to the cost of living crisis and Brexit.
Imports still dwarf sales of home-grown flowers, however, and the production of perfect blooms grown abroad and flown or freighted in has a significant environmental impact. About 90% of flowers sold through florists, supermarkets and wholesalers are imported not just from Holland but also as far afield as Ecuador, Colombia, Kenya and Ethiopia.

Research has concluded that imported flowers produce far higher CO_2 emissions given long-distance transport and energy-intensive cultivation methods. It found that a mixed bouquet imported from abroad can generate up to ten times more emissions than one grown in the UK, emphasising the environmental benefits of supporting local growers

Commercial floriculture plants are propagated through seeds, cuttings, grafts, and tissue culture with most flowers grown in greenhouses, open fields, or hydroponic systems. There is no known flower production integrated with solar as agrovoltaic currently.
Post Brexit locally-grown flower demand is increasing as domestically grown flowers can last longer than imported flowers because they haven't been sprayed.

The most popular fresh cut flower species with potential for UK commercial production include ;

- Peonies – showy with a lasting impression
- Zinnias – easy flower to grow, grow quickly and bloom heavily
- Cosmos – free flowering annual, extremely easy to grow
- Tulips – spring blooming perennial, many different colours
- Sunflowers – big, bright large stemmed
- Snapdragons – short-lived perennial that may not come back every year, wide variety of colours and heights
- Irises – showy perennial
- Pansies
- Marigolds

The species above are mainly shade-tolerant flowers can be grown for ornamental purposes or for cutting. Flowers can be grown for fresh cut & sale, drying and sale as pressed flowers, or as edible flowers to augment culinary dishes. Costing and profitability on flower production are hugely variable depending on species, route to market, season etc. Example field scale costings for UK flowers are set out below.

Flowers	**£/ha**	**£/ha**	**£/ha**	**£/m2**
Production level	**Low**	**Average**	**High**	
Yield t/ha	1.1	1.3	1.5	
Output @ £550/t	**605**	**715**	**825**	**0.0715**
COSTS				
Seed	150	150	150	
Fertaliser	96	96	96	
Sprays	85	85	85	
Other	0	0	0	
TOTAL VARIABLE COSTS	**331**	**331**	**331**	**0.0331**
GROSS MARGIN	**274**	**384**	**494**	**0.0384**

Source : various * wholesale values only

Edible / Pressed Flowers

Pressed flowers is an alternative route to market. Cut fresh and dried/pressed – these can be edible or just decorative but is another way in which the wildflowers that are great for biodiversity can be utilised further in farming. Pressed flowers suitable in an agrovoltaic system include;

- Alyssum
- Viola
- Fennel (florets and heads)
- Calendula
- Catmint
- Dill
- Hollyhock
- Lavender
- Lemon Verbena Leaves
- Nigella Frills
- Tagetes
- Amaranth Fronds
- Cola Herb Trees
- Cosmos Frills
- Oregano Flowers
- Parsley Clusters
- Yarrow Feathers/Fronds/Leaves

Many flowers, in addition to improving biodiversity and supporting pollination, can also be edible, offering alternative routes to market. Edible flowers can be used as decoration in restaurants, on cakes, cocktails, at weddings, to name a few examples. Edible flowers suitable in an agrovoltaic system include;

- Amaranth Pom Poms
- Calendula / Marigold
- Cornflower
- Gladioli
- Dahlia
- Viola
- Lavender

Examples of farms in the UK growing edible flowers:

https://awesidefarm.co.uk/ - this farm offers edible flowers for cakes, decorations etc. It is also organic

https://nurturedinnorfolk.co.uk/

For both fresh cut flowers and edible flowers there is potential to add value through direct sales / ethical & local floristry. An example of value added is set out below;

Gift Bouquets	**£**
MATERIALS	
6 Focal flowers @ 80p average (here Dahlias)	4.80
19 Secondary flowers @ 50p average (here Sweet Williams, Cosmos, Acidanthera, Statice)	9.50
5 Spires / Air @ 60p average (here Antirrhinum)	3.00
5-9 Pieces of Foliage @ 40p average (here Aster, Physocarpus, Eucalyptus)	3.60
LABOUR	
15 mins to pick + 15 mins to wrap @ £20/hr	10.00
Vase	2.79
Paper wrap	0.10
Bag	0.69
Card/tag	0.10
Ordering (i.e paypal)	1.79
TOTAL COST PRICE	**36.37**
profit margin 33%	12.00
Retail price	**48.37**

For fresh cut, dried, pressed flower production (and floristry) the graphics below set out seasonal availability and price per stem value (retail);

	April	May	Early June	Late June	Early July	Late July	Early August	Late August	Early Sep	Late Sep	October	Price per stem from
Flowers												
Acidanthera												75
Achillea												60
Allium Purple Sensation												60
Allium Christophii												75
Allium Sperecephalon												50
Alstroemerias												60
Anemones												50
Antirrhinum												70
Chrysanthemums												£1.00
Cornflowers												40
Cosmos												50
Dahlia												75
Eryngium												75
Foxglove												75
Gladioli												75
Hellebores												£1.20
Hesperis												50
Helichrysum												50
Larkspur												60
Nectaroscordum												75
Nerines												£1
Orlaya												50
Phlox												60
Ranunculus												80
Roses												£1.80
Scabious												40
Sunflowers												90
Sweet Williams												45
Sweet Peas												50
Tulips												60
Tulips Parrot												85
Zinnia												50

	April	May	Early June	Late June	Early July	Late July	Early August	Late August	Early Sep	Late Sep	October	Price per stem from
Foliage and Fillers												
Achillea the Pearl												50
Alchemilla Mollis												45
Amaranthus												50
Ammi Major												50
Ammi Visnaga												50
Aster												45
Basil purple leaved												45
Bulpleurum												50
Cerinthe maj Purp												50
Clary Sage (bunch)												£1
Cynoglossum												45
Daucus Carota												50
Dill												45
Dusty miller New look												50
Feverfew												45
Grasses (bunch)												£1
Honesty												45
Honesty seedheads												45
Hypericum magical												75
Jasmine trails												75
Lavender Oregano (bunch)												£1
Lemon Balm												35
Mint												35
Nigella (bunch)												£1
Orlaya												50
Poppy Seed heads (bunch)												£1
Rosemary												40
Sedum												45
Stachys												45
Statice												50
Verbena Bonariensis												35

Viticulture and agrovoltaic systems

The UK planted area of vines in 2024 is estimated at 5250ha. This is a seven fold increase since 2004. The average size of vineyards in the UK is 4ha, with several produces with over 100ha, with the 25 largest vineyards accounting for over 50% of UK production. Around 15% of the vineyard area is juvenile and not yet in full production. There are no restrictions on vine establishment in terms of area, geography or varieties used. There were 221 wineries registered in Britain in 2023.

The market in Britain for sparkling wines is c 245 million bottles per year and growing. In 2023 21.6 million 75cl bottles of UK wine were produced (33% still & 66% sparkling). Average UK yields are c 3000L/ha compared to 7000L/h in Bordeaux.

Still wines come to the market faster than sparkling and can be on sale in 3 years of planting vines.

Historically most British wines were white, but the proportion of red and rose has risen to c 15-20% in 2024. Around 66% of the harvest is made into Sparkling wines in the UK.

The reputation of English wines has risen dramatically over the last 20 years, with more outlets now stocking them. Many producers find that, at least initially, before they have built a strong reputation, selling direct or from the ‘farm gate’ is the best route to market and helps build the brand presence.

The quality of the wine produced depends on the site and in a cool maritime climate like Britain, south facing sloping sites less than 100m above sea level are best suited.

Research in France by the consortium of the "Sun'Agri3" program, including 6 INRAE units (LEPSE, PSH, SYSTEM, PECH ROUGE, G-EAU, MISTEA), ITK and Sun'Agri has shown that dynamic agrivoltaic systems (AVD) installed above crops, and providing transient shading, are a tool for protecting and adapting vines to climate change, which optimizes wine production in its quality , while preserving high yields, by;

Limiting excess solar radiation and high heat : Controlled shading can reduce the temperature of vines under AVD to -5°C during heatwaves; the foliage flourishes better, resulting in a denser canopy.

Reducing the risk of frost : with an average temperature difference of +2°C when 0°C approaches in spring, the AVD thermal cover helps prevent harmful frost episodes at bud break.

Improving water comfort while limiting irrigation : measured by a plant growth time up to +14 days longer than the control zone, and a potential evapotranspiration (ETP) reduced by 40%. The irrigation schedule is also adapted by triggering the water supply later in the season and reducing the quantity of water delivered by up to -34%.

Leading to a better aromatic balance of the wine produced : Berries from the AVD modalities contain more anthocyanins (from +10% to +15%), and have a Brix degree 2 to 3° lower on a given day thanks to maturation in a cooler period, and are up to 15% more acidic than those in the control.

Viticulture is the first agricultural sector to benefit from the dynamic agrivoltaic solution (AVD) in terms of surface area. Experimental data on vines under panels of different sizes were carried out in 2018 and 2019 on the Montpellier SupAgro campus, supplemented by a history of experiments from INRAE in Pech Rouge on a fixed device since 2016. In 2018, young vine plants were planted in the Nidolères estate (Tresserre) on 7.5 ha, above which the first AVD demonstrator is built on 4.5 ha, agronomically monitored by the Pyrénées-Orientales Chamber of Agriculture (CA66). At the same time, the commissioning of an experimental system in 2019 in Piolenc (Grenache grape variety planted in 2000) provided numerous results analyzed by the Vaucluse Chamber of Agriculture (CA84) and INRAE.

Layout

Most commercial vineyards in Britain are planted with rows 1.75-2.25m with an inter row vine distance of 1-1.4m on a Double or single Guyot system. A vine density of 5000 vines per ha (row width of 2.00m and inter row spacing of 1.00m) gives the best quality and economic yield in British conditions. This layout is therefore well suited to an agrovoltaic system.

With good establishment and pruning, most vines will start yielding in year 3 with full yields by year4.

Capital for vineyard establishment (including vines, trellis, labour) is c £35-£40,000 per ha). The need for expensive deer fencing would not be required in an agrovoltaic systems where the solar PV is already surrounded by security fencing.

For processing, many UK wineries are small, in modest buildings but with good quality processing equipment. Many producers choose to take their grapes to be made into wine under contract by the larger more established wineries, proving access to state of the art equipment and expertise. Secure, temperature controlled storage space for wines to mature, especially sparkling wines, is required weather or not you establish your own winery.

Depending on the quality of the site, the varieties grow,, type of wine produced and management, typical British yields are c 7.5t/ha. For still wine, c 950 75cl bottles can be produced from 1.00 tonne of grapes. For sparkling wine, between 675-800 75cl bottles per tonne are produced from 1.00 tonne of grapes.

The costings below refer to commercial enterprise on a suitable site producing sparking wine sold via retailers. Any direct sales to the public will have higher profit margins.

Sparkling wine - white (Double Guyot)	per ha	per ha	per ha	Per m2
	£	£	£	£
Production Level	**Low**	**Average**	**High**	
Yield - Tonnes per ha	4	7.5	10	
Yield - 750ml Bottles per ha	3000	5625	7500	
OUTPUT (@£14.13 per bottle)	**42390**	**79481**	**105975**	**7.9481**
Variable Costs				
Establishment (Over 30 yrs)	1230	1230	1230	
Annual material costs	5000	5000	5000	
Labour (Growing)	6500	6500	6500	
Labour (Harvesting) @ £250/t	1000	1875	2500	
Winery Costs @ £7.5/bottle	22500	42188	56250	
General Overheads	2500	2500	2500	
TOTAL COSTS	**38730**	**59293**	**73980**	**5.9293**
GROSS MARGIN	**3660**	**20188**	**31995**	**2.0188**

Source : John Nix Farm management 55th ed 2025

Sales		
Bottles per tonne of grapes	750	
Retail proce of bottle	30	
Less : retail margin of 30%	21	
Less : duty £2.65 & VAT 20% per bottle		
Wholesale price per bottle £	**14.23**	
	per ha	**per m2**
	£	**£**
Establishment Costs		
Crop longevity (Years)	30	30
Plants per ha	3500-5000	0.5
Materials	22000	2.2
Labour	15000	1.5
Total Establishment	**37500**	**3.75**

Source : John Nix Farm management 55th ed 2025

Consideration would need to be given to support structures (posts/wires/trellis) and the pruning management of the vines to manage crop height so as to minimise and overshading of solar PV and to allow access with machinery.

Vineyard grape ,mechanical harvester illustrating support structures (posts, wires etc)

One mitigation is that full vine production would be in mid summer when the sun is high in sky, thus minimising any shading PV panels. In contract during autumn, winter and early spring, when the sun is lower in aspect and more shading occurs, the vines would be dormant and this not competing for light.

Herbs

Herbs can be grown and sold fresh or for essential oil extraction. Many herbs can thrive in partial shade and benefit from the microclimate created by solar panels in agrovoltaic systems. There are a wide range of herbs that can be grown for essential oils in agrovoltaic systems including;

- Camelina sativa
- Crambe
- Echium
- Evening primrose
- Rosemary
- oregano
- sage
- fennel
- Parsley
- Cilantro (Coriander)
- mint

Yields and wholesale values of essential oil crops are highly variable. A summary of potential productivity and Gross margins is given below.

Essential Oil production				**Gross output**		
crop		**yield t/ha**	**£/t**		**£/ha**	**£/m2**
camelina sativa		1.5	750		1125	
Crambe		2	400		800	
Echium		0.25	3500		875	
Evening primrose		0.3	3500		1050	
borage		0.35	3250		1137.5	
	Av.	**0.88**	**2280**		**997.5**	**£0.10**
Output	0.88t per ha (0.25-2.0t/ha range)				**Per ha**	
	av sale value @ £2280/t				**2006.4**	**£0.20**
Variable costs						
Seed					170	
Weeding					55	
Fertaliser					35	
Harvesting					135	
TOTAL VARIABLE COSTS					**395**	**£0.04**
GROSS MARGIN					**1611.4**	**£0.16**

Source : various

Borage

Borage is an indigenous plant to Britain grown for use as a dietary supplement as the oil has a high gamma linolenic acid (GLA) content. The UK area grown has risen from c 1000ha in the 1980s to c 6000ha in 2024, almost all grown on contract.

The crop is spring sown. Its aggressive growth provides reasonable weed control. There are no significant pest or disease issues, except for powdery mildew. Harvesting takes place in early August after swathing and drying (2 weeks), with seed dried to 9% moisture content for safe storage.

Borage is a low yield, high risk but high value crop. Yield range from 0.3-0.5t/ha with values of c £3250/t in 2024.

Borage					
		£/ha	**£/ha**	**£/ha**	**£/m2**
Production level		Low	Average	High	
Yield - Tonnes per ha		0.3	0.4	0.5	
Price £/tonne		3250	3250	3250	
OUTPUT		**975**	**1300**	**1625**	**£0.13**
Variable Costs					
Seed		165	165	165	
Fertaliser		134	134	134	
Sprays		55	55	55	
TOTAL VARIABLE COSTS		**354**	**354**	**354**	**£0.04**
GROSS MARGIN per ha		**621**	**946**	**1271**	**£0.09**

Source : John Nix Farm management 55th ed 2025

Camelina

Camelina is a genus within the flowering plant family Brassicaceae. The Camelina species, commonly known as false flax, are native to Mediterranean regions of Europe and Asia. Most species of this genus have been little studied, with the exception of Camelina sativa, historically cultivated as an oil plant

Camelina, also known as Gold of Pleasure, has been grown in England for thousands of years for its tasty seeds and oil. Sprinkle on salads, use in baking, add to smoothies, or use as a vegan egg replacement.

Camelina is a major ingredient in Biodiesel which has a variety of benefits. First, traditional petroleum or diesel fuel is not renewable resources, the production of these resources is finite. Camelina biodiesel, however, is a renewable resource. Camelina based aviation fuel could save 84% of carbon emissions. Camelina biodiesel can be produced in large quantities as feedstocks are enough. Moreover, camelina biodiesel can reduce a country's dependence on fossil resources, which can ensure a country's energy security. In addition, camelina biodiesel is an environmentally friendly fuel, and it is biodegradable.

Camelina				
	£	**£**	**£**	
Production level	Low	Average	High	
Yield - Tonnes per ha	0.5	1	1.5	
Price £/tonne	750	750	750	
OUTPUT	**375**	**750**	**1125**	**£0.08**
Variable Costs				
Seed	120	120	120	
Fertaliser	143	143	143	
Sprays	45	45	45	
TOTAL VARIABLE COSTS	**308**	**308**	**308**	**£0.03**
GROSS MARGIN per ha	**67**	**442**	**817**	**£0.04**

Source : John Nix Farm management 55th ed 2025

Herb production

Many UK herb producers don’t just sell fresh or dried herbs, they turn these herbs into high quality products e.g., essential oils, herbal balms, soap, massage oils, bath salts, face oils etc.

Import and Export

There is little accessible data regarding the volume of medicinal and aromatic plants are imported into the UK currently. MAP-EXPO reported that in 2014, 10,000 tonnes of medicinal and aromatic plants and a further 5,000 tonnes of plant extracts were imported into the UK. This equates to around £100 million pounds worth of imports every year. (MAP-EXPO, 2016)

Herbal raw materials have a relatively short shelf life, as with time the products and the phytochemicals within the plant material degrade. Growing herbal products in the UK would reduce the time that herbs spend in transportation and storage, providing a fresher and higher quality product.

Products from Herbs can include;

Essential oils – volatile oils extracted from a plant through a distillation process

Tea or infusions – dried herbs used to produce single or mixed herbs used in teas for culinary or wellbeing.

Herbal tinctures – alcohol extract of a herb that is used for therapeutic purposes. Extraction of phytochemicals from fresh or dried plant material through steeping or percolation with alcohol

Cosmetics – soaps, creams, balms, shampoos etc.

Herb production is well suited to smaller units c 20ha or less. Small herb farms see increased environmental benefits – increased biodiversity, topsoil improvements, social benefits e.g., public education about farming and building community. A focus on local supply chains was also an important value for two of the farms that chose only to sell their products within a certain proximity to their farm. Many products sold are high quality, artisan products which set them apart from other high street products. There is often a focus on retaining the aromatic properties of the plants throughout the processing. The average number of workers employed per hectare on a small herb farms is higher (an average of 0.68 FTW per hectare, compared to the average of 0.026 per hectare). (Allwood, 2019).

Harvesting and drying Herbs

Harvesting usually by hand propelled equipment (mowers etc). Drying herbs using this can take up to a week and required drying equipment and Dehumidifier equipment. These are relatively cheap to set up, so a good option for new entrants with a low start up budget. Self-built insulated rooms with dehumidifiers and specialised warm air condensing units as a heat source are best suited. Energy from the agrovoltaic system would be well suited for integration.

Machine harvesting herbs

Post harvest herb drying (and other crops) can use significant amounts of energy in the drying process. There would be good synergies for direct sales of electricity from the solar PV in the agrovoltaic system to the agricultural production element for drying. There would also be a good case for using electrically powered machinery/harvesters/cultivators etc if direct sales of electricity from the solar PV in the agrovoltaic system were available.


Herb drying

Essential Oils

Essential oils are highly concentrated extracts from plant raw material that carry the natural fragrance and therapeutic properties of the plant, making them valuable for various purposes. These oils are extensively used in aromatherapy as they can promote relaxation, relieve stress, and improve overall well-being.

Herbs are harvested and the plant material dried by spreading out in a single layer or using specialised equipment. The raw material is then placed in stainless steel vessel and cold water is heated to a specific temperature. The essential oils have a lower boiling point and therefore vaporise and rise to the top of the vessel. The vapor travels through a condenser, it is cooled and converted to liquid. Essential oil floats on the surface of the condensed liquid. The collected liquid is stored in airtight containers in bulk or lacquer-lined aluminium flasks (out of direct sunlight), which are non-reactive and protect the precious oils. Most essential oils have a shelf life of 2-5 years if stored correctly.

In terms of capacity a 300L still needs ~50-100kg of raw materials + water. A 60L still needs ~10-12kg of raw material + water. This will produce c 30-120 ml of essential oils per batch in a 60L still.

UK essential oil potential in agriovoltaic systems:

- Chamomile
- Lavender
- Peppermint
- Spearmint
- Rosemary
- Sage
- Thyme
- parsley

Growing herbs for wholesale as fresh cut is unlikely to be viable economically, especially on a small scale. With essential oils it is the processing of the herbs and value added activities that make this an economically viable option. The post harvest herb drying and essential oil processing (vat heating) can use significant amounts of energy in the drying process. There would be good synergies for direct sales of electricity from the solar PV in the agrovoltaic system to the processing element of essential oil production.

References

https://neoils.com/about/

https://naturallythinking.com/lavender-farm-london

https://media.churchillfellowship.org/documents/Allwood_B_Report_2019_Final.pdf

https://copper-pro.com/collections/commercial-essential-oil-distillation-equipment/products/commercial-essential-oil-distiller-39g?variant=41681367924872

https://copperbrothers.com/product/essential-oil-distiller-30-l/ https://downderry-nursery.co.uk/lavender-care/#:~:text=For%20informal%20plantings%20we%20recommend,type%20%E2%80%93%20the%20effect%20is%20stunning!

Bees and Honey production

Bees are important for pollination in agriculture, horticulture and for biodiversity. In agricultural systems, providing pollinator habitat can boost local pollinator abundance and pollination to nearby crops (Blaydes et al., 2021). Bees integrate well with PV solar farms and would equally integrate well with agrovoltaic systems as part of a multifunctional land use approach.

Honey can provide an income source, but the scale required is significant. Start up costs are c £500 per hive, which can produce c 11.3kg/honey per season (Nix 2025), although production can vary considerably based on many factors.

Honey		**per hive**		**per ha**	**per m2**
		£		**£**	£
yield (jars)		33		99	0.01
price per 340g jar		6.5		19.5	0.01
OUTPUT		**216**		**648**	**0.06**
COSTS					
jars		23		69	0.01
miticides		8		24	0.01
food		7		21	0.00
losses and replacements		32		96	0.01
Attributable costs		**70**		**210**	**0.02**
Gross Margin		**146**		**438**	**0.04**
			3 hives per hectare		

Source : John Nix Farm management 55th ed 2025

These costing exclude capital costs, labour, processing and marketing – all of which can easily exceed the total income from production, unless adequate scale is developed.

The number of bee hives needed per hectare depends on the crop being grown, the strength of the bees, and the weather conditions:

Blueberries: Six to nine hives per hectare

Strawberries: At least six large hives per hectare if no other pollinators are present

Oilseed rape: Two honey bee colonies per hectare

Bees typically forage within a radius of one to two kilometers, so the optimal number of colonies per hectare can range from two to nine. For the purposes of this study a density of **3 hives per hectare** has been used.

Where Honey production is employed the site can also benefit by using the surrounding areas to the PV site to attract bees. Choosing flowers and herbs that actively attract bees to the area, increasing biodiversity and creating a larger output of honey.

A survey of 11 UK solar parks (Blaydes et al., 2021) indicated greater bumble bee abundance in solar parks with higher floral diversity. On average (across all scenarios), there were more than twice as many bumble bees foraging per 100 m2 inside solar parks managed as unimproved meadow, compared to those with meadow margins. Relative bumble bee density was three times greater in zones surrounding parks managed as unimproved meadow, compared to improved grassland. Increasing floral resources provide more forage for the nests inside the solar park, resulting in nests producing more foraging bumble bee workers and therefore increasing foraging bumble bee density.

Blaydes et al 2021 also found that as floral resources inside PV areas increase, the PV farm becomes a more attractive place for bumble bees to forage. In the model, bumble bees preferentially spend more time in better quality foraging habitat. Solar farms offer more foraging resources may therefore retain and attract more bumble bees, supporting evidence from field surveys suggesting pollinator abundance is greater on solar parks with higher botanical diversity and interventions in place to support biodiversity.

The best flowers for honey bees are: sunflowers, comfrey, salix/willows, catmint, hellebores, spring blossom, Michaelmas daisies, heathers, wallflowers, centaurea.

Agricultural / Horticultural crops for bees: alfalfa, clover, sanfoin, birdsfoot trefoil, cover crops, fruit trees, cucumbers, squash and pumpkins, berries (raspberries, blackberries, strawberries), field peas, beans

References

Blaydes, H., et al. (2022) “Solar park management and design to boost bumble bee populations.” Environmental Research Letters, Vol. 17, No. 4, 044002. https://iopscience.iop.org/article/10.1088/1748-9326/ac5840

7 Opportunities to optimise yields to unlock potentially profitable farming opportunities when distributed between panels with reduced light and cultivated ground

Solar systems are designed to capture sunlight as energy to fuel PV panels and create electricity. However, when you look at ground mounted Solar systems there is c 50% of the land area not covered by PV panels – for shade management, access, maintenance etc. This results in c 50% of the available solar radiation not actually being captured and used for a form of production.

Ground mounted Solar PV showing c 50% land coverage

So why not integrate agricultural production with Solar Pv as an agrooltaic system. This the uses a much higher proportion of the land area for productive output. Part PV for electricity and part crop production for food.

Agrololtaic system - 50% land use as PV for energy + 50% land use for food crops

Crops can be grown in the alleys between PV panels as depicted below

or crops can be grown under PV panels (where panel structure raise the panels up to permit access) as shown below for both perennial and annual crops.

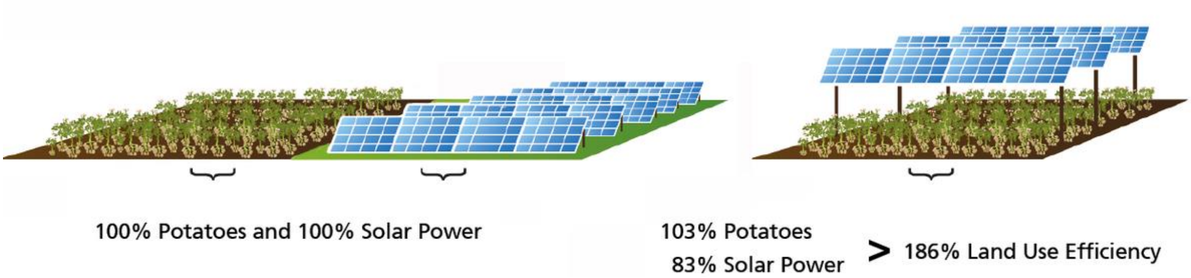
Light management

The biggest challenge in designing an agrivolatic system is to find a compromise between electricity generation and agricultural yields.

Providing sufficient and homogeneous light for crops can be achieved in numerous ways. These include a deviation from a southern orientation to the east or west, the use of narrow modules such as in Japan, or targeted light management through tracking systems.

With tracking systems, the shading can be actively controlled according to the respective requirements of the plants

Agrivoltaic systems have a better land use efficiency. When installing agrivoltaics, the competition for land-use can be reduced while ensuring the expansion of solar energy and preserving valuable soils at the same time. In addition, agrivoltaic systems can protect agricultural crops from extreme weather events



In order to achieve the climate protection targets, photovoltaics will be the most important pillar of energy supply alongside wind power.

The expansion of ground-mounted systems could play a key role in this, but will meet with massive resistance from the population, because in addition to advancing urbanization, the ground-mounted systems are also competing for land, such as farmland and meadows.

Agrivoltaic systems could be pivotal to reduce the competition for land and to ensure the expansion of solar energy while at the same time preserving valuable soils.

Agrivoltaics to replace crop protection measures

To meet the challenges of climate change and protect crops from extreme weather and pests, crop protection measures such as frost or in the EU hail nets are increasingly used in agriculture. Hail is not currently a major issue in the UK, but with the impacts of climate change hail may well become an issue for the UK in the future.

These agricultural protection structures can be partially or even completely replaced by an agrivoltaic systems

Stabilization of yields in agrivoltaic systems

The results of the research project in Germany https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2019/agrophotovoltaik-hohe-ernteertraege-im-hitzesommer.html show that partial shading resulting from the modules causes a slightly changed microclimate under the modules. This can have a yield-stabilizing effect, especially during periods of drought.

Other Agri-PV systems in the USA and North America confirm these results and additionally show lower water consumption and reduced water loss from evapotranspiration https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?referer=https://scholar.google.

de/scholar?hl=de&as_sdt=0%2C5&q=Barron+%26+Gafford+2017+Agrivoltaics&btnG=&httpsredir=1&article=1475&context=star .

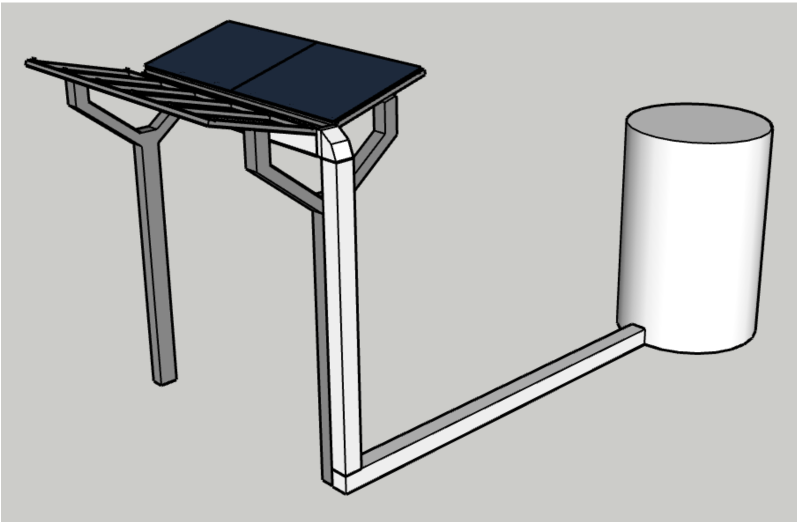
Water management

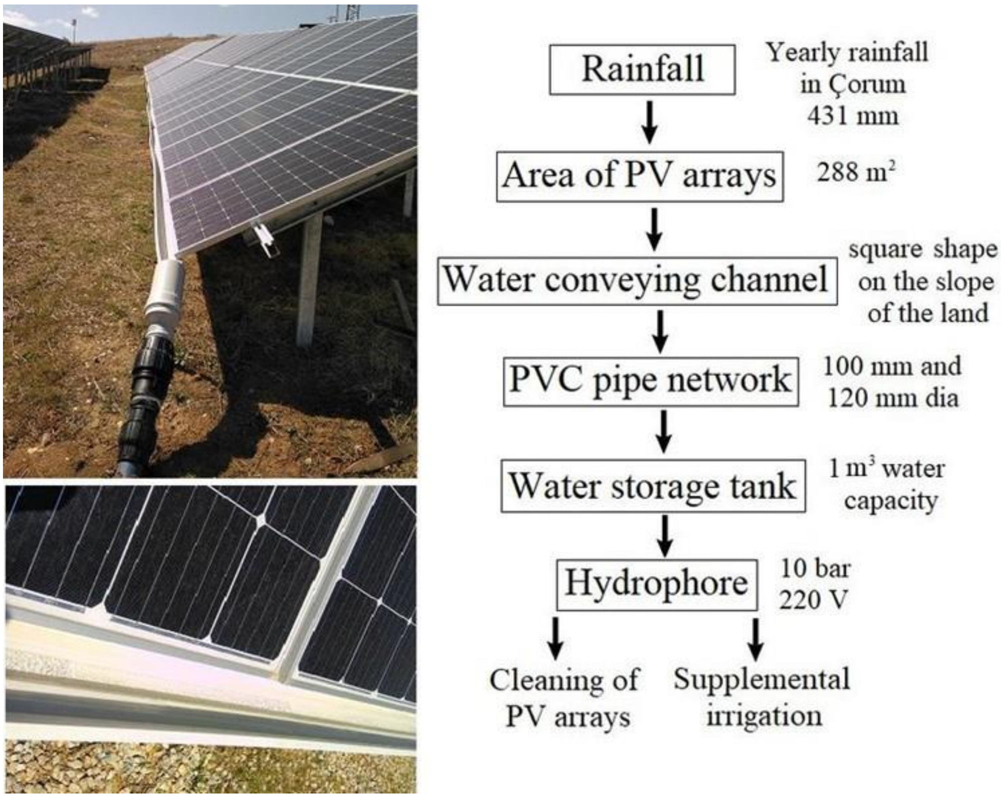
Agriculture already consumes around 70% of the world's freshwater through irrigation, and the amount of land that needs to be irrigated has more than doubled since the 1960s. With climate change, water shortage will become severe in many parts of the world and become a more important issues in the UK. From 2024 the Environment Agency will no longer be issuing new summer water abstraction licenses to farmers unless water storage and recycling is undertaken.

Thus, agriculture needs solutions to save water and use it efficiently. The partial roofing of the area as with agrovoltaics changes the distribution of precipitation.

In a system design, this must be considered in order to avoid negative effects of the PV modules' drip edges on soil and plants.

Measures that can be used to achieve this include the use of special modules (narrow, tubular) or a complete system approach with integrated rainwater harvesting.





Water savings through shade in agriculture

When plants are exposed to too much solar radiation, their water consumption increases and their photosynthesis performance decreases. By implementing agrivoltaics, solar radiation can be regulated so that plants have the best possible light conditions for their growth and need less water.

Technical Synergies

The combination of solar power generation and agriculture creates advantages on both sides. Placing solar panels over agricultural land also makes sense from a purely technical perspective, because the efficiency of the modules can be increased by the changed conditions in an agrivoltaic system. At the same time, land use efficiency is improved.

PV modules benefit from microclimate

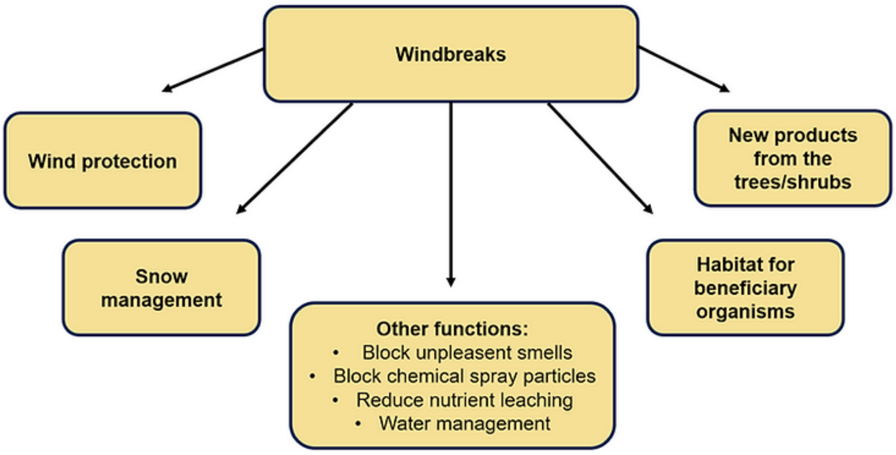
PV modules are very sensitive to heat. If the temperature exceeds 25 °C, the efficiency of conventional photovoltaic modules decreases. Thus, due to climate change, increased average temperatures as well as extreme hot summers have a negative effect on the efficiency of solar power generation.

Recent studies show that PV modules in an agrivoltaic system heat up significantly less than modules in a conventional ground-mounted PV system. The plants underneath the system evaporate water and create a microclimate that cools the backs of the modules, reducing PV panel temperature and increasing efficiencies.

Agrovoltaic systems also influence wind patterns, which in turn effect microclimate and evapotranspiration from crops. Recent studies on the impact of wind in agroforestry/agrovoltaic systems are from EU studies and show that the wind velocity reductions have a positive impact on microclimate and crop performance. Wind reduction in the UK's maritime climate has a greater importance than in a continental climate where wind velocities are typically and thus impacts on microclimate and crop performance reduced.

In agroforestry systems using windbreaks, shelterbelts, and rows of trees or shrubs planted in order to protect crops and animals from the wind and create a 3D multifunctional farming system. Windbreaks can decrease soil erosion, reduce evapotranspiration and increase yields. The same principles and impacts apply to agrovoltaic systems.

In Agroforestry systems the four main functions that impact on microclimate are: (1) wind reduction/protection (2) snow management (3) habitat for beneficial organisms, and (4) new products from the trees and shrubs (for agovoltaics substitute this for energy). Other functions that windbreaks may have are: blocking chemical spray particles, reducing nutrients leaching and water management.



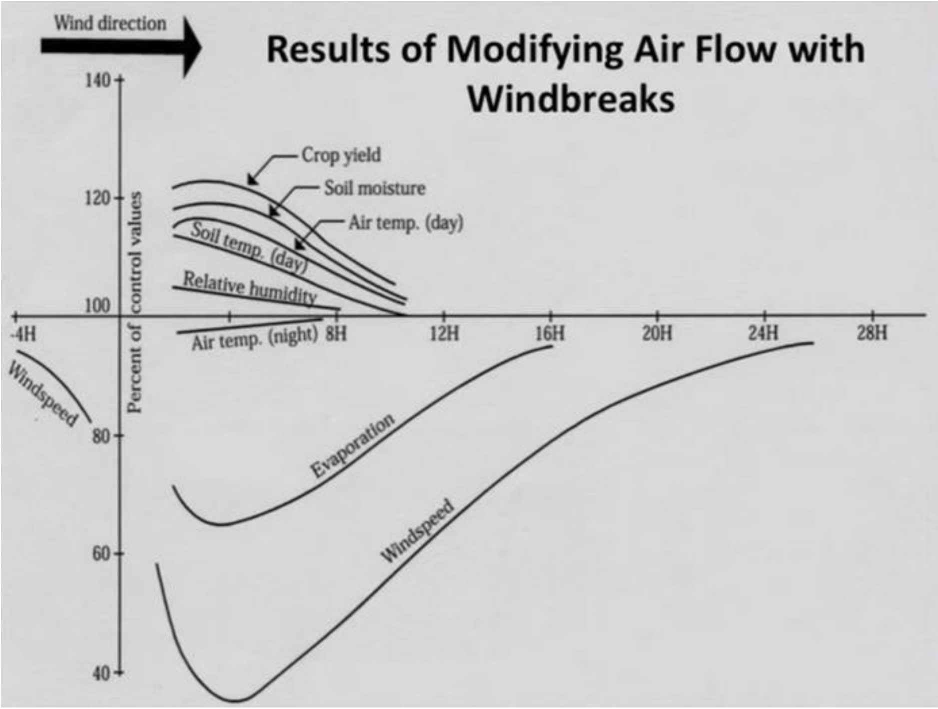
The most common functions of a windbreak © *Mauricio Sagastuy*

Wind protection is the most evident function of a windbreak. Protecting your crops and livestock from the wind will allow them to grow better and produce better yields. The benefits of windbreaks include;

- Higher concentrations of soil moisture
- Higher daytime air-temperatures and lower evening air-temperatures
- Higher soil temperatures
- Higher relative humidity during the day

The image below shows the effect that windbreaks have on the lee side (the side of your field that is protected by wind). A good rule of thumb is that for every meter of height of the windbreak, you get 10 times the shelter in width. Thus, a 3 meter high windbreak provides 30 meters of wind protection. As you can see in the image below, the effect that windbreaks have on the microclimate is not evenly distributed throughout the field. The longer the distance from the windbreak the less effect it has on the microclimate.

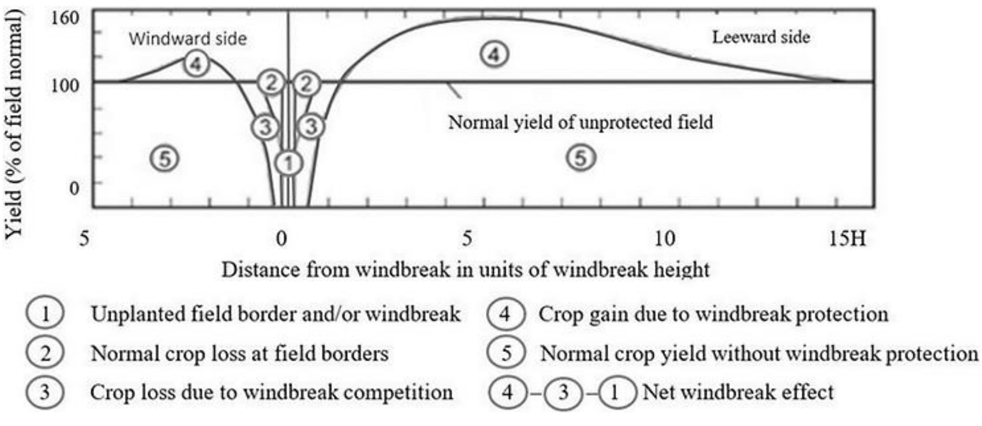
Patterns of microclimate and crop production



Source: Marshall, J.K. (1967), 'The effect of shelter on the productivity of grasslands and field crops', Field Crop Abstracts, Vol. 20, pp 1-14. "H" stands for multiples of windbreak height.

The area that will experience most of the positive effects is the leeward area that is approximately between 1-10 x H of the windbreak (as seen in the figure below). Additionally, you can also expect your yields to increase in the windward side of -1 to - 5 x H and in the leeward side area of 10 - 15 x H, even though these increases in yields won´t be as significant as for the leeward area between 1-10 x H.

Crop field response for a field windbreak



Source: Osorio, R. J. (2018), GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska.

Improvements in crop yields from wind reduction and microclimate modification will vary for different crops. Not all crops benefit equally as much from wind protection.

Data from Bagley et al below summarises yield impacts on different crops with wind protection. Positive impacts range across a 6%-56% increase from reduced wind speed and microclimate impacts.

Crop	Number of field years	Mean yield increase (in %)
Oats	48	6
Spring wheat	190	8
Maize	209	12
Soybeans	42	16
Rye	39	19
Grass hay	14	20
Winter wheat	146	22
Barley	30	25
Raspberry	2	27
Tomatoes	3	29
Plum	2	34
Snap beans	2	40
Millet	18	44
Strawberry	3	56

Source: Data from Bagley (1964), Baldwin (1988), Brandle et al. (2009), Norton (1988), Kort (1988), and Osorio et al. (2018)

In general, one can say that fruit, nuts and berries are the agricultural crops that benefit most from wind protection. The creation of a more stable microclimate is especially beneficial during flowering and fruit development. Additionally, reduced wind speeds can improve pollination (Bees don't fly well in the wet or in strong winds) and minimize damage to delicate fruit and reduce fruit drop. Raspberries (27%) and Strawberries (56%) yield increases respectively from wind protection will benefit particularly well in an agrovoltaic system.

Vegetables are the second group of agricultural crops that benefit most from windbreaks, particularly those with large and vulnerable fruits. Cereals, root vegetables and legumes are the third group of agricultural crops that benefit from windbreaks. These crops are in general less vulnerable to wind damage and exposure.

Co-incidentally, when considering livestock based agrovoltaic systems, Studies have demonstrated that sheltered areas can increase dairy milk production by 17%, and increase sheep live weight by 10-21%. Windbreaks can also significantly decrease livestock mortality rates at birth or in extreme weather conditions and reductions in 'wind-chill' in cold weather. Trials in south/east Australia demonstrated that losses of newborn lambs were reduced by 50% where there was effective shelter in place. Another study in New Zealand showed that wind protection decreased twin mortality by 14 - 37% and overall mortality by 10%. Shelter also reduces the risk of ewe mastitis.

Sheep sheltering from heat & Cold

Additionally, livestock need substantially more energy to maintain their health in exposed conditions. Sheltered animals use less energy to maintain their core body temperature than those without wind protection, resulting in lower feed costs.

The synergies between PV-technology, agriculture and microclimate can also be achieved by the use of bifacial modules. This special type of module allows solar power to be generated on the front as well as the back of the modules, producing higher energy yields than in conventional PV modules. The higher and further apart bifacial modules are installed, the more light can reach the reverse side.

Bifacial agrovoltiac modules in Germany

8 Routes to market

For the agricultural and horticultural produce produced as part of the agrovoltaic system there are multiple routes to market depending if wholesale commodities are produced, processing and value added is employed, the shelf life of the products and the investment and manpower developed and deployed.

Options for routes to market include;

- Direct sales of produce to the local community (scale dependant)- to address local enterprise and community food security
- Community supported agriculture – forward community payment during production for discounted provision of food products
- Commercial box scheme
- Direct sales to local retail i.e *Maxeys* farm shop
- Local and on site processing and value added
- Drinks processing facility oat milk processing DEVOATED (Soft fruit for flavourings)

Field scale production figures suggest a gross margin of c £0.67p/m2 (wholesale). Experience from Hockerton (pers comm.) would suggest potential for c. £3-4 m2 retail prices from box scheme's or direct sales. See section 6 (potential cropping systems including adapted gross profit analysis) above for gross margins.

There is potential with agrovoltaic systems to create areas where the public can pick their own produce. The produce could alternate throughout the seasons i.e

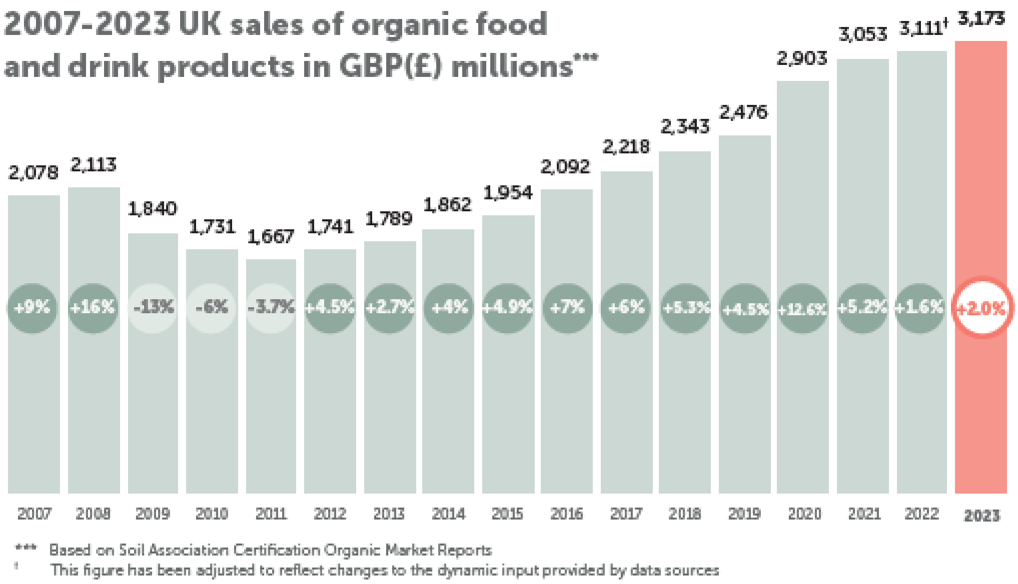
- Summer: strawberries, raspberries, blackberries, vegetables/salads
- Autumn: pumpkins, squash, vegetables/salads

However, compared to open field sites, there are complexities regarding health and safety associated with the PV infrastructure and any site would need to ensure this was safe to do in between panels. Pick your own has been discounted as a viable option at Hockerton due to scale and health and safety issues.

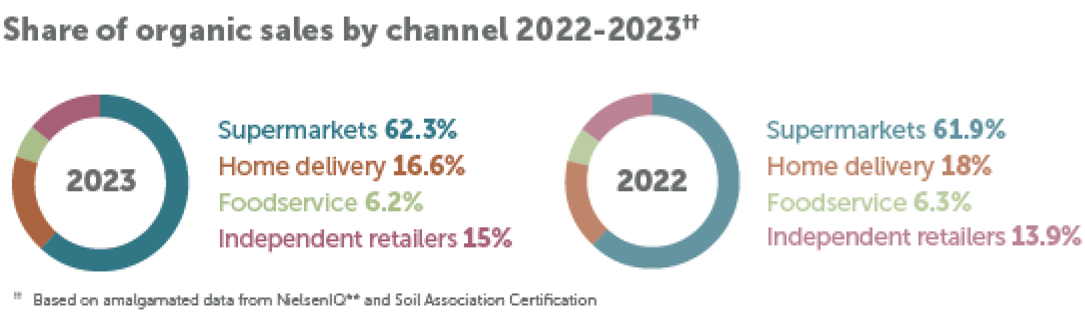
Other opportunities for increasing revenue within agrovoltaic systems, hinge around targeted market access and segmentation, such as specify growing for certified organic and or vegetarian /vegan markets.

Organic market opportunities

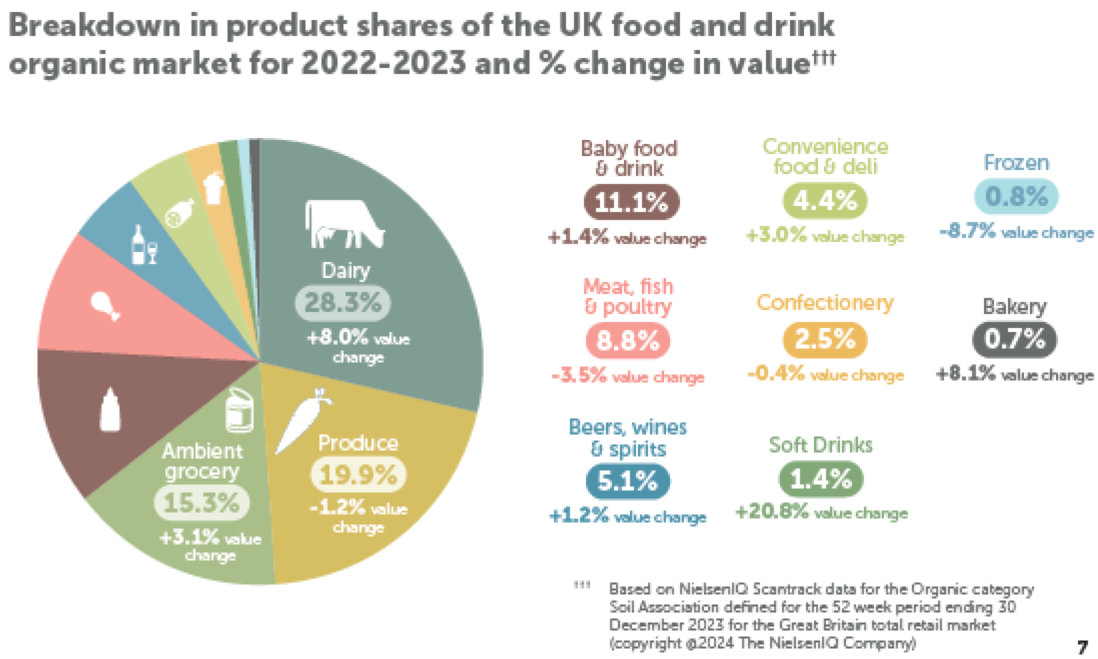
The Organic market grew by a further 2% in 2023 and was worth £3.2 billion by the end of 2023, with twelve years of solid growth in the organic market in the UK. Almost 30% of all sales of organic are through independent retailers and home delivery, and growing faster than supermarket sales.



Growth in food service has grown from 3.8% in 2017 to 6.2% in 2023, home delivery grew from 12.9% to 16.6% over the same period. Independent retailer sales slowed from, 16.3% down to 15% – with Supermarket sales still accounting for the largest market share at 62.3%.



There is considerable variation in growth between food sectors. Chilled foods/deli growing fastest but with alcohol, frozen and fresh produce seeing considerable growth, all outperforming the non organic sector in terms of market growth.



There are many reasons people buy organic food. Research by the Soil Association (2023 and Kantar worldpannel identified six key beliefs, opinions and behaviour's that shoppers are using to decide what they buy;

1. **Healthiness.** Consumers seek products that help them have a holistically healthy lifestyle. They want balance and moderation and are looking for natural and less processed foods, products that give energy or sustenance, help provide weight management and meet specific dietary needs (such as gluten-free).
2. **Taste and inspiration.** Consumers see the quality of a product as being central to how good it tastes. Taste is about two things: finding new and interesting dishes and having a repertoire of firm favourites which can be made without recipes.
3. **Fits around me.** Consumers' lives are busy and hectic. Shopping and making food is time consuming and so consumers try to achieve a balance between price, quantity, quality, time to prepare and tastes everyone will love.
4. **Pleasure.** Most consumers allow themselves some products that are more special, indulgent, a 'treat', or that deliver more flavour.
5. **Value.** For some consumers, price is the main reason they bought a product. For others, it's the inherent quality of a product. Many make different decisions depending on what item of food they are buying. For example, they might buy organic vegetables but non-organic meat. Value is a personal 'equation' consisting of price, quality and convenience.
6. **Making a statement.** Consumers often buy products because the food and/or packaging look beautiful. This increases their appetite or gives them something to talk to their friends about.

The research also revealed five growing outside influences on what food people buy.

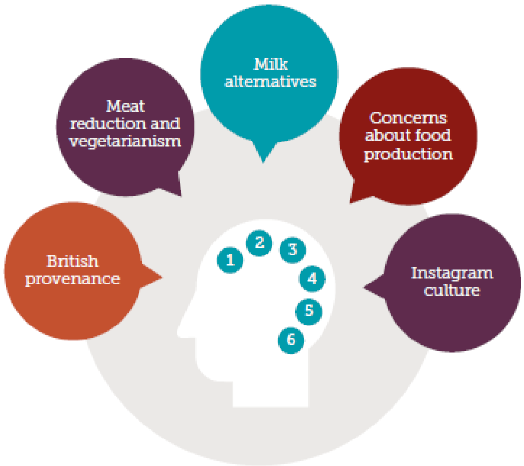
1. British provenance. This is an increasingly important influence on what food people buy, especially with the uncertainty of Brexit. Consumers expressed frustration at food that can be grown in the UK but is shipped in from overseas.

2. Meat reduction and vegetarianism. In our focus groups, we found a marked increase in the number of consumers reducing the amount of meat they eat (predominantly red meat). Many had tried, or were converting to, a vegetarian diet and everyone felt this was a growing trend.

3. Milk alternatives. Many consumers had tried alternatives to milk for taste rather than dietary reasons. Some tried them because of fears over animal welfare or milk production techniques. Many consumers are now using them day to day as part of their choice alongside dairy.

4. Concerns about food production. Consumers are particularly concerned about how animals are cared for and high-profile news stories and documentaries have clearly influenced them. There continues to be ongoing frustration over food and packaging waste.

5. Instagram culture. Instagram is seen by many as a harmless way of getting food inspiration. Some, however, feel it portrays an overly idealistic view of the world of food, something that's impossible to recreate. Either way, it's an important influence on what people eat today.



1 Healthiness
2 Taste and inspiration
3 Fits around me
4 Pleasure
5 Value
6 Making a statement

What's hot in organic?

- Turmeric
- Seaweed
- Fermented foods
- Fruit tea
- Soft fruits
- Nutty spreads
- 'Dirty' vegan
- Mushrooms
- Healthy seed toppings
- Milk alternatives, including nut milk yoghurts
- Organic wine

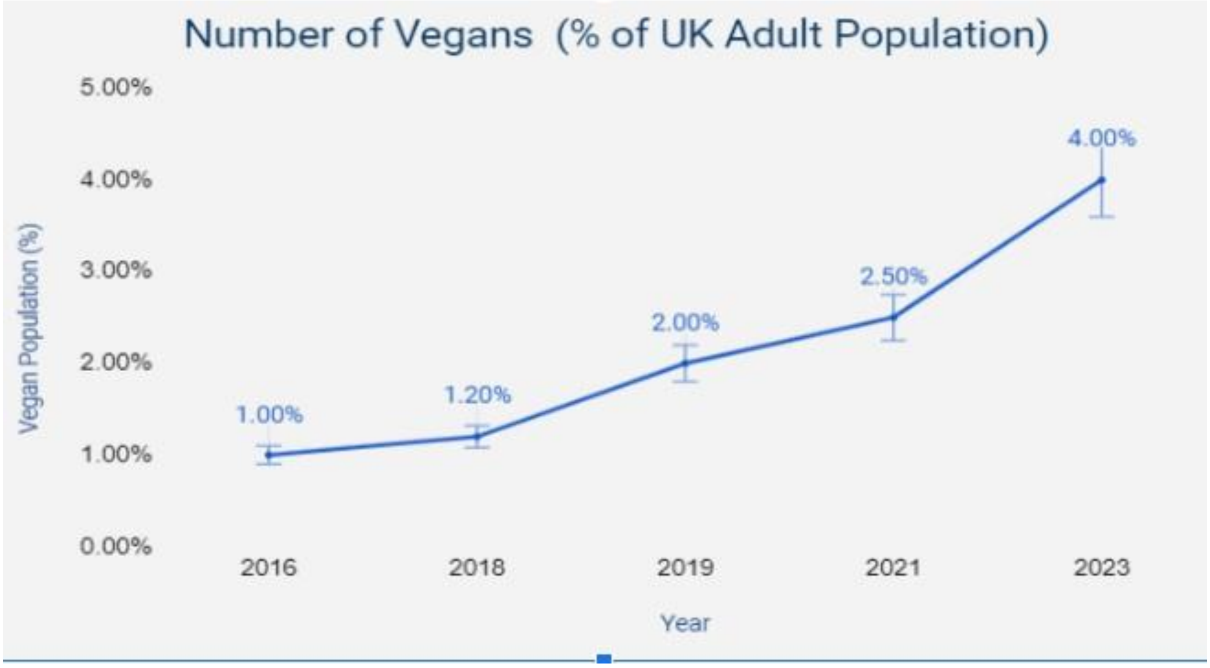
Vegan and vegetarian markets

More than a quarter of all evening meals in the UK are vegan or vegetarian, research shows. Kantar Worldpanel research - collected from a consumer panel of 30,000 households - reflects a year-on-year move to more vegetarian meals (26.9% of evening meals were vegetarian in 2014 and 27.8% in 2024).

A 2022 study by comparethemarket.com found that approximately 7% of British people are vegan, while 14% are vegetarian. As well as this, 31% are eating less meat - either for health or ethical reasons, and 19% are eating fewer dairy products

An alternative poll by the vegetarian society in 2020 put the figure at 5.7 per cent. This means there are over three million vegetarians in the UK today. Vegetarians and vegans are both becoming increasingly common in UK culture. BBC research shows a significant rise in interest in veganism when looking at 'Google' search records.

The UK vegan food market is valued at approximately £2.8 billion as of 2023, with the meat-free segment accounting for £622 million and dairy alternatives reaching £450 million. The market is projected to grow significantly, with a compound annual growth rate (CAGR) of 11-12% through 2030



Source Kantar Worldpannel

The growth in Veganism is faster than for other food choices including Gluten free, Low-Carb, Paleo and Organic.

The above data suggests that there is significant scope to develop production on a very focused and targeted basis aimed at consumers seeking highly traceable vegan, vegetarian and organic products. This is not easy in the UK as the majority of the 212,000 farm holdings and 126,000 farmers in the UK have some form of livestock.

EU and DEFRA statistics show that only 13.4% of farms are specialist cereal crop farms, with 2.8 % as horticulture units. It is impossible to verify how many of these also operate livestock enterprises alongside, have animals grazing on an occasional basis or use livestock manures.

The Vegan Organic network has only 22 registered 'organic stock free' farms in the UK http://veganorganic.net/producer-directory/ . This is some 0.010% of UK farm holdings. There is therefore significant potential for supplying stock free, vegan and organic markets.

9 Recommendations

Different agrovoltaic options are set out in section 5 above. It is recommended that the most promising crops/cropping systems for 50KW Hockerton are shortlisted as ;

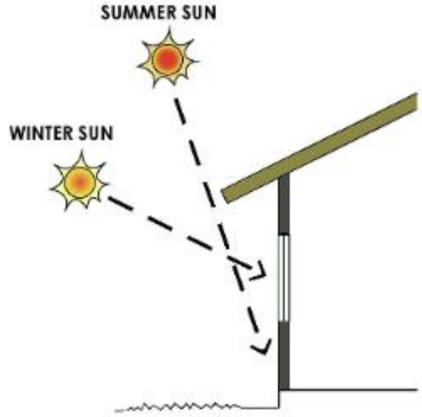
- **Lettuce salad crops**
- **Raspberry & strawberry soft fruit**
- **Viticulture**

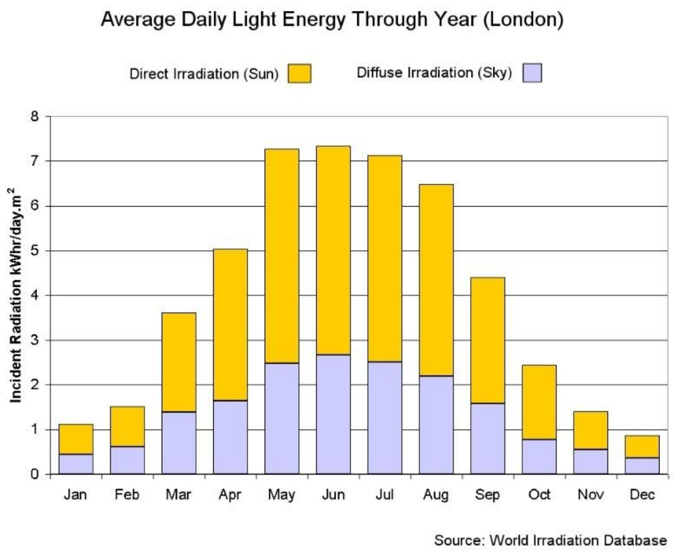
It is recommended that the pilot adopts across one third of the available crop area for each option (1/3 salad, 1/3 Soft fruit, 1/3 viticulture) at the Hockerton agrivoltaics project, so as to demonstrate agronomic, economic and management viability from the pilot. These have the greatest potential for integration into the proposed agrovoltaic system, to provide foods through local short supply chains, to generate income through value added (processing) activities.

Agronomic reasoning

Raspberries (27%) and Strawberries (56%) yield increases respectively from wind protection will benefit particularly well in an agrovoltaic system. Data on the impact of shade for salad crops and viticulture is less available.

From an agronomic perspective Soft fruit, Salad crops and Viticulture all exhibit maximum growth (and thus sunlight demand) between late spring and late summer, when the sun is high and any PV panel/Crop shading competition is minimised. Conversely, salads would not be grown in the winter, and soft fruit and vines will largely defoliate in the winter, removing any shade to PV panels during winter months when the suns aspect is lower. This is particularly important for optimising solar utilisation during different seasonal periods.





10 Outline business model - Hockerton

Economic returns from UK agrovoltaic systems

Economic returns from agrovoltaic systems in the UK—where agricultural activities and solar energy generation are integrated—can be appealing but involve unique considerations. Here's an overview of the factors influencing the economic viability of agrovoltaic systems:

1. Revenue Streams

1. **Energy Production**
   - **Power Purchase Agreements (PPAs)**: Solar energy generated can be sold through PPAs to businesses, utilities, or other buyers. These agreements can provide stable and predictable revenue.
   - **Export Tariffs**: Excess electricity can be sold back to the grid under export tariffs, providing additional income.
   - **Direct energy sales** : there is considerable potential for the drect sales of electricity produced from the agrovoltaic system direct to the Hockerton community and / or to be used for agricultural production or processing for value added activities.
2. **Agricultural Products**
   - **Crop Sales**: Revenue from the sale of crops grown under or between solar panels. Suitable crops include leafy greens, root vegetables, and certain fruits.
   - **Livestock**: If integrated with livestock, revenue can come from the sale of meat, milk, or wool, depending on the type of animals used.
3. **Government Incentives**
   - **Renewable Energy Incentives**: Depending on the specific policies in place, agrovoltaic systems may benefit from various subsidies or tax incentives for renewable energy production.
   - **Agri-Environment Schemes**: Some schemes provide financial support for sustainable agricultural practices, which can potentially be integrated with agrovoltaic systems.

2. Cost Considerations

1. **Initial Capital Investment**
    - **Installation Costs**: Initial costs include solar panels, inverters, mounting systems, and integration with agricultural operations. Higher costs are associated with more advanced or customizable installations.
    - **Land Preparation**: Costs related to preparing the land for both solar infrastructure and agricultural use.
2. **Operational and Maintenance (O&M) Costs**
    - **Maintenance of Solar Equipment**: Regular maintenance of solar panels and associated equipment to ensure optimal performance.
    - **Agricultural Operations**: Costs associated with farming, including seeds, labor, irrigation, and pest management.
3. **Financing Costs**
    - **Loan and Investment Costs**: Costs related to financing the initial capital outlay. Interest rates and financing terms can impact overall returns.

3. Economic Returns and Financial Metrics

1. **Return on Investment (ROI)**
    - **ROI**: Typically, ROI for agrovoltaic systems is a combination of returns from both energy production and agricultural revenue. The combined ROI may vary but can be competitive with traditional solar-only installations, particularly if crop yields are optimized.
2. **Payback Period**
    - **Payback Time**: The payback period is influenced by the capital investment and operational costs. It can be longer than traditional solar projects due to the added complexity of integrating agriculture.
3. **Internal Rate of Return (IRR)**
    - **IRR**: IRR for agrovoltaic systems can vary widely depending on the efficiency of both the solar and agricultural components. An effective integration can result in favourable IRR, often between 8% and 12%.
4. **Net Present Value (NPV)**
    - **NPV**: Positive NPV indicates that the project is expected to generate more value than the cost of investment. The NPV calculation will consider both energy and agricultural revenues and associated costs.

4. Market Conditions and Policy Impacts

1. **Energy Prices**
   - **Electricity Prices**: Fluctuations in energy prices can impact revenue from solar energy. Stable or rising energy prices are favourable for profitability.
2. **Agricultural Market Prices**
   - **Crop Prices**: Revenue from agricultural products is affected by market prices for different crops. Market volatility can impact the overall returns.
3. **Government Policies**
   - **Supportive Policies**: Government policies that support renewable energy and sustainable agriculture can enhance financial returns. Changes in policies, such as shifts in subsidies or tax incentives, can impact profitability.
4. **Grid Access and Infrastructure**
   - **Connection Costs**: Costs associated with connecting to the grid and any required upgrades can affect overall economic returns.

5. Long-Term Considerations

1. **System Lifespan**
   - **Maintenance and Replacement**: Regular maintenance and potential replacement of solar panels or agricultural infrastructure will affect long-term returns.
2. **Technological Advances**
   - **Improved Technology**: Advances in solar technology, energy storage, and agricultural practices can improve efficiency and profitability over time.
3. **Sustainability and Resilience**
   - **Environmental Benefits**: Agrovoltaic systems offer environmental benefits, such as enhanced biodiversity and soil health, which can be valued alongside economic returns.

Agrovoltaic systems in the UK offer the potential for diverse economic returns through a combination of energy production and agricultural revenue. While initial costs and the complexity of integrating two systems can be higher, the potential for stable revenue streams and additional benefits from dual land use can make these systems economically viable. Careful planning, technology selection, and management are crucial for optimizing returns and ensuring long-term success

Recommended options for Hockerton - economic comparisons

The Gross margin comparisons between Soft fruit (Raspberries & Strawberries), Salad crops and Viticulture at Hockerton using the economic data from section 5 (above) is detailed below;

Gross Margin	£/m2	£/ha
Soft Fruit (Raspberries)	£ 2.57	£ 25,719.00
Soft Fruit (Strawberries)	£ 1.15	£ 11,511.00
Viticulture	£ 2.02	£ 20,188.00
Salads (Lettuce)	£ 0.68	£ 6,750.00
Herbs (Camelina)	£ 0.04	£ 442.00

When applying the gross margin projections to a single 1.25m x 49m PV alley for the Hockerton agrivoltaics pilot, the following economic projections result;

Enterprise (Pilot)			1 Row	1 Row		Gross Margin Total £
	Row L (m)	Row W (m)	M2	Ha		1 Row
Soft Fruit (Raspberries)	49	1	49	0.0049		**£126.02**
Soft Fruit (Strawberries)	49	1	49	0.0049		**£56.40**
Viticulture	49	1	49	0.0049		**£98.92**
Salads (Lettuce)	49	1.5	73.5	0.00735		**£49.61**
Herbs (Camelina)	49	1.5	73.5	0.00735		**£3.25**

Hockerton infrastructure adaptation for agrivoltaics

Lettuce salad crops and soft fruit (raspberries/strawberries) would need no or little adaptation of the PV array system to integrate an agrovoltaic system.

Vines would need support infrastructure to be established as single row trellis between the panels, this could impair or restrict access. This pilot project is an ideal opportunity to test and trial the integration of viticulture with PV as an agrovoltaic system.

Design and layout

The area for PV 50kW AC system has been revised from Location (A) shown in red to the new adjacent field location (B) shown in green, with the site measuring approximately 50m by 20m as in the schematics below.

Location A (no longer being used)

Location B - revised Agrovoltiac trial now sited in the field east of the track to the wind turbine at the northern end of the Wyton Lodge Farm field (in red) as depicted by the green and red demarked area in figures below :

PV Layout

Assuming the PV panels are JAM54S30-410/MR (v3) from JA Solar Holdings Co., Ltd. Size 1722 1134mm with area ~ 2m2, with a capacity assumed at 50kW AC = 67kW DC.

Each panel is 410W so 67kW operates as 164 panels (67 240W) which occupies an area of 328m2 for the panels only.

Two panels in portrait are 3.464m (ie 1.722 +1.722 + 0.02 = 3.464 or two panels in portrait with 20mm gap). Panels in portrait mode but with two stacked on each other. This would create a block of panels. A row would have 41 x 2 panels equalling 82 panels in the block. Two blocks results in 164 panels.

The panel orientation runs east- west and the panels to be in portrait north south or the depth of the row.

Area calculations

Row length of panels are ((1.134 + 0.02) x 41) = 47.314m (20mm spaces but There could be different spaces depending on design). Panels they are parallel to ground – this will probably not be the case as they will be tilted up to face the south – however the ground does slope to the south.

The actual used length of the two rows are 49.1m long, allowing 2.7m for access.

It is recommended that you leave a 3m alley at back of the row block for access and 5m in the middle and front of the row blocks to reflect standard spacing the length north south will be 3 + 3.44 +5 +3.44 + 5= 19.88m

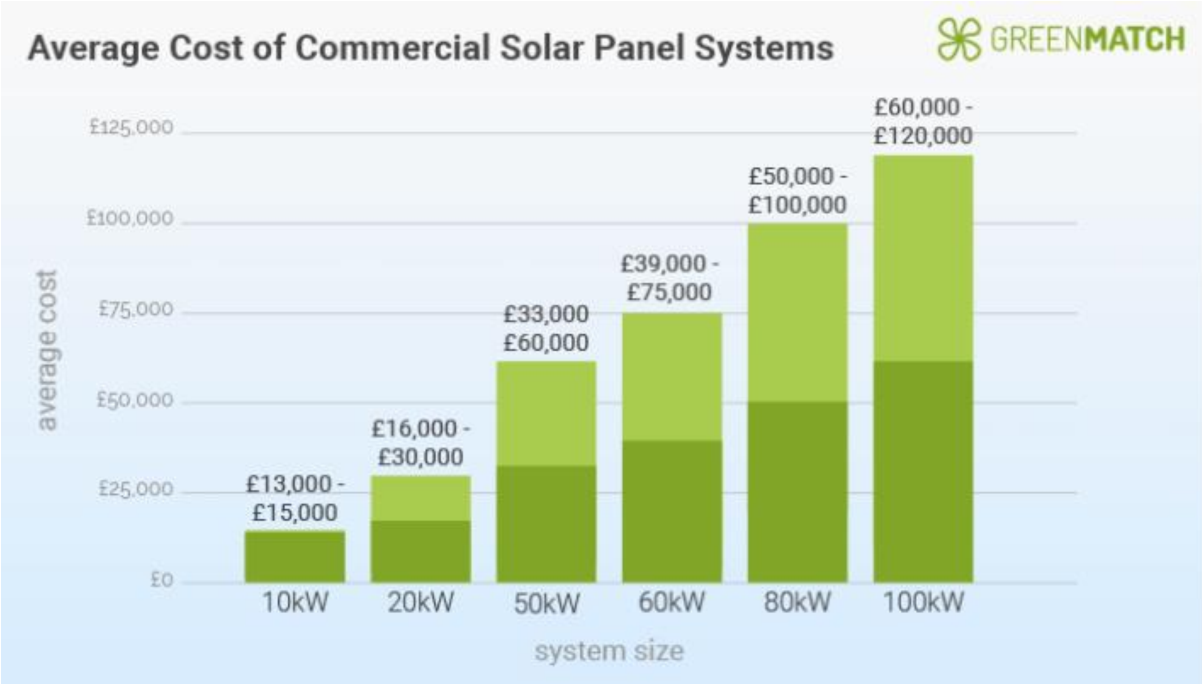
The fence will need to be low enough not to impact on panels light access

The approximate area of agrovoltaic plot is 50m x 19.88m = 0.99ha or 0.24 acres or 994m^2

Capital costs (commercial)

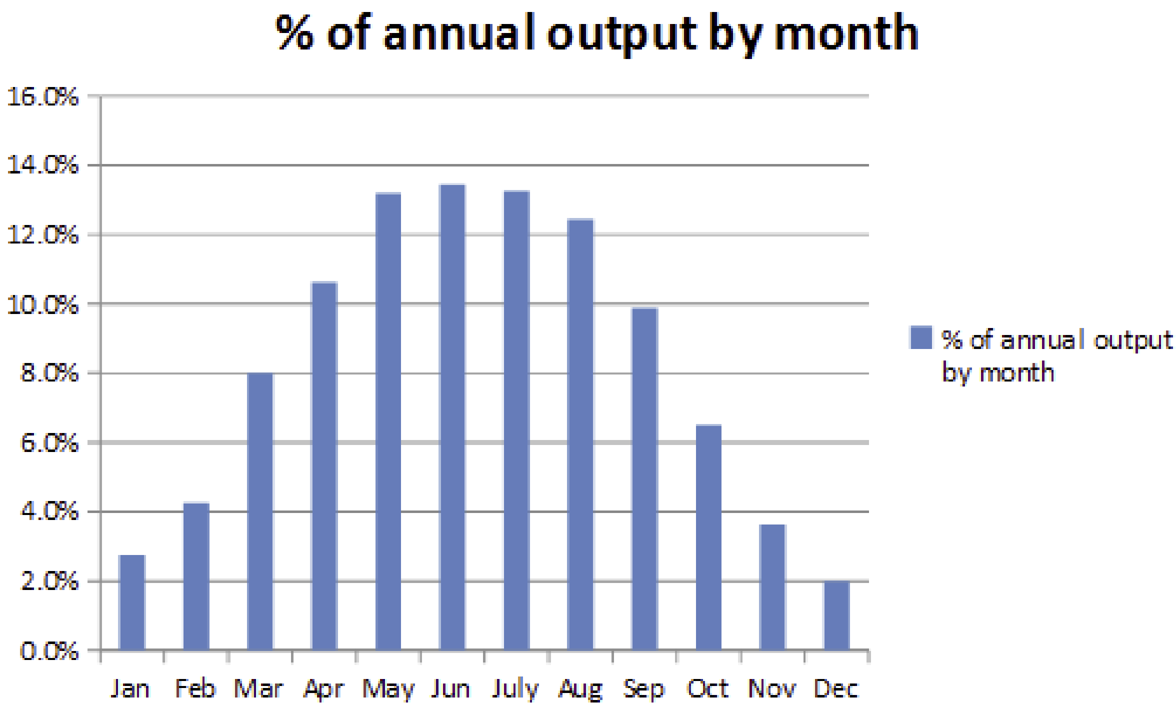
For the installation of a commercial ground mounted PV system where an agrovoltaic approach can be integrated, the typical capital costs for a 50kW array will be in the region of £1,000/kW, so c £50,000.

Greenmatch publish figures for a range of different installation sizes. Athey report that a 50Kw array would cost between £33,000 - £60,000 depending on layout, site and connections.



Energy generation and income potential

A 50 kW solar system typically produces around 46,342.73 kWh annually. This will be influenced by location, any shading and weather conditions. The generation profile in the East Midlands is shown below;



Revenue from Electricity export / sales to the grid or the community (or savings from on site use) should increase as energy prices rise. At present (late 2024), this price increase is around 7% to 9% each year (according to DECC).

Loss Factor	System Size	Annual Irradiance	Shade Factor	Annual Energy Output
0.8 x	50000 kW x	913 x	1 =	36,520 kWh/yr

Income is subject to the Smart Export Guarantee (SEG) payments which are guaranteed by the Government to increase in line with inflation.

Smart Export Guarantee (SEG) rates vary by supplier and tariff, and can range from 1p to 40p per kWh. The amount you earn depends on several factors, including:

- **Tariff**: Whether you choose a fixed or variable tariff, and if it's bundled or unbundled
- **Electricity production**: How much electricity your solar panels produce
- **Electricity exported**: How much of that electricity you export to the grid

The following table shows the accumulated earnings over the next 1, 5, 10 and 25 years for a typical 50KW array

Fuel savings are based upon you using 100% of the electricity you generate at an electricity pricing of 26.0 pence per unit.

SEG payments are based on feeding all to the National Grid based on 11.0 pence per unit.

The annual CO_2 saving of 19,246 kg is based upon 0.529kgCO2/kWh

Year	Fuel Savings	SEG	Carbon Savings (kg)
1	£9,130	£4,017	19,246
5	£53,547	£23,561	94,457
10	£132,176	£58,158	184,602
25	£666,123	£293,094	431,095

Site Rental

The site for the PV agrovoltic project is based on a 6% of revenue model. Assuming a 5 year electricity export sale value with an average yield of £4.7K/yr (year 1-5) and c. £11.7k (year 5-25 incl price inflation @ 7-9%/yr). With a 6% of revenue for site rental the income to the land owner will range between £282 /yr to £702/yr.

Revenue from the agricultural activity needs to be added to this at c £3 - £7.50 (based on 6% of £50-£126/yr).

Cropping considerations

Lettuce salad crops

Improving soil conditions with additions of compost would significantly improve the potential for salad crops. This could easily be achieved by creating 1.25m wide beds and spreading compost via a rear discharge spreader fitted with doors to create a windrow.

Grass strips immediately adjacent to the cropping area (under the panels) risks the build up of aphids *Aphidoidea* spp (above ground) or wireworm *Agrypnus* spp. & leather jackets Tipula spp (below ground) and slugs which can migrate into the crop and cause crop damage. This may limit crop production choices. Eliminating 'grass' and planting legumes and wildflowers will help lessen this risk as grasses are the main host.

The addition of water harvesting from solar panels would be beneficial with regard to reducing irrigation requirements

Raspberry soft fruit

For soft fruit (Raspberries) depending on variety and vigour, there may be a need to provide support structures (posts/wires/trellis). The pruning management of raspberries (and other berry fruit) to manage crop height can be used to minimise and overshading of solar PV and to allow access with machinery.

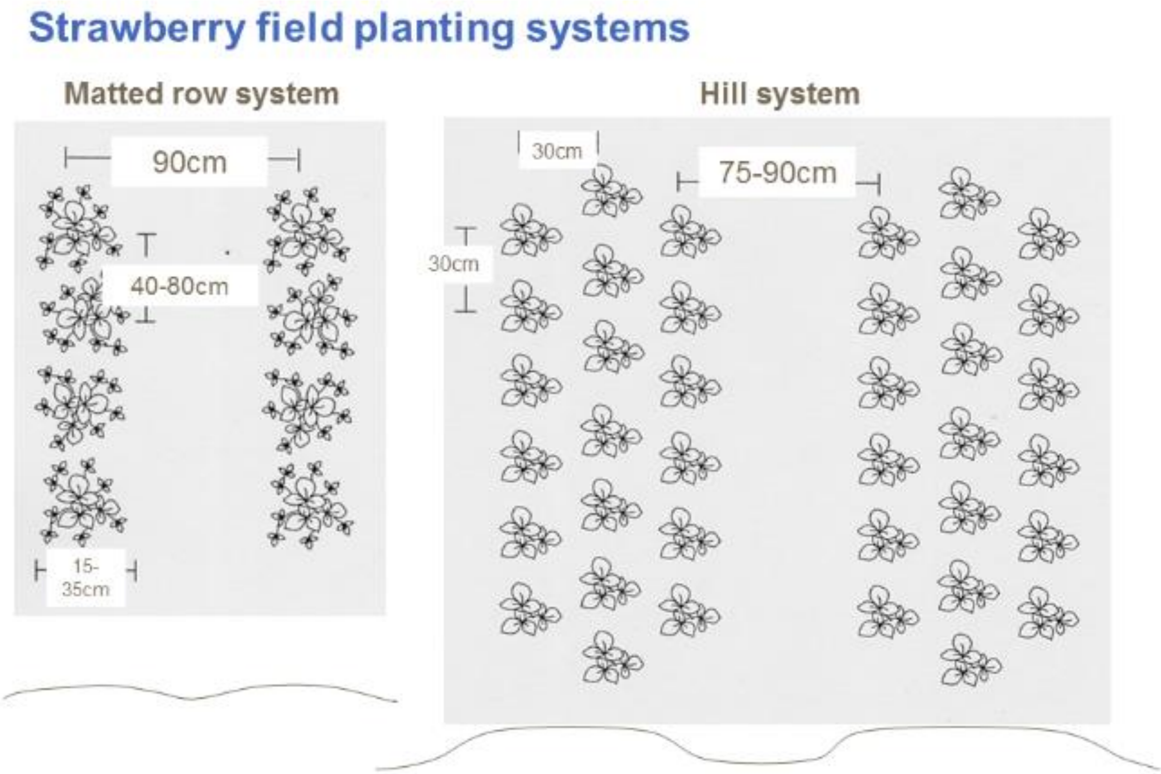
Raspberry support wires with intermediate posts in an agrovoltaic system

Source https://biooekonomie.de/en/news/agri-voltaics-sustainable-fruit-cultivation

Harvesting will most likely be by hand. Raspberry can be harvested and sold fresh. There is also potential for post harvest crop processing (freezing, drying, juicing, jam making etc) which can use significant amounts of energy. There would be good synergies for direct sales of electricity from the solar PV in the agrovoltaic system to the agricultural production element for processing. There would also be a good case for using electrically powered machinery/ harvesters/ cultivators etc if direct sales of electricity from the solar PV in the agrovoltaic system were available.

Strawberry soft fruit

For field grown strawberries, two main production systems are practiced with; the hill- and matted-row system (depicted below). Each requires different planting densities and cultivation techniques. With the space / access restrictions imposed by the PV array, an amalgam of the Matted row/Hill systems based on a 1m wide bed and 3 rows of strawberries is probably best suited, so as to provide 4 year production before plant replacement.



Strawberry plants grown using the hill system are planted more densely to produce high yields and remain viable for only a couple of years before plants need replacing. A typical planting density for hill production is 50,000 plants/ha in single rows or 75,000 plants/ha as a double or three row set. More prolific varieties are spaced further apart


Plastic ‘hills’ ready for planting


New planting in plastic covered hills

Matted row production allows the mother and daughter plants to grow side by side with plants trained to run in narrow rows. Grown over a two year production cycle, spacings are less dense at around 35,000–40,000 plants/ha. Matted-row production, although less intensive and lower yielding, is lower cost and is commonly practiced where hill production is not possible, particularly in cooler climates. Seasons are extended by the use of day neutral types in warmer climates.

One option would be to grow strawberries using raised bed ‘table top’ systems i.e using rows of straw bales between the PV rows, topped with compost/growing medium and plastic. This could help reduce pest pressure from grass insects and improve the ability to pick.
Plants can be grown in bags or under plastic film filled with the desired soil mix or substrate which are then placed on top of the ground or bales at planting densities of 12 plants per m2 (120,000/ha). When strawberries are grown in bags/under plastic film, soil born pests such as nematodes and slugs are more easily controlled in this relatively closed environment, through the effective use of natural parasites and crop management approaches.


Raised table top system in polytunnel

Alternatively, strawberries can be grown through landscape fabric on mounded beds (this would also help manage water runoff and mitigate flood issues). In the UK most strawberry field crops are mulched, either with straw or with plastic /fabric to aid weed control, conserve moisture, to help reduce contamination by keeping the fruit off the soil surface (fruit is cleaner) and bring forward harvest.

Strawberries grown through plastic film

Strawberries would require irrigation. Using water harvesting techniques from the PV arrays as described later in this report, could feed drip irrigation systems to partly meet this demand.

Strawberry plants will last 4 years before they need to be replaced but in commercial situation usually just kept for 2 years as yield and quality decline sharply in year 3.

Viticulture

For viticulture there will be a need to provide support structures (posts/wires/) for the vines. The pruning management is important to manage crop height and density to minimise and overshading of solar PV and to allow access with machinery. Normal vineyard layouts in the UK use post and wire systems as shown below.

Traditional post and wire systems can be adapted to provide single post and wire support centrally down each panel alley as depicted below

Consideration will need to be given to harvesting methods. This can be done by hand at small scale.

If the agrivoltaics viticulture system is developed for wider adoption, utilising of mechanical harvesting would be possible as the machinery pictured below has a maximum working width of 3.3m (10' 3") and a maximum crop clearance of 2.97m https://agriculture.newholland.com/en-gb/europe/products/grape-harvesters/braud-9090x-grape-harvester

11 Recommendations for working with local farmers and solar developers to highlight the potential of agrivoltaics

The expansion of renewable energies can intensify competition for different land use and in some cases lead to social controversy and resistance. Many farmers and land owners remain conflicted between the need to produce food, conserve natural assets and improve biodiversity with the imperative to generate income – with Solar being a solid income stream.

The challenge is for land owners and solar developers/operators to move beyond the binary land use choices of energy vs food and to adopt multi-functional land use approaches such as agrivoltaics where multiple, integrated land use systems deliver multiple benefits (energy, food, biodiversity etc) whilst simultaneously progressing towards a low carbon economy which is more resilient to challenges of climate change. To strengthen the social acceptance of agrivoltaics, such concepts which include public participation are needed. Below are some of the key factors for success when engaging the local farmers and landowners;

Factors for success

- Fully understand the aspirations, aims, objectives and limitations of local land owners and managers - with respect to integration of agricultural and energy operations
- Provide clear models of production, income, costs and profits from agricultual, solar and agrovoltaic comparative systems
- Clearly articulate the issues relating to access, risks, sustainability/biodiversity
- Have answers to and articulate the implication of agrovoltaic systems on land status (agricultural/non agricultural) and Tax implications, especially with regard to Inheritance Tax Relief (IHT) and Business Property Relief (BPR) (see next section)
- Food production commitment under agrivoltaic systems.
- Demonstrate opportunities for local food security
- Demonstrate opportunities for local employment and economic growth
- When constructing and operating agrivoltaic systems, give preference to local farms, energy cooperatives or regional investors.
- Limit the size and distribution of facilities and take into account local site characteristics and societal preferences.

- Locate agrivoltaic systems in locations where dual use of land will increase agricultural yields and protect crops

12 Recommendations for wider agrivoltaics adoption

To overcome regular operational, planning and land use choices between energy and food and in order for wider adoption of multi-functional land use approaches such as agrivoltaics, the following recommendations are set out below;

Factors for success

- Fully understand the aspirations, aims, objectives and limitations of local land owners and managers - with respect to integration of agricultural and energy operations
- Provide clear models of production, income, costs and profits from agricultual, solar and agrovoltaic comparative systems
- Clearly articulate the issues relating to access, risks, sustainability/biodiversity
- Have answers to and articulate the implication of agrovoltaic systems on land status (agricultural/non agricultural) and Tax implications, especially with regard to Inheritance Tax Relief (IHT) and Business Property Relief (BPR) (see next section)
- Food production commitment under agrivoltaic systems.
- Demonstrate opportunities for local food security
- Demonstrate opportunities for local employment and economic growth
- When constructing and operating agrivoltaic systems, give preference to local farms, energy cooperatives or regional investors.
- Limit the size and distribution of facilities and take into account local site characteristics and societal preferences.

Land use in England

The 2024 DEFRA census shows that the total area used for agriculture is 8.7m ha or 67% of the total area of the country. The Cropping area accounts for 57% and pasture 38% of land used for agriculture in England. Between 2023 and 2024 there was a 6.7% drop is cropped area (as a result of poor weather and SFI uptake) to 3.5m ha. The shift being 581,000ha of uncropped land of which 276,000 ha was bare fallow and 305,000ha being managed under environmental schemes.

There has ben a further 3.2% fall in horticulture area down to 113,000ha in England. The area of ground mounted solar PV is now 7,300 ha, with c 40% where there is some form (i.e grazing) of agricultural activity. Therefore, with solar only occupying 0.084% of agricultural land in the UK, there is considerable scope to expand the role out of solar by integrating with agricultural activity as agrivoltaic systems.

Tax and Inheritance tax issues

Solar farms have become a particularly attractive option in recent years as land owners look to diversify and increase income streams. However, turning land over to solar can have significant Inheritance Tax (IHT) consequences which must be considered at the earliest stages of the project. Sensible tax planning upfront can dictate major structural changes to the overall project and ensure that opportunities to minimise a later IHT liability are not lost. Leaving this until the solar farm is operational is likely to be too late...

The key issue

The main problem from an IHT perspective is that a solar farm will usually take land out of agricultural use (on which Agricultural Property Relief (APR) would likely have been available) and also out of the farming trading business (which may otherwise have qualified for Business Property Relief (BPR)) and instead turns it into an investment asset.

With an agrovoltaic system It may be possible to retain the right to grow crops/graze animals around the solar panels and to claim direct / Environmental payments, but this may result in a lower rent being offered by the solar operators.

The following IHT reliefs would be available :

Agricultural property relief (APR) – *TBC% relief on the agricultural value of the land

Business property relief (BPR) – *TBC % relief on the value of the land

- **With recent changes to the status of IHT & BPR in the October 2024 autumn budget, specialist tax advice is recommended prior to proceeding with the project.**

If the land subject to the lease is no longer farmed and is let with exclusive access to a solar farm, then APR will be lost. If the land owner maintains the right to grow crops/graze animals as with an agrovoltaic system, APR may be available on some of the land at its agricultural value.

When considering whether BPR would be available, you would have to look at the business as a whole. BPR could be available on the full value of all the land if it is run as part of a larger trading business, and the rental income formed a small part of the total income.

Solar farm development in-house

Although less common, land owners undertaking the development of the solar farm themselves may provide the opportunity to claim BPR in relation to the solar business.

While the complexities of such a structure are beyond the scope of this report, an example would be for the landowner to lease the land on which the solar farm/agrovoltaic operation will be built to a partnership (LLP) for a peppercorn rent and take fixed drawings from that partnership equivalent to the rental payments had the lease been granted on arm's length terms. The landowner brings the land to the partnership and the developer the solar development expertise. The partnership develops the solar agrovoltaic enterprise and holds the contracts with the grid. There should then be an opportunity after at least two years of ownership for the partnership interest to be transferred to the next generation, either outright or in trust, and BPR claimed as and when a taxable event arises.

Conclusion

A solar farm development can have a significant impact on the IHT treatment of the land and so this should be considered early on in the process. Dual use under an agriovoltaic system can potentially help maintain IHT and BPR. Detailed tax advice may be required and new ownership structures put in place prior to signing the option agreement with the solar developer or undertaking the development, so plenty of time should be allowed for this and the cost included in the overall project budget

13 Recommendations on infrastructure adaptation and design suggestions for scaling up in a larger phase 2 II.

Integrating cropping into existing solar farms

Integrating cropping into existing solar farms, known as agrovoltaics, can optimize land use by combining solar energy production with agricultural activities. Here are key steps and considerations for successfully integrating cropping into existing solar farms in the UK:

1. Stakeholder aspirations

- **Land owner**: Fully understand the aspirations, aims, objectives and limitations of land owners and managers – with respect to integration of agricultural and energy operations, access, risks, economics, sustainability/biodiversity and Tax implications.
- **PV developer/operator** : Fully understand the aims, objectives and limitations of PV developers/operators – with respect to integration of energy and agricultural activity, access, maintenance, security and other risks, economics, sustainability/biodiversity and Tax implications.

2. Site Assessment

- **Solar Panel Configuration**: Evaluate the layout and height of the existing solar panels. Determine if there is sufficient space and appropriate shading patterns to accommodate crops.
- **Soil Quality**: Assess soil health, fertility, and drainage. This information will help in selecting suitable crops and planning soil management practices.
- **Water Availability**: Ensure there is adequate water supply for irrigation, as the microclimate under solar panels may require adjustments in watering practices.

3. Crop Selection

- **Shade-Tolerant Crops**: Choose crops that can thrive under partial shade, such as leafy greens (lettuce, spinach), root vegetables (carrots, beets), and certain herbs (parsley, mint).
- **Crop Rotation**: Plan for crop rotation to maintain soil health and prevent pest and disease buildup.

- **Seasonal Crops**: Consider planting crops that are well-suited to the seasonal variations in light and temperature.

4. Adaptation of Farming Practices

- **Irrigation Systems**: Install efficient irrigation systems, such as drip irrigation, to optimize water use under the shaded conditions created by the solar panels.
- **Machinery Access**: Ensure there is sufficient space for farm machinery to operate without damaging the solar panels. This may require adjustments in panel height or spacing.
- **Soil Management**: Implement soil management practices that enhance soil fertility and structure, such as adding organic matter and using cover crops.

5. Structural Adjustments

- **Panel Height**: If possible, adjust the height of the solar panels to provide more space for crops to grow and for machinery to move underneath.
- **Movable Panels**: Consider using adjustable or tilting solar panels that can be moved to optimize sunlight for both crops and energy production.

6. Monitoring and Management

- **Microclimate Monitoring**: Continuously monitor the microclimatic conditions under the solar panels, including temperature, humidity, and light levels. Adjust farming practices based on these observations.
- **Crop Health Monitoring**: Regularly check for signs of stress or disease in crops and take corrective actions as needed.

7. Economic and Environmental Considerations

- **Economic Viability**: Analyze the cost-benefit ratio of integrating cropping into the solar farm. Consider potential additional income from crop production and any cost savings from improved land use efficiency.
- **Environmental Impact**: Evaluate the environmental benefits, such as improved biodiversity, soil health, and water conservation, and consider these in the overall sustainability assessment of the project.

8. Case Studies and Best Practices

- **Learn from Existing Projects**: Review successful agrovoltaic projects for best practices and lessons learned. For example, the *Heggelbach agrovoltaic* project in Germany integrates various crops under solar panels and provides valuable insights into optimal designs and practices.

9. Community and Regulatory Engagement

- **Community Involvement**: Engage with local communities and stakeholders to gain support and address any concerns about changes to land use.
- **Regulatory Compliance**: Ensure the project complies with local regulations and land use policies. This may include obtaining necessary permits and adhering to environmental guidelines.

Integrating cropping into existing solar farms can enhance the sustainability and productivity of the land. By carefully selecting suitable crops, adapting farming practices, and continuously monitoring and managing the system, farmers can successfully combine agriculture with solar energy production, benefiting both food and energy security.

Coverage rate

The coverage rate corresponds to the percentage of the surface area occupied by photovoltaic panels in relation to the total surface area of the agricultural plot.

For example, for a plot of 10,000 m^2 (1 hectare), an area of 3,500 m^2 of photovoltaic panels will give a coverage rate of 35%.

In France where the agrivoltaic decree of April 8, 2024, the regulatory framework authorizes a “coverage rate” of less than 40% for agrivoltaic projects greater than 10 MWc of installed power (i.e. an area of around 12 hectares, depending on the technologies); does not set limits for installations below 10 MWc.

Now, this is a fundamental factor for anticipating the agricultural virtue of an agrivoltaic project, because:

too high a coverage rate would not allow enough light to pass through to the crop below and would degrade agricultural yield;

too low a coverage rate would not provide the climate protection expected as an agronomic service.

Agronomic management of photovoltaic panels is the way to balance these contradictory options: it allows maintaining a "coverage rate" capable of protecting against climatic hazards, while allowing light to pass through when the plant needs it.

Ultimately, it is essential to find a balance to preserve both crops and energy production

Technical considerations for agrovoltaic

Implementing agrovoltaic systems involves various technical considerations to ensure the effective integration of solar panels with agricultural activities. Here are the key technical factors:

Design and Layout

1. **Panel Configuration**: The arrangement and orientation of solar panels must balance energy production and agricultural productivity. Common configurations include fixed-tilt, adjustable-tilt, and vertical installations. The height and spacing of panels should accommodate machinery and crop requirements.
2. **Shading Patterns**: Understanding and managing shading is crucial. Panels should be arranged to provide optimal shade without excessively blocking sunlight needed for crop growth. Computational modelling can help simulate and optimize shading patterns.
3. **Dual-Use Efficiency**: The design should ensure that both agriculture and energy production are optimized. This might involve innovative solutions like bifacial panels, which capture light on both sides, increasing efficiency and providing more diffused light for crops.

Crop Selection and Compatibility

1. **Crop Types**: Different crops have varying light and shade requirements. Crops that can tolerate partial shade, such as leafy greens, certain root vegetables, and berries, are generally more suitable for agrovoltaic systems.
2. **Growth Cycles**: The planting and harvesting cycles of selected crops should align with the energy production cycles of the solar panels to maximize the efficiency of both systems.

Structural Engineering

1. **Mounting Systems**: The mounting structures for solar panels need to be robust and designed to withstand local weather conditions, including wind, snow, and rain. Elevated mounting systems can facilitate agricultural operations beneath the panels.
2. **Foundation**: The foundation for the mounting structures should minimally impact the soil and agricultural activities. Options include ground screws, concrete footings, or ballasted systems.

Electrical Considerations

1. **Grid Connection**: Ensuring a reliable connection to the grid is essential for energy distribution. This includes considering the capacity of local grid infrastructure and potential upgrades needed to handle additional power.
2. **Energy Storage**: Incorporating energy storage systems, such as batteries, can help manage the intermittency of solar power and provide a steady energy supply for farm operations and grid feed-in.
3. **Inverters and Cabling**: The selection and installation of inverters and cabling should optimize efficiency and minimize energy loss. Proper insulation and protection against environmental factors are necessary.

Environmental and Agronomic Impact

1. **Microclimate Management**: Solar panels can create microclimates by altering temperature, humidity, and wind patterns. Understanding these changes and their impact on crop growth is essential for successful agrovoltaic implementation.
2. **Soil Health**: The shading and physical presence of panels can affect soil moisture and temperature. Monitoring and managing soil health through appropriate agricultural practices and technologies is necessary.

3. **Water Management**: Irrigation systems might need to be adapted to account for changes in rainfall distribution and water requirements due to shading. Drip irrigation systems can be effective in such setups.

Maintenance and Operation

1. **Panel Cleaning**: Regular cleaning of solar panels is necessary to maintain efficiency. Automated cleaning systems or easy-access designs can reduce maintenance efforts.

2. **Agricultural Operations**: The design should facilitate routine farming activities, including planting, harvesting, and pest management. This might involve considering the types and sizes of machinery used.

Monitoring and Control Systems

1. **Performance Monitoring**: Implementing systems to monitor the performance of both the solar panels and the crops can provide valuable data for optimizing operations and addressing issues promptly.

2. **Automation and Smart Technologies**: Using smart technologies and automation for both solar and agricultural operations can enhance efficiency and productivity. This includes automated tracking systems for panels and precision agriculture technologies.

Regulatory and Safety Compliance

1. **Safety Standards**: Ensuring compliance with electrical and structural safety standards is essential to protect workers and equipment.

2. **Regulatory Approvals**: Navigating the regulatory landscape, including planning permissions and environmental impact assessments, is necessary for the legal operation of agrovoltaic systems.

Future-Proofing and Scalability

1. **Scalability**: Designing systems with scalability in mind allows for future expansion and adaptation as technology and practices evolve.

2. **Technology Integration**: Staying updated with advancements in solar technology, such as more efficient panels and better storage solutions, can improve long-term viability.

By addressing these technical considerations, agrovoltaic systems can be effectively integrated into agricultural settings, maximizing both energy production and crop yield while ensuring sustainability and operational efficiency.

Agrovoltaic technical Challenges

Solar farms in the UK face several technical challenges that can affect their efficiency, reliability, and overall performance. Here are some key technical problems and considerations:

1. Weather Variability

- **Cloud Cover and Rain**: The UK's often cloudy and rainy weather can significantly reduce solar energy generation compared to sunnier regions.
- **Seasonal Variations**: The variation in sunlight between summer and winter months leads to inconsistent energy production, requiring robust energy storage solutions or complementary energy sources.

2. Grid Integration

- **Grid Capacity**: The existing electrical grid may struggle to accommodate the variable output from solar farms, especially in rural areas where the grid infrastructure might be less robust.
- **Grid Stability**: Fluctuations in solar power generation can cause stability issues in the grid, necessitating advanced grid management and storage solutions to balance supply and demand.

3. Energy Storage

- **Battery Storage Costs**: Effective energy storage systems are essential to balance the intermittent nature of solar power, but high costs and limited lifespan of batteries can be a barrier.
- **Efficiency**: Current storage technologies may have limitations in efficiency and capacity, impacting the overall feasibility of solar farms.

4. Land and Environmental Issues

- **Land Availability**: Suitable land for solar farms can be limited, and there may be competition with agricultural land use or conservation areas.
- **Environmental Impact**: The installation and operation of solar farms can impact local ecosystems, wildlife habitats, and biodiversity.

5. Maintenance and Reliability

- **Panel Degradation**: Solar panels gradually lose efficiency over time due to factors such as UV exposure, temperature fluctuations, and physical damage.

- **Cleaning and Maintenance**: Regular cleaning and maintenance are necessary to keep panels operating efficiently, which can be labor-intensive and costly, especially in remote or large installations.

6. Technical Failures

- **Inverter Issues**: Inverters, which convert DC power from the panels to AC power for the grid, are critical components that can fail and require regular maintenance.
- **Electrical Failures**: Wiring issues, connections, and other electrical components can suffer from wear and tear, leading to potential outages or reduced efficiency.

7. Regulatory and Policy Challenges

- **Planning Permission**: Securing planning permission for solar farms can be a lengthy and complex process, with potential objections from local communities and stakeholders.
- **Subsidy Changes**: Changes in government policies and subsidies for renewable energy can affect the financial viability of solar farms.

8. Technological Advancements

- **Integration of New Technologies**: Keeping up with rapid advancements in solar technology, such as higher efficiency panels or new storage solutions, requires ongoing investment and potential retrofitting of existing farms.
- **Smart Grids**: Implementing smart grid technologies to better manage the integration of solar power can be technically challenging and expensive.

Solutions and Mitigation Strategies

1. **Advanced Energy Storage**: Investing in high-capacity, long-duration energy storage systems, such as lithium-ion batteries or emerging technologies like flow batteries, to manage energy supply during low-production periods.
2. **Hybrid Systems**: Combining solar with other renewable sources like wind or bioenergy to provide a more stable and reliable power supply.
3. **Grid Modernization**: Upgrading the electrical grid infrastructure to handle increased renewable energy inputs and implementing smart grid technologies for better energy management.
4. **Regular Maintenance**: Implementing predictive maintenance and monitoring systems to detect and address issues before they lead to significant downtime or efficiency losses.

5. **Policy Support**: Engaging with policymakers to ensure stable and supportive regulatory frameworks that encourage investment in solar energy and infrastructure.
6. **Community Engagement**: Working with local communities to address concerns, secure support, and potentially share benefits, such as through community-owned solar projects.
7. **Research and Development**: Continuously investing in R&D to improve solar panel efficiency, durability, and overall system performance.

By addressing these technical problems through innovation, investment, and collaboration, the UK can enhance the efficiency and reliability of its solar farms, contributing to its renewable energy goals

14 Opportunities for agricultural and grant based funding support

Public funding

Innovate UK, part of **UK Research and Innovation**, is the UK's innovation agency. Our mission is to help companies to grow through their development and commercialisation of new products, processes and services, supported by an outstanding innovation ecosystem that is agile, inclusive and easy to navigate

https://www.ukri.org/councils/innovate-uk/

There is strategic funding available through UKRI towards tackling energy network challenges to achieve net zero https://www.ukri.org/news/tackling-energy-network-challenges-to-achieve-net-zero/

Smaller PV agrovoltaic systems may be fundable through the **DEFRA** the "Improving Farm Productivity grant" https://www.gov.uk/government/publications/improving-farm-productivity-grant-round-2-applicant-guidance/about-the-improving-farm-productivity-grant-round-2-who-can-apply-and-what-the-grant-can-pay-for

If an application is for solar PV equipment only, the minimum grant you can apply for is £15,000 (25% of £60,000). The maximum grant is £100,000 per applicant business. If you want to apply for both a Solar grant and a Farm Productivity grant, you must submit 2 separate applications. The maximum grant across all submitted applications is £500,000 in total, per applicant business.

Banks

Bank financing is probably the most popular route for landowners and developers as it relieves the initial burden. Plus, the financing comes from a trusted source that is unlikely to falter during the construction process. And when you're financing renewable projects, reliability and communication are both key.

Several UK banks currently offer investments for new renewable energy projects. This includes solar PV, battery storage plants, and wind farm projects. A summary is set out below;

Santander

Santander has been supporting low-carbon projects since 2004. They support landowner-developers during the construction phase and operational phase of a project's life.

They currently offer: Senior debt facilities sized over the operational period with up to 10 years of legal maturity.

Minimised set-up costs by using trusted advisors and liaising closely with treasury experts.

Participation in syndicated facilities for larger projects.

A centralised portfolio management team.

These solutions are offered to UK-based projects and can significantly reduce the initial financial burden of a project.

The co-operative bank

The Renewable Energy Funding Scheme offered by the **Cooperative Bank** allows you to borrow money for investing in energy technologies. It's geared more toward projects that are looking to improve the efficiency of an existing business. So, it's worth bearing that in mind before diving in. They currently offer:

Up to 100% funding for renewable energy projects to boost the sustainability of your business.

The Bank of England Base Rate plus an agreed interest margin (this is worth investigating beforehand!).

Loans from £25,000 to £250,000, depending on the scale of your project.

Arrangement fees at 1% of the total loan.

70% of the market value in funding depending on the sector.

It's worth noting that the amounts offered here likely won't be enough to cover large-capacity projects. The maximum cap of £250,000 could be used alongside other funding to construct a wind farm. But in terms of financing wind power projects in full, it's probably not going to be enough.

Clydesdale Bank

If you're looking for project-based lending solutions for a wind power project, Clydesdale Bank is another financing option. Their specialist team of 4 is based in Scotland, but they operate on a UK-wide basis. If you're wondering who they help, their current customers range from SME developers to landowners, farmers, and private equity firms. They currently offer:

Development and operational stage finance.

Execution and portfolio management.

If you're financing renewable projects with high initial investments, **HSBC** is another bank to look at. They offer the Green SME Fund which is designed to make sustainable solutions more accessible for businesses. They currently offer:

1% cashback on the loan value (for loans of £25,000 and below, a Representative 7.1% APR applies).

Loans to SMEs with a group annual turnover of up to £25 million. The maximum loan value is up to £25 million but can be as low as £1,000.

90% of the loan proceeds must be applied in alignment with one of the categories in the Green SME Fund Eligibility Guide.

Although you'll need to jump through the Eligibility Guide's hoops, the potential maximum loans here are worth investigating.

Barclays offers a Green Loan to farmers who are thinking of diversifying their income and want to sell surplus energy back to the grid. They currently offer:

A dedicated team of Energy Relationship Directors to help guide you on your renewable energy journey.

Loans to help finance eligible green projects.

Agricultural finance to help farmers through challenging markets, sustain their businesses, and grow.

NatWest **Natwest** is another bank that offers dedicated Green Loans to support sustainable businesses in the UK. They currently offer:

Borrowing options from £25,000 with fixed and variable interest rates.

Repayment terms from 3 months up to 25 years.

Capital Repayment Holidays.

A note on bank financing

Although bank financing is incredibly useful if you need to secure an immediate investment, you'll need to consider interest. Virtually no bank will offer financing without some kind of interest to improve their initial ROI. So, before diving in, it's important to consider how interest repayments will factor into your overall financial plan.

Triodos Bank

Triodos is known for providing finance for renewable energy and environmental sector projects. Thus far, they've financed 610 small and large-scale energy projects in the solar, hydro, and wind sectors. They currently offer:

Project and structured finance with loan sizes of up to £20 million.

Construction finance, operating finance, and re-financing.

Long-term senior debt facilities with terms of up to 18 years.

Sterling fixed and variable interest-rate facilities.

Assistance with raising capital.

Triodos Bank is particularly well-known for financing solar projects in the renewable energy sector. They even provided £3 million of new senior debt to bring a solar farm in Shropshire into full community ownership. They also offer: Project and structured finance of up to £20 million. Long-term senior debt facilities with terms of up to 18 years. Sterling fixed and variable interest-rate facilitieshttps://communityenergyengland.org/news/new-finance-from-triodos-bank-brings-solar-farm-into-full-community-ownership

NFU Mutual

If you're financing wind power projects, **NFU Mutual** offers leading installers, finance, and insurers for the job. They currently offer:

Technical experts to identify appropriate solutions for your circumstances.

Accredited installers to prepare a no-cost proposal.

Help with securing finance and insurance.

Ongoing support throughout the investment and construction process to keep everything running smoothly.

If you need it, they can even assess the feasibility of your land and make a formal grid application on your behalf. For landowner-developers worried about balancing too many plates, this can be incredibly beneficial. And if you want to go with a developer, NFU can even help you run a competitive process to narrow options down.

Financing from external investors

With green projects becoming all the rage with global attempts to meet net-zero, you may get decent interest from personal investors. High-net-worth individuals with assets totalling at least £1-2 million are a good starting point for one-on-one investing. But it's also worth looking into crowdfunding and angel personal investors who seek a minority stake in the project. Although all of these options involve splitting a share of the profits, it can help you gather those initial upfront costs.

Aldermore https://www.aldermore.co.uk/business-finance/asset-finance/agriculture/?gad_source=1&gclid=CjwKCAjw9p24BhB_EiwA8ID5Bj1WSjhwEmSY8md44gjZeppxvgyw7Z4sOKaAUoRrJ26adrPpEb_GphoCgqwQAvD_BwE&gclsrc=aw.ds

ESFC Investment Group offer financial models with a minimum contribution of 10%. These companies can get large-scale solar power plants started and offer funding from €50 million. They only offer investments of up to 90% of the project's cost, but the loan term gives you 10 to 20 years to repay. This way, you'd have the chance to get the project up and running (and profitable) before needing to start your repayments.

Better yet, their team of European experts (yep, that's why they quote their costs in Euros) provide the following services:

Financial advisory services, Calculations of project parameters, Models for financial performance, Tailor-made solutions

It’s also worth mentioning that renewables investment manager **NextEnergy Capital** has announced £327 million of new funding for up to 60 solar farms across the UK.

Power purchase agreements

The final option for financing solar projects is a Power Purchase Agreement (PPA). PPAs are essentially an agreement between a seller and a buyer. The seller generates electricity (in this case, the developer/site) and sells it to the buyer at a predetermined rate. These agreements finance large-scale projects and offer long-term cash flow benefits to developers and investors. Parties usually sign the agreements for 10-20 years, and the contract is legally binding.

Although they will provide less profit than other financing options, they’re an excellent way to bypass external investment or bank loans. For most solar projects, a developer will get a PPA set up and will then use it to go to a bank and prove that they’ve secured buyers. This essentially provides security that helps with raising funds for the project (as it proves that it WILL be sold on)

Research and Development (R&D) tax credits

The manufacturing and deployment of renewable technologies including agrovoltaic systems, require a large up-front investment. That’s not new, but with government subsidies drying up and supply-chain uncertainty driving up raw materials costs, uncertainty lies ahead. There is potential to overcome some of these challenges when research and development is fully rewarded by **R&D tax credit relief**. If you're looking for an R&D tax specialist can assist in securing R&D tax relief payment to help fund this initial activity.
https://forrestbrown.co.uk/sectors/renewables/?gad_source=1&gclid=CjwKCAjw9p24BhB_EiwA8ID5BpiDxG6XvAESTOkthHhHkCiROvK1-H4ivouG1uFo2ux1UQYCsgxVWBoCn3MQAvD_BwE

Annex 1

Terms of Reference

Stephen Briggs Terms of reference from Deliverables in quote.

Desk based research and analysis to evaluate and recommend potential cropping systems

Provide case study examples of business models utilised with agrivoltaic systems elsewhere.

Work primarily with Luke on the desk-based research and evaluation of potential cropping systems working from sources such as The John Nix handbook for farm management and The Organic Farm Management Handbook and other online sources.

Adapt gross profit analysis from source material to make informed recommendations of the most promising crops/cropping systems when distributed between panels with reduced light and cultivated ground. Develop an outline for a business model.

Make recommendations and design suggestions for the field trial at the 80kW site in Hockerton as well as strategic suggestions for scaling up in a larger phase 2.

Recommendations on infrastructure adaptation for agrivoltaics

Analyse feasible design interventions on a 'standard' PV field array (we want to base our system on the layout of the Great North Road solar park which is probably a conventional installation). Summarise opportunities to maximise the yield of the novel ecosystem created to unlock potentially profitable farming opportunities.

Write report section on recommendations for build and cropping in alignment with agricultural and land use policy. Recommendations opportunities for agricultural grant based income support

General support in compiling, writing and formatting the above research for the final report. The goal is to provide a coherent, useful and convincing source material for farmers and Solar Farm managers

Annex 2

SoilBioLab
Specialists in soil testing

T: + 44 (0) 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213 The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England
Company Reg. No: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd

Contact: Luke Justice

Date: 24.07.2024

Sample ID: SBL5730 - Top of site

Soil Chemistry Report

Analysis	Units	Result	Guideline	Low	Optimal	High
pH	(1:2:5)	7.2	5 - 7			
EC ($CaSO_4$)	µS/cm	2820	1900 - 2200			
Organic Matter LOI	%	5.1	4 - 8			

Short Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	10.0	10 - 20			
Potassium	ppm	774	120 - 174			
Magnesium	ppm	358	> 100			
Calcium	ppm	2323	500 - 1250			

Middle Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	11	30 - 100			
Copper	ppm	5.9	1.5 - 8.5			
Zinc	ppm	3.0	1 - 10			
Iron	ppm	424	50 - 100			
Manganese	ppm	11.0	2 - 20			
Sulphur	ppm	8.0	8 - 50			
Boron	ppm	0.3	0.4 - 3.0			

Basic Cation Saturation Ratio

Analysis	Units	Result	Guideline	Low	Optimal	High
Calcium	%	60.8	65 - 85			
Potassium	%	12.5	2 - 7			
Magnesium	%	19.3	10 - 20			
Sodium	%	2.6	0 - 5			
Other	%	4.8	0 - 6			
CEC	meq/100g	20				
Ca/Mg Ratio		9.7	6 - 7			

Long Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Copper	ppm	14.33	< 110			
Zinc	ppm	78.56	< 450			
Iron	ppm	28452.6	< 25000			
Manganese	ppm	892.29	< 2000			
Sulphur	ppm	466.40	< 2000			
Boron	ppm	25.69	0.5 - 4.0			
Molybdenum	ppm	0.35	0.1 - 2.0			
Cadmium	ppm	0.20	< 3			
Nickel	ppm	32.32	< 100			

SoilBioLab
Specialists in soil testing

T: 00 44 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213, The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England
Company Reg. No.: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd

Contact: Luke Justice

Date: 24.07.2024

Sample ID: SBL5730 - Top of site

Soil Carbon Chemistry		
Analysis	Units	Result
Organic Matter - DUMAS	%	1.8
Organic Carbon	%	0.26
Organic Carbon Stock	t/ha	3.1
Total Carbon	%	1.8
Total Carbon Stock	t/ha	27.3
Bulk Density	g/cm3	1.01
C:N Ratio		7
Soil Respiration	mg/kg	55
Microbial Biomass	mg/kg	1240
Total Nitrogen	%	0
Potentially Mineralisable Nitrogen	kg N/ha	37
Active Carbon	mg/kg	544

Soil Microbiology Report

Organism Biomass						
Analysis	Units	Result	Guideline	Low	Optimal	High
Moisture content	%	20	15 - 55			
Active Bacteria	µg/g	20.5	20 - 40			
Total Bacteria	µg/g	673	200 - 400			
Active Fungi	µg/g	1.7	20 - 40			
Total Fungi	µg/g	191	200 - 400			
Hyphal Diameter	µm	2.78	>2.5			

Organism Ratios					
Analysis	Result	Guideline	Low	Optimal	High
Active/Total Bacteria	0.03	0.10 - 1.00			
Active/Total Fungi	0.01	0.10- 1.00			
Active Fungi/Active Bacteria	0.08	1.00 - 2.00			
Total Fungi/Total Bacteria	0.28	1.00 - 2.00			

Protozoa						
Analysis	Units	Result	Guideline	Low	Optimal	High
Flagellates	No/g	5311	> 10000			
Amoebae	No/g	57	> 10000			
Ciliates	No/g	35	50 - 100			

Nematodes						
Analysis	Units	Result	Guideline	Low	Optimal	High
Total Nematodes	No/g	0	10 - 20	Insufficient number to count		
Nematode types	Fungal feeders: %; Bacteria feeders: %; Predators: %; Plant parasitic: %; Juveniles: %					

Mycorrhizal Colonisation						
Analysis	Units	Result	Guideline	Low	Optimal	High
Ectomycorrhizae	%	NA	10 - 50			
Endomycorrhizae	%		10 - 50	Insufficient roots in sample		

Potential Nitrogen in Soil			
Nitrogen (N)	kg/ha	28-56	Potentially cycled for a period of 3-6 months*

*Please note that this value is related to the microbiological activity and is not a chemical measure of nitrogen.

SoilBioLab
Specialists in soil testing

T: + 44 (0) 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213 The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England

Company Reg. No: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd

Contact: Luke Justice

Date: 24.07.2024

Sample ID: SBL5731 - Middle of site

Soil Chemistry Report

Analysis	Units	Result	Guideline	Low	Optimal	High
pH	(1:2:5)	7.6	5 - 7			
EC ($CaSO_4$)	µS/cm	2130	1900 - 2200			
Organic Matter LOI	%	5.3	4 - 8			

Short Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	32.0	10 - 20			
Potassium	ppm	461	120 - 174			
Magnesium	ppm	415	> 100			
Calcium	ppm	2808	500 - 1250			

Middle Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	145	30 - 100			
Copper	ppm	2.5	1.5 - 8.5			
Zinc	ppm	6.6	1 - 10			
Iron	ppm	409	50 - 100			
Manganese	ppm	106.0	2 - 20			
Sulphur	ppm	45.0	8 - 50			
Boron	ppm	1.4	0.4 - 3.0			

Basic Cation Saturation Ratio

Analysis	Units	Result	Guideline	Low	Optimal	High
Calcium	%	69.4	65 - 85			
Potassium	%	7.6	2 - 7			
Magnesium	%	21.2	10 - 20			
Sodium	%	1.7	0 - 5			
Other	%	0.1	0 - 6			
CEC	meq/100g	19.1				
Ca/Mg Ratio		6.3	6 - 7			

Long Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Copper	ppm	17.09	< 110			
Zinc	ppm	89.78	< 450			
Iron	ppm	29953.0	< 25000			
Manganese	ppm	1114.52	< 2000			

Sulphur	ppm	374.23	< 2000	
Boron	ppm	27.30	0.5 - 4.0	
Molybdenum	ppm	0.56	0.1 - 2.0	
Cadmium	ppm	0.20	< 3	
Nickel	ppm	34.31	< 100	

SoilBioLab
Specialists in soil testing

T: 00 44 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213, The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England
Company Reg. No.: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd
Contact: Luke Justice
Date: 24.07.2024
Sample ID: SBL5731 - Middle of site

Soil Carbon Chemistry

Analysis	Units	Result
Organic Matter - DUMAS	%	1.9
Organic Carbon	%	0.22
Organic Carbon Stock	t/ha	3.3
Total Carbon	%	2
Total Carbon Stock	t/ha	29.4
Bulk Density	g/cm3	0.98
C:N Ratio		8.8
Soil Respiration	mg/kg	96
Microbial Biomass	mg/kg	2142
Total Nitrogen	%	0.1
Potentially Mineralisable Nitrogen	kg N/ha	64
Active Carbon	mg/kg	556

Soil Microbiology Report

Organism Biomass

Analysis	Units	Result	Guideline	Low	Optimal	High
Moisture content	%	16	15 - 55			
Active Bacteria	µg/g	17.5	20 - 40			
Total Bacteria	µg/g	734	200 - 400			
Active Fungi	µg/g	5.0	20 - 40			
Total Fungi	µg/g	219	200 - 400			
Hyphal Diameter	µm	2.80	>2.5			

Organism Ratios

Analysis	Result	Guideline	Low	Optimal	High
Active/Total Bacteria	0.02	0.10 - 1.00			
Active/Total Fungi	0.02	0.10- 1.00			
Active Fungi/Active Bacteria	0.29	1.00 - 2.00			
Total Fungi/Total Bacteria	0.30	1.00 - 2.00			

Protozoa

Analysis	Units	Result	Guideline	Low	Optimal	High
Flagellates	No/g	8311	> 10000			
Amoebae	No/g	51	> 10000			
Ciliates	No/g	69	50 - 100			

Nematodes

Analysis	Units	Result	Guideline	Low	Optimal	High
Total Nematodes	No/g	2	10 - 20			
Nematode types	Fungal feeders: 10%; Bacteria feeders: 83%; Predators: 0%; Plant parasitic: 0%; Juveniles: 7%					

Mycorrhizal Colonisation

Analysis	Units	Result	Guideline	Low	Optimal	High
Ectomycorrhizae	%	NA	10 - 50			
Endomycorrhizae	%		10 - 50	Insufficient roots in sample		

Potential Nitrogen in Soil

Nitrogen (N)	kg/ha	28-56	Potentially cycled for a period of 3-6 months*

*Please note that this value is related to the microbiological activity and is not a chemical measure of nitrogen.

SoilBioLab
Specialists in soil testing

T: + 44 (0) 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213 The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England
Company Reg. No: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd

Contact: Luke Justice

Date: 24.07.2024

Sample ID: SBL5732 - Top of site

Soil Chemistry Report

Analysis	Units	Result	Guideline	Low	Optimal	High
pH	(1:2:5)	7.7	5 - 7			
EC ($CaSO_4$)	µS/cm	2080	1900 - 2200			
Organic Matter LOI	%	5.6	4 - 8			

Short Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	4.0	10 - 20			
Potassium	ppm	300	120 - 174			
Magnesium	ppm	379	> 100			
Calcium	ppm	2895	500 - 1250			

Middle Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Phosphorous	ppm	34	30 - 100			
Copper	ppm	2.4	1.5 - 8.5			
Zinc	ppm	2.8	1 - 10			
Iron	ppm	382	50 - 100			
Manganese	ppm	90.0	2 - 20			
Sulphur	ppm	44.0	8 - 50			
Boron	ppm	1.4	0.4 - 3.0			

Basic Cation Saturation Ratio

Analysis	Units	Result	Guideline	Low	Optimal	High
Calcium	%	75.1	65 - 85			
Potassium	%	4.8	2 - 7			
Magnesium	%	18.6	10 - 20			
Sodium	%	1.5	0 - 5			
Other	%	0.0	0 - 6			
CEC	meq/100g	21.9				
Ca/Mg Ratio		6.8	6 - 7			

Long Term Analysis

Analysis	Units	Result	Guideline	Low	Optimal	High
Copper	ppm	14.98	< 110			
Zinc	ppm	70.49	< 450			
Iron	ppm	28904.5	< 25000			
Manganese	ppm	964.66	< 2000			
Sulphur	ppm	322.83	< 2000			
Boron	ppm	32.28	0.5 - 4.0			
Molybdenum	ppm	0.53	0.1 - 2.0			
Cadmium	ppm	0.20	< 3			
Nickel	ppm	29.21	< 100			

SoilBioLab
Specialists in soil testing

T: 00 44 1264 749761
E: info@soilbiolab.co.uk
W: www.soilbiolab.co.uk
A: 213, The Commercial Centre
Picket Piece, Andover
Hampshire, SP11 6RU, England
Company Reg. No.: 9122781
VAT No: 194967247

Client: Sustainable Hockerton Ltd
Contact: Luke Justice
Date: 24.07.2024
Sample ID: SBL5732 - Bottom of site

Soil Carbon Chemistry

Analysis	Units	Result
Organic Matter - DUMAS	%	2
Organic Carbon	%	0.22
Organic Carbon Stock	t/ha	3.4
Total Carbon	%	2.3
Total Carbon Stock	t/ha	36.2
Bulk Density	g/cm3	1.05
C:N Ratio		9.2
Soil Respiration	mg/kg	53
Microbial Biomass	mg/kg	1196
Total Nitrogen	%	0.3
Potentially Mineralisable Nitrogen	kg N/ha	36
Active Carbon	mg/kg	578

Soil Microbiology Report

Organism Biomass

Analysis	Units	Result	Guideline	Low	Optimal	High
Moisture content	%	20	15 - 55			
Active Bacteria	µg/g	31.2	20 - 40			
Total Bacteria	µg/g	628	200 - 400			
Active Fungi	µg/g	17.8	20 - 40			
Total Fungi	µg/g	287	200 - 400			
Hyphal Diameter	µm	2.97	>2.5			

Organism Ratios

Analysis	Result	Guideline	Low	Optimal	High
Active/Total Bacteria	0.05	0.10 - 1.00			
Active/Total Fungi	0.06	0.10- 1.00			
Active Fungi/Active Bacteria	0.57	1.00 - 2.00			
Total Fungi/Total Bacteria	0.46	1.00 - 2.00			

Protozoa

Analysis	Units	Result	Guideline	Low	Optimal	High
Flagellates	No/g	3446	> 10000			
Amoebae	No/g	715	> 10000			
Ciliates	No/g	715	50 - 100			

Nematodes

Analysis	Units	Result	Guideline	Low	Optimal	High
Total Nematodes	No/g	2	10 - 20			
Nematode types	Fungal feeders: 10%; Bacteria feeders: 87%; Predators: 0%; Plant parasitic: 0%; Juveniles: 3%					

Mycorrhizal Colonisation

Analysis	Units	Result	Guideline	Low	Optimal	High
Ectomycorrhizae	%	NA	10 - 50			
Endomycorrhizae	%		10 - 50	Insufficient roots in sample		

Potential Nitrogen in Soil

Nitrogen (N)	kg/ha	<28	Potentially cycled for a period of 3-6 months*

*Please note that this value is related to the microbiological activity and is not a chemical measure of nitrogen.

References:

Ames, D.R. (1978). The concept of adjusting energy level in maintenance rations for cold weather. Cattlemen’s Day Report. pp. 94-97. Kansas State University, Manhattan, KS

The Agroforestry Handbook: Agroforestry for the UK 1st Edition (2019) https://www.soilassociation.org/media/19141/the-agroforestry-handbook.pdf#page=143&zoom=100,0,0

Bagley, W. T. (1964). Responses of tomatoes and beans to windbreak shelter. J. Soil Water Conserv, 19(2), 71-73.

Baldwin, C. S. (1988). 10. The influence of field windbreaks on vegetable and specialty crops. Agriculture, Ecosystems & Environment, 22, 191-203.

Brandle et al., (2009) Windbreak practices. P. 75-104

John Nix Farm management 55th ed 2025

Kort, J. (1988). 9. Benefits of windbreaks to field and forage crops. Agriculture, Ecosystems & Environment, 22, 165-190.

Norton, R. L. (1988). 11. Windbreaks: Benefits to orchard and vineyard crops. Agriculture, Ecosystems & Environment, 22, 205-213.

Marshall, J.K. (1967), 'The effect of shelter on the productivity of grasslands and field crops', Field Crop Abstracts, Vol. 20, pp 1-14.

Organic Farm management Handbook 2017

Osorio, R. J. (2018), GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska

Osorio, R. J., Barden, C. J., & Ciampitti, I. A. (2019). GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska. Agroforestry Systems, 93, 1567-1576.

Simms, D.D. (2009). Feeding the Beef Cowherd for Maximum Profit. SMS Publishing, Amarillo, TX

Smith, M. et. al. (2021) Windbreaks in the United States: A systematic review of producer-reported benefits, challenges, management activities and drivers of adoption.