Foresight study to compare the relative gains, costs, feasibility and scalability of current and future ‘industrial horticulture’ models

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Abstract

This study presents a comparative analysis of current and emerging future industrial-scale controlled-environment agriculture (CEA) practices for edibles, primarily industrial-scale glasshouses, with a focus on energy efficiency improvement measures and novel energy conversion and supply technologies that may help reduce dependency on natural gas, reduce the greenhouse gas emissions of the sector and contribute to the UK's net zero transition, while at the same time enabling sustainable growth of the sector. Using a combination of expert interviews, desk research and a workshop with experts, qualitative analysis and marginal abatement cost curve analysis, the study builds a picture of a complex set of interacting technologies and the contextual parameters, including policy, that define their significance for CEA. It identifies a significant opportunity to increase food security, boost the economy, export expertise, and envisages the UK becoming a strategic food producer while achieving net zero goals. The technical solutions for this transition in CEA are available today, and therefore the challenge is no longer technical, but rather an economic and political issue with a need to achieve economies of scale. Policy mechanisms are crucial for overcoming challenges to help the sector survive the current energy and cost of living crisis in the short-term, and to support the ambition to become a net-zero sector in the longer-term. This report sets out a transition pathway from the current status quo towards a net-zero carbon CEA sector by 2050, and identifies the priority technologies and potential challenges this entails and the implications for the industry and for policymakers. This will be of interest to industrial growers and the broader industrial eco-system of technology developers and suppliers, the investment community, and policymakers alike.

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Abbreviations

AD	Anaerobic Digestion
AEMWE	Anion Exchange Membrane Water Electrolyser
AHDB	Agriculture and Horticulture Development Board
AI	Artificial Intelligence
ATES	Aquifer Thermal Energy Storage
BECCS	Bioenergy with Carbon Capture and Storage
Bio-CNG	Bio-Compressed Natural Gas
BUS	Boiler Upgrade Scheme
CAPEX	Capital Expenditure
CCA	Climate Change Agreement
CCGT	Combined Cycle Gas Turbine
CCL	Climate Change Levy
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture, Usage and Storage
CEA	Controlled Environment Agriculture
CfD	Contract for Differences
CHP	Combined Heat and Power
CHPQA	Combined Heat and Power Quality Assurance
CNI	Critical National Infrastructure
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CPS	Carbon Price Support
DAC	Direct Air Capture
EfW	Energy from Waste

EII	Energy-Intensive Industries
EIP-AGRI	European Innovation Partnership for Agricultural Productivity and Sustainability
ESG	Environmental, Social, and Governance
ETFE	Ethylene Tetrafluoroethylene
FIT	Feed-in Tariff
GGR	Greenhouse Gas Removal
GGSS	Green Gas Support Scheme
GHNF	Green Heat Network Fund
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HNIP	Heat Network Investment Project
HNTP	Heat Network Transformation Programme
HPS	High-Pressure Sodium
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IETF	Industrial Energy Transformation Fund
IFS	Industrial Fuel Switching
IHA	Industrial Hydrogen Accelerator
IRENA	International Renewable Energy Agency
LED	Light-Emitting Diode
LNG	Liquefied Natural Gas
LVGA	Lea Valley Growers Association
LZC	Low and zero carbon
MACC	Marginal Abatement Cost Curve
MWe	Megawatt Electrical
MWth	Megawatt Thermal
NDRHI	Non-Domestic Renewable Heat Incentive
NPV	Net Present Value
NFU	National Farmers Union
NGG	Next Generation Growing
NZHF	Net Zero Hydrogen Fund
NZIP	Net Zero Innovation Portfolio
OCAP	Organic CO_2 for Assimilation by Plants
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PACE	Protected And Controlled Environment (horticulture)
PCM	Phase Change Material
PEMWE	Proton Exchange Membrane Water Electrolysis
PV	Photovoltaic
R&D	Research and Development
RES	Renewable Energy Systems
RHI	Renewable Heat Incentive
RO	Renewables Obligation
ROC	Renewables Obligation Certificate
RPI	Retail Price Index
RRC	Reduced Rate Certificate
RTFO	Renewable Transport Fuel Obligation
SIC	Standard Industrial Classification

SFI	Sustainable Farming Incentive
SRC	Steam Rankine Cycle
tCO_2e	Tonne Carbon Dioxide Equivalent
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UKETS	UK Emissions Trading System
USDA	US Department of Agriculture
UTES	Underground Thermal Energy Storage
VC	Venture Capital
WTW	Wastewater Treatment Works

Executive Summary

Key messages

- Controlled environment agriculture (CEA) is high yielding, water and land efficient, and historically allowed for cheap food production, but is energy intensive, and in the UK predominantly runs on natural gas-fired combined heat and power (CHP) or boilers which cannot be low carbon.

- Despite the value of CEA, the sector is likely to fall to its lowest production levels in 30 years, it is facing challenges over economic viability, and the situation has significantly worsened with the current gas/energy crisis. The sector is concerned about seasonal labour availability in the future. Growers are reluctant to plant out, are scaling back out-of-season growing, or shutting down permanently. A supportive policy framework is required to protect the sector.

- The UK has the climate and renewable energy resources to be a major global player in low carbon CEA food production. Energy efficiency measures should be encouraged throughout the sector, with a focus on integrating low/zero carbon energy supply systems into new CEA builds. The necessary technologies already exist for low carbon CEA and are largely proven – the challenge is primarily economic.

- Policy support is required for CEA moving forward, low carbon or otherwise, and political ambition needs to be articulated to inform scale of CEA requirement and associated support. Low carbon CEA presents a significant opportunity for the UK, and the positive impact on both local and national economies as well as strategic importance of securing food supplies, long-term maintenance of food affordability, along with contribution to net-zero goals needs to be considered in future policy support.

- The investment timelines in CEA are 20 to 50 years, so beyond the immediate crisis, for the sector to reach net-zero carbon by 2050 action is needed now.

Background

The purpose of this study was to conduct a comparative analysis of current and future energy supply technologies and solutions in industrial-scale controlled environment agriculture (CEA) practices for edibles, primarily industrial-scale glasshouses. CEA offers year-round growing seasons, 10 to 20 times the volume of food from the same land footprint as field-grown crops, using less than 10% of the water resources, along with economic benefits to the local economy, and has historically been a cost-effective system for food production. However, these benefits come at the expense of CEA being one of the most energy intensive sectors in agriculture due to high demand for heating, and electricity for supplementary lighting as well as other electrical equipment such as ventilation systems and pumps. Energy, aside from labour, is the most important cost factor in the industry and hence a critical determinant of the economic viability of operations. The CEA sector is facing pressures from multiple directions, and this situation has deepened significantly over the past year due to the gas/energy crisis. Unaffordable energy costs, combined with uncertainties over labour availability have already caused shutdowns across the sector, and indications and reports from the industry identify reluctance to plant out produce and predict significant further closures over the coming years without immediate action. Given the current energy crisis and widespread dependency on natural gas in the sector, there is a pressing need to reduce energy use for economic reasons, but additionally CEA is under considerable pressure to comply with the UK's carbon emissions targets and net-zero policies.

Aims and objectives

This study sought to identify opportunities and future potential of energy efficiency improvement measures and novel energy conversion, storage and supply technologies that may help to reduce dependency on natural gas, reduce the greenhouse gas emissions of the sector and contribute to the UK's net-zero transition, while at the same time enabling sustainable growth of the sector. Specifically, this entails a move away from the current dominant system design based on natural gas, using boilers to provide heat or Combined Heat and Power (CHP) plants used to co-generate electricity and heat, where the combustion process also provides CO_2 which is used for supplementation into the glasshouse in order to increase plant growth/yield. A variety of technologies and integrated energy solutions and alternative sources for CO_2 have been reviewed in this report, which are proven and have potential to enhance energy efficiency and to decarbonise the energy supply of CEA, and some are already being used successfully in the sector in the UK and abroad. The study also identified current challenges faced by CEA and its requirements for accelerating the large-scale implementation and deployment of these technologies as well as the resulting implications on different areas of the sector's ecosystem. In addition, a number of policy areas were identified that directly impact on the future development of the sector and its ability to overcome these challenges.

Methods

Expert interviews, desk-based research and an expert validation workshop were used to gain a detailed understanding of the current and evolving technologies and solutions for energy demand and supply in CEA and their relevant sector specific contextual factors. To structure the data collection and to conduct the analyses, methodologies from the field of technology and innovation management, including "fast-start" strategic roadmapping, innovation velocity and policy development frameworks were deployed. Assessment tools including marginal abatement cost curves (MACC) were also used to provide insight into the relative costs/emissions benefits of the alternative technologies under consideration.

Key findings

Energy efficiency measures

A broad range of energy efficiency measures were reviewed in this study, including:

- Maintenance and operations management (enhanced routine maintenance and repair, and operations monitoring and control systems).
- Equipment optimisation (high-efficiency pumps and motors, high-efficiency boilers/other thermal energy generation, improved ventilation and cooling systems)
- Building/glasshouse structure and materials (system insulation, thermal screens, novel glazing technologies, and closed/semi closed glasshouses).
- Energy storage (diurnal thermal energy storage, and seasonal thermal energy storage solutions).
- Enhanced crop production (Optimised LED lighting duration and wavelengths, CO_2 management, and selective crop breeding/genetic modification).

Some of these energy efficiency measures can be utilised at a low investment cost, such as improved maintenance, monitoring and control systems, and installing thermal screens, and are already widely deployed in the UK. Retrofitting is often expensive though, and some of the more impactful measures, such as advanced glazing materials and closed/semi-closed glasshouses will only be viable for new builds, so it is essential that new builds are future-proofed at the outset. Economic justification remains a barrier to the more impactful innovations, so incentives and/or changes in building regulations are required to drive uptake.

Decarbonising energy generation and supply

Glasshouses are intrinsically inefficient in terms of energy preservation, so compared to many other industrial sectors the potential for efficiency improvements is somewhat limited and therefore focus on transition to alternative more cost effective and lower carbon energy supply systems is of paramount importance. The study discusses the potential of the low-carbon energy generation and supply technologies in the following areas:

- Electrical power generation (on-site/co-located renewable power generation including solar photovoltaic and wind generation).
- Alternative fuels for co-generation of thermal and electrical power (including biogenic fuels such as biomethane, synthetic fuels, and hydrogen).
- The potential for CHP retrofit, and biogenic fuel boilers.
- Electrification of thermal energy supply (heat pumps and electric heat boilers).
- Heat recovery as a source of thermal energy for CEA (use of industrial waste heat and geothermal energy).

Aside from hydrogen, which is considered unlikely to be viable in the short- to medium-term, most of the above solutions are already well proven and deployed. However, the design of an appropriate energy system is strongly dependent on the energy demand profile of the operations and crop types, size of operation, local context, available local and regional resources, and other technical and ecosystem constraints. For example, for solutions based on industrial waste heat, planning consent and a supportive business ecosystem are key considerations, whereas for geothermal and underground thermal seasonal storage, geological factors are critical factors.

Underpinned by selected case studies in the UK and abroad, this report finds that neither internationally nor in the UK is there a single “one-size-fits-all” technical system design that is suitable for all growing operations. Therefore, the major difference from the system based on natural gas-fired CHP is that in the future a combination of different technologies and measures will be needed to decarbonise the electrical and thermal energy demand of CEA.

CO_2 supply for enhanced plant yield

A key consideration for industrial CEA is the need for supplementary carbon dioxide (CO_2) to enrich the atmosphere within the glasshouse to maximise photosynthesis potential and plant growth. Currently most CEA operations in the UK obtain CO_2 directly from the combustion of natural gas in CHP units or boilers. Alternative sources of CO_2 are available from fossil-fuel based industrial processes, biomethane/biomass combustion, biogenic processes such as in the brewing industry and anaerobic digestion, and in the future possibly Direct Air Capture (DAC) technologies that extract CO_2 from the atmosphere. However, while technologies for decarbonisation of the energy supply are relatively well proven now, the alternative solutions for CO_2 supply are not as well developed and are expensive at present. Until these are resolved, and technologies for alternative supplies are available at scale, the requirement for supplemental CO_2 will remain a considerable limiting factor in the transition to net-zero CEA.

Conclusions

The CEA sector has long operational timelines of 20–50-years, and historically technology transitions tend to happen slowly in large scale industries, so if the sector is to reach net-zero by 2050 the transition away from natural gas towards alternative technologies and decarbonisation needs to start now. This study suggests a phased approach towards net-zero carbon, with a pathway consisting of parallel initiatives:

- Short-term focus on low-energy farming
- Continuation with gas-powered CHP and fossil-based CO_2 into medium term
- Ongoing innovation in energy efficiency improvement measures
- Decarbonising the energy supply with biogenic fuels, industrial waste heat use, and renewables
- In the longer term, geothermal and large-scale seasonal energy storage
- Towards a possible end objective of 100% electrification by 2050

In parallel, innovation in CO_2 supply technologies will be a critical factor for success.

Most of the technical solutions for the transition of CEA to a net-zero industry are available today, however these will only be commercially viable with appropriate regulation and incentives and at scale, and therefore the challenge is no longer really a technical issue, but rather an economic and political one. New policy mechanisms across Government departments may be needed for removing barriers and overcoming the challenges to help the sector survive the current energy and cost of living crisis in the short-term and support the ambition to become a net-zero sector in the longer-term. The challenges and aspirations of the sector are highly interdependent and would require a holistic approach for designing any interventions with consideration for the influencing contextual factors discussed in this report. Three main considerations for such an approach are:

- Any new energy model would need to allow for flexibility of choice of energy source because energy requirements in CEA are directly related to type of crop being cultivated as well as other locally specific factors for each CEA operation.

- Incentives and obligations built into future policy mechanisms to encourage net-zero energy solutions and to discourage maintaining the status quo. A long-term view of revenue streams is essential in any support schemes and encouraging the future-proofing of new projects is important as retrofitting is usually not economical.
- Creating horticulture specific policies to support the sector through the transition toward net-zero could support the sector's evolution and give government the ability to shape the emerging industry.

The CEA sector is currently at a crossroads on the journey towards net-zero. The UK can decide to actively support and build a dominant CEA sector or risk losing ground and seeing the industry fall into decline. The expert consultations for this study highlighted that the importance of CEA to UK society and prosperity today and in the future has several dimensions: contribution to food security, the potential to take a leading role in research and development and export of sector-specific technologies, and last but not least, integration with other sectors, particularly the energy sector, to promote and accelerate the transition to a net zero future.

Further work

This study provides a solid foundation for policy development and technology adoption for the sector, but further research can be recommended to gain a more quantitative understanding of the sustainability of the sector, to gather data on current levels of deployment of low-carbon technologies and efficiency levels, and other economic and societal impacts of CEA. This would give a clearer indication of the areas of the industry requiring greater attention. The Netherlands is a global leader in CEA, and this study presents a brief look at the similarities and differences with the UK. A more thorough investigation of policy approaches and best-practice abroad and identification of potential technological and operational areas where the UK may be able to develop competitive edge would be highly beneficial.

1 Introduction

The purpose of this study was to conduct a comparative analysis of current and emerging future industrial-scale controlled-environment agriculture (CEA) practices for edibles, with a focus on their energy requirements. The study sought to identify opportunities and future potential of novel energy supply technologies and energy efficiency improvements that may help to reduce the carbon footprint of the sector and contribute to the UK's Net Zero transition while at the same time enabling sustainable growth of the sector.

1.1 Background

Controlled environment agriculture, using industrial-scale glasshouses offers year-round growing seasons, 10 to 20 times the volume of food from the same footprint as field-grown crops (although specific crops grown may differ), using less than 10% of the water resources, along with economic benefits to the local economy. Historically, these growing systems have delivered cost effective food production in the UK. However, these benefits come at the expense of CEA being one of the most energy intensive sectors in agriculture due to high demand for heating, and electricity for ventilation, pumps, and supplementary lighting. An estimated 26% of all direct energy use in UK agriculture goes to protected crops overall, and 15% to protected edibles, while protected edibles make up only a small fraction of total food production in the UK. Total energy consumption of the agricultural sector in 2015 in the UK was 117 thousand TJ at an energy intensity of 9.8 TJ per £m of value added.[1] Energy costs were in the past up to 30% of the overall variable production costs in CEA, and with recent price shifts in the cost of gas this is increasing dramatically.[2]

Energy, aside from labour, is the most important cost factor in the industry and hence a critical determinant of the economic viability of operations. Profitability has long been challenging for the sector, but with historically high energy prices and industry concerns over seasonal labour availability, combined with a cost-of-living squeeze on consumers and retailers, the UK CEA sector is now under intense economic pressure. Sector production has fallen to its lowest levels in 30 years (since records began), with tomato production down from 92,000 tonnes in 1985 to less than 68,000 tonnes in 2022.[3] The past year particularly has seen a significant reduction in output with growers choosing not to plant-out, and an increasing exodus from the industry threatening the future of the sector and the UK's future food sufficiency.[4] Energy use reduction is therefore critical for the sector.

Apart from the pressing need to reduce energy use for economic reasons, CEA is also under considerable pressure to comply with UK carbon emissions targets and net-zero policies. The UK government has set the legally binding target to become net zero regarding greenhouse gas (GHG) emissions by 2050 [5], and the National Farmers' Union (NFU) has set the goal for agriculture in England and Wales to reach net zero a decade earlier, by 2040.[6]

Over the past two decades, established policy for supporting energy supply in industrial applications have focused on the use of combined heat and power (CHP) solutions, primarily running on natural gas. Although support and fiscal benefits did not specifically target CEA, many growers grasped the opportunity to adopt CHP. In CHP, electrical power and thermal energy are co-generated, and by utilising both power and heat outputs together these systems offer energy conversion efficiencies approaching 80-90% and have played an important role in minimising energy use and emissions. This in turn reduces operating costs, and CHP has therefore played a key role in enhancing competitiveness and expansion of CEA in the UK. Industrial CHP is typically sized for the thermal heat demand of the operation, with excess electrical power exported, playing a role in the national grid supply, which can form an important element of the economic model of the CEA business. Indeed, many large CEA operations are net electricity exporters, and this has provided a useful hedge against fluctuations in the price of gas. Industrial CHP across all industry sectors in 2021 contributed about 7% of the UK's electricity supply.[7]

However, as the UK power grid decarbonises through greater use of renewables such as wind and solar, and expansion of nuclear power, the use of gas-powered CHP plants for new CEA operations will increasingly be at odds with net-zero objectives. Indeed, it is understood that BEIS plans to adjust current fiscal benefits of good quality CHP and move away from incentivising unabated for fossil fuel/natural gas-fired CHP completely in the longer-term. Moreover, with growth of novel types of CEA operations such as vertical farming for which direct heat input is less significant, and potentially increased requirements for cooling in CEA as the climate changes, the benefits of CHP may become less relevant to the sector going forward. Given this evolving context, an understanding of which energy solutions should be recommended and encouraged for the future will help policymakers. Given that the CEA sector has long operational timelines of 20–50 years, and innovations in the sector happen slowly, if the sector is to reach net-zero by 2050 the transition away from natural gas CHP and boilers towards alternative technologies and decarbonisation needs to ramp up significantly now.

1.2 Objectives

The objectives of this study are to:

- Understand the energy generation technologies that could be commercially and operationally feasible and practical to establish over the next 5 to 10 years, including those that are used internationally and could be applicable to the UK.
- Explore the economic, social, and environmental benefits and limitations, as well as scalability potential of current and future technologies that can contribute to decarbonisation of the generation and supply of energy (power and heat) for CEA operations.
- Explore the potential for demand-side energy reduction through energy efficiency measures and present a marginal abatement cost curve (MACC) comparing the relative benefits of these measures.
- Gain insights into the commercial, environmental, and societal case for a potential expansion of CEA growing operations and suitable energy supply systems to support policy decision-making.

1.3 Methodology

This study is based on a combination of expert interviews, desk-based research and a validation workshop to gain a detailed understanding of the current and evolving technologies and solutions for energy supply and demand-management in CEA. To structure the data collection and to conduct the analyses, methodologies from the field of technology and innovation management, including "fast-start" strategic roadmapping[8] and innovation velocity frameworks[9] developed at the Institute for Manufacturing (University of Cambridge) as well as for the structured policy analysis the policy development framework (developed by Camrosh Limited) were deployed (see further information on the methodology in Annex B).

Experts from academia and industry practitioners were interviewed in three phases. First, to gain an overview perspective of the sector and the key challenges and opportunities facing the sector; second, to explore individual energy generation and supply technologies in detail; and third to explore CEA systems integration and real-world case studies. Accordingly, experts with overarching expertise in the CEA sector in the UK were selected for the first round of interviews, followed by the selection of international experts in a specific technology area. The experts were identified from existing networks of the consortium and Defra within the industrial sector and academia, as well as through secondary research. The list of experts interviewed as well as the interview guides are included in Annex C.

Using publicly available sources such as academic and industry literature and technical studies, the interviews were complemented by extensive secondary desk-research to provide a comprehensive analysis of the strengths, weaknesses and market opportunities as well as threats/challenges for each of the key technologies. This data informed a comparative technology analysis leading to key recommendations on technology combinations. Additionally, a marginal abatement cost curve (MACC) analysis was undertaken to further explore the relative costs and benefits of the technologies under consideration.

Finally, the outputs of this study were validated through the validation workshop. The delegates were UK CEA sector experts, who also contributed to the previous data collection stage with interviews, along with Defra and BEIS representatives who were selected by Defra's core project team. The workshop agenda is shown in Annex D. The aim of the workshop was to share the research findings with the experts and policy representatives, to review the challenges identified and to discuss in small groups the potential system-level solutions that can help to address the key challenges.

1.4 Structure of this report

- Chapter 2. Presents an overview of the CEA sector, its current scale and significance to the UK economy, and key trends and drivers impacting the sector.
- Chapter 3. Presents energy use in CEA and identifies three primary energy use-types (energy models) to be considered based on primary energy demands.
- Chapter 4. Explores technical options for energy use reduction as a means to decarbonisation (energy efficiency measures) for the CEA sector.
- Chapter 5. Presents a broad range of technical solutions for decarbonisation of energy generation and supply. In the transition away from fossil-fuel combustion for heat, alternative sources of CO_2 are required to support crop growth which are also discussed.
- Chapter 6. Presents a comparative assessment of the key efficiency and energy system technologies, including a marginal abatement cost curve (MACC) analysis and qualitative assessment of broader system-level factors.

- Chapter 7. Presents a summary of the current policy and regulatory landscape with respect to energy and CEA and contrasts the UK situation with policy approaches in the Netherlands.
- Chapter 8. Synthesises the results of this study to identify potential energy transition pathways, key challenges, and implications for the sector.
- Chapter 9. Concludes the report with a summary and implications and proposed priorities for policymakers to support CEA and the net-zero transition.

2 Overview of controlled environment agriculture

In this chapter we present a brief overview of the CEA sector in the UK, with a focus on defining the contextual parameters that are relevant for its current status and the objectives of this report with a view to requirements for expansion of the sector.

2.1 Definitions

CEA is a sub-category of the broader category of protected horticulture[i] where cultivation is undertaken within structures that create a barrier between the growing area and the external environment, such as glasshouses, polythene-tunnels and other sheet material covered structures. In addition, CEA uses various technologies to tightly control and modify parameters, such as temperature, humidity, nutrients, and light, within the enclosed growing space, often using hydroponics, to create optimal growing conditions.[10] Keeping these parameters optimised in CEA for high quality, yield and uniformity of produce is particularly important for certain vegetables and fruits, such as tomatoes, peppers, cucumbers, aubergines, lettuce, leafy greens, and berries. In countries with a temperate climate, such as the UK, growing these crops in CEA operations, enables multiple harvests, and extending of the growing season beyond that possible in open field agriculture.[11]

Control of environmental parameters in CEA requires energy intensive technologies, in particular for heating, ventilation, dehumidification and for additional lighting to enable out-of-season growing.[10] It is this form of industrial-scale technology and energy intensive growing practices that are meant when the term CEA is used in this report. However, we are aware that findings and implications of this report may also apply to other types of horticultural operations.

2.2 Size and significance of the UK CEA sector

The UK CEA sector is a comparatively small industry, with production volume of 262 thousand tonnes and a market value of £374 million of UK home-grown market supply of vegetables in 2021.[12] This represents in the range of 10% by tonnage, and 22% by market value of UK vegetable production.

In terms of cultivation area under CEA conditions according to Defra’s published statistical data, as of 2021 there are around 798 hectares of protected vegetables and just over 217 hectares of soft fruit grown in the UK.[13] Including all forms of protected horticulture such as unheated polytunnels there are approximately 2,275 hectares representing around 2% of total overall productive edible horticultural land in the UK.[14] This compares with the Netherlands, which forms a useful benchmark against which to compare the UK, with just over 10,000 hectares of total glasshouse horticulture, of which 5,808 hectares are vegetables, making the

[i] ‘Protected horticulture’ as defined by Defra for reporting purposes includes any fixed or mobile structure high enough to walk through, which is glazed or clad with film, rigid plastics or other glass substitutes. It excludes lights, low plastic tunnels, French and Spanish tunnels. Statistics on industry size include protected horticulture operations >0.1 hectares.[14]

Netherlands currently the largest CEA producer in Europe and the third largest exporter of fresh vegetables by value globally, with a climate very similar to the UK's.[15] The total market value of exported Dutch vegetables was €7.2b in 2021.[16]

The current state of the UK sector needs to be considered against a background of year-on-year declining cultivation area for protected vegetables since 2015, and according to reported Defra horticultural statistics, a decline of 8.7% of growing area in 2021 alone.[ii][12] Overall output declined in 2021 by 2.9%, most likely also due to labour shortages caused by the Covid-19 pandemic and EU Exit. Further reduction is anticipated in 2022-2023 in the UK and in Europe due to the high energy costs driven by the Ukraine war. However, over the same period since 2015, the most widely produced CEA edible crops, such as tomatoes, cucumbers peppers, salad and berries have increased in commercial value in line with increasing consumer demand.

As of 2021, approximately 57% of fresh produce was produced domestically (open-field and CEA production combined) in the UK. With increasing pressure on land availability and resources, any attempts to increase the UK domestic production share will probably require considerable expansion of the CEA sector. This will most likely only be possible by adding more large-scale operations in line with the current structure of the CEA sector, which is, according to industry experts, made up of a small number of around 50 large growers (>10 hectares), another 50 medium-to-large growers, and possibly well over 1000 smaller glasshouse/polytunnel operators of varying technical standards. These structural trends within CEA emphasise the importance of scale of operations for commercial viability and the necessity for implementing the latest high-tech glasshouse innovations, both demanding substantial upfront investments.

2.3 CEA crop types

The protected horticulture sector including CEA can be subdivided by crop type into three main categories, which also have distinct energy requirements.[17]

- **Protected vegetables and herbs:** Predominantly tomatoes, cucumbers, lettuce and peppers, and to a lesser extent courgettes, aubergines, chillies, and herbs.
    - Typically, annual total energy demand in the range of 350-1000kWh/m^2.
    - Dependent on whether grown out of season and whether artificial lighting is used. In addition, CO_2 is required for increasing yields.

- **Protected soft fruits:** Berries: strawberries, raspberries, blueberries.
    - Typically, annual total energy demand in the range of 50-400kWh/m^2, depending on crop type.
    - Dependent on crop type, for example strawberries, particularly out of season, requiring above 400kWh/m2 per year often heated and with some artificial lighting usually in higher tech glasshouses, and cold grown berries, such as raspberries requiring significantly less energy.

[ii] The data sets of the years 2015 and 2021 are not covering the same commodity lists as the data for some crops is no longer recorded.

- **Protected ornamentals** (excluded from this report): mostly pot and bedding plants (in the UK very few flowers are grown under protection).
    - Typically, annual total energy demand in the range of 50-400kWh/m^2 per year, mostly not heated and without additional lighting.

Energy figures given here for different crop types are the total energy demand of thermal and electric energy. However, upper range limits may not necessarily reflect crop need, but total energy use reported, including for example thermal energy used for generation of electricity sold to the grid.

Although these three crop categories are currently grown in a variety of operational settings, such as heated and unheated low-tech glasshouses, heated and unheated polythene tunnels, and high-tech glasshouses with supplemental heating and lighting, it is the latter more advanced, high-tech and high energy CEA operations that contribute more significantly to the overall sector output of high market value crops.

There is a significant sector of mushroom growers in the UK, who in 2021 produced £118 million-worth of mushrooms and over 45% of the total domestic supply of mushrooms.[18] However, mushroom production is very different from the above CEA, and is not within the scope of this report.

2.4 Vertical Farming a novel technology-driven growing practice

A currently still small sub-segment of CEA that has evolved over the past decade is based on integrating indoor growing technologies into a closed system, called vertical farming. Vertical farms use entirely artificial lighting and heating, ventilation and air conditioning (HVAC) -based technologies for climate control for all year production of mostly leafy greens, such as salads and herbs, in multi-layered growing structures within completely closed buildings or containers.[19,20] The major attraction of vertical farming is the reduced footprint in terms of land use, high water efficiency (over 90% less water use than in open field growing) and high yields per m^2. Currently the largest vertical farming grower in the UK is able to supply around 30% of UK basil sold in supermarkets, grown from a site of only 0.5 hectares (see Annex A for further details of Jones Food Company). Moreover, operating in entirely closed indoor environments largely eliminates the risks of pests, contamination and the effects of weather and climate, improving yield consistency.

The number of vertical farming operations has expanded rapidly over the past five years mainly driven by investor interest perceiving them as technology ventures, rather than a part of agriculture. Innovation continues at pace, and a number of novel, multi-layer growing formats are emerging, such as for example growing towers[21] and climate and resource control systems using machine learning and artificial intelligence (AI) are currently being implemented at scales beyond half a hectare at a small number of sites in the UK, such as for example at One Farm in Suffolk[22], or Jones Food Company site 2 in Gloucestershire with a final size of 1.5 hectares.[23] Smart energy use models for electricity, such as demand side response solutions combined with on-site renewables for integration with the grid are also developing, offering opportunities to make income from grid connectivity and grid balancing services.

Currently, it appears that this approach to growing is evolving in parallel to developments in the glasshouse CEA sector, although using very similar technology components. Although vertical farming is at present perceived by some CEA players as ultimately competing with CEA glasshouse growers, rather than acting as a technology facilitator or contributor to CEA, changing energy use models and reduced energy inputs resulting from future technology innovation may lead to efficient hybrid glasshouse-VF growing systems. Vertical farming may also serve a complimentary role in, for example, very rapid plantlet production for glasshouse (and field) production. However, at present the range of produce grown in vertical farming operations is limited (mostly to leafy non-flowering non-fruiting crops), and operating costs are high, particularly for energy, so the majority of the industry experts consulted during this study suggest that vertical farming is unlikely to significantly disrupt more conventional glasshouses in the near future, particularly in temperate growing environments such as the UK.

Public data on vertical farming energy use is limited, but efficiencies are improving in vertical farming and there are anticipated benefits with economies of scale, in particular in combination with the increasing requirement for use of renewable energy in agriculture. At present, vertical farms still have significantly higher average energy use than conventional glasshouses operating in summer months in the UK, as vertical farms require artificial lighting and significant mechanical cooling. Energy consumption data is difficult to obtain for the sector, but one report suggests that for operations <1000m^2, 38.8 kWh/kg of produce is required, compared to an average 5.4 kWh/kg for glasshouses, dropping to possibly about 8.3 kWh/kg for vertical farming operations >5000m^2.[24] Given current energy prices, vertical farming seems to have most utility in climates of extreme heat or cold or limited daylight, such as in the Middle East, or during the winter months in Scandinavia where also renewable sources for electricity such as solar or hydropower are abundantly available.

2.5 Trends and drivers affecting CEA in the UK

Several trends and drivers impact on the CEA and are presented here from a perspective of how they specifically might affect the potential for sector growth.

2.5.1 Political trends and drivers

The past three years have seen an increased volatility in energy costs, supply chains and availability of labour due to the Covid-19 pandemic and EU Exit, exacerbated further by the war in Ukraine since spring 2022. These events have raised political awareness around issues such as national food security, and political dependencies related to energy supply.[25,26] Together with national and international obligatory legislation to reduce GHGs and fossil fuel use, the CEA sector is strongly affected currently by these developments but might be part of a solution for some of the issues in the future. Should the political will exist to indeed increase domestic food production then growing the CEA sector would be part of such a solution. This would however require long-term policy support to reduce the current considerable pressures on the sector due to unprecedented high energy costs, decarbonisation requirements and low profit margins.[27–29]

The second area of policy decisions directly affecting the sector concerns seasonal workers, as it is estimated that until 2020 99% of the seasonal workforce in agriculture came from outside the UK.[30] Policy makers have acknowledged the urgent need for more seasonal labour specifically for horticulture to remain productive by increasing the seasonal worker numbers for 2023, however whether the implemented current schemes, such as the Seasonal Workers scheme and intended further recruitment support mechanisms can be effective in time for the sector remains to be seen.[31] In particular, current visa restrictions of 6 months may be unsuitable for CEA growing operations that can grow through most of the year, as is also the case for the mushroom sector. There is a concern within the industry about potential labour shortages in the future, despite the increase in seasonal worker visas for horticulture (45,000 visas for year 2023 were announced by the Government).[32]

2.5.2 Economic trends and drivers

Energy costs dominate the economics of CEA, in particular as the sector, although part of agriculture, has no access to rebated fuels as for example open field agriculture does with the ability to use excise duty rebated red diesel. Addressing this disparity between field agriculture and CEA and vertical farming would provide a necessary boost to the sector. Energy costs have made up on average around 30% of operational costs within the CEA sector for many decades. However, with the wholesale Dutch gas price, the European benchmark, rising more than 400% between July 2021 and July 2022 [33], UK gas prices have reached historic high levels (Figure 1), creating new impetus for energy reduction measures. Apart from the current cost increases and inflationary pressure, there are some longer-term economic trends that might shape the future development of the sector.

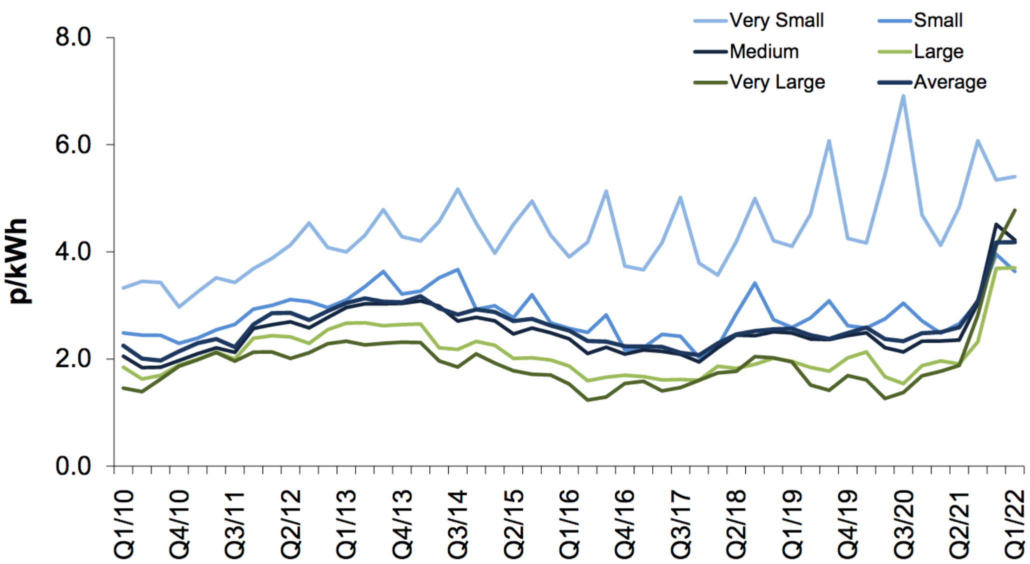
Given the importance of large amounts of source energies for large CEA operations, it has become commercially attractive, and possibly even a necessity, for many to be net power generators themselves in order for their business models to be viable.

The positive impact of large glasshouses for rural area development has been demonstrated in the past and might create more interest in growing the sector with strategic local development goals as well as climate goals, such as reducing food miles, in mind.[34,35]

Figure 1 Average non-domestic gas prices including climate change levy

Source: BEIS, 2022 [36]

Non-domestic consumer bands: Very small <278 MWh; Small 278 – 2777 MWh; Medium 2,778 – 27,777 MWh; Large 27,778 0 277,777 MWh; Very large 2777,778 – 1,111,112 MWh



Large new glasshouse builds over the past five years have also created interest with large investors, most notably in the UK, Greencoat Capital, who have financed the build of three major new low-carbon CEA operations (see Low Carbon Farming case study in Annex A).[34] Institutional investors such as pension funds are also now showing willingness to provide capital with long-term re-payment terms to an industry that has traditionally not been of much interest to the financial sector.[iii] The Dutch horticulture industry is also an investor in the UK industry, including Thanet Earth in Kent which at 91 hectares is the UK's largest CEA operation to date.[37] Government backed, retail price index-linked (RPI-linked) income streams such as the non-domestic renewable heat incentive (NDRHI) have proven to be a key driving factor by providing long-term financial viability and risk reduction for investors. In addition, investment in the CEA sector is at present perceived as contributing to environmental and climate goals, which might attract further ESG (environmental, social, governance) investor interest in new large-scale low carbon greenhouse projects.

A strongly growing market for high value medicinal plants, such as cannabis, and plant-based production of molecules such as vitamins, amino acids and food supplements will be driving some of the growth of CEA, as it has done in the past 5-7 years.[38–40] However, these developments, while contributing to sector growth and contributing to the adoption of high tech solutions such as semi-closed glasshouses and net-zero operations in the UK, will not contribute to food security (see Annex A for discussion of the transition of British Sugar away from tomatoes to Cannabis cultivation, which at the time eliminated 20% of the domestic tomato supply).

Recent years have also seen an increasing market value of fresh produce and rising consumer demand, which might support market-driven growth of the sector. However, given the current precarious situation of the industry, and cost-of-living challenges facing the country, it is questionable whether the low profit margins that have been imposed by supermarkets on growers for decades will allow any market driven growth without substantial government support.

2.5.3 Societal trends and drivers

Trends in consumer behaviour that might impact the CEA sector longer-term are an increasing awareness that local food production is important for climate goals, such as reducing food miles, as well as for food security, besides a general slow increase in demand for fresher and healthier foods.[41,42] Given recent political events, the trend to seek out locally produced food might increase further and might influence choices of shoppers in supermarkets in the future more than is currently the case. These developments may support growth of the sector in the future; however, some form of collaboration on pricing between supermarkets and producers might be needed to ensure that growers can supply at a price that supports sector growth but remains affordable to consumers. However, research into consumer trends often reveal that price of product is still the deciding factor for food choices for most, and that these choices are generally rather fickle and fast-moving.[43]

Further, there is a concern of the sector about seasonal labour availability in the future, and further policy initiatives will likely be required to help increase the domestic skilled and unskilled labour pool for the sector in addition to the already implemented measures.[32] Also,

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[iii] As advised by industry experts consulted for this project

whether a more positive, technology and environment focused image of the horticulture sector might help attract a new generation of UK workforce remains to be seen.

2.5.4 Technological trends and drivers

Apart from general technology trends, such as the increasing use of digital technologies accompanied by reducing cost for control software and hardware such as sensors, increasing automation, and the shift to sustainable source energy solutions, there are specific technology areas that will directly impact CEA. For operations using artificial lighting, latest innovations in light emitting diode (LED) technologies will enable considerably lower energy use for lighting as well as use of specific wavelengths to support plant growth. Many technologies for increasing energy efficiencies are well developed, such as thermal screens, glass panels with optimised insulation and light transmission properties, heat storage systems, (see Chapter 4 for details).

Renewable source energy technologies such as heat pumps, geothermal, anaerobic digestion (AD) plants, solar photovoltaics (PV) and wind power are widely available and used to some extent in UK CEA, but would need wider deployment quickly throughout the sector, given the pressures to decarbonise. The barriers to scale-up of these technologies are not technical, but primarily social, economic and political. Currently high capital costs and policy uncertainties around future energy price support is holding back wider implementation. In addition, as most CEA operations need a source of CO_2 to increase plant growth and yields, novel CO_2 production or capture technologies are required as most CO_2 is currently produced from fossil sources, (see Chapter 5 for details).

Given that CEA is still a very labour-intensive industry, labour availability and increasing wages are driving interest in the role of automation. Improved robotics systems for harvesting are currently tested, but the industry experts consulted in the course of this study see limited progress to-date and significant automation still at least ten years away.

The currently applied latest technologies in CEA have been optimized for crop yield to an extent that further technological improvements are thought to lead only to incremental yield increase. Hence, novel genetic engineering methods in plant science might be required to produce modified crops for any significant further improvement in efficient growing.

2.5.5 Environmental trends and drivers

Apart from the effects of climate change leading to a tightening of legislation concerning GHG emissions and decarbonisation requirements of energy sources, lasting changes of climate (more frequent and extended heat waves, and drought) will impact the UK's food supply system. Climate change impacts in the UK may lead to less rainfall in parts of the country where horticulture had traditionally a strong presence due to more sunshine hours, which might not only affect local ground water levels, but also the use of rainwater collection and storage, a common practice in most modern horticulture operations. Persistently higher summer temperatures and frequent heat waves in the UK may also impact on CEA, necessitating increased ventilation and cooling in peak summer months. Furthermore, the potential increase of more unpredictable weather events, such as storms and temporary flooding might require that more crops be grown indoors for protection. Hence, a strategic review of regions in the UK not traditionally known for horticulture for future development initiatives might be useful for longer-term planning of sector growth. Moreover, the UK is heavily dependent on imported fresh produce from Southern European and North African countries, such as Spain and Morocco. The term "exporting drought" has been used to describe these countries' extensive horticulture sectors, and with advancing climate change the pressures on their water resources and domestic food supply will intensify, leading to a decline in exports which may well necessitate more domestic production in the UK to maintain current levels of food supply.[44]. Growers in these regions are already seeing climate change effects impacting on growing conditions, and for example, the EU Commission Agricultural outlook published in 2020 predicts a permanent decline in Spanish tomato production of about 20% by 2030.[45] These trends would indicate the need for expanding domestic CEA to contribute to longer-term food security.[46]

2.5.6 Legislation trends and drivers

Current national and international trends in planning regulation with regards to protecting the natural environment run often counter to planning for large horticulture operations in rural areas, a tension that might need regulatory attention to be resolved when looking to grow the CEA sector in the UK. Co-locating horticulture operations close to an industrial waste heat source is well tested and technically implemented at scale in other countries, however incentives for industry to make use of their waste heat, already existing across the EU and Switzerland, are currently lacking in the UK, as is stakeholder awareness around this opportunity and related willingness to enter mutually beneficial contracts between waste heat providers and growers.

The second area impacting on the sector is regulation around energy cost support schemes and decarbonisation of energy sources. Given low profit margins, and high energy use in CEA, recent energy price increases pose a serious challenge to most growers using natural gas and grid power, and are already forcing many smaller operations to close, or at least mothball operations in 2022. Moreover, all the low carbon thermal energy supply technologies are still economically unviable for the sector without subsidies. Past energy cost support schemes, such as the NDRHI closed to new applications in 2021, and Feed-in Tariffs (FIT) in 2019, which have been successful in the past in supporting the CEA sector and also for securing investment in larger new builds based on low-carbon technologies, have currently not been followed up with similarly effective long-term schemes. A number of schemes introduced with the intention to support wider application of sustainable energy sources, such as the Green Gas Support Scheme (GGSS) or Contract for Differences (CfD) have so far not delivered significant benefits for the CEA sector, (see Chapter 7 for details). Given that energy prices may remain high for quite some time, a lack of support mechanisms might lead to overall contraction of the sector and prevent investment in new large-scale projects.

3 Energy use and emissions in CEA

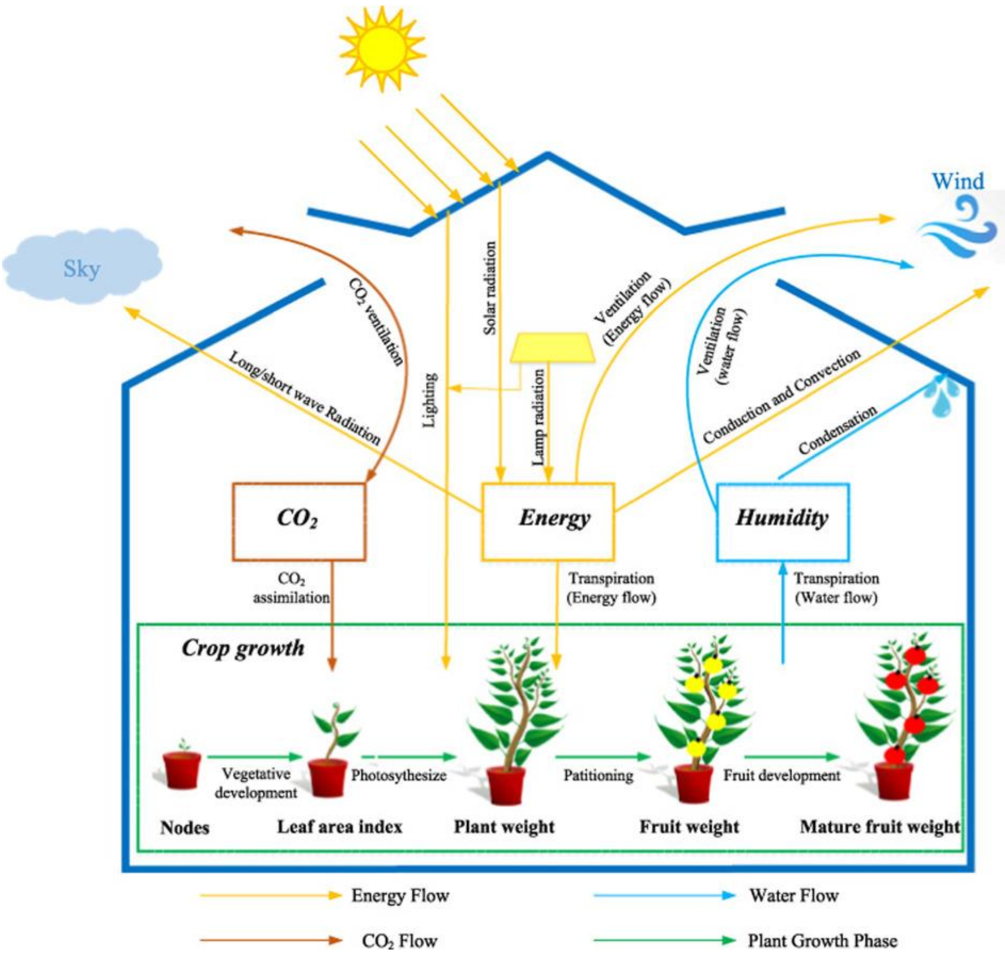
This chapter presents an in-depth look at the current energy use and emissions in the sector.

3.1 Energy use and emissions overview

The primary flows of interest in CEA are energy from the sun and other thermal and electrical energy inputs, CO_2, and water/humidity, as illustrated in Figure 2. The focus of this report is primarily on the energy systems used to supply heat and power for CEA operations, and the GHG emissions associated with these operations. Unlike field agriculture, in CEA, GHG emissions are almost exclusively CO_2, from fossil-fuel combustion, but these emissions also play an important role in CEA as their CO_2 component is used to enrich the air in the greenhouse to increase plant growth. Ventilation plays a key role in moderating temperatures and humidity levels but also leads to significant loss of thermal energy and supplemented CO_2.

Figure 2 Energy, humidity and CO_2 flows in a conventional glasshouse

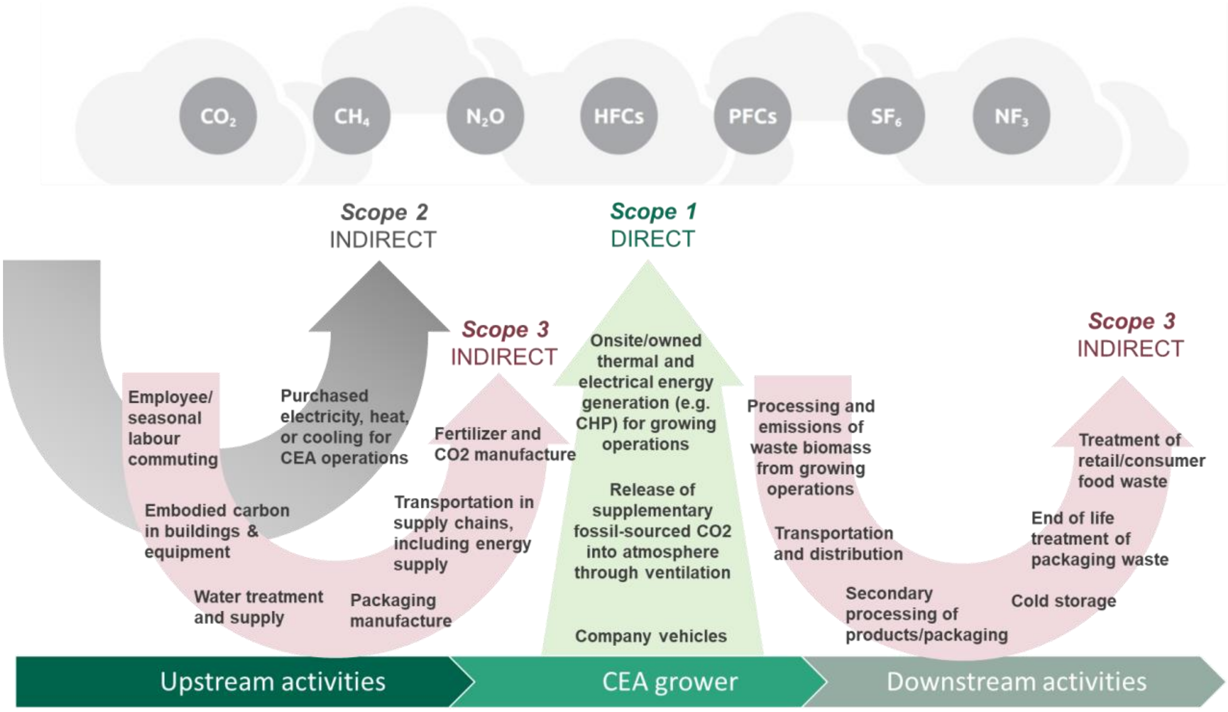
Source: Golzar et al., 2018 [47]



GHG emissions can be categorised as scope 1, 2 and 3 emissions depending on where they are generated in the supply-chain. Figure 3 presents an overview of these three categories in typical CEA operations. The main focus of this report is on "scope 1" direct GHG emissions associated with energy generation onsite in CEA operations, and "scope 2" indirect GHG emissions associated with purchased energy. For this study other scope 1 emissions (e.g., company vehicles), and scope 3 emissions in upstream and downstream activities are excluded. Impacts vary by crop type, but for example, energy supply for heating and lighting, primarily linked to natural gas is estimated to generate around 90% of GHG emissions footprint for lettuce growing out-of-season in the UK (Figure 4).[48] Figure 4 shows the range of emissions for lettuce growing in different operating contexts in the UK, compared to growing in Spain.

Figure 3 Sources of Greenhouse Gas Emissions in CEA

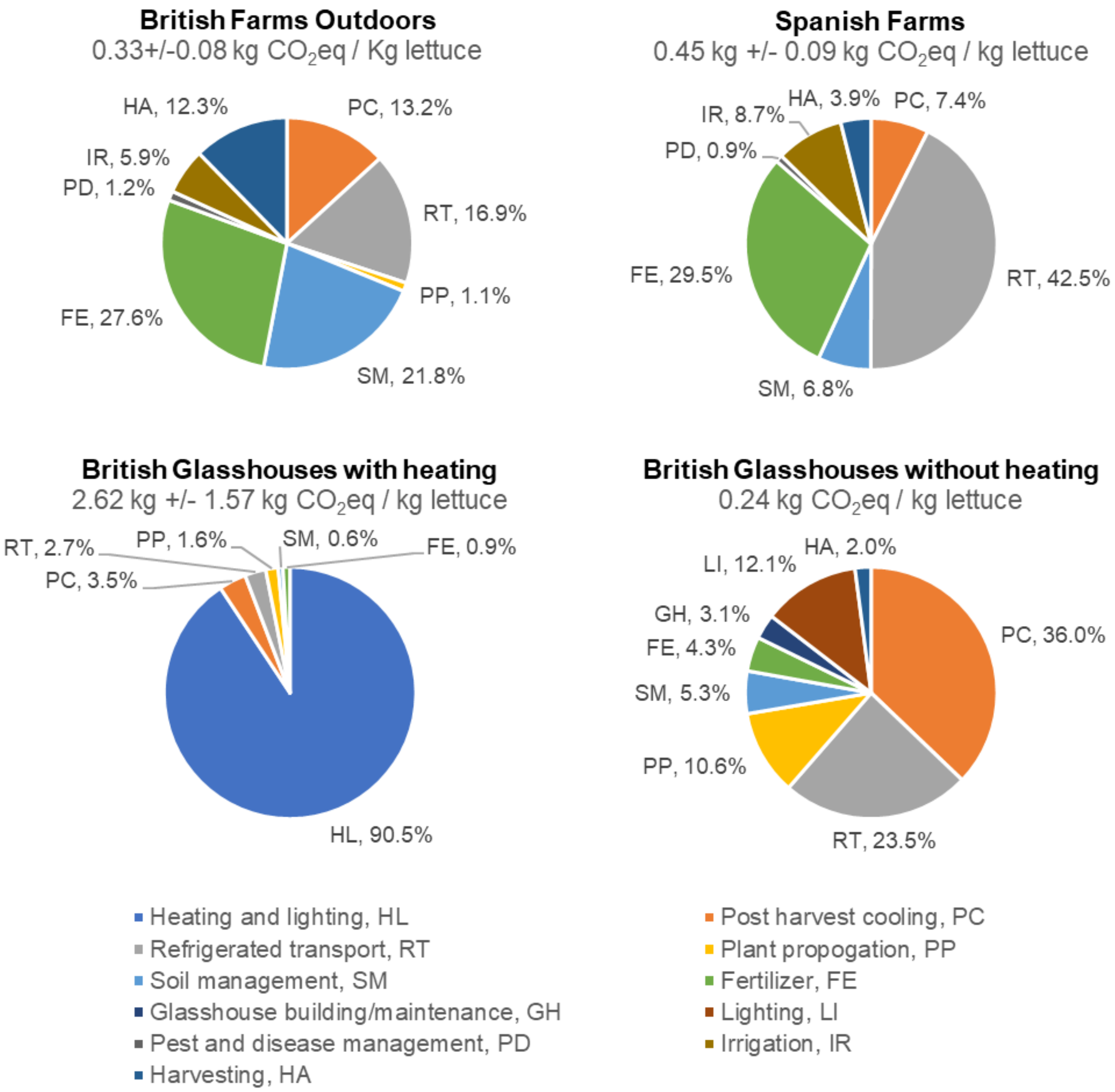
Based on WRI/WBCSD [49]



It is beyond the scope of this study to explore transportation and distribution costs and emissions. However, as Figure 4 illustrates, these are relevant when comparing domestic production versus imported produce. Various studies have found that growing produce in unheated glasshouses in the summer months in the UK offers significant carbon emissions benefits over imported produce due to reduced transportation. However, out-of-season crops grown in energy-intensive operations in the UK currently have significant energy costs and more than twice the carbon footprint of imported produce grown in unheated operations in Italy, Spain and Morocco, despite the transportation requirements.[50,51]

Figure 4 GHG emission sources in CEA (Lettuce)

Source: Hospido et al, 2009 [48]



3.2 Controlled environment agriculture energy use types

Energy is not only one of the main operational cost elements defining commercial viability of CEA, but also future energy technologies are a key factor for decarbonisation of the sector. For the purposes of this report, a categorisation of CEA operations has been developed based on source energy inputs for heating and lighting. Unheated glasshouses and simple unheated polythene tunnels were excluded from the analysis, although findings of this report may be relevant to these types of operations. The aim is to distinguish CEA operations in terms of their energy demand, in particular with respect to the type of energy that is most significant for the viability of their operation as the predominant energy type is crucial for the identification of relevant decarbonisation options. Three energy use types are defined as illustrated in Figure 5, and discussed below.

Figure 5 Energy use types and prevalent energy systems

TYPE 1

Using natural light and solar radiation with supplementary heating (glasshouse/poly tunnel) **Crops**: Cucumber, pepper, etc.

Energy carrier	Conversion	Demand
- Natural light and solar - Natural gas - Electrical power	- CHP for heating, electric power, and CO_2 - Gas boiler for heating and CO_2	- **Thermal energy for heating** and operational processes - Electrical power for operations, e.g. irrigation systems, ventilation - CO2

TYPE 2

Using natural light, solar radiation, supplementary artificial light & heat (extended season glasshouses) **Crops**: Tomato, strawberry, etc.

Energy carrier	Conversion	Demand
- Natural light and solar - Natural gas - Electrical power	- CHP for heating and electric power, and CO_2 - Gas boiler for heating and CO_2	- **Thermal energy for heating** and operational processes - **Electrical power for artificial lighting** and operations, irrigation, ventilation - CO2

TYPE 3

Using exclusively artificial lighting or no lighting at all (e.g. inside a building, container, underground, "vertical farms") **Crops**: Greens, mushrooms

Energy carrier	Conversion	Demand
- Electrical power	- HVAC systems	- **Electrical power for LED lighting, cooling**, heating, de-humidification, operational processes - CO_2 purchased separately

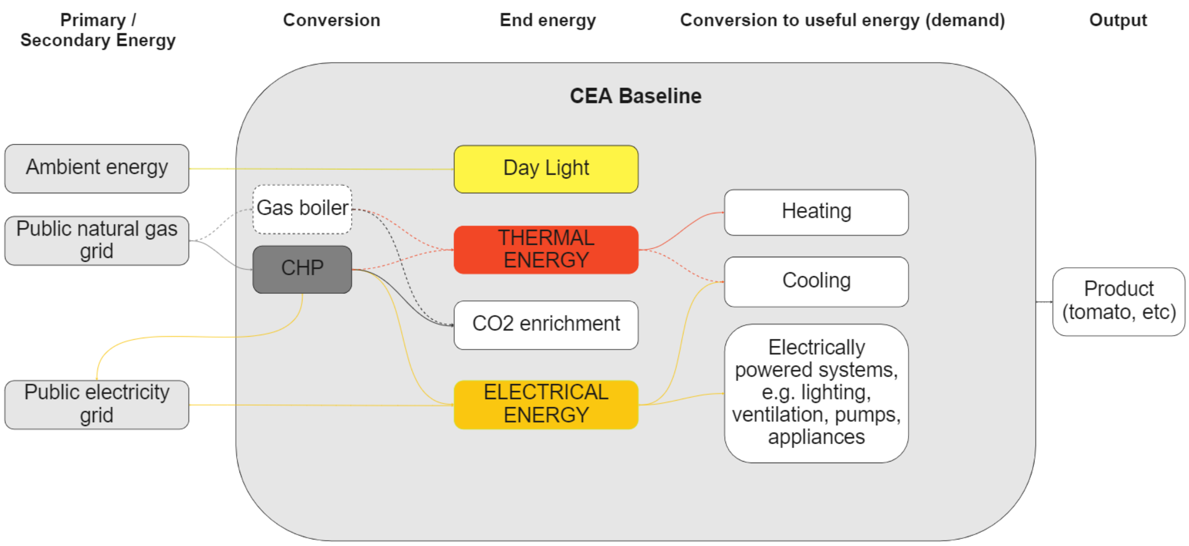
*Red bold – Dominant energy demand

Cold glasshouses are excluded from the analysis

CHP generation plants play a central role in the current energy system design of most large use-type 2 and some use-type 1 operations, and even the latest generation of low-carbon CEA based on electrical heat pumps still usually make use of CHP as part of their operations or as a backup system in case of primary system failure (see case studies in Annex A). The main advantage of CHP is the energy saving due to combined co-generation of electrical and thermal energy, which achieves an overall efficiency of 80-90%, compared to 50-60% overall for separate heat and power generation (e.g., using a gas boiler and grid electrical power supply). The most common models deployed in CEA are CHP units with reciprocating internal combustion engines (ICE), where the engine drives an electrical generator, and a heat recovery unit extracts heat from the engine cooling, lubricating oil and exhaust gases. Other forms of CHP include steam boilers with steam turbines, gas turbines, combined cycle gas turbines (CCGT), and fuel cells. CHP units are commonly run with natural gas, although systems running on diesel and biomass (boiler and steam turbine) are also in use. The heat from a CHP can be used, for example, to heat a secondary circuit with water up to 90ºC, which can be piped through the glasshouses for heating.[52]

A second key reason for the widespread use of CHP in CEA at present is the supply of supplementary CO_2. This will be discussed further in section 3.3. A system map, Figure 6, illustrates the typical set up of the energy conversion process in such growing operations.

Figure 6 Technology system map for current energy use types 1 and 2



In the following sub-sections, the three use types are explained and the difference in total energy demand between the three use types is visualised using Sankey diagrams (in kWh/m^2). A Sankey diagram is a frequently used method for visualising energy flows. The size of the individual arrows corresponds to the proportion of the energy flow shown. These Sankey diagrams are illustrative only, based on empirical data for average end-energy demand provided by the consulted experts. The diagrams are based on the currently predominant types of energy supply in the CEA sector which is still heavily dependent on fossil fuels: natural gas for heating, and grid electricity of which over 40% is still generated from coal, oil and gas. [53]

For all glasshouse operations sunlight and solar radiation are key inputs and these vary considerably across the UK (see Annex H for a map of the solar radiation levels across the UK). While CEA offers the possibility of growing almost anywhere in the UK, lower levels of light and solar radiation, and stronger winds require greater levels of supplementary heat and light so are an important operational cost and carbon emissions consideration in location of CEA.[54] See Annex H for 21-year daily simulation of (a) annual heating and (b) cooling requirements per unit area maps in the UK for glasshouse, illustrating that energy input requirements for supplementary heating in southern locations may be half that of some more northerly locations in the UK.

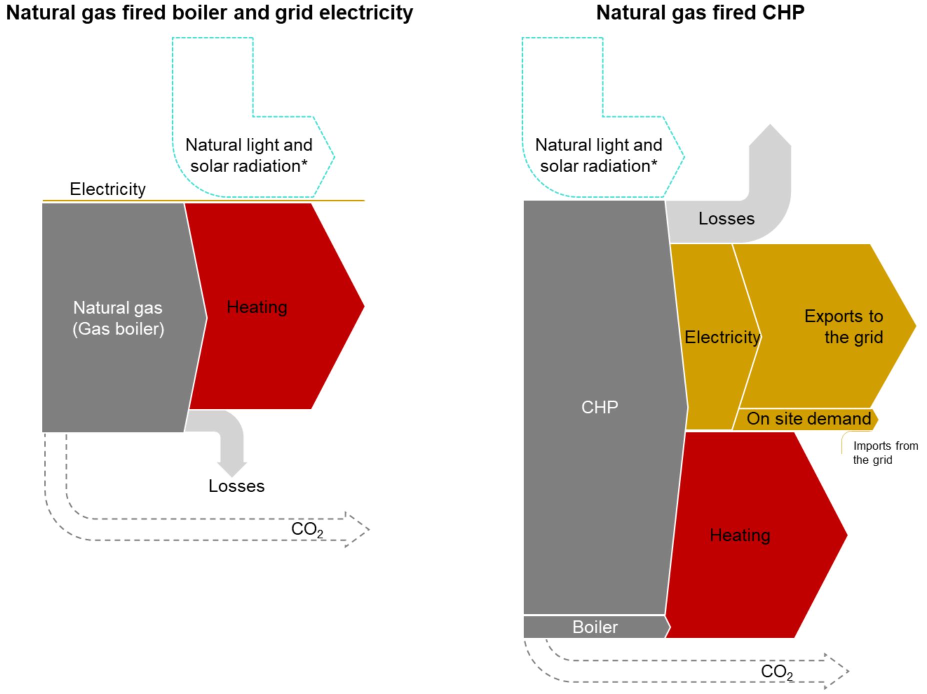
3.2.1 Energy use type 1

This type makes use predominantly of natural light and heat from solar radiation for mostly in-season production but uses additional heating to manage overnight and early and later season low temperatures and morning humidity. Energy source for heating is predominantly natural gas at present, although biomass boilers, and one or two diesel fired CHP are in use. Electricity is used for operational processes such as ventilation and irrigation systems, pack houses and cold storage facilities, but the predominant energy demand is for heating. Even though electricity demand is low in energy use type 1 CEA, CHP is economically attractive, with the electricity exported to the grid. Exhaust CO_2 from the heating supply system can be supplied into the glasshouse for increasing plant yield. Crop types grown under these conditions include tomatoes, cucumbers, peppers, aubergines, lettuce, and strawberries, mostly in-season, as well as early and late shoulder seasons.

Figure 7 Energy use type 1 indicative energy demand profiles

Energy requirement: Heating 500 kWh/m^2; Electricity: 3kWh/m^2

**Note: Losses illustrated occur in the conversion process (combustion) of natural gas as well as distribution of the energy flows within the CHP system.*



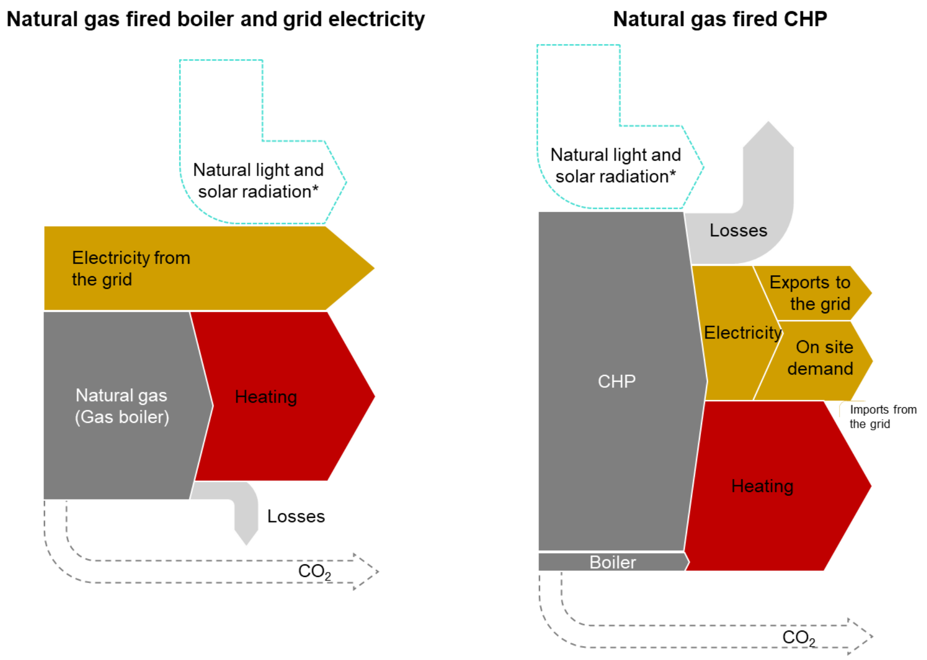
3.2.2 Energy use type 2

This model also makes use of natural light and heat from solar radiation, but uses additional heating *and* artificial lighting, which allows extending the growing season, and multiple harvests for flowering crops. The energy source for heating is predominantly natural gas. Electricity is used for operational processes *and* artificial lighting. The largest amount of energy is used for heating, mainly through natural gas fired boilers and CHP systems, but electricity use is significantly higher than in use type 1. As a result, CHP is used in most large CEA operators of use type 2 in the UK. Exhaust CO_2 from the heating system can be supplied to the glasshouse to increase plant yield. Crop types grown under these conditions include tomatoes, cucumbers, peppers, aubergines, lettuce and strawberries, but can be produced early and late of season, as well as out of season.

Figure 8 Energy use type 2 indicative energy demand profiles

Energy requirement: Heating 400 kWh/m^2; Electricity: 200kWh/m^2

**Note: Losses illustrated occur in the conversion process (combustion) of natural gas as well as distribution of the energy flows within the CHP system.*



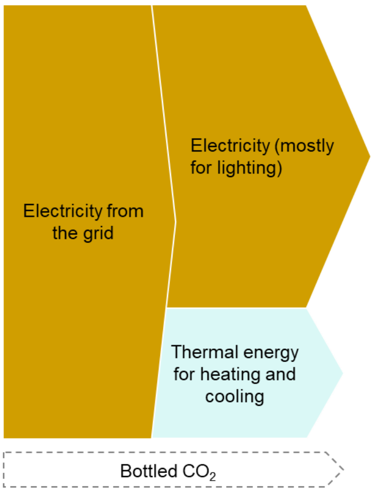
3.2.3 Energy use type 3

This use type refers to indoor and vertical farming, where crops are grown at high density in closed, insulated buildings or containers without natural sunlight in a multi-layered/stacked configuration.

All light is supplied by electric artificial lighting, and internal climate is controlled via electrical heat, ventilation and cooling (HVAC) and dehumidification systems. Electricity is the main, and often only energy source, and is also used for other operational processes including irrigation and automation. Demand for cooling is generally much more significant than heating in vertical farms, because the lighting itself, even highly efficient LEDs, is a significant heat source. CO_2 needs to be purchased separately for these operations, mostly in the form of liquid CO_2, although required at much lower quantities compared to large glasshouses due to the closed nature of the operations. Crop types grown under these conditions are currently: non-flowering, leafy greens, such as lettuce, herbs.

Figure 9 Energy use type 3 indicative energy demand profile

Energy requirement: Heating / Cooling: 300kWh/m^2; Electricity: 700kWh/m^2



3.3 The importance of carbon dioxide supply in CEA

While there is a recognised need to reduce the carbon emissions of the sector, supplementary CO_2 supply is also an unavoidable requirement in modern CEA for many crop types, and the dominant glasshouse designs currently in use result in much of this supplemented CO_2 being vented to the atmosphere.

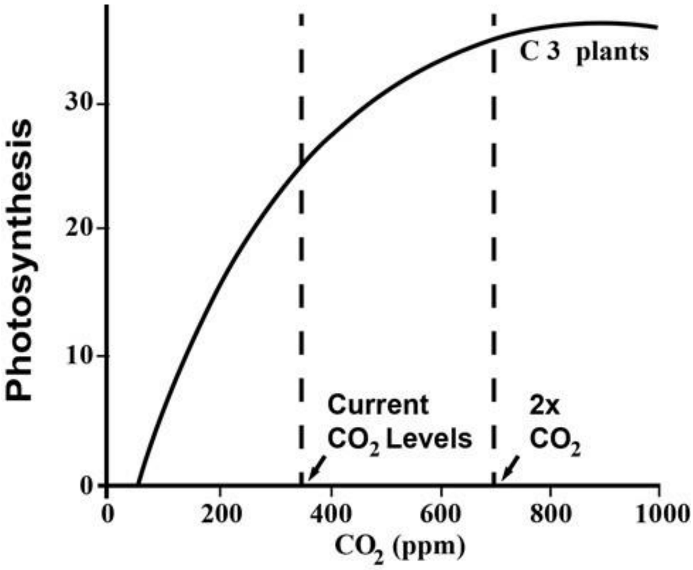
CO_2 enrichment of the glasshouse atmosphere plays an essential role in ensuring crops deliver fully on their photosynthesis potential, increasing growth rates and biomass production, enabling plants to reach maturity more quickly, and helping to reduce transpiration so increasing water use efficiency.[55] CO_2 levels can quickly drop during photosynthesis in enclosed environments where crops are planted at high density and proximity, particularly so during peak sunny days, and if CO_2 levels are not replenished crop growth and plant health can suffer. Moreover, depending on crop type, CO_2 enrichment (typically about 800 ppm to 1000 ppm for tomatoes) can increase yields by 30-40% relative to ambient atmospheric CO_2 levels of about 380ppm, as illustrated Figure 10.[56]

In smaller glasshouse operations it is possible to grow without supplementary CO_2 although yields will be reduced. However, in all industrial-scale high intensity growing operations CO_2 enrichment is considered essential.[iv]

[iv] Opinion of industry experts consulted for this study

Figure 10 Relationship between CO_2 levels and plant growth

For plants such as tomatoes, peppers (C3 plants).[v]
Source: Keiser and Drennen, 1993 [57]



Traditionally CO_2 supply has been coupled with the energy supply system, with flue gases from gas boilers, gas-fired CHP, and kerosene or propane air heaters being the most used sources of CO_2 in CEA. However, the requirement for CO_2 supplementation does not completely match the need for heat supply – that is, enrichment requirements are highest due to high photosynthesis rates on summer days when heating requirements are minimal, while peak heating demands are highest in the winter months when supplementary CO_2 is barely needed. This means a significant surplus of CO_2 is generated over the course of the growing season, while in summer months storage systems are required, and, or possibly running boilers or CHP even when heat is not required.

Additionally, only a fraction of the CO_2 supplied to enrich the glasshouse environment is sequestered by the crops because conventional Venlo glasshouses use window vents to control temperatures and humidity that releases much of the CO_2. Reliable data on CO_2 use is difficult to find, but an Agriculture and Horticulture Development Board (AHDB) report in 2019 suggests that a CO_2 dosing capacity of 70-130 kg/ha/hour is needed to achieve an atmosphere of 900ppm when glasshouse vents are closed, rising to 580+ kg/ha/hour when vents are full open. In summer particularly, with glasshouse ventilation windows fully open, it can be challenging to maintain high CO_2 levels.[17]

Gas fired CHP has traditionally been the most cost-effective source of CO_2. In 2019 the cost of CO_2 from burning natural gas solely for CO_2 was about £68/tonne, whereas from a CHP plant about £20/tonne. Growers using CHP might even consider the CO_2 a 'free' by-product if they are exporting electricity to the grid at a higher price than the operational costs of the CHP. This compared with £65-120/tonne for bottled CO_2 depending on the source – typically fossil-fuel based and supplied from the ammonia/fertilizer industry.[17] In 2022, with natural gas prices

[v] C3 refers to the most common of three metabolic pathways for carbon fixation in photosynthesis. C3 plants include around 95% of the world's shrubs, trees, and plants.

at an all-time high, prices for CO_2 are almost eight times 2019 rates. Any transition away from fossil fuels and CHP needs to consider how supplementary CO_2 might be provided in a carbon neutral and cost-effective way in the future.

For reference, for a conventional industrial Venlo intensive glasshouse operation for tomato growing, AHDB estimates CO_2 usage requires a supply of 1200 tonnes of CO_2 per hectare per year, which for the tomato sector overall over 225 hectares represents 0.27million tonnes per year (based on average application rates of 370 kg/ha/hour, 12-hour days and 270 day growing season). At £80/tonne, CO_2 enrichment costs the UK tomato industry almost £21.6 m per year.[58] Of this, an AHDB study determined CO_2 offtake (used by the crops for photosynthesis) ranges from just 6.2% to 26.4% representing significant waste.[58] Moreover, the required supply represents only about 20-30% of the CO_2 that is annually generated by a typical CHP system sized for the heat requirements of the glasshouse, with the balance exhausted directly to the atmosphere.[vi]

3.4 Summary

The first step in reducing energy use and decarbonising any sector is to introduce energy efficiency measures. The spectrum of energy efficiency measures in CEA ranges from simply improved maintenance procedures through to sophisticated gene editing of crops, as described in detail in Chapter 4.

Beyond demand-management approaches, decarbonisation of the energy supply is key. A shift away from natural gas as the main energy source in the CEA sector, in particular for heat generation, has become an economic imperative and a prerequisite for decarbonising the sector. However, a shift away from natural gas CHP creates a challenge around the supply of supplementary CO_2 for growing operations. Solutions for decarbonisation of energy generation and supply, along with alternative sources for CO_2, are described in Chapter 5.

[vi] Advice provided by expert advisors based on Low Carbon Farming project.

4 Demand-side energy efficiency measures in CEA

Compared to other buildings, glasshouses are inherently inefficient with regards to preserving heat, as the need to maximise the amount of natural light results in the use of low U-value cladding materials such as glass – consequently significant energy can be lost through the glass on cooler days and nights. The use of ventilation windows to moderate temperatures and humidity is standard practice in conventional glasshouses, with the air exchanged frequently throughout the day due to ventilation and leakages, resulting in significant loss of thermal energy and supplemented CO_2.

The role of efficiency improvement measures must be considered within this context, with recognition that there are limits to what is achievable, and even the best operations are highly energy intensive. This implies that decarbonising the energy supply is of paramount importance on the path to net-zero. Notwithstanding this, for established operations retrofitting or replacing entire energy systems is often financially or technically unviable. Therefore, in the short-term, efficiency improvements that aim to reduce energy consumption, and so reduce operating costs and reduce emissions may be more affordable and expedient. Moreover, for any new builds, efficiency measures should be at the forefront of design considerations from the outset.

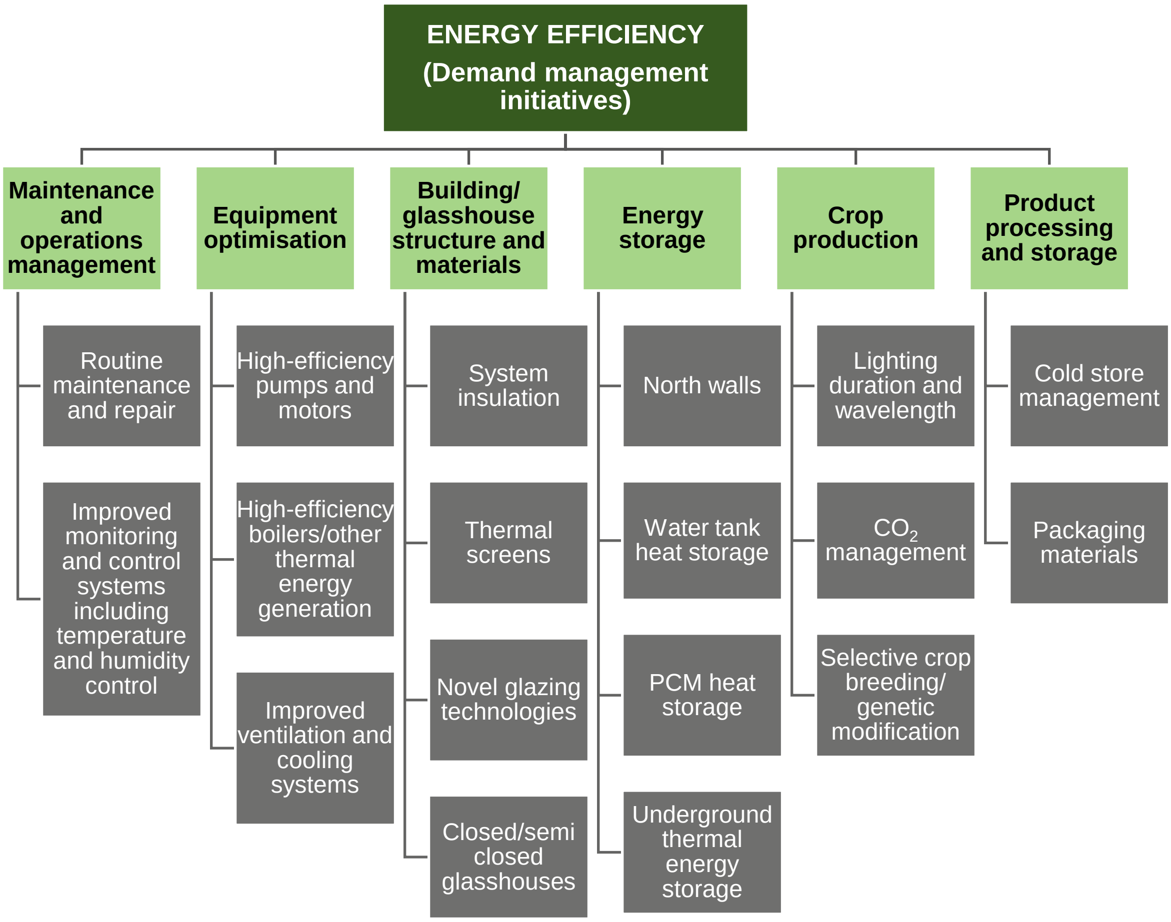
Over the past decade there has been improvement in efficiencies across the sector, facilitated in part by the Climate Change Agreement (CCA) scheme (see 6.1.2.1).[59] According to the interviewed industry experts, the most cost-effective solutions have been deployed widely, and the latest large-scale builds in the UK have incorporated the best available technologies. Such energy efficiency improvements often make sound business sense and should be pursued even when a fully decarbonised energy supply system is in place.

This chapter explores the more significant efficiency measures, many of which are now proven technologies. Figure 11 presents a summary of these measures, based on 2019 and 2021 efficiency scoping exercises by the UK Agriculture and Horticulture Development Board (AHDB), existing literature reviews, and validated with input from our expert panel.[10,17,60,61]

Figure 11 Summary of main efficiency measures identified for CEA

Developed from AHDB report prepared by Townsend et al., 2021[60]

(For completeness, product processing and storage are included this figure, but are beyond the scope of this study).



4.1 Maintenance and operations management

4.1.1 General efficiency measures

As a starting point, good energy management practices including ongoing monitoring and appraisal, regular equipment maintenance and sensor recalibration, and prompt repair, can deliver energy savings of about 10% with little or no additional cost.[17] For example, maintaining good sealing between panes of glass, and repairing broken panes promptly. Cleaning the glazing of glasshouses (inside and out), and cleaning thermal screens, can enhance sunlight transmission, hence growing conditions, with studies in the Netherlands indicating a 10% increase in light transmission can reduce energy consumption by 2%.[17] Automated glass cleaning systems and practices to avoid dust and algae build up on screens are advisable and a majority of growers are already doing this, even if not fully automated.

General efficiency measures require allocation of responsibility for energy use to a key individual, appropriate training, ideally a defined energy policy document, and may require some new investment in sensors, but according to AHDB, in general, particularly for larger operations, these costs will be easily recouped in energy savings.[17] That said, experts interviewed for this study suggest the majority of the UK industry, particularly the larger operations, is already well run so further opportunities for improvements in this area are limited.

4.1.2 Intelligent solutions for energy optimisation

Energy monitoring systems enable a systematic and transparent data capture and provide a basis for comprehensive analytics. The data helps to link energy demand to production and identify key influencing factors. Energy efficiency measures can be derived from the findings, and their implementation progress and effectiveness can be continuously monitored, and readjustment interventions undertaken as required. Monitoring equipment can be purchased directly or purchased as a service to provide real-time assessment of pulsed supplies (water, electricity, gas, CO_2), alongside data on temperature, humidity, CO_2 levels, and crop growth, and data on external climatic conditions (temperature, solar radiation, and windspeed) and external weather predictions which are essential to understand and control variations in internal energy use.

CEA is already advanced in these monitoring technologies and systems for controlling growing conditions (e.g., control systems providers such as TomTech[62] from the UK, and Hoogendoorn[63] and Priva[64] from the Netherlands). But as industry experts suggest, there is a requirement for greater education and a need for greater experimentation, e.g., with different set-points, to enable growers to get more out of these systems. Although climate control systems are advanced, installation of more distributed sensors throughout the glasshouse operations would be beneficial to enable more localised control and more uniform growing conditions. The currently most advanced engineering integration of control systems in glasshouse design is called Next Generation Growing (NGG), named after a Dutch initiative that started over ten years ago with the aim to make NGG the industry standard for CEA in the Netherlands. NGG practices and newly built glasshouses have meanwhile been implemented in a number of UK operations over the same period. NGG has two aims, namely to optimise glasshouse conditions for maximum plant growth and yield, and at the same time, to minimise heat and overall energy consumption – hence also contributing to energy efficiency and sustainability goals.[65] Solutions for optimising performance are now emerging using wireless sensors, vision systems, Internet of Things, digital twins, AI, and so on, to provide real-time automated monitoring and continuous adjustment of temperature, humidity, CO_2, air circulation, light, and nutrient supply, to watch for symptoms of fungal disease, and to optimise growing conditions and yields.[66,67]

While the use of advanced sensors and systems to regulate internal climate conditions likely has benefits for energy use and emissions, there are a lack of case studies or evidence, particularly in the UK context, and so the potential scale of benefits are not well understood to date.[60] Moreover, many operators measurement of energy use is only at the site level, but more detailed submetering can help identify underperforming areas within the operation. Variations in performance plotted over time are often a good indicator of inefficiencies or problems in the system, and opportunities for comparison with other growers or industry benchmarks can often prove insightful. “Degree-days” are a standard industry measure of heating or cooling and can be used for planning the planting of crops, for energy monitoring, benchmarking with other operations, and for estimation of future costs.

Networked machine learning also offers the potential for the industry to rapidly learn from experiences across the entire sector, and for example, to factor in broader climatic changes, and prepare for forecast heatwaves, higher solar radiation, storms, and other external variables that can influence performance. However, although technically feasible and demonstrated in academic research, lack of available data and standards for data collection, combined with commercial sensitivities and resistance to sharing of data, has to date limited the application.[68]

4.2 Equipment optimisation

4.2.1 High efficiency motors and pumps

Electrical motors, fans and pumps are used extensively in CEA operations for heating (circulation of heated water), ventilation fans for air and CO_2 circulation, irrigation and supply of nutrients, actuators to open and close vents, and increasingly for automation. Older legacy motors are often operated at partial load, with the motor running at full speed, while the flow is controlled mechanically with valves or brakes. This introduces inefficiencies and waste. Variable speed drives are now widely available which allow motor speed and torque to be controlled directly, avoiding this waste, offering improvements of up to 30% energy savings over older legacy operations.[52] Data on the uptake or otherwise of newer motors and pumps is not available for the UK CEA sector specifically, but for example, it is estimated that 60% of industrial motors in use in the US are over a decade old and would benefit from upgrading.[69]

4.2.2 High efficiency boilers and heaters

Boilers with condenser units are now widely deployed, with seasonal efficiencies approaching 90%.[17] This compares with older technologies that can be less than 70% efficient. The industry experts consulted for this project observe that the large-scale CEA operators in the UK have largely transitioned to these more efficient technologies already where it made economic sense, but there may still be some opportunities for upgrading technologies to enhance efficiencies, in particular on smaller/older CEA sites that operate old boilers. For example, larger heat exchangers to ensure optimum heat transfer, higher levels of insulation, accurate control of the air/fuel mix, and careful matching of the boiler with the load to ensure returning water temperature is kept low enough to allow condensation to occur. Additionally, growers should consider whether one single large boiler or several smaller boilers might be more efficient. Multiple boilers are more expensive and require more maintenance but allow better matching of demand and can reduce transmission loses across a large site.[8,]

A related issue is the requirement for insulation of pipework, valves, and flanges, which can be major sources of heat losses. Investment in insulation such as aluminium clad glass fibre, and rock mineral fibre for unclad warm surfaces can reduce loses by more than 90% in some cases, with payback in less than two years.[17] It is widely adopted, but there might be still potential on older sites with degraded insulation.

It should be noted that even with the transition to innovative new energy supply systems, there will always remain a need for low-cost emergency back-up heating systems to protect crops in the event of a system failure – if a heating system fails there is risk of losing the entire crop and hence the entire year’s revenue, so a back-up is critically important. These backup solutions are typically gas boilers or kerosene or propane air heaters. While they may not be used extensively, optimising for efficiency should still be encouraged, as any forced extended use could significantly impact on operating costs.

4.2.3 Improved efficiency of ventilation and cooling systems

Ventilation and cooling systems are a key requirement for vertical farms and are also relevant for refrigerated storage of crops before distribution. In order to achieve higher energy efficiency of the HVAC systems and to reduce the need for thermal energy generation and de-/humidification, it is important to have a detailed understanding of the requirements of the humidity and temperature levels, allowed pollution thresholds and the inner thermal loads. Often, adjusting the temperature to the level actually needed is the first easy-to-implement and effective measure. Various demand-side measures can be considered such as:

- Air velocities and air exchange rate reduction: thermal energy demand (for cooling) and electric energy demand of the fans are determined by the air exchange rate.
- Heat and moisture recovery help to reduce energy demand on the generation side to up to 45%.
- Reduction of leakages.
- Insulation of rooms and doors/windows as well as pipe system.
- Keep heat exchanger surfaces clean.
- Intelligent control systems support demand-driven thermal energy generation.[70]

The selection of the technology to supply cooling systems depends on the targeted temperature level. In general, it can be differentiated between passive and active cooling. The passive cooling systems, i.e., dry cooler, cooling tower or hybrid cooler, use the ambient air to transport the heat generated by convection or (water) evaporation. Therefore, their performance may be insufficient during the warm season. The functioning of the active cooling systems is based on a thermodynamic cycle process. Their performance depends on the target temperature and selected refrigerants. They can be powered electrically, e.g., compression chiller machines and heat pumps, thermically through utilisation of for instance waste heat streams with absorption and adsorption plants, or mechanically.[70]

Exploiting the potential for passive cooling can help to reduce energy demand and thus energy costs. However, if the output is insufficient, additional potential can be found by exploiting synergies, for example, by using an existing waste heat flow or by coupling a heat sink and a cooling sink with a heat pump. Co-location of refrigeration systems or vertical farming operations with heated CEA operations can offer beneficial heat exchange opportunities to enhance efficiencies, albeit seasonal matching of sources and sinks may be problematic.

There is a potential for learning from cooling systems of data centres in two aspects. When the first data centres started their operation, energy efficiency was not a focus topic for them, and they just installed air conditioning. However, data centres tend to overheat even during cold periods. Appropriately filtered and clean ambient air can be used for passive cooling in winter rather than operating air conditioning that has high electricity demand. Moreover, there are advantages of co-locating CEA and data centres. For instance, the excess electrical power from a CHP at a CEA site can be utilised as demonstrated in the Agriport data centre area[71] in the Netherlands, or data centres can be a waste heat source for CEA.

Adoption of the energy efficiency measures and latest cooling technologies may yield energy efficiency improvements of up to 30% [52], and in addition, remove GHG warming gases traditionally used as refrigerants.

4.3 Building/glasshouse structure and insulating materials

4.3.1 System insulation

Some solutions are already well established to improve insulation in CEA. Insulating the wall areas that are not important for sunlight, primarily the lower part of north walls (~1m hights), reduces energy losses with minimal impact on crop growth for operations in latitudes like the UK, and can have a payback period of less than 2 years.[17] Additionally, external windbreaks such as plastic screens or trees and shrubs can be useful to reduce airspeed over the glasshouse and hence slow heat loss – although it is important that they do not result in crop shading. Windbreaks should be placed on the north and northwest sides of the glasshouses, and are estimated to have potential to reduce annual heating requirements by 5-10%.[61]

4.3.2 Thermal screens

Retractable fabric thermal screens (thermal curtains) are now commonplace in modern glasshouses. Such screens form a false ceiling between the glass roof and the crops below and are installed on mechanical rollers so they can be retracted during the day to allow light into the glasshouse. Various materials are used for thermal screens, including aluminised thermal screen, isotex 60, polyester screen, black polyethylene, polypropylene monofilaments, and ethylene thermal screen.[61] Screens minimise thermal losses at night and can also be used to provide shading and protection against over-heating on sunny days. As the UK looks to increasing frequency of heat waves in the coming decades thermal screens to protect against over-heating seem likely to become more important.

Double screens and even triple screens are now in use, with variations in permeability and light transmission that allow screens to be used during the day and to assist with temperature and humidity control. For example, water vapour can pass through the screens and be vented above the screens without the need for additional heat, representing significant energy saving.

Screens are relatively inexpensive and are readily retrofitted to most glasshouses, and studies have demonstrated energy savings of 20-60% depending on the location and external climate and materials used.[61] Average energy savings of 20% are generally considered possible in large commercial glasshouses.[10,17,60,61] Screens do have some limitations in that they block some of the available sunlight even while retracted, and add weight and cost to the glasshouse structure, but the benefits outweigh these costs and as a result adoption of screens is already widespread and well-understood. Given widespread deployment already, the potential for significant further contribution to efficiency improvements of the sector may now be limited.

4.3.3 Innovative glazing materials

Innovation in glazing technologies for glasshouses aims to increase sunlight transmission, enhance thermal performance (reduce heat losses, and moderate incoming solar thermal heat), and reduce manufacturing costs. The choice of glazing generally represents trade-offs between these three dimensions.

Double glazing is available to enhance insulation performance, but it is expensive and impacts on light transmission levels (a 1% drop in light transmission is associated with a 1% drop in plant yield)[17], and requires significantly greater structural materials to support the increased mass, and consequently single glazing remains the most widely used option to date even in the newest CEA operations (e.g., Low Carbon Farming discussed in Annex A). However, to achieve considerably lower energy use, a number of novel glasshouse designs are currently coming on the market, such as 2SaveEnergy greenhouse (which uses a double walled section with a layer of glass and a layer of film)[65], and VenloW-energy® [72] claiming 50-70% less energy use due to innovative glass properties and coating technologies.

Other recent innovations include novel coatings for glass, and new polymers such as ETFE (Ethylene tetrafluoroethylene). The benefits of new light-weight polymers are that double-walled sections are more affordable offering greater thermal insulation, they allow UV to reach the plants which has been proven to be beneficial to support growth, and are available in a variety of shades enabling specific light wavelengths to be selected to suit the crop. ETFE also has a non-stick surface providing resistance to mould, chemicals, and making them largely self-cleaning.[73] Polymer panels can be retrofitted to conventional glasshouses. Moreover, for new builds the use of light-weight polymer materials offers significant benefits in terms of the glasshouse structure, requiring fewer steel supports, and a reduced need for concrete foundations. This delivers capital expenditure savings and significantly reduces the embodied carbon emissions in the structural materials.[74] Reduced structure also reduces the effective shading within the glasshouse and so further aids crop growth. One disadvantage of polymer-based greenhouse panels at present is the need for changing them after several years as light transmission degrades with aging of the material, although newer materials are tackling this problem.

A related area of innovation is the introduction of diffuse glass that is etched to better scatter sunlight to the crops and reduce harsh light and shading – this is more expensive, but research has shown that relative to unetched glass, yield improvements of 5-10% and shortened growing times may be achievable for certain crop types.[17] Diffuse polymer panels are also available.

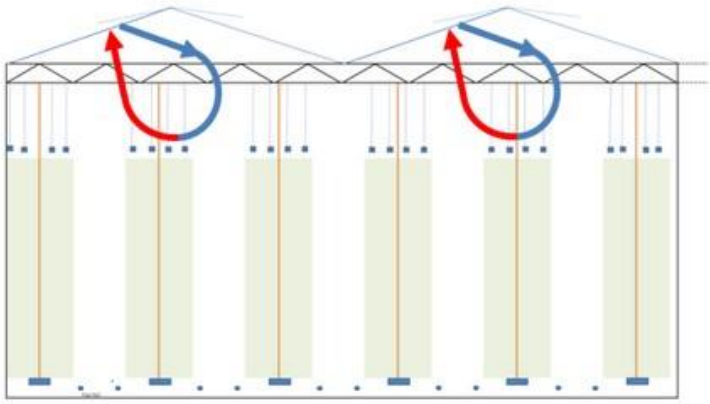
4.3.4 Closed/Semi-closed glasshouse systems

A significant percentage of thermal energy demand in conventional glasshouses is attributed to air losses, estimated to be between 5% and 30% of instantaneous energy demand.[17] Conventional glasshouses vent warm air by design to release humidity and alleviate excessive daytime temperatures, and consequently the air inside a typical glasshouse is exchanged once every one to two hours, or even much more in summer months. While this method is well proven and requires only simple technologies it is not an efficient use of energy nor supplemented CO_2.

Solutions to this issue are closed/semi-closed glasshouses (Figure 12) or closed vertical farm operations. In such systems air leakage/exchange is minimised by design of the building structure and the ventilation systems, with window ventilation replaced partially or fully by mechanical ventilation systems that regulate air exchange, treat the air to moderate humidity, and in some systems extract and store heat for later reuse.

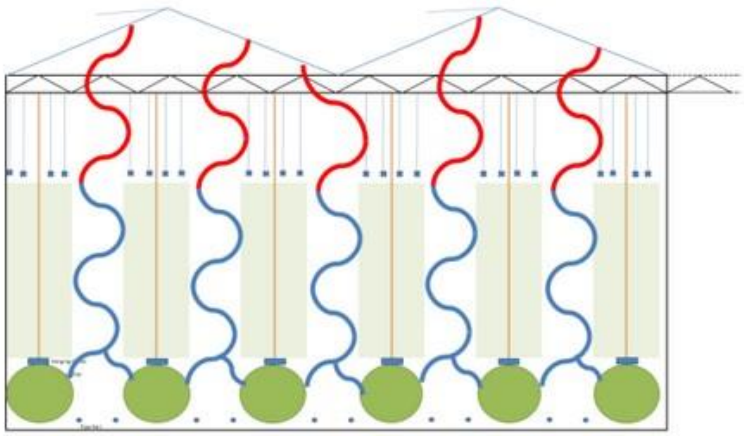
Figure 12 Comparison of airflow in conventional and semi-closed glasshouses

Source: Godfrey Dol (2019) [75]



Conventional glasshouse

The green areas represent fully-grown vine crops. In conventional glasshouses most of the air exchange occurs above the crop through the roof windows. Internal temperature is largely determined by external conditions.



Semi-closed glasshouse

Air enters the glasshouse from the bottom, and to leave must move upwards past the plants. Air can vent through pressure-relief vents in the roof, or in a fully closed system is recirculated

In closed and semi-closed systems, the airflow is quite different from a conventional glasshouse, as illustrated in Figure 12. This allows greater control over the growing environment, and homogenous growing conditions throughout the glasshouse in terms of temperature, humidity, CO_2 concentration, can reduce evaporation so make better use of water resources, and can decrease risks of pests and disease so reduce needs for pesticides.[76] Importantly, closed or semi-closed glasshouses enable growing conditions that are not possible in conventional glasshouses – that is, conditions of high light intensity plus high CO_2 concentration with a low rate of CO_2 supply (peak summer growing conditions when heat is not required).

The available data on the benefits of these systems is limited, and benefits will vary depending on the operating environment and the external climate, but nonetheless, studies have shown that semi-closed glasshouses can reduce the requirements for supplementary CO_2 by 50-80% during peak summer periods where much of the CO_2 in conventional greenhouses is lost through open ventilation.[77] Moreover, by enabling higher CO_2 concentrations to be maintained within the glasshouses, semi/closed glasshouses have been show to enhance crop yields by 5-8%.[77] Studies of semi-closed glasshouses in Belgium demonstrated lower gas consumption for heating, but greater electrical power requirements for additional cooling, with an overall energy saving of about 20% compared to conventional glasshouses.[77,78] A similar study in

Germany demonstrated overall energy savings of 43% when semi-closed glasshouse was combined with energy storage.[77,79]

A downside of these systems is that temperatures increase if the system is closed, requiring much higher electricity to power the mechanical ventilation system (fans especially) and active cooling. Cooling can be a particularly significant factor for fully closed glasshouses, and consequently various studies have concluded that semi-closed operations may be the more energy efficient and cost effective option.[77]

These systems require a more complex design of the glasshouse or vertical farm, which is a closed system with forced air circulation, fans to pressurise the glasshouse, dehumidifiers, cooling systems and heat exchangers to extract excess heat, and more sophisticated automated monitoring and control systems. An integral element of such systems is also ideally a large heat sink or seasonal storage (see 4.4.2) to enable the heat extracted from the building to be stored for later cost-effective reuse. Consequently, while there can be significant benefits of semi-closed and closed glasshouses, significantly higher capital costs, and the more sophisticated operational demands they entail have limited their financial viability to date. This, combined with uncertainties over perceived risk factors such as fungal growth for some crops has also limited interest and uptake in the glasshouse sector. The fact that such systems are not widely deployed at a commercial scale in the Netherlands, where they were developed, points towards their limited economic viability at present.

These systems seem most relevant for extreme hot or cold climates, while in the UK only one large-scale semi-closed glasshouse has been built. This was the £15million 5.6-hectare Sterling Suffolk site, which commenced operations in early 2019. Despite its purported 25% efficiency benefit over conventional glasshouses, the energy crisis of 2022 forced the business to close.[80] The business has been bought out of administration, but it is not currently known when operations will recommence (see Annex A for further details of Sterling Suffolk).

Vertical farm operations are highly sealed environments already, and are successfully operating in the UK, and so there may be potential for technologies and experience developed in the vertical farm space to inform future glasshouse development (see Annex A for further details of Jones Food Company).

4.4 Energy storage

Thermal energy storage (TES) systems for short-term diurnal (daily) storage are well established technologies and easily implemented. Longer-term and seasonal storage can utilise similar technological solutions and they become increasingly important for the transition of energy systems not only in CEA but across all sectors due to the rising fluctuation of generation from intermittent renewable energy sources. Their wider implementation will be a tipping point of the energy transformation. However, currently the realisation of most types of longer-term and seasonal storage including underground seasonal storage solutions is difficult in respect to economic viability.

4.4.1 Short-term, diurnal, thermal energy storage

4.4.1.1 Solid north walls

Solid north walls are discussed in the literature for their role as cost-effective passive energy storage[17,61], however, their utility in large-scale CEA is negligible.[60] Solid north walls in glasshouses absorb excess heat during the day, and then slowly release it back into the glasshouse during the night/cooler periods. A highly insulating layer is used on the external surface to minimise losses, and a dense material such as brick, clay or concrete able to absorb significant energy on the inner surface. Some wall solutions also incorporate additional thermal storage, as discussed below. Reduction in energy losses of 35-50% are estimated to be possible from installation of north walls in small glasshouses.

4.4.1.2 Large insulated hot water tanks

Hot water tanks are an integral part of most modern glasshouses, used to smooth out the highly variable heat demand of a CEA and maximise the efficiency and use of CHP, biomass boilers, heat pumps etc. as well as to provide backup storage for heating systems. They can be used to store excess heat generated from boilers and CHP units when these are operated for CO_2 generation during the day, for use of the heat later in the day/night when CO_2 is not required. Typically, they are sized for diurnal requirements, but larger storage capacities are feasible, albeit bulky. Water tanks may also be used to buffer heat supply from intermittent industrial waste streams. In combination with electrically driven heat pumps, water tanks can be used to capture and store excess solar thermal energy that builds up during the day within larger glasshouses, for later reuse. The tank material and insulation are key factors determining efficiency.

4.4.1.3 Phase change materials

Phase change materials (PCM) are materials with high latent heat storage capacities that change states at constant temperatures and can therefore store large quantities of energy. Examples include ice, salt hydrates, paraffins and polyethylene glycol.[47,81] PCMs can be used in similar ways to water tanks but offer more compact solutions, but in general space is not a constraint for CEA and hot water tanks are equally effective so PCMs are not common in CEA. However, an under-explored application for PCMs maybe in providing longer-duration storage (days or weeks) to facilitate greater smoothing of energy flows – compact thermal storage becomes more important for larger quantities of energy, and research is ongoing to develop PCMs that are better able to retain thermal energy over longer periods.[82,83] From a theoretical perspective, such systems using heat pumps might be used as a means of benefiting from off-peak low-cost electrical energy and storing it as thermal energy as a form of grid load balancing during periods of over-supply. However, the combination of heat pumps with insulated hot water tanks is the sufficient solution for the CEA requirements at present.

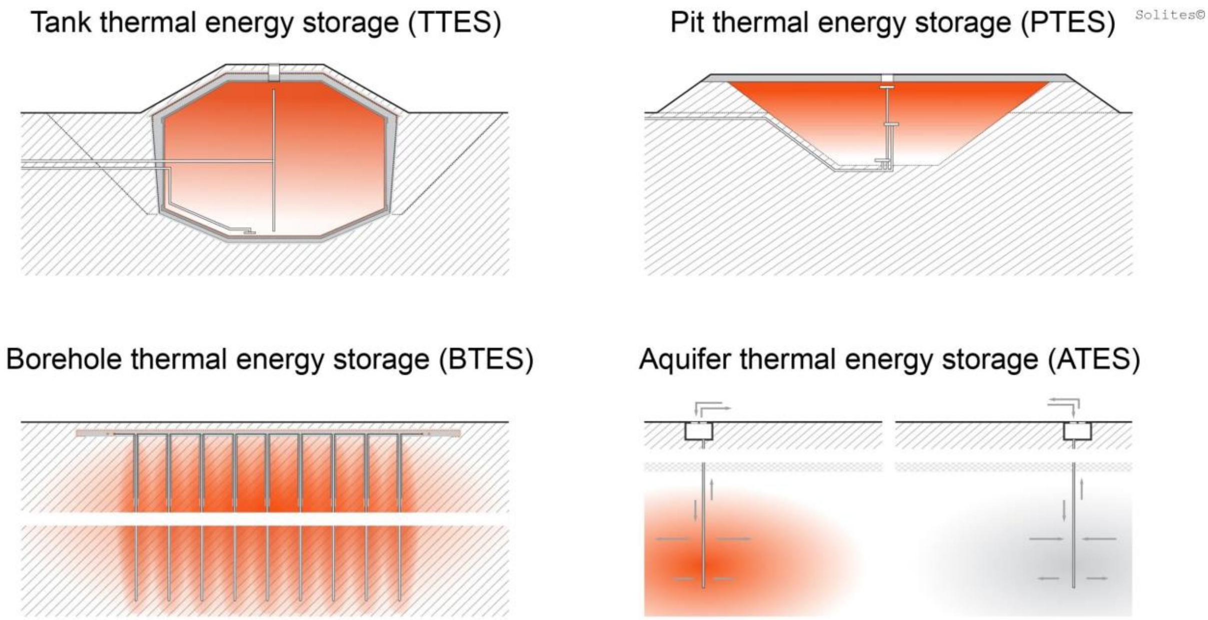
4.4.2 Seasonal thermal energy storage

A closed glasshouse can accumulate two or three times its own energy requirements for annual heating in latitudes like the UK and the Netherlands, so a system for long-term seasonal storage that can extract excess heat during the summer for use in cooler periods of the year can eliminate the need for supplementary heating. A semi-closed glasshouse will not accumulate as much thermal energy, but still seasonal storage can considerably reduce supplementary energy costs. Trials in the Netherlands demonstrated semi-closed systems to be overall more economical than fully closed glasshouses, due to the higher cooling capacity requirements during summer months associated with fully-closed systems in the Dutch climate, and could deliver 20-30% savings in primary energy use, but at the time due to the price for electricity vs gas it was more economical to use CHP with a standard glasshouse.[84]

Various underground thermal energy storage (UTES) systems are available and proven mature technologies, see Figure 13, but the costs of large excavations, or drilling bore holes, remain a significant barrier to adoption, making them only suitable for large-scale schemes such as district heat networks.

Figure 13 Large-scale thermal energy storage systems

Source: IEA Technology collaboration programme [85]



Aquifer and bore hole thermal storage are proven in the Netherlands for CEA, particularly in ornamentals such as orchids where there is often a need for both heating and cooling together throughout the growing season which makes such storage systems more viable. These two options for UTES are discussed below.

4.4.2.1 Aquifer thermal energy storage

Aquifer thermal energy storage (ATES) systems capture surplus energy from glasshouse operations during the summer months using heat exchangers to store the energy in underground aquifers at usually between 20 to 200m depth depending on the geology, at modest temperatures of about 20ºC for reuse during the winter. In this system heat pumps are used to raise the temperature of stored heat to levels suitable for horticulture operations. An ATES system constitutes two wells (1 doublet) storing heat in an underground aquifer, as Illustrated in Figure 13. The technology is predominantly used for buildings and district heating/cooling schemes, and the Netherlands is the market leader with about 3,000 of the 3,500 operational ATES across the world to date. Characteristics that make the Netherlands particularly well suited to ATES are suitable geology and aquifer resources, high density of buildings which makes large-scale ATES district schemes viable, and advanced drilling and hydrological and geological expertise from the oil and gas sector. In the Netherlands, policy has also played a role in encouraging adoption, with building efficiency requirements creating a market for these technologies. The coefficient of performance (COP) of an ATES system in cooling mode can reach as high as 10-20, compared to just 4 for a ground source heat pump (GSHP). In heating mode COP is 5. Upfront fronts are high, possibly as much as £1m per hectare of glass, but typically costs are recouped within 2-10 years (see Annex A, case study of Koppert Cress for an example of ATES from the Netherlands.[86]

Due to differing geology and aquifer flow rates the UK is thought to have fewer suitable sites for ATES than the Netherlands, and experience with ATES in the UK is therefore very limited in any sector and there are no known examples in CEA in the UK at present.

4.4.2.2 Borehole thermal energy storage (BTES)

Where there is no suitable aquifer, which may be the case in many parts of the UK, subsoil can be used for thermal energy storage. In such case a series of boreholes are used that act as heat exchangers to transfer thermal energy to and from the ground, as illustrated in Figure 13. Again, heat pumps are used to raise the stored temperature to levels suitable for CEA operations.

4.4.3 Electrical energy storage

For CEA operations using CHP for electrical power generation, or with onsite renewable energy generation, it may be cost effective to store excess electricity locally in chemical batteries rather than export to the grid at wholesale feed-in rates.

Onsite battery storage also provides the opportunity to take in cheap power during off-peak periods or periods of surplus renewables generation, for use later during periods where energy costs are higher. As such, the CEA operation can benefit financially, while increasing its independency from the public electricity supply by using own onsite renewables as well as also using the storage capacity to contribute to national grid balancing. However, the cost of chemical batteries remains high, and the current economics do not justify the investment, limiting the likely application at present.

4.5 Enhanced crop production

4.5.1 Novel lighting solutions

Lighting for glasshouse operations and vertical farms have evolved significantly over the past decade. High-pressure sodium (HPS) lamps have been and remain the preferred choice for glasshouse growers, in part because their contribution to growing is well understood, and because they provide some radiant heating that can be beneficial for growth. However, with innovations in high efficiency light-emitting diodes (LED), growers are now beginning to transition to LED lighting. In contrast, for vertical farms, lighting is a significant source of unwanted heat, and low energy lighting can significantly reduce the cooling demands and hence operating costs of the operation, and so LEDs are already the preferred option. Growers still using HPS lighting may see a significant reduction in energy costs by switching to LEDs, and as LED technologies continue to evolve even operations that are already using LEDs may find it advantageous to upgrade to the latest technologies. This can save up to 70% of electricity needed for lighting.[52]

An additional benefit of LED lighting is the potential to 'tune' the colour spectrum of the light to the specific crop type and the stage in the growing cycle to target photomorphogenic, biochemical, or physiological responses, and maximise photosynthesis performance. Tuning of LED grow lights is an area of ongoing development in the edibles glasshouse sector, but it is already established in vertical farming where, for example, broadband red light can promote dry mass gain and leaf area expansion for leafy greens. LED tuning is also used widely in the ornamentals sector with specific wavelengths used to help control the seasonality of flowering plants, for example, to accurately schedule uniform flowering based on predetermined market dates.[87] In general, controlling the light spectrum can affect fruiting, flowering yield, growth rate, compactness, biomass weight, stem length, root development, plant health, colour, flavour and nutrition.[88] However, light spectrum is just one factor and response will depend on crop type, light intensity, duration of exposure, stage of plant development, and other environmental factors. Furthermore, specific wavelengths can assist in controlling physiological disorders in plants, and pest control, e.g., ultraviolet LEDs can effectively control powdery mildew in strawberries, and blue light can inhibit black leaf mould in tomatoes.

Research is also ongoing to determine optimum timing and intensity of lighting – for example, periods of intense light, longer lighting periods to simulate longer days, and dynamic adaptation of light spectrum over the growing season. In some trials with lettuce growing pulsed light has been demonstrated to deliver the same level of growth with reduced energy input.[89]

Oversupply of light is unbeneficial so to save energy, growers should ensure lighting systems are designed to reduce supplementary lighting when natural sunlight is available. Positioning of the lights is also an important consideration to minimise shading, allow for radiant heating of lamps, and ensure optimum photosynthesis. For the majority of growers, both measures are already a standard mode of operation.

4.5.2 Crop selective breeding/genetics

An alternative approach to energy reduction/decarbonisation is to reduce or remove the need for heating and cooling in the first place by selecting crops that are better suited to growing in ambient protected environment. In the UK this means selecting crops that are better able to thrive in cooler growing conditions and survive out-of-season cold nights. Studies in the Netherlands in the past explored selective breeding for crop hardiness, and some naturally occurring varieties are found to be better suited to cold than others. However, although these studies did yield positive results, these plants also perform better with heat and so in an era of cheap energy, growers chose to continue, and indeed expand high-temperature growing operations.[vii] Use of supplementary CO_2 to enhance growing necessitates use of higher temperatures. As growers now face high energy prices and pressure to decarbonise, lower temperature CEA may potentially regain some appeal.

Genetic engineering and gene editing may offer the potential for further innovation in edibles, and research work is ongoing to enhance yields, disease resistance, and so on.[90] The experts

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[vii] Information obtained during expert interview with Wageningen University

consulted for this work were sceptical of the prospects for step-change improvements in crop yields of the primary crops such as tomatoes, but recently announced successes in increasing photosynthesis performance of soy by 20% through gene editing offer an example of what may be possible in the future.[91] Although there has been a proposed relaxation around regulation of gene edited crops (The Genetic Technology (Precision Breeding) Bill is currently going through parliament)[92], societal resistance remains high in the UK and Europe, so large-scale deployment of modified crops seems relatively unlikely in the short to medium-term.

5 Technical options for decarbonisation of energy generation and supply

Understanding the energy demand of the CEA sector depending on crop type and energy use type as described in Chapter 3 allows reviewing of different technologies and solutions for energy generation and supply with respect to their potential for increasing energy efficiency and reducing fossil fuel use and associated emissions.

5.1 Overview of the technological options

Overall, a distinction can be made between the thermal energy demand, primarily for heating but also for cooling, and the electrical energy demand for lighting and the operation of electrical equipment. Table 1 shows potential decarbonisation options and the associated technologies to generate and supply the energy.

Table 1 Decarbonisation of energy generation and supply

<table>
<tr><th>Energy demand</th><th>Decarbonisation options</th><th>Energy Use Type 1</th><th>Energy Use Type 2</th><th>Energy Use Type 3</th></tr>
<tr><td rowspan="2">Electrical Energy</td><td>Renewable energy carriers and waste heat</td><td colspan="3">Public electricity grid, local renewable energy systems (RES) such as photovoltaics (in different implementation forms, e.g., as agrivoltaics) and wind, Steam Rankine Cycle (SRC) and Organic Rankine Cycle (ORC)</td></tr>
<tr><td rowspan="2">Alternative fuels (for co-generation of thermal and electric demand or solely for thermal)</td><td colspan="2" rowspan="2">Biogenic fuel-based CHP (incl. anaerobic digestion for biogenic fuel production), hydrogen mix or 100% hydrogen CHP, fuel cells

Thermal only: biogenic fuels and hydrogen boilers</td><td rowspan="2">n/a</td></tr>
<tr><td rowspan="3">Thermal Energy</td></tr>
<tr><td>Electrification of thermal energy supply</td><td colspan="2">Heat pumps, electric boilers</td><td>Heat pumps for cooling</td></tr>
<tr><td>Heat recovery (usage of existing external/ waste heat sources)</td><td colspan="2">Industrial waste heat, geothermal, absorption chiller</td><td>Energy efficient cooling, including cooling through waste heat (see Chapter 4.2.3)</td></tr>
</table>

The following sections 5.2 to 5.5 provide an overview of alternative energy technologies. With phasing out of fossil fuel combustion, alternative CO_2 sources will be required, which is discussed in Section 5.6. Finally, net-zero goes hand in hand with sector coupling, bringing traditionally distinct industries together, where a holistic approach to system innovation and novel business models is required. This opens up new potential opportunities for CEA growers, see Section 5.7. This chapter concludes with a summary of the technical insights on the potential alternative technologies.

5.2 Electrical power generation

In 2021, 40% of the UK's electricity was generated from renewable sources, however only 7.3% was used for heat generation.[93] Wind power contributes the largest share with 20.5% in the electricity mix, being followed by bioenergy and waste with 13%. Although currently, solar energy generation only contributes 12TWh/year (4%) to the National Grid, it has a potential to increase by a factor of 100.[94]

5.2.1 On-site/Co-located power generation

While the decarbonisation of the electricity mix in the public grid remains a central pillar to the net zero transition of the energy systems, there are advantages for CEA to consider an on-site or co-located renewable generation. A 2016 study by the National Farmers Union (NFU) identifies the following benefits:[95]

1. Energy independence and reduction of energy costs: market prices for electricity reflect political considerations and are currently tied to gas prices through the costs of electricity generation from gas-fired power plants, which can be significantly higher than renewables. The risk of a sudden price increase as observed in 2022 can be reduced by onsite generation.

2. Revenue generation: while for example CEA of energy use type 1 (predominantly thermal energy requirements) do not currently require large amounts of electricity for their operation, an investment in renewables can help to create additional revenue by selling the electrical power to the grid. Further, grid ancillary services can be provided using electric and thermal load flexibility leading to diversifying the grower's income streams. CEA with CHP already participate to some extent in such models offering their flexibility, but the revenues for these services (in comparison to electricity sales) are just a small add on to their business case.

3. Efficiency improvement and reduction of emissions: local renewable energy generation contributes to emissions reduction through reducing dependence on fossil fuels as well as by mitigating the grid losses that occur through the transmission of electricity (8% in 2021 in the UK [96]). In this way, not only is the CEA environmental impact improved, but it also contributes to the increase of the grid efficiency. As demand for electricity increases over the coming decades with electric vehicles, electrification of heating and industry, it will be increasingly expensive to operate a centralised power generation system, and therefore distributed local renewable energy generation will become an imperative.

4. Multi-functional use of land: the environmental impacts of agricultural activities, including CEA, include emissions, land use, and impacts on ecosystems and biodiversity. Making more efficient use of land, using the same land resources to contribute to energy and food security at the same time increases efficiency and reduces these broader impacts.

5. Sustainability as a unique selling point (USP): Potentially, sustainably sourced, local food production can help to differentiate a grower from the competition and secure premium pricing. Even though interest from both consumers and retailers is increasing, the expectation of low prices remains.

Solar and wind power generation are increasingly widely deployed at different scales and across various sectors, and to some limited extent to date in CEA (see Annex H for a map of the solar potential and wind power capacity as of 2020 across the UK). However, a system combining solar with an electric heat pump is, despite the technology readiness levels of both individual components, not a common practice, and is complicated by the mismatch between peak solar generation and when heat is required. Additionally, CEA sites rarely have unused land themselves, or may struggle to obtain planning permission for large scale PV arrays, and therefore use of PV is often limited to date to rooftops of packhouses or similar. That said, the transition to renewables presents new opportunities for the sector to capitalise on cheap energy and has the potential to transform food production in terms of sustainability and also location of production. Parts of the country that traditionally may have been uncompetitive for CEA may in the future be more suitable if they have local access to major wind farms, solar farms, or other renewable sources of energy.

5.2.2 Glasshouses and photovoltaics systems

Agrivoltaics is another emerging solution for utilisation of solar energy in agriculture, whereby crops are grown underneath photovoltaic panels, thereby generating energy and food from the same area. It is generally deployed with shade tolerant plants; however, advances in photovoltaic technology, particularly perovskites, is enabling a new generation of semi-/transparent PV panels that are better suited to a wider range of crops.[97]

Photovoltaic panels can be installed on glasshouse roofs. Here, semi-/transparent photovoltaic materials may play a crucial role in the future, but their technology readiness level is currently low, and the impact on light transmission can be substantial. The impact of shading on crop yields requires detailed consideration on a crop-by-crop basis, but due to the UK's geographic location and the levels of the solar radiation, this concept is not seen as economically viable as the shading of the plants is expected to reduce yields significantly, particularly outside the peak summer months.

One major challenge to be addressed with solar energy, is the mismatch between generation and demand. While solar panels generate the highest energy output on summer days, the demand for supplementary heating and lighting is at night and is greatest in times of low irradiation/cooler temperatures like winter. Due to the daily volatility of solar and wind generation and aiming to achieve a greater self-sufficiency, energy storage capacities are therefore needed (either batteries or thermal (seasonal) storages). The cost and maturity of battery technology as well as the costs of larger seasonal thermal storages are currently a barrier to adoption as discussed in Chapter 4.

In general, the UK has world leading research in renewables, e.g., in materials for low-carbon energy systems (solar, hydrogen, fusion). New innovative technologies like dye-sensitized solar cells, semi-transparent organic and perovskite solar cells, that can be deployed on greenhouses are still under development and may ultimately become an important part of CEA in the future, but seem unlikely within the coming decade.[97]

5.2.3 Organic-Rankine-Cycle process

In addition to the use of renewables for electricity supply, waste heat for example from industrial processes, can be utilised for electricity generation through Steam- and Organic-Rankine-Cycle process (SRC/ORC). The SRC process describes the operating principle of a typical steam power plant (steam turbine) in which mechanical work is obtained by the alternate evaporation of water in a closed circuit with the addition of heat at high pressure and, after expansion, by condensation with the removal of heat at low pressure with the release of work. The ORC process runs based on the same principles but uses organic fluids such as ammonia or silicone oils. The difference is that these liquids have a lower boiling temperature and are therefore suitable to utilise low-temperature heat sources to generate electricity. ORC applications are still rare in the industrial waste heat recovery, but are more common in combination with geothermal and biomass plants.[70] The electrical efficiency of SRC is up to 45%; whereas 10-20% of ORC.[70] However, if ORC uses waste heat, biogenic or synthetic fuels, such efficiencies may be acceptable from an environmental point of view. The economic viability of SRC and ORC depends on the consistency of their operation, which means achieving as many full load hours in year as possible and avoiding many interruptions. Finally, waste heat is rarely available at the required temperature levels and in sufficient quantities to produce electric power with an SRC/ORC, so that the potential of connecting electricity demand of CEA to other sectors' waste heat streams is considered to be low in the UK.

5.3 Alternative fuels for co-generation of thermal and electrical power

5.3.1 Anaerobic digestion and biogenic fuels

Anaerobic digestion (AD) is a process through which organic materials such as plant biomass, food waste, municipal waste, wastewater biosolids, or animal manure, are broken down by bacteria in the absence of oxygen, to produce primarily methane and carbon dioxide. To maintain this process efficiently, a well-controlled balance of feed stock addition, and residual digestate removal, has to be maintained. The totality of gases produced in the process are known as biogas, a mixture depending on the feedstock of approximately 60% CO_2 and 40% methane. The methane (biomethane) purified via a biogas upgrading installation is usable as a direct replacement for natural gas. Biomethane can be injected directly into the national gas grid or used in co-location settings by other industries. In the case of CEA, biomethane can be used to power CHP units and boilers, providing an efficient, low-emissions heat source, and a direct supply of CO_2 for growing operations. The AD process also generates considerable waste heat from digestate pre-heating, digester heating, pasteurisation, biogas upgrading to biomethane (heat is required for the process, but most can be reused), and digestate concentration, which could be captured and reused for CEA thermal energy requirements.

Key advantages: The technology is mature and proven, with more than 1,000 plants now in operation in the UK, and widely used across Europe (see Annex H for a map of the current AD installations in the UK). Technical capabilities are readily available in the UK. Innovation over the past decade has increased efficiency, stability, and reliability of AD plants, and the potential to contribute to net-zero objectives and benefiting from related energy incentives such as ROCs and the Green Gas Support Scheme (GGSS) has enhanced cost-effectiveness and hence stimulated demand. The residual waste digestate can be used as a fertilizer, reducing the need for synthetic petroleum-based fertilizers, and also providing an important revenue stream to support AD operations. Combined with Carbon Capture and Sequestration (CCS), AD offers the potential to deliver carbon-negative operations.

Key challenges: The GHG impact of biogenic fuels depends on multiple factors such as the feedstock used, purification activities, application purpose (heat generation, co-generation of heat and electricity or electricity production), geographic co-location of the feedstock source (as transport costs of feedstock over distances greater than 20km can be prohibitive). In case of utilisation of purpose-grown fuel crops, the impact on land and water as well as on use of both should be considered in addition to GHG emissions. By following best practice it is possible to achieve GHG emissions of biofuels in the range of 60-80% lower than natural gas, but they are not an entirely carbon-neutral solution.[98]

Combustion of biogenic fuels also needs an environmental permit, which may be a significant limitation due to the effort needed for compliance with the requirements.[99]

CEA operations typically only generate a fraction, according to our expert interviews, perhaps only 20%, of the organic biomass needed to fulfil their biomethane requirements, so alternative crops or waste streams are required – unless these sources are located locally within 20km the transportation impacts can offset the emissions and cost benefits of AD, while dependency on external sources introduces supply and price volatility risks.[53] Purpose-grown crops for AD can conflict with food production, so increasingly policy favours use of waste streams as feedstock. However, the trend, driven by government policy towards use of mixed waste/municipal waste rather than purpose-grown crops in AD, impacts on emissions and quality of biogas and levels of purification required. To make use of the resulting biogas in the CEA sector, purification to remove contaminants such as sulphur and CO_2 is necessary, and even so there is currently a reluctance to use biogas and CO_2 sources generated from such waste streams as input to the food system. Besides high upfront capital costs, large, industrialised AD systems require skilled operators and long-term contracts securing high quality feed streams at an economically viable price, which may act as barriers to broader adoption. Biomethane is still considerably more expensive than natural gas, so AD plants are only currently viable with subsidies or support levies such as the NDRHI or GGSS.

In summary, the scale and complexity of AD is such that they are typically stand-alone businesses and not just a simple add-on/diversification for CEA.

5.3.2 Synthetic fuels

Various conversion processes are possible in which biomass and solid feedstocks as well as fossil fuels, natural gas or coal, are used to produce synthetic gaseous or liquid fuels. In general, a distinction can be made between indirect and direct conversion. In indirect conversion by gasification or methane steam reforming of the primary fuel produces synthetic gas (syngas) as an intermediate product, which is liquefied in the following process steps. In the case of direct conversion through pyrolysis and carbonisation or hydrogenation, the synthetic gas generation step is omitted. Synthetic gas is a low to medium caloric mix of gases, mainly carbon monoxide and hydrogen, and smaller amounts of methane, carbon dioxide, nitrogen and other hydrocarbon gases. It usually requires purification to remove hydrogen sulphides, tars and other impurities.[100]

CEA can use synthetic fuels similarly to biogenic fuels to operate a boiler or a CHP. Thus, the key advantages and disadvantages are similar to those already mentioned above in the section 5.3.1. However, given the number of processing steps involved these fuels are unlikely to be cheap so will most likely be used for applications such as aviation where there are limited alternatives, and probably not CEA.

5.3.3 Hydrogen

Hydrogen is often touted as the fuel of the future as a low-carbon alternative to natural gas for heating and industrial uses, and liquid fuels for transportation. In general, its feasibility for CEA is determined by the overall economy and not by the sector itself. A cross-sectoral analysis needs to provide evidence whether the use of hydrogen for relatively low-temperature heating, as required by CEA, is a sensible use of hydrogen or whether priority should be given to other application areas. Nevertheless, and in order to show an overall picture of the technically available options, hydrogen is discussed in this and the following section as an alternative fuel for CHP.

There are two main options to produce hydrogen: (1) steam reforming and pyrolysis of fossil fuels, currently representing 95% of hydrogen production today, and (2) using renewable energy sources a) to split water into hydrogen and oxygen, e.g. through electrolysis and b) to biologically or thermochemically process biomass to produce so-called "green" hydrogen.[101] The first of these generates significant CO_2, so is only viable as a route to net-zero if undertaken in conjunction with large-scale carbon capture and sequestration (CCS). Green hydrogen is therefore seen as playing the more important role in the transition to net zero. The UK's National Hydrogen Strategy aims to increase the production of green hydrogen to 10 GW by 2030 and to meet 35% of total national energy consumption with hydrogen by 2050.[102] The government has therefore committed to significant investment of £4 billion by 2030 and an additional £105 million to support the industrial transition and deployment of hydrogen.[52] BEIS has recently launched a series of funds starting from 2022 and 2023 to support various hydrogen projects aiming to address uncertainties regarding economically and environmentally viable applications of hydrogen.[103] These include development and CAPEX support through the industrial hydrogen accelerator (IHA) programme, support for industrial fuel switch enabling technologies (IFS), the existing net zero industrial energy transformation fund (IETF), and the Net Zero Hydrogen Fund (NZHF). Revenue support will be available to subsidise the cost of hydrogen production through the Hydrogen Business Model development funding. From 2025 an industrial levy is anticipated much like the renewables levy to support hydrogen production.

One of the proposed benefits of hydrogen is its use as a medium for storing energy from intermittent renewable energy sources such as wind and solar, in a form that can be transported relatively easily to locations where there is demand. Specifically for the CEA sector, it might be used as an alternative fuel to natural gas in CHP plants, boilers, or perhaps hydrogen fuel cells. Furthermore, agriculture including CEA can provide the biomass source needed for biological or thermochemical hydrogen generation. As part of the Net Zero Innovation Portfolio, the hydrogen bioenergy with carbon capture and storage (BECCS) Innovation Programme is supporting up to 22 projects (in phase 1) that explore the potential of this technical approach and showcasing deployment of low-TRL technologies, including feedstock pre-processing, gasification and novel biohydrogen technologies.[104]

Hydrogen production is however less energy efficient as five to six times more primary energy input, for example sustainable electricity, would be required to generate the hydrogen compared to the electricity demand of a heat pump.[101] In addition, if the availability of hydrogen is limited, there are other applications, such as industrial processes that require high temperatures and cannot be decarbonised in other ways, that should be prioritised (e.g., steel, cement), and heavy transportation applications. Overall, CEA operators may be able to benefit from local integration of renewables with hydrogen production if implemented at scale and in a cooperative approach involving all stakeholders.

In addition, green hydrogen can also replace fossil fuel demand for transportation of produce if hydrogen filling stations and relevant vehicle types running on hydrogen are becoming more readily available.[105]

Key advantages: Several electrolysis technologies are commercially mature such as alkaline water electrolysis. Proton Exchange Membrane Water Electrolysis (PEMWE) as well as Anion Exchange Membrane Water Electrolyser (AEMWE) technologies are expected to have higher efficiencies and be better suited to operations with fluctuating energy sources in the future.[106] There are already common appliances such as gas boilers that are "hydrogen-ready".[107]

The source of electricity is the main factor defining the environmental impact of green hydrogen. However, further analysis is needed in order to fully understand the environmental impact of and emissions reduction potential of green hydrogen.[108]

Key challenges: The engineering of suitable distribution systems for hydrogen is one of the main challenges that needs to be solved to make this technology economically viable. Currently the hydrogen market is dominated by transportation of compressed, bottled gas. The existing natural gas grid may be utilised at scale only after a significant upgrade.[107] Additionally, for CEA operations, combustion of hydrogen provides no source of CO_2 for growing operations.

The levelized costs of hydrogen are largely dependent on the demand, which is at present still driven by a small number of industries such as chemicals production. Furthermore, the prices of the alternative fuels, changes in the price components (taxes, levies, etc.) and the availability of the infrastructure are influencing factors. The International Energy Agency (IEA) expected hydrogen costs to fall by 30% by 2030, but at present it is neither available, nor cost effective without price support schemes for use in CEA.[109]

Handling hydrogen is linked to legally binding high safety requirements and there is currently no broad experience of its application when distributed at scale.[107]

5.3.4 CHP retrofit

To reduce the environmental footprint of predominantly natural gas fired CHP plants, other fuel types, especially biogenic fuels and hydrogen, are an alternative. Currently, there are no policy incentives for retrofitting of existing CHP installations, hence in most cases new equipment is purchased even though from technical perspective retrofit is possible and there may still be significant life remaining in discarded systems.

BEIS recently issued a call for evidence to explore the potential for decarbonising existing CHP plants, for instance by switching to alternative fuels, and the potential role of policy incentives in addressing any challenges, the results of which were published in 2022.[110]

5.3.4.1 Biogenic fuels

Key advantages: Biofuel-fired CHP is a well-tested and established technology. In cases when retrofitting is economically feasible, e.g., through an on-site AD, this solution is often implemented. The lifetime of CHP plants can be up to 20 years, which is much longer than their average payback period (~ four years). The production of the equipment creates an environmental impact as such, therefore, optimising the technical runtime of installations is also an important consideration. From an environmental point of view, retrofitting might therefore be better than buying a new technology, and indeed is often an easier, and perhaps the only viable option compared to switching to an entirely new low-carbon energy generation system based on different technologies. Suppliers and expertise needed for a retrofit of CHP to biofuel are readily available in the UK.

As far as financing a retrofit is concerned, contracting models offer a possibility to share the investment risk, which is common for example in Germany. Here, a third-party such as an energy service provider invests in the CHP plant and leases it to the CEA operator. The attractiveness of this solution is particularly given in cases where the payback period exceeds four years (a typical threshold for the manufacturing sector) but the internal rate of return is more than 10% (with a lifetime of 10 years), which is still attractive to a third-party investor.[70]

Key challenges: Many plants use the biogas coming directly from an AD plant. However, biogas contains other accompanying substances that can damage the engine or lead to higher pollutant emissions in the exhaust gases. Therefore, it is important to review the manufacturer's recommendations on the concentration of the accompanying substances; in many cases, purification of the raw biogas is to some extent required to ensure the permitted/required methane concentration.[111] Compared to natural gas or pure biomethane, biogas CHP requires generally more maintenance. In addition, if there is a need to utilise the flue gases, purification is needed such as using sulphur dioxide scrubbers.

5.3.4.2 Hydrogen

In addition to section 5.3.3, further specifics are provided here on utilisation of hydrogen as fuel for CHP systems.

Key advantages: Two options are available here, (1) a mixture of hydrogen with natural gas/biomethane, with 10-30% being technically possible, or (2) 100% hydrogen. Due to the chemical and physical properties of hydrogen, both options require technically feasible retrofitting measures at the plant, e.g., replacement of the vents, seals, and pipes to match safety standards required for hydrogen. The combustion of hydrogen or natural/biogas-hydrogen mixtures require a special sensor technology to optimise engine control.[112]

Converting CHPs to hydrogen-mix costs about 15% of the original investment.[113] However, for a 100% hydrogen solution, investment in a new plant is economically more viable. Hydrogen CHP have been showcased in successful pilot projects and there are some technology manufacturers offering hydrogen-ready solutions, such as 2G in Germany [114] and Jenbacher in Austria.[115]

Key challenges: Hydrogen causes corrosion, is highly flammable and is lighter compared to natural gas. In addition, its energy density per volume is much lower than that of natural gas (~12.7 MJ/m3 compared to natural gas at ~40.6 MJ/m3).[116] Therefore, blending hydrogen with natural gas reduces the energy density per volume of natural gas and a higher flow rate must be used.

Converting an existing CHP to 100% hydrogen requires the replacement of the entire engine including alternative turbocharger and pistons and special hydrogen injection valves, along with different control software.[107] In addition, the safety requirements for operation are higher due to the explosion hazard of hydrogen.[112] If the size of a CHP plant is determined by the heat demand, which for CEA is mostly a low temperature heat, hydrogen is not an ideal fuel for combustion due to its high calorific value (~141.7 MJ/kg compared to natural gas at ~52.2 MJ/kg).[116]

5.3.5 Biogenic fuel and hydrogen boilers

5.3.5.1 Biogenic fuel boilers

The functional principle of biofuel-based boilers is the same as for the conventional technology with a similar high efficiency rate. They operate on biomass (pellets or wood chips), biogas or liquid biofuels such as hydrotreated vegetable oil or biodiesel.

Key advantages: Technically, a retrofit of a fossil fuel boiler to biofuels is a widely used practice and the equipment needed is commercially readily available at all scales.[117] Biomass boilers particularly are increasingly used across the UK, mainly due to the NDRHI financial support scheme (see Section 7.1.5). The source of the fuel can include the organic biomass waste stream of the CEA operation, but the quality aspects such as level of water content, can be a barrier. The exhaust gases can be used as an alternative source of CO_2 after purification; however, few CEA operations have such purification equipment (flu gas scrubbers) due to the cost and there are few commercial installations in operation worldwide, so unless the fuel is very ‘clean’ an additional source of CO_2 may be required. Technically, a retrofit of a fossil fuel boiler to biofuels is a widely used practice and the equipment needed is commercially readily available at all scales.[117]

Key challenges: Biomass boilers are significantly more expensive than natural gas-fired units (5x the price or more for a given thermal output). The system complexity is also higher, and they require considerably more space. Burning a fuel with a much lower calorific value requires an increase in the size of the combustion chambers and longer flue gas paths to meet environmental requirements.

One key disadvantage is the need for securing sufficient volumes of biofuel for the longer-term future (without using purpose grown crops) as discussed above. When comparing the efficiency of a biofuel boiler (~90%) to a heat pump, heat pumps require much lower input energy (electricity) to generate the same thermal energy output with efficiencies of 300-400% (Coefficient of performance (COP) of 3-4).

5.3.5.2 Hydrogen boilers

It is technically possible to convert gas-fired boilers to hydrogen, which can serve as a bridging solution for the switch to carbon neutral fuels. Acceptance of this measure among industrial users is currently low. Therefore, BEIS initiated an industry-wide consultation with equipment manufacturers, user industries, the energy sector, and other value chain stakeholders to understand the barriers and challenges associated with this technical solution and how they can be addressed with government support.[118] The key finding from this consultation was that the participants believed that installing new boilers that can be fired by natural gas at the point of installation, but are built in such a way that they can be easily converted to run on hydrogen, so called ‘hydrogen-ready boilers’, is more appropriate than retrofitting existing gas-fired boilers. This technology is likely to be more expensive than conventional gas-fired boilers and its deployment will require additional capability building in industry. Therefore, policy can be a key enabling factor for the wider adoption of hydrogen-ready boilers.[118]

5.4 Electrification of thermal energy supply

5.4.1 Heat Pumps

Heat pumps are a technology that uses electrical power to pump a refrigerant gas or phase-change fluid to transfer thermal energy between a source and a sink (where the energy is transferred to). They offer efficient use of energy, and when combined with renewable/low-carbon electricity generation heat pumps can contribute to low-carbon CEA. For low-temperature industrial waste heat or low-temperature geothermal, heat pumps are generally required to deliver the needed step-up in temperatures for CEA. For example, the energy in wastewater at 15 ºC can be captured and transferred using heat pumps to deliver water at 40-50 ºC for CEA. Heat pumps can also be run in reverse for cooling, making them a versatile solution where both heating and cooling may be required.[119]

Key advantages: Heat pumps are a well-established technology for operations at ~50ºC (a typical temperature level for operations at CEA), with the primary market being residential buildings at present. Heat pumps typically have COP3-4, denoting up to 4x energy equivalent of heat output relative to the electrical input for the heat pump (for example, this compares to a gas boiler efficiency of COP0.89).[120] Matching of cooling/heating is possible, e.g., vegetable storage and packaging areas that require cooling can be matched with glasshouses that require heating.

Key challenges: Costs for larger industrial applications of heat pumps are high and lack economies of scale because bespoke solutions are often required, needing to be tailored to each application depending on availability of heat sinks/sources, flow rates, and size of operation. Investment costs can be 10x higher than for a natural gas boiler, but over the lifetime total costs can be comparable, but this depends on the COP and the cost ratio of the market price for electricity to drive the heat pump versus the energy carrier for boilers.[121] Currently, electricity costs in the UK are high compared to competing energy carriers like gas, undermining the economic case for heat pumps, and to date, heat pumps in CEA have only been economically viable with subsidy through the non-domestic renewable heat incentive scheme (NDRHI). Skills and capabilities for industrial scale heat pumps are not widely available in the UK, so will require import of technologies, and upscaling of installation/maintenance capabilities for wider deployment. An alternative CO_2 source is required for CEA operations deploying heat pumps.

5.4.2 Electrical boilers

Thermal energy for heating can also be generated directly from electrical power, e.g., by immersion heaters or electrode boilers. Immersion boilers contain an electric heating element that heats up under voltage. In an electrode boiler, there are two electrodes in the liquid and heating takes place through electrical resistance. Electric boilers are deployed by industry to supply heating systems or generate hot water and steam, in district heating systems and many other applications.

Key advantages: These technologies have seasonal efficiency rates of over 90% and have advantages such as small footprint, low installation and maintenance efforts as well as relatively low investment costs. In electricity systems with a high share of renewable generation, electric boilers offer the key advantage that they can be used as power-to-heat systems to increase the use of renewable electricity in times of overproduction. This makes it an interesting technology for a back-up/peak demand system that can also be used to make energy demand more flexible by switching between different supply systems, e.g., electricity and biogenic fuels/hydrogen (see Chapter 5.7).

Key challenges: In comparison to heat pumps, (see 5.4.1), electric boilers are a less efficient technology measured by the primary energy [viii] demand needed for their operation (particularly so considering that fossil fuels are still deployed for electricity generation).[ix] Furthermore, supply of heating with electricity, which is a qualitatively higher-grade (exergy) energy form, remains an inefficient solution. In addition, currently high electricity prices have increased the operational costs of electric boilers significantly. As in the use of heat pumps, an alternative CO_2 source is required when using electrical boilers in CEA. Finally, their operation is likely to require an upgrade of the grid connection capacity, which might be technically a limitation itself as well as economically difficult to realise.

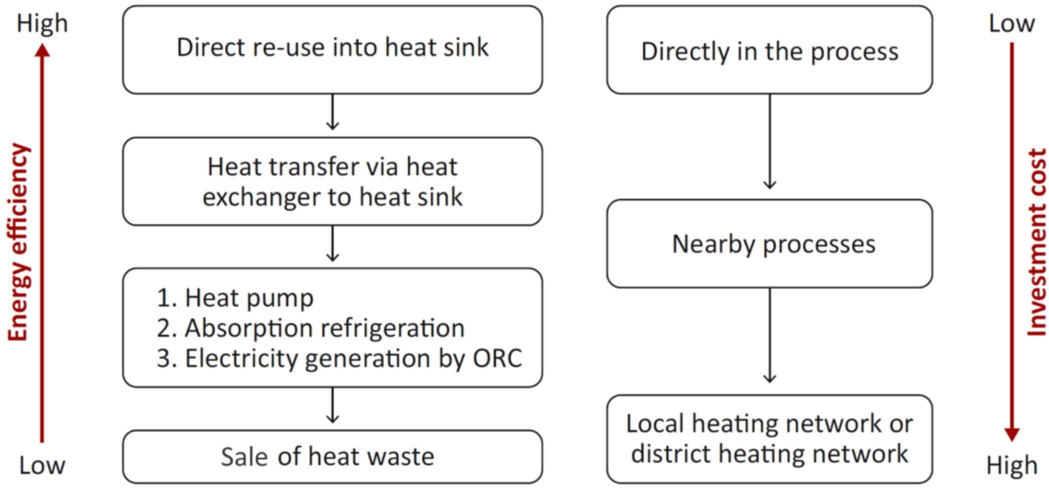
5.5 Heat recovery as a source of thermal energy for CEA

Beyond the options for generating thermal energy directly, a range of proven technologies enable the capture and reuse of external and waste heat sources for CEA. The most relevant of these are industrial sources of waste heat, ambient heat, and geothermal. The technology requirements and commercial viability depend on the proximity between the heat source and sink, the flow rates and temperatures of the sources and sink, as illustrated in Figure 14. The most relevant of the technologies to CEA are discussed below.

[viii] Primary energy is the energy content of natural energy sources such as solar, wind, natural gas, coal, etc. before conversion processes and transport that result in losses.

[ix] For 10kW thermal output, a heat pump, with a COP of 4 and supplied by grid electricity and under assumption of a primary energy factor of electricity mix in the UK of 1.501, would require 3.8kW primary energy input; whereas an electric boiler (with 95% efficiency) almost 15.8kW.[212]

Figure 14 Energy efficiency and cost relationship of heat recovery options from industrial sources
Source: Schlüter & Bernabé-Moreno, 2022 [52]



5.5.1 Use of industrial waste heat

An estimated 300TWh of heat is dissipated annually in industrial processes including the energy sector across Europe.[122] Capturing and reusing this waste heat is an attractive solution from a waste reduction perspective, and waste heat for CEA operations has been proven and would offer a path toward lowering the carbon footprint of CEA. This can be achieved using heat exchangers and heat pipes to transfer waste heat, or using heat pumps for lower-grade waste heat streams to deliver the temperature levels required for CEA. The best candidate sources should have long-term business stability, 20 years or longer, to guarantee availability of the heat source for the life of the CEA operation (glasshouses have a lifespan of potentially 40-50 years).[x] Primary candidates are infrastructure and utility providers such as power generation, wastewater processing works (WTW), and municipal energy from waste plants (EfW). Ambient heat can also be extracted from rivers and reservoirs.

Key advantages: Many industrial and commercial processes in the UK generate low-grade waste heat, and it is often difficult to find an appropriate sink for this heat. Utilising waste heat (for heating or cooling) from other industrial processes offers the potential to reduce carbon emissions for both sides and can be a very cost-effective source of thermal energy for the recipient business.

Key challenges: In practice opportunities for use of waste heat streams are quite limited, because cross-industrial collaboration is challenging due to differing geographical, business, operational characteristics and skillsets, the need for close co-location (maximum of a couple of kilometres to avoid significant heat losses), and potential mismatch between the heat source and sink in terms of temperatures and flow rates. For example, Energy from Waste (EfW) plants tend to be in urban areas where there is no space to co-locate CEA. The required investment costs and risks can be high, and if either business must shut down or downsize operations the partnership is likely to collapse. Moreover, as pressure mounts on industry to

[x] Obtained from expert interviews.

reduce waste (for example EU regulation to reduce waste heat), industry can be expected to continuously work to improve efficiencies in their operations which may undermine heat supply arrangements with co-located CEA. No industrial partner will take on the risk of guaranteeing the heat supply, and without a guaranteed heat source for at least 20 years any new CEA project based on waste heat recovery will generally be unfinanceable. Moreover, a fee is usually charged for the waste heat, and this may or may not be competitive with a conventional CHP solution.

The fuel used to create the waste heat source in the first instance dictates the overall environmental impact, so although use of waste heat offers efficiency benefits and reduces waste and mitigates the additional burning of fossil fuels by the CEA operation, the heat may still have a high carbon footprint. At present there is no standardised carbon emissions allocation methodology for allocation of impact between source and sink so assessing the benefits for the parties involved is problematic. An additional challenge is that use of waste heat does not provide a direct source of CO_2 for glasshouse operations.

5.5.2 Geothermal

Geothermal energy is a regenerative sub-surface thermal energy source stored in aquifers and hot dry rocks (granite batholiths) due to an average temperature increase (geothermal gradient) of the earth's crust between 25-30ºC/km. According to a British Geological Survey report in 2020, geothermal resources in the UK are estimated to be sufficient to deliver about 100 years of heat supply for the entire UK at present consumption rates, and to provide up to 2280 MWe (MW electrical) capacity for generating power from 4.5 km depth.[123] However, as of 2020 the installed capacity for direct use heat in the UK was only about 2 MWth (MW thermal).

The heat source is accessed through bore holes of between a few hundred meters to up to 5 or more km in depth depending on the geology of the site, and heat is typically extracted through circulation of water. Thermal output depends on the temperature at target depth and the flow rate of circulated water, and can range from low temperatures where ground-source heat pumps (GSHP) are required to step-up extracted heat, through to high-temperature steam suitable for direct power generation (see Annex H for a map of distribution and type of geothermal sources across the UK). The greatest energy efficiency benefits and carbon reduction potential are from sources suitable for direct heating for CEA rather than using heat pumps, at temperatures above 40ºC.

Geothermal is a well-established heat source in horticulture in many parts of the world but generally not at scale to date. However, the Netherlands are currently pioneering the use of geothermal energy in CEA on a large industrial scale with an ambition to provide 65% of the country's CEA heat demands from geothermal by 2050 (see Section 7.4 for geothermal deployment in Netherlands).

Key advantages: There is good potential for low-temperature heat at shallow surface depths in the UK, and opportunity to utilise closed coal mines and for repurposing of on-shore oil and gas wells, and some limited areas suitable for high temperature geothermal energy extraction. The technology for exploiting geothermal is relatively mature and proven and when coupled with renewable electricity for pumping offers a fully renewable clean source of energy. The benefits are easily communicated to the public, and there is potential for combination with district heating and in some parts of the country (Cornwall) with geothermal power generation.

Key challenges: Although ground-source heat pumps can be used widely for low-temperature geothermal, the sites for higher-grade geothermal heat are geographically dispersed across the UK, with significant regional limitations and requiring co-location of CEA with the heat source. Surveying, drilling and setup costs for geothermal wells are high, typically £2-£4m per MW[124], and there is significant risk associated with prospecting for new geothermal sources (until the bore hole has been drilled the performance of the site is not certain and costs can rise significantly). Generally deep geothermal (1km or deeper) is not viable for operations of under 6 hectares of glass, and even for quite large 20-hectare CEA operations in the UK is not currently economically viable without subsidies.[123] The Dutch government addressed these issues by 'insuring' the early projects and paying out if the well did not deliver the expected capacity. Despite the experience and data already collected in the Netherlands that has enabled the insurance industry to support drilling operations, geothermal exploitation still requires governmental subsidy. Operations would likely need to be coupled with larger power generation or district heating schemes involving the local community and other heat users, or other CEA operators, creating complexity. Moreover, seasonal energy demands of CEA and matching of source/sink may not be the best use of geothermal. There is also a risk of over-exploitation and contamination of geothermal resources that needs to be managed.

5.6 Supplementary carbon dioxide supply for yield increase

CO_2 supplementation from combustion of fossil fuels is a relatively simple and cheap solution, but it has some disadvantages. There is a cost associated with the generation system, and, as discussed in section 3.3, there is a mismatch between supply and demand – peak CO_2 demand occurs on hot sunny summer days when there is no demand for supplementary heat, whereas peak heat demand occurs on cold nights, when the crops do not require supplementary CO_2. Combustion has the potential for contamination from pollutants from incomplete combustion that can affect plant growth and taste.

For many of the proposed decarbonisation options, alternative CO_2 sources will now be required. Several alternative sources are identified and discussed below.

5.6.1 Efficiency improvement in CO_2 use

This first option is not an alternative supply, but demand efficiency. CO_2 is heavier than air, so adequate air circulation is essential to ensure CO_2 is distributed throughout the glasshouse and reaches the plants and used efficiently. Furthermore, optimal use of supplemental CO_2 is dependent on light levels, water, nutrients supply, temperature, and stage of plant development. With higher CO_2 levels for example, warmer temperatures are required to realise maximum photosynthesis.[56] Adequate monitoring and control systems and alarms, are required to make best use of CO_2, and if these other factors are not optimised accordingly then the supplemental CO_2 may have little value.

As discussed in Chapter 3, in conventional glasshouses only a small percentage of the CO_2 supplied to enrich the greenhouse environment is actually sequestered by the crops, with the majority lost to the external atmosphere. Semi-closed and closed glasshouses, and fully enclosed vertical farming offer far higher utilisation of supplemental CO_2, and hence a significant reduction in CO_2 requirements (and CO_2 emissions) as discussed in section 4.3.4. Technologies to support closed CEA are available and proven; however, the capital costs and operating costs of these systems are higher and are currently not economical in the UK for protected vegetable and soft fruit crops. Policy incentives would be needed to encourage adoption of these technologies.

5.6.2 CO_2 from biomethane/biomass-fired boilers and CHP

A ready solution for growers is to use existing boilers and CHP with biogenic fuels such as biomass, biogas, biomethane (from anaerobic digestion), or other synthetic fuels. As discussed above, the requirements in respect to the gas purification are more stringent. As the carbon released during combustion of these fuels will have been previously sequestered from the atmosphere these solutions can deliver a low-carbon supply of CO_2 to growers (as discussed in section 5.3.1).

However, there are increasing concerns regarding over-exploitation of forestry biomass resources and the potential for conflict between crops-for-energy and crops-for-food that limits the availability of biomass and biomethane in the UK. CEA operations themselves do not generate enough waste biomass from growing operations to meet their operational energy needs so an additional external source must be found.

Moreover, as discussed above, with combustion, regardless of the fuel type, the CO_2 and heat demands in CEA are not well aligned. This necessitates significant heat storage capacity, or for boilers or CHP to be run purely to generate CO_2 on occasions. There are already examples for 24 hours heat storage to balance demand, but longer-term storage is uncommon in the UK.

5.6.3 CO_2 from biogenic processes

Various biogenic processes can yield CO_2 for provision in CEA. Potential sources include AD of biomass that creates biogas (a mix of approximately 40/60 biomethane and CO_2), aerobic composting, fermentation (e.g., of sugar, in the brewing industry), and CO_2 yielding crops such as mushrooms.[56,125] Such sources vary from supply of very pure CO_2 (which attract a premium and are therefore more usually used in food and beverage production) through to sources that may require significant purification before use. Such generation of CO_2 could be on-site with the CEA, or received as bottled liquefied CO_2 or piped from industrial producers. Anaerobic digestion of horticulture waste biomass or collecting gas from compositing would appear to offer a good circular economy solution; however, although capturing and reusing these sources offers an alternative solution for CEA, supply is limited, separation and purification is required, there may be concerns over contamination and odours particularly from use of manure and other waste streams. These sources are generally expensive compared to CHP combustion, and none of these biogenic sources are currently able to provide CO_2 at the scale required to supply the whole UK CEA sector.

5.6.4 CO_2 from fossil fuel-based industrial processes

Many industrial processes produce CO_2 from fossil fuels, including petroleum refinery, ammonia and fertilizer production, steel and cement, and power generation. In the Netherlands CO_2 networks have long supplied CO_2 from refineries in the Rotterdam port area via a network of pipes to the extensive co-located CEA industry, while in the UK industrial sources of CO_2 are supplied as bottled liquefied gas generally from the ammonia/fertiliser industry. CO_2 networks are uncommon, requiring a critical mass of industry to justify the network construction, and the cost of bottled gas is also high compared to direct provision through fuel combustion on site. Moreover, prices have risen steeply in the past year, and critical sources of CO_2 were moth-balled for several months in 2022 as high gas prices rendered ammonia and fertilizer production temporarily unviable.

In the longer-term, as industry decarbonises, sources of industrial CO_2, particularly from power generation plants, would be expected to decline. However, at least in the interim as the world moves towards net-zero carbon it seems likely that industry will have to embrace carbon capture and sequestration (CCS) on a large scale, and therefore industrial sources of CO_2 will likely become widely and perhaps cheaply available. For example, power generator, Drax UK, announced in 2022, a plan to build the world's largest CCS facility at its North Yorkshire biomass power station, with the CO_2 from Drax and other industrial operations to be transported via pipeline to the Endurance storage site, under the North Sea.[126,127] Potentially CEA sites could be connected to this or similar networks in the future.

Production of "blue-hydrogen", generated from fossil fuels, produces CO_2 as a by-product, could also become a more significant source of CO_2 in the future if hydrogen becomes more widely adopted. As the source of this industrial CO_2 is fossil-fuels, there is no overall contribution to net-zero of using it in CEA, and in fact its use in open glasshouses somewhat might negate the benefits of switching to renewable energy sources. Nevertheless, if CEA makes use of CO_2 that would otherwise be vented directly to the atmosphere it is beneficial.

5.6.5 CO_2 from municipal waste incineration

Similar to the above CCS from industrial processes, CCS from municipal waste incineration could offer a source of CO_2 for CEA. Depending on the types of waste and percentage of biomass and food waste involved, this could offer a lower-carbon footprint alterative to purely fossil-fuel based CO_2 generation. However, the mixed waste stream in municipal waste is unlikely to be carbon-neutral and may introduce contamination and purification challenges for cost effective use of the resultant CO_2. At present there are no financial incentives to capture CO_2 from municipal waste incineration as it falls outside the EU carbon trading scheme.[128]

5.6.6 Direct Air Capture technologies

Direct Air Capture (DAC) technologies extract CO_2 directly from the atmosphere using a chemical medium to absorb CO_2, which is then heated to release CO_2 to generate a concentrated source for sequestration or utilisation in industry.[129] Several well-funded ventures are working on possible solutions, such as Climeworks of Switzerland, who have recently broken ground on the world's largest DAC plant to-date designed to capture 36,000 tonnes of CO_2 per year.[130] As discussed in section 3.3 the required CO_2 requirements can approach 1200 tonnes per year per hectare of glasshouse. Considerable progress appears to have been made since the early laboratory proof of concept; however, the process is energy intensive, and consequently expensive, and it is far from clear yet whether DAC will become a relevant solution to anthropogenic GHG emissions on the scale required for meaningful global impact. With a current carbon price of 1000€/tonne it is certainly unaffordable for CEA. Climeworks targets a price of 100€ by 2030, but this is still far above the costs of CHP generated CO_2 (see section 3.3). Nonetheless, DAC offers the potential for an alternative source of CO_2 provision in CEA, and perhaps on the scale of provision for a glasshouse operation it might eventually prove economically viable, although the timeframes for this are unknown at present. To have any relevance to net-zero DAC must of course be coupled with a renewable energy source. According to the experts interviewed, further R&D investments are needed to bring DAC to a higher technology readiness level (TRL). Therefore, this technology is expected to play a role only in the longer-term.

5.7 Further measures for decarbonisation

Renewable energies are an important pillar of the energy transition and are fundamentally reshaping the energy system. Fluctuating generation from photovoltaic and wind power plants increases the need for flexibility in energy consumption. If not managed appropriately, strong fluctuations can affect grid stability and security of supply. In order to balance volatile generation and accommodate ever greater amounts of renewable energy in the public grid, energy systems must be able to decouple energy supply and demand. Demand flexibility and the ability to shift loads is one way to address this challenge. There are four main approaches to it:

- Use of accumulators, e.g., batteries
- Conversion of electrical energy into other forms of energy
- Demand adjustment with the help of energy switching / hybrid supply
- Flexibility of operational planning and control of electrical systems.[52]

CEA has great technical potential to contribute and benefit from demand flexibility by acting as a consumer, an energy storage, and energy generator. The facilities such as co-located and on-site renewable systems, biofuel boilers, heat storage, heat pumps, electric vehicles and some batch processes such as washing and drying can be operated based on the four principles above.

Electric vehicles are similar to battery storage used to store renewable energy as required (1). Similarly, when there is a surplus of renewable generation, electrical energy can be converted into thermal energy (by heating water in the heating system), which can be stored in a thermal storage (a water tank) and used to provide heat later in the day (2). To stay with the example of a heating system, CEA would normally have a peak demand / backup system. With two conversion alternatives such as an electric heat pump and a biogas boiler, a grower could switch between the two alternatives depending on grid demand. During the midday peak of photovoltaic generation, the heating system can be supplied by a heat pump and during the night by a biogas boiler (3). Finally, the operation of some ancillary electrical machinery needed for processes such as washing, drying or packaging can to some extent be planned based on the availability of excess renewable energy (4).

There are examples of CEA sites in the UK where CHP plants are operated to provide grid balancing services, e.g., by reducing their power output when there is a generation surplus on the grid, and vice versa. However, only a small part of the potential in this sector is utilised, in part because it requires a system able to use electrical energy (e.g., heat pumps), and ideally some form of energy storage. The concept provides benefits to both sides: CEA, and the energy supply system. For a grower, it is an option for reducing energy costs, and potentially new revenue streams and even completely new business models, while for the energy supplier it provides load balancing and reduces the need for dedicated energy storage solutions on the grid. But currently, the revenues for the grower are not sufficient to increase their flexibility capabilities or create a new business model. An important enabler for these new opportunities is the increasing digitisation and automation, as well as the availability of data through the increased use of energy monitoring systems (see also chapter 4.1.2), which not only enable

CEA to optimise their energy consumption, but also help them provide services to the grids or benefit from periods of cheaper energy prices.

6 Technology comparative assessment

To assess the suitability of the various energy efficiency and energy generation technologies presented in the preceding chapters, a system-level assessment of the key emerging energy systems was undertaken, taking into account technological readiness, commercial considerations, environmental aspects, and broader societal aspects of deployment (Section 6.1). A marginal abatement cost curve (MACC) was also developed (Section 6.2) to explore the economic implications and potential for emissions reduction across the CEA sector.

6.1 Insights on supply-side decarbonisation strategies

Technology readiness levels of the existing low carbon/renewable technologies varies, and successful, commercially viable implementation of some of them, for example hydrogen, requires first establishing of a new economy and market design. However, most of the solutions can be deployed immediately or can be expected to play a role within the next decade. In the following, three example combinations of existing technologies that are already deployed in the sector, in particular in energy use types 1 and 2 (where there is a large thermal energy requirement), and can contribute to decarbonisation are discussed in comparison to the currently dominant baseline systems design (natural gas-fired CHP):

i) Biogenic fuel CHP/boiler and AD located on site or co-located,
ii) Electric heat pump sourcing from low-grade thermal energy (industrial, geothermal, or ambient sources) and renewable electricity generation on site or co-located,
iii) Heat exchanger and heat pipes for waste heat recovery from industrial processes, and renewable electricity generation on site or co-located.

By replacing CHP, that currently also acts as a source of CO_2, with a heat pump or a waste heat recovery solution, the CO_2 has to be purchased separately. It is important to note that the technology combinations listed above are not mutually exclusive and can also be used together. For example, a heat pump can be operated with electricity generated by CHP driven by biogas from an anaerobic digester or can be used with an industrial waste heat stream. In case of industrial waste heat recovery, there are a variety of ways to realise its utilisation; here, technically simple solutions are considered, such as the construction of a pipe system and the use of heat exchangers.

A qualitative evaluation of the alternative technology combinations in comparison to the baseline systems design is shown in Figure 15, and summarises data collected through the desk research and expert interviews and the detailed analysis. The technical system maps for the three technology combination options are illustrated in Annex G.

The analysis indicates that there are pros and cons to each of the combinations and picking just one is problematic. Moreover, the potential of these options differs by their energy demand as well as location, and available energy sources and supporting infrastructure. In cases where a heat source is not readily available, access to biomass or waste resources to drive an AD plant in combination with CHP (as demonstrated by Dyson Farming, described in Annex A) may be an option, and also takes care of the CO_2 supply issue. For heat recovery schemes, availability and access to reliable existing heat sources may be a cost effective and low-carbon option, be they geothermal (as in the Netherlands), low-grade waste heat from water treatment works (WTW) (demonstrated by Low-Carbon Farming in the UK), or higher-grade waste heat from industrial processes (such as British Sugar's Wissington plant in the UK). In many cases though, this waste heat is from fossil fuel combustion so although it is reusing waste which is beneficial, it is not necessarily a low carbon solution.

Notwithstanding the constraints raised above, there are many opportunities in the UK to utilise one or more of the above approaches. Further details of a selection of representative industry case studies are presented in Annex A.

Figure 15 Comparison of baseline and alternative energy system design

The methodological approach to this table is described in Annex B, including the definitions of the factors.

** On site or co-located*
*** Operated with ambient energy*
**** Only pipes and heat exchangers, no heat pumps*

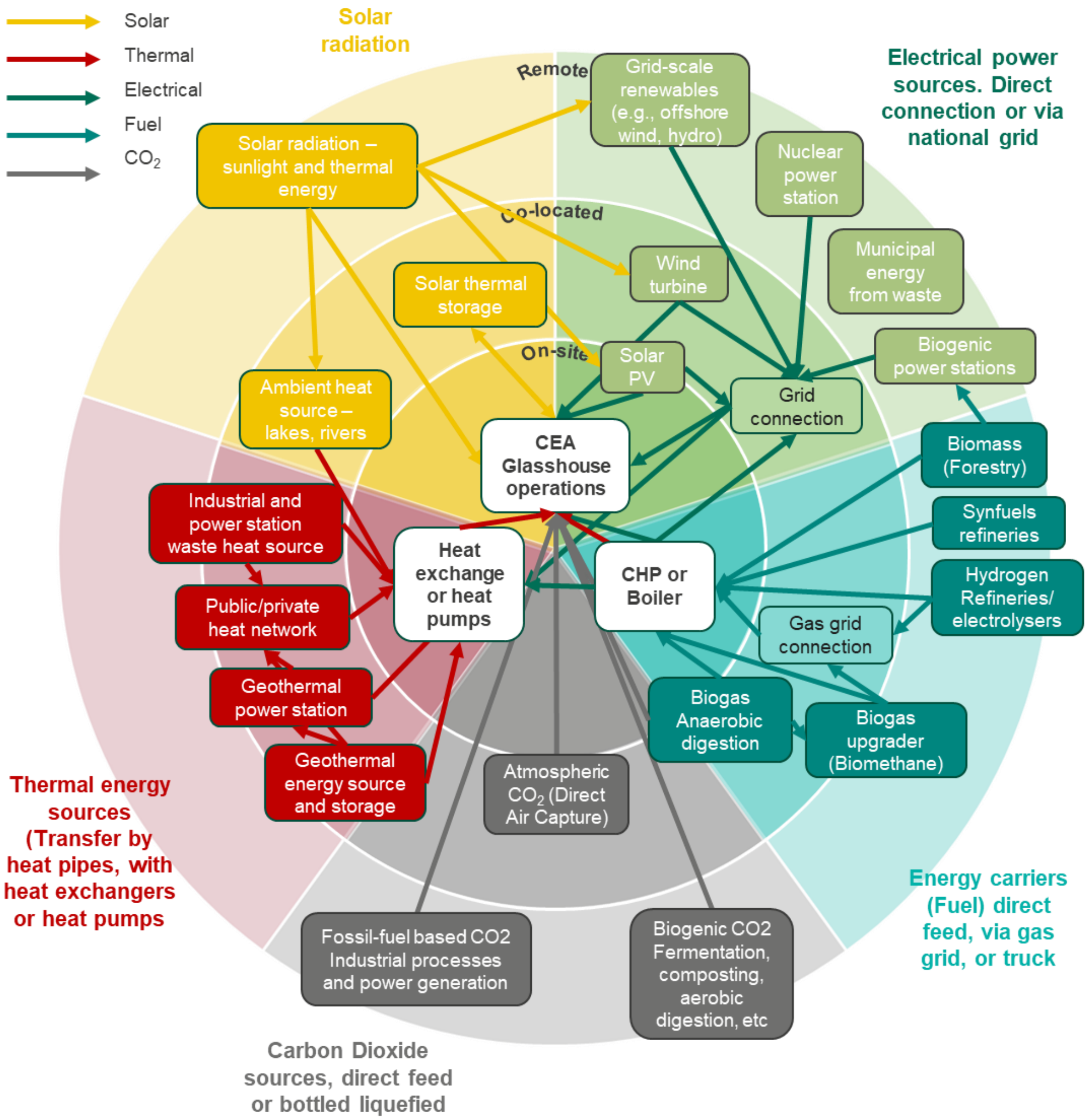
		Baseline design: Natural gas-fired CHP	1. Biofuel CHP/boiler and AD*	2. Heat pump** and RES*	3. Waste heat*** and RES*
1	Technical feasibility	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
2	Commercial feasibility	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
3	Environmental performance	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
4	Organisational/eco-system requirements and capacity	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
5	Suitability of existing policy, regulatory and fiscal incentives	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
6	Societal value creation potential	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
7	Societal/Consumer/Retailer acceptance	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2	-2 -1 0 1 2
	Example case studies (Annex A)		10.1; 10.2	10.6	10.1; 10.3; 10.7

The shift of heat supply from CHP to a heat pump or waste heat recovery requires an alternative for electricity generation. Therefore, local electricity generation from renewables, such as solar and wind, is seen as a beneficial option in terms of energy efficiency (sourcing electricity from the grid, even if it is 100% renewable, is less efficient due to the transport losses and the grid operating costs that are paid in grid usage fee). Moreover, the direct costs of renewable energy can be substantially lower than the prevailing grid cost, making direct connection particularly attractive. However, co-located renewable energy solutions are subject to availability of land, planning permission, a grid connection, and financial capital for investment. In the current climate, all businesses would be well advised to generate their own renewable energy on-site, but as the grid decarbonises grid energy is a viable and possibly more expedient alternative particularly for smaller growers.

In the case of energy use type 3 operations (exclusively electrical power), their energy system is already fully electrified. This means that their environmental impact is mainly driven by the electricity-mix emissions. In order to decarbonise these operations, electricity generation from renewable energy is the key pathway.

Figure 16 summarises the available energy and CO_2 sources, their location and their possible uses for a CEA operation. The multitude of connections makes it clear that focusing on one of the energy forms has an impact on the other as well as on the CO_2 supply. As such, decarbonisation of energy supply and CO_2 supply must be thought of holistically and approached with a systemic approach.

Figure 16 Systems map of energy and CO_2 sources



In summary, the design of energy supply systems in CEA will in the future have to shift away from a focus on one particular technology to a systems perspective strongly impacting the overall business model of CEA growers. Selection and integration of technology modules into a CEA system needs to consider locally available resources and capabilities as well as overall renewable energy markets.

6.2 Marginal abatement cost curve

So called marginal abatement cost curves are used as an analysis and visualisation tool to inform decision makers about which technologies/measures are most cost effective in respect to their GHG emissions reduction potential and which have the greatest potential for total GHG savings. A MACC plots the net present value (NPV) costs of abated emissions measured in £ per tonne of carbon dioxide equivalents (£/tCO_{2e}) based on the cost of implementing the measure taking into account capital expenditure and energy and operating cost savings over the life of the project, against the amount of abated GHG emissions (measured in tCO_{2e}) for each technology/measure considered, and orders these in ascending sequence. Each abatement measure is plotted as a column in the MACC, where the height of the column represents the cost, and the width of the column represents the project's abatement opportunity. A project that is below the X-axis results in emission reductions and financial savings. Items that appear above the X-axis are those that result in emission reductions but at a cost.

The MACC shown in Figure 17 provides a sector-level view of the potential for emissions abatement through energy efficiency measures and alternative energy supply technologies and is intended to aid policymakers in deciding how and where to support the sector with market interventions such as regulation, subsidies or tariffs to encourage adoption of low-carbon technologies and discourage use of older polluting technologies. However, the specific costs and benefits will vary for each individual growers' operation so the MACC should not be used to make individual investment decisions.

6.2.1 Measures considered and assumptions in generating the MACC

The MACC shown in Figure 17 presents the forecast abatement potential across the UK CEA glasshouse sector over a 30-year time horizon for a series of abatement measures. The following technologies/measures for efficiency improvements discussed in Chapter 4 have been considered, along with several energy system changes discussed in Chapter 5, split broadly into three categories of intervention:

Working practices and behaviour changes:

1. Routine maintenance & repair: General regular maintenance and repair activities including a regular sensor calibration.
2. Intelligent solutions for optimisation of growing conditions: Physical benefits of installing more sensors, software updates etc. for intelligent solutions for energy optimisation including thermostatic control, climate control computers and destratification, optimised airflow and temperature gradient control.
3. Better use of the computer capabilities & NGG: Management element of the measures above describing a better use of the computer capabilities including next generation growing (NGG).

Energy efficiency measures:

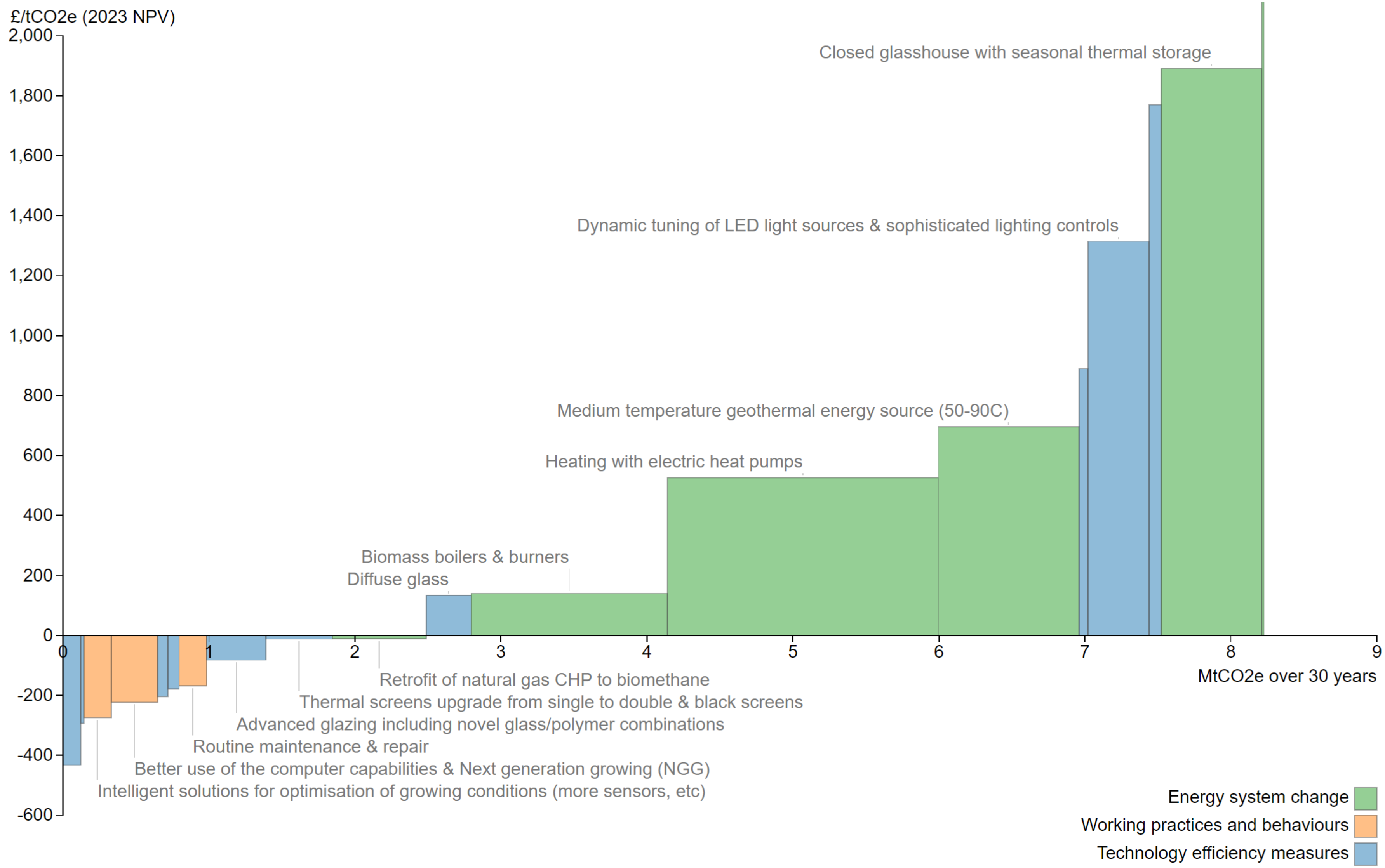
4. High efficiency boilers & optimised boiler control: Solutions for improving efficiency of the boilers and optimisation of their control.
5. Variable speed drives, improved efficiency of fans & motors: Upgrade to variable speed drives and measures that improve efficiency of fans and motors.
6. Improved cooling & refrigeration system: optimisation measures including winter relief and free cooling usage.
7. Daily & longer-term thermal storages for heat buffering: Daily and longer-term thermal storages to buffer the non-synchronized requirement for CO_2 and heat.
8. Thermal screens upgrade from single to double & black screens: Thermal screens and upgrade from single to double screens and black screens.
9. Advanced glazing including novel glass/polymer combinations: Advanced glazing incl. double glazing and glass/polymer combinations and air leakage minimisation related to vent ceiling.
10. Diffuse glass: Deployment of diffuse glass.

11. Energy efficient light sources (LEDs to replace HPS lamps): Energy efficient light sources (LEDs to replace HPS lamps).
12. Dynamic tuning of LED light sources & sophisticated lighting controls: LEDs and lighting controls including dynamic LED system for photosynthetic colour spectrum tuning, illumination intensity, and duration of lighting.
13. Semi-closed glasshouses: Deployment of the semi closed glasshouse concept for new builds including frameless vented glasshouses and advanced dehumidification.

Energy systems change:

14. Retrofit of natural gas CHP to biomethane: Retrofit of the existing CHP plants to biomethane.
15. Biomass boilers & burners: A significant replacement of fossil fuels boilers with biomass boilers and burners to generate thermal energy.
16. Electric boilers for electrification of thermal energy generation: A significant replacement of fossil fuels boilers with electric boilers to generate thermal energy.
17. Heating with electric heat pumps: A significant replacement of fossil fuels boilers with electric heat pumps to supply thermal energy.
18. Heating using medium temperature geothermal energy source (50-90C).
19. Closed glasshouse with (underground) seasonal thermal energy storage for storing summer heat for winter use.

Figure 17 Marginal abatement cost curve (MACC) for CEA efficiency measures



* Electric boilers in this MACC are the far-right bar and extend off the chart at the current electricity price.

6.2.2 Assumptions applied to MACC

The calculations for the MACC and associated assumptions applied for the selected measures are summarised in Annex F, and based on the following:

i. Data gathered by the NFU under the CCA programme over the two-year reporting period 2019-2020 provided the details of sources of energy, usage rates, use of CHP, and energy intensity per m^2 by site, within the CEA sector. The CCA data included 87 operations (anonymised) covering 370 hectares across the UK in the edible horticulture sector, including vegetables and soft fruits. For this study the ornamentals sector and mushrooms were excluded. For the purposes of this study, the CCA sample is considered representative of the overall market make-up, and the final MACC diagrams are scaled-up to represent the current 1000 hectares of the edibles glasshouse sector.

ii. Details on potential capital costs, operational costs, and energy and emission savings per measure were gathered through desk research and detailed discussion and review with industry experts in particular including NFU Energy. It should be noted that costs and savings can vary greatly depending on the individual site and deployment context, so figures used are average approximations only.

iii. The MACC study factors in current levels of deployment and future potential deployment for each of the measures in order to calculate the potential for impact on the overall sector. These figures are estimates developed in consultation with industry experts and based on the best available data to-date. Deployment potential may change in the future as new technologies evolve and costs change, and so the MACC should be revised over time.

iv. The MACC presented below is based on current energy market prices and carbon intensities, and assumes use of grid-supplied electricity. Variation in the price ratios between natural gas, electricity, biomass and biomethane will influence the overall findings. For example, a future electricity price that reflects the marginal costs of renewable energy generation rather than gas-fired generation, and, or reduction in the carbon intensity of the electricity grid (UK grid intensity is currently 193 gCO2/kWh) would shift the MACC towards electrical solutions for CEA. On-site generation of biomethane or electrical power using renewables would also shift the relative costs/benefits.

v. To calculate the marginal abatement cost, a discount rate of 5% was used to calculate the net present value (NPV) of future cashflows relating to operating costs and savings, and a discount rate of 2% was applied to future emissions reductions, recognising the benefit and greater certainty associated with nearer-term reductions over those further in the future. Sensitivity analysis to higher discount rates associated with inflationary periods is also discussed in Annex F.

vi. The confidence level of the final MAC outcome for each measure is rated based on the level of uncertainty and availability of data on each measure (expected efficiency gain, current and future potential deployment levels, CAPEX and operating cost savings). The assessment of the confidence in the MAC of each measure is shown in Annex F, Figure 24.

vii. For the interpretation of the MACC results is it important to consider that some measures are mutually exclusive, for instance investment will be in a biomass or an electric boiler, but not both. This is the case for all of the energy systems transformation initiatives, and for these measures the emission savings potential shown in the MACC cannot be aggregated. Measures that are complementary on the other hand, such as maintenance, efficiency improvements, can be combined and implemented in the same project or in a staged series of projects. The mutual exclusivity or otherwise of the measures is shown in Annex F, Figure 25.

6.2.3 Interpretation of the MACC

6.2.3.1 Cost-saving emissions reduction solutions

Priority cost saving initiatives are largely changes in working practices and behaviours, such as enhancing maintenance and repair, better control of growing conditions and greater exploitation of computing capabilities for enhanced growing control. Other impactful and relatively simple improvements are switching to variable speed drives and high efficiency fans and motors and replacing older boilers with high-efficiency gas boilers and ensuring optimised boiler control. Advanced polymer-based double-glazing systems are not commonly used to date, but newer technologies offer potentially cost-effective retrofits to augment existing glass with good potential for emissions reduction. Thermal screens are now widely used throughout the sector, but upgrade to double or triple thermal screens is still an important and relatively straightforward upgrade for emissions reduction and cost saving. Retrofit of CHP to biomethane is a viable option while natural gas price are high, and delivers significant carbon reduction, but uptake will be constrained by the limited supply of biomethane.

6.2.3.2 Cost-positive emissions reduction solutions

Beyond the solutions above are a series of measures that can contribute to significant emissions reductions through changes in the energy generation and supply system relative to the current baseline technologies of natural gas-power boilers and CHP. However, these require significant upfront investment and the alternative fuel costs or electricity result in a net cost over the life of the project at present. These include biomass boilers, electric heat pumps, and geothermal in order of overall cost per tCO_2e abated. In particular, the MACC illustrates that electrically driven heat pumps could offer significant emissions reductions across the sector.

Despite the costs, there has already been a transition to biomass boilers, some biomethane, and several heat pump systems have been deployed in the sector under the support of the non-domestic renewable heat incentive scheme NDRHI (see 7.1.5). Assumptions built into the MACC are that support schemes will incentivise further uptake, particularly of heat pumps, but these support costs are not included in the MACC. Biomass boilers (burning biomass with a carbon intensity of 20 gCO_2/kWh compared to carbon intensity of natural gas at 183 gCO_2/kWh) have already been widely deployed, but further uptake is somewhat uncertain as concerns grow over deforestation, and conflict with land use for food (see Section 5.3.5). Moreover, the role of biomass depends on the future market design, as it can be used primarily to produce biomethane for injection into the grid so long-term this may not be a desirable option. Geothermal, while significant on the MACC, has to be treated with considerable caution, firstly because it is location specific so will not be deployable in many locations, and secondly, the costs are highly uncertain, with significant risks involved in surveying and drilling (See Section 5.5.2).

For most clean energy generation technologies, an alternative source of CO_2 is required, the costs of which are not included in this analysis as they are difficult to predict and require separate comprehensive analysis. For the purposes of the MACC, we assume growers transitioning to alternative technologies would retain natural gas boilers for at least 20% of their thermal capacity in order to meet peak heating demands and provide a source of CO_2.

Efficiency improvements related to supplementary lighting, and advanced glasshouses such as semi-closed and closed glasshouses with seasonal energy storage are much less cost effective at present. Moreover, aside from lighting, these initiatives are unsuitable for retrofit so deployment and hence impact across the sector is likely to be low at least in the near-term.

Notably, in this MACC, electric boilers, on the right of the figure, are the least attractive option due to the high cost of electricity and high carbon intensity of grid electricity (grid carbon intensity is currently 193 gCO_2/kWh, compared with natural gas at 182 gCO_2/kWh).

6.2.4 Sensitivity analysis of the MACC

The MACC allows exploration of alternative scenarios by modification of parameters within the model. Annex F presents comparison charts of six alternative scenarios based on different future assumptions on energy pricing and grid power emissions differences and illustrates how priorities may shift going forward. The sensitivity analysis can also be used to explore the potential impacts of policy interventions.

6.2.4.1 Scenario one: Baseline settings (based on Q3 2022 prices)

Discussed above, in the baseline scenario (at Q3 2022 prices) about a quarter of the market abatement potential can be delivered through measures that will save money for the growers over the long term. This represents an opportunity to leverage the historically high energy prices to drive behavioural change in the sector with efficiency measures that reduce energy consumption the priority. The more sophisticated energy system changes would all require market intervention to make them economically viable relative to the base case of gas-fired CHP/boilers at current market pricing.

6.2.4.2 Scenario two: "Pre-Covid/ Ukraine" (based on Q1 2020 prices)

A return to “business as usual” prior to the market impacts of Covid, Ukraine conflict, and other inflationary pressures, shifts many of the measures above the X-axis - that is, reduces the economic case for implementing energy efficiency and emissions reductions measures. Boiler efficiency measures, improved control systems, routine maintenance and repair, and technologies such as variable drives remain important, but much of the potential for emissions reduction will have an economic cost and therefore little uptake is expected without policy intervention.

6.2.4.3 Scenario three: Decarbonised grid, electricity/gas price ratio unchanged

This scenario explores the impact of approximately halving of the carbon intensity of the power grid (reducing from an average of 193 gCO_2/kWh today to 90 gCO_2/kWh) while retaining the current electricity-to-gas price ratio. This is a reasonably probable scenario in the short to medium term as investment in renewable energies advances, while the electricity price continues to be based on the marginal cost of generation of electricity with natural gas. This scenario could reasonably be used as the baseline scenario to reflect the reducing carbon intensity of the grid over the duration under consideration. In this scenario the electrification-based energy system initiatives, such as transition to electric boilers, heat pumps, and closed glasshouses become significantly more attractive for carbon abatement. However, even at half of today's current grid emissions intensity, these electrification solutions are not cost-effective options for abatement in the sector. This highlights the importance of shifting the ratio in price of grid power relative to natural gas to shift the balance away from fossil fuels.

6.2.4.4 Scenario four: Decarbonised low-cost electricity grid

BEIS forecasts predict that by 2040 the average grid electricity emissions intensity will reduce from today's average of 193 gCO_2/kWh, to 15 gCO_2/kWh, falling further to 2 gCO_2/kWh by 2050).[131] Decarbonisation will be based on a combination of renewables, nuclear, and extensive carbon capture, but will take time to realise. However, combination of CEA with local or self-owned renewable energy systems such as wind and solar energy generation can make decarbonised low-cost power a reality today for CEA operators. A decarbonised, cheap electrical supply as explored in this scenario (carbon intensity of 50 gCO2/kWh, and a price of 4p/kWh) would greatly improve the economics and benefits of electrification. Electric boilers become a cost-saving option. Heat pumps and geothermal also become more viable, although still at a cost, while on the other hand the case for electrical energy efficiency improvement measures such as variable speed drives, and supplementary LED lighting reduces. The stronger case in this scenario for electric boilers compared to heat pump raises questions over whether heat pumps should be a long-term policy initiative, particularly given that electric boilers are cheap and easy to install, and relatively simple to operate and maintain. Assumptions on the potential market penetration for electric boilers are low in the MACC, but a shift in the economics could greatly expand uptake and their contribution to carbon abatement.

6.2.4.5 Scenario five: Decarbonised electricity grid and high gas prices

Building on the previous scenario, a decarbonised, cheap electrical supply combined with a doubling in natural gas prices would dramatically shift the economics of carbon abatement and make most of the measures considered in the MACC viable. Such a scenario may not emerge in the short term, but the scenario illustrates the potential impact of higher carbon pricing on fossil fuel usage, or policy intervention through subsidies to increase the relative attractiveness of clean energy systems. In this scenario, electric boilers become the most cost-effective solution for carbon abatement. For those still using natural gas, efficiency improvements gain further importance of course, and biomass boilers, geothermal and heat pumps all become viable technologies (relative to natural gas). In this scenario the case for semi-closed glasshouses is still weak, but closed glasshouse with seasonal storage may be viable.

6.2.4.6 Scenario six: Low biomethane prices

This scenario illustrates how a reduction in biomethane costs would make retrofitting existing CHP plants more attractive. The urgent need to replace natural gas as an energy source is driving a shift to biomethane, which is easily retrofitted and can be relatively easily integrated into the grid supply. Currently, biomethane is mainly used by growers who own or are co-located with an AD. Therefore, only one biomethane-related measure is considered in the analysis, namely retrofitting existing CHP plants. The emission reduction potential may be even greater, as a lower market price would also incentivise the use of biomethane boilers. However, biomethane supply constraints and uncertainty about the future business model for biomethane producers may limit the potential.

6.2.4.7 Additional sensitivity analysis explored

- Changes to the investment period under consideration. Reducing the period to 20 years, or 10 years, increases the MAC £/tCO_2e cost for all the higher capital expenditure projects making these less attractive, while the low cap ex projects that have a cost negative impact (i.e., operational savings) become more attractive.

- Financial NPV discount rate. For a previous MACC undertaken for Defra in 2010 a discount rate of 4.5% was used.[132] With inflation running at ~10% and rising interest rates higher discount rates may be appropriate (rates of between 5-10% are probably appropriate, but these should be determined directly with the industry). Higher discount rates impact on the cost effectiveness of the measures.

- Carbon emissions NPV discount rate. Application of a discount rate to carbon emissions is optional. Reducing this to zero reduces the MAC £/tCO_2e, both for positive and negative costs. (Guidelines suggest using a rate of between 2-5%, but there is no standard agreement on this).

- Coefficient of performance (COP) for heat pump. Reducing the COP of the heat pump, as would be expected reduces the economics of heat pumps. Equally, increasing the COP, for example, by using higher temperature heat sources improves the economics (assuming the costs of the waste heat source do not outweigh these benefits). Similar applies to the use of geothermal.

- Further in-depth scenario analysis can be undertaken by adjusting assumptions on costs, anticipated efficiency and emissions benefits, and market penetration levels for the individual measures. This was beyond the scope of this study but could be undertaken to explore the effects of changes in capital and operating costs as a technology evolves. The values used are estimates and where more specific data becomes available it may be beneficial to rerun the MACC.

7 Current policy landscape for energy supply shaping the CEA sector

Several policy areas directly impact the CEA/horticulture sector, such as planning regulation with the National Planning Policy Framework (NPPF), latest update in 2021 with an increasing focus on sustainable development, water abstraction licencing, legislation of energy production and consumption as well as carbon taxation schemes. In addition, policy decisions affecting labour, such as the Seasonal Worker Scheme and legislation affecting wages have a direct impact on commercial viability of CEA operations. In addition, there have been government efforts to provide horticulture specific support schemes. Producer Organisations (collaboratives of fruit and vegetables growers) have received funding through the EU Fruit and Vegetable Aid Scheme[133], with the main aims to increase competitiveness and market orientation of UK growers through productivity and collaboration. This legislation has currently been retained by the UK Government and is set out in the UK's National Strategy for Sustainable Operational Programmes published in 2020[134], mainly with the aim to increase competitiveness of UK growers in the face of EU imports and pressure by retailers to keep prices of produce low. These schemes, however, appear to have had only limited impact on the recent developments in CEA, and a persistent theme identified by industry experts is a concern over commercial viability at current retail pricing and concerns over unfair buying tactics and practices that many growers face during discussions with retailers.[4]

In this section, we focus mainly on the energy and carbon taxation schemes because energy generation and consumption has been the central focus of this report and in discussions with industry stakeholders energy policy was considered the key area with most impact on addressing costs and shaping the long-term future of the industry. This does not mean that labour and planning policy or water licensing are not important, however, all stakeholders interviewed for this report considered those as secondary to energy policy, which so far has been key for most of the sector development over the past two decades.

Despite there currently being no energy support policy specifically for CEA, the sector has realised innovation, restructuring and growth of high-tech glasshouse operations in the past, mainly benefiting from energy policies targeted at reduction of carbon footprint and the promotion of renewable energy sources in industry more generally.

When looking at policy design to support the sector it has to be taken into consideration that the current horticulture industry as a whole is not a homogenous industry with operations at very different levels of technological advancement. However, there is a strong trend, driven by efficiencies of scale toward large high-tech glasshouses equipped with latest technology (digital and otherwise) for optimising operations and energy efficiency. It is against this backdrop that the industry has utilised relevant existing and past energy and climate policies to its benefit. Any new, more targeted policy design must consider the current trends affecting the sector as well as the existing legacy industry structure.

7.1 Current and past policies

Adoption and utilisation of the following policies by the CEA sector was, and is, the result of the technical and structural boundaries that are defined by its energy use patterns as large energy consumers. The following presents the primary legislation of relevance, in chronological order.

7.1.1 Combined Heat and Power Quality Assurance

The Combined Heat and Power Quality Assurance (CHPQA) scheme is a government initiative for assessing CHP schemes across all industry sectors, and has been running since 2001.[135] It aims to monitor, assess and improve the quality of UK CHP installations. It is a voluntary annual certification program with the certificate enabling access to a range of benefits including the Renewable Obligation Certificates, Renewable Heat Incentive, Carbon Price Floor (heat) relief, Climate Change Levy exemption (with respect to electricity directly supplied) and preferential Business Rates.

CHPQA assesses CHP installations on the basis of their energy efficiency and environmental performance and ensures that the associated fiscal benefits are in line with environmental performance.

For participating organisations, their CHP plant is evaluated based on its fuel use, power generation and heat supply leading to a Quality Index (QI) and power efficiency score for the plant. A certificate of 'Good Quality' CHP will unlock the financial benefits from other schemes mentioned above.

Impact on the CEA sector

CHPQA for gas-fired CHP, and to some extent for renewable fuel-powered CHP, has been used predominantly as a mechanism to obtain CCL levy exemptions for the gas being combusted in CHP installations. In addition, renewable source CHPs could obtain a more favourable tariff rate when the installation reached a certain energy efficiency mark (although only very few such installations are currently operational in the CEA sector).

With current high gas prices and past incentive schemes expired, and a stronger focus on net zero policies, the future for natural gas fuelled CHP in the UK is unclear. This is putting pressure on growers that currently mainly use natural gas CHP or boilers, representing a large proportion of the sector. Any phasing out of this technology will require a good deal of consideration and support given that the investments in these technologies over the past decade will still need to pay off before replacement. Recent calls for evidence to inform future policy on use of CHP in the future up to 2050 have identified a number of contextual factors that were considered important for the remaining lifetime of the scheme.[136] These included the necessity of longer-term recognition of natural gas as a "bridging fuel" while transitioning to more sustainable energy options, a perceived erosion of government support in renewables CHP damaging investor confidence in long-term future investments, policy uncertainty with regards to future developments of the Emissions Trading Scheme, and the general importance of financial benefits through the scheme for the competitiveness of UK businesses.

7.1.2 Climate Change Levy

Climate Change Levy (CCL) is a tax measure introduced in April 2001 to encourage businesses, industries, and other large organisations to reduce their carbon emissions by charging a levy on taxable commodities for heating, lighting and power purposes such as natural gas, electricity, petroleum and coal.[137] The levy is paid either at the main CCL rate by all businesses in the industrial, commercial, agricultural, and public services sectors or at

Climate Change Agreement (CCA) discount or Carbon Price Support (CPS) rates. This is an industry wide obligation across all industries initially intended to be a carbon reduction scheme that has evolved into a scheme for increasing energy efficiency. It is estimated by experts consulted for this study that it has over its lifetime helped increase overall energy efficiency of the sector.

7.1.2.1 Climate Change Agreement

The Climate change agreement (CCA) scheme was first established in 2001. The current scheme commenced in April 2013 and has recently been extended to run until March 2025. A consultation on future proposals for the scheme was held in 2021/2022.[138] CCAs are voluntary agreements entered into between industry and the UK Environment Agency[139] with the objective of encouraging energy intensive sectors to reduce energy consumption and emissions. Participating businesses are required to establish baseline data on energy used and carbon emitted for their site over a 12-month period, and then monitor and report their performance on an two-year basis, with a commitment to target reductions over a period of years.[140] Targets are set and agreed by the sector association, which for the horticulture sector is the National Farmers Union (NFU). If the business meets its reduction targets at the end of each reporting period, it receives a CCA reduced rate certificate (RRC) which provides a discount on the CCL. Failure to meet the target can either be offset by using banked surplus accrued through over-performance during previous target periods, or payment of a 'buy-out fee' of £14 for each tonne carbon dioxide equivalent (tCO_2e) which was the cost for previous target period TP3 (2017-2018) and TP4 (2019-2020) – for target period 5 (TP5, 2021-2022) is £18 per (tCO_2e).[59]

<u>Impact on the CEA sector</u>

Overall, the scheme is considered to have been a success to date, with 80% or more of businesses in eligible sectors participating, and the NFU observing it is one of the few effective policies for encouraging efficiency improvement. Target setting and ongoing audit of the scheme can be problematic, but according to a scheme review published in 2020, almost half of the participants met their defined improvement targets over the first three annual periods, with low under-performance. Average energy savings per sector ranged from 4% to 11% for energy-intensive sectors, while the scheme reduced energy costs by about 5%, and contributed to industrial competitiveness, more than outweighing the costs of administering the programme.[141]

A review published in 2021 of phase TP4 of the scheme (covering Jan 2019 – Dec 2020), listed 102 facilities or groups of facilities in the horticulture sector (covering all forms of horticulture), with an average 19.46% emissions improvement as percentage of emissions against a defined target for the sector of 12.30%.[59] As of 2022, 149 horticulture sites held CCA reduced rate certificates (RRC).[142]

7.1.2.2 Carbon Price Support scheme

The Carbon Price Support rate is used for electricity generators or operators of gas-fired CHP installations of >2MW. Businesses that generate their own electricity and also generate revenue through the feed-in Tariff may be classed as small generators and be exempt from CCL.

7.1.3 Renewable Obligations (expired)

Renewable Obligations (RO) was the main scheme for promoting the new build of large-scale renewable electricity projects in the UK.[143] It came into effect in 2002 in all parts of the UK except Northern Ireland, which adopted it in 2005. It was aimed at encouraging electricity suppliers to increasingly source electricity from renewables.

The mechanism rewards generators of eligible renewable electricity with a specific number of Renewable Obligation Certificates (ROC) for each MWh of eligible renewable output they generate for over 20 years. These certificates can then be purchased by electricity suppliers who have not met their renewable electricity obligations. Biomass CHP, and biogenic fuel CHP, are eligible for 'Good Quality' Certification.

The scheme is closed to new generation capacity since 31st March 2017, but existing scheme participants will continue to receive certificates through to 2038.

7.1.4 UK Emissions trading system

On January 1, 2021, the UK Emissions Trading Scheme (UK ETS) replaced the EU ETS following completion of EU Exit. The previous EU scheme had been in place since 2005. The scheme applies to energy intensive industries, the power generation sector and aviation covering activities resulting in greenhouse gas emissions, including combustion of fuels on site with a total rated thermal input exceeding 20MW, with exception of operations aimed at incineration of hazardous or municipal waste.[144]

Similar to other emissions trading schemes, UK ETS also works on the "cap and trade" principle. The participating sector will receive a cap on the total amount of certain greenhouse gases it can emit to limit the total emitted carbon by the sector. This threshold decreases over time and should contribute to reaching Net Zero by 2050. The scheme allows participants to trade their batch of free allowances and/or buy allowances at auction and secondary market as needed.

Impact on the CEA sector

The CEA sector is not classified as an energy intensive industry yet. Expert interviews and workshop discussions carried out for this study indicate that only a limited number of CEA sites are participating in the scheme as not many CEA operations are large enough to qualify, and some that are just large enough to reach the threshold, deliberately stay below the threshold as a strategic decision. This is mainly because the cost of being in the scheme is high with most impact on the CEA operations when using CHP due to higher fuel consumption. Experts estimate that even sites using boilers for heat generation may have increased costs of c. £70K/Ha when entering the scheme, becoming prohibitive and limiting economies of scale. Sector players are not all aligned in their approach to using this scheme and their choice is dependent on the economics of their operations.[xi]

7.1.5 Non-Domestic Renewable Heat Incentive (expired)

The Non-Domestic Renewable Heat Incentive (NDRHI) policy was introduced by the Department of Business, Energy, and Industrial Strategy (BEIS) on 15th of July 2009 and launched on 28th November 2011 with the aim to encourage increased use of renewable heat by businesses, public sector and not for profit organisations, in essence a general policy aimed at any industry to encourage reduction of carbon emissions through changing the heat source in their business.[145] The policy provides long-term financial support for heat generated by biogenic fuel boilers or CHP and other renewable sources, and use of heat pumps. If an operation has a capacity of 200kW or more, biogas is also eligible for payments under the scheme. Scheme participants are subsidised to generate and use renewable energy for their onsite heat needs or provision of heat to other sites. The tariffs vary depending on type of technology involved and the date of commissioning and are payable for 20 years.[146] The policy came to an end on 31st March 2021 from when no new applications for new installations were accepted with an extension to March 2023 for some exceptional cases. The latest figures from 2022 show that the NDHRI has helped produce a total of 56 TWh of renewable heat in total over the life of the programme so far across all sectors (and will continue to deliver benefit over the remaining lifetime of the scheme until 2040).[147] The 'Crop and animal production, hunting and related activities' Standard Industrial Classification (SIC), which includes CEA, is the largest industry segment, with a total installed capacity of 1,778.8 MW of renewable heat capacity as of 2022. A specific breakdown of the impact and effectiveness of the scheme within CEA is not available, but across all industry sectors 78.72% of accredited schemes were for solid biomass boilers, 10.56% for ground source heat pumps, 3.95% air source heat pumps, biogas 3.51%, and biomethane and solid biomass CHP together representing just 1%.

Impact on the CEA sector

The NDRHI has contributed to decarbonisation efforts of the sector and has been used to some extent to provide guaranteed income streams for securing large capital-intensive projects with long repayment times, hence helped supporting the financing mechanisms for new builds of high-tech glasshouses (See Annex H case study of Low Carbon Farming). It incentivised investments in alternative energy generation technologies such as biomass boilers, heat pumps and AD, mainly by guaranteeing revenue. In the case of biomethane-fuelled CHP installations the excess electricity generated could also be sold to the grid generating an additional source of revenue independent of the NDRHI, with eligibility for ROCs.

Industry experts interviewed for this project considered NDRHI to have had the single biggest impact on CEA in recent years with respect to energy use. Its impact as a mechanism for guaranteeing long-term revenue streams to support investments is estimated to have contributed to a 10% to 15% increase of high-tech glasshouse area in the horticulture industry during its lifetime.

[xi] Views of industry experts interviewed for this study

7.1.6 Feed in Tariff (expired)

The Feed-in Tariff (FIT) scheme aimed at promoting the uptake of renewable and low-carbon electricity generation.[143] It differs from RO scheme by covering renewable generators such as Solar PV, wind, micro-CHP, hydro and AD. The scheme was introduced in on 1 April 2010 and has expired with some exceptions for AD plants in April 2019. Like RO, the scheme required participating licensed electricity suppliers to make payments on electricity generated and exported by accredited installations. FITs pay for the electricity produced as well as additional payments for electricity exported to the grid for a 20-year period, The mechanism is closed for new applications, but participants in the scheme will benefit from FITs up to 2040.

7.1.7 Contract for Difference

The Contract for Differences (CfD) scheme was introduced in UK in October 2014 aiming to replace RO system in the UK, designed to support deployment of large-scale renewable projects (more than 5MW). It is the government's main mechanism for supporting low-carbon electricity generation by incentivising investment in new renewable power installations.[148] The mechanism of support works by protecting developers' projects with high capital costs and long lifetime from volatile wholesale electricity prices, by paying developers a flat (indexed) rate for the electricity they produce over a 15-year period. The delivery of the CfD scheme is administered by the Low Carbon Contracts Company, and responsibility for running the CfD allocation process lies with the Electricity Settlements Company, both private companies owned by BEIS.[148,149]

Impact on the CEA sector

In the context of horticulture projects, AD plants used to generate fuel for CHP, and wind and solar installations may benefit from CfD.

7.1.8 Green Heat Network Fund

Opening in March 2022 to application, the Green Heat Network Fund (GHNF) is a three-year funding programme for capital grants of £288m. The scheme aims to incentivise the transition of the heat network market to low carbon heat sources using targeted financial support for deployment of low carbon technologies at scale. Organisations from public, private and the third sector can apply for grants in England. The fund is a core element of the government's Heat Network Transformation Programme (HNTP) and a continuation of and building on the development and progress made by the Heat Network Investment Project (HNIP) that was piloted in 2017 and launched in 2018 and, the Green Heat Network Transition Scheme, which started in July 2021. GHNF is at the centre of the government's HNTP initiative. The objectives of the scheme are to:

- Decrease carbon intensity of heat supply and realise carbon savings
- Increase total amount of low-carbon heat used in both retrofitted and new heat networks
- Prepare the heat network for further decarbonisation by contributing towards market transformation across supply chain and investment landscape

The scope of GHNF support is in provision of capital grants for both commercialisation and construction of new low- and zero- carbon heat networks as well as retrofitting and expansion of existing networks. Eligibility will be assessed based on the volume of low carbon heat delivered by the project and selection is based on a principle-based approach for cost eligibility.

The Committee on Climate Change estimates that in order to meet the UK's carbon targets by 2050, around 18% of UK heat has to come from heat networks. The advantages of heat networks are:

- Already established method of distributing heat
- Can utilise otherwise wasted energy
- Provide grid balancing services in an increasingly electrified heat market
- Offer low carbon heat at competitive prices to households and businesses
- Can accommodate large scale renewable heat from often inaccessible sources
- Can work within a hydrogen economy
- Can be used to provide cooling helping cities to adapt to climate change

Round 3 of the scheme was to applications until 25th November 2022 with quarterly application rounds until the closure of the scheme in 2025. The current scheme offers up to £1million commercialisation support (capped at 50% of project costs).

Impact on horticulture industry:

So far there is no publicly available evidence of the CEA sector having accessed the fund to date and in our discussions with sector stakeholders the fund was not mentioned as a source of capital investment. Glasshouse operations could potentially be integrated into residential and industrial heat networks and benefit from this fund. However, the complexity of such projects may be one reason for the sectors' lack of uptake.

7.1.9 Future Support for Low Carbon Heat

To reduce carbon emissions from heating of homes, businesses and industry, which is responsible for a third of all greenhouse gas emissions in the UK, the government set out a consultation in 2020 for replacement of the NDRHI and announced the outcomes with a latest update in February 2022. The outcome of the consultation led to support to create incentives for cost effective installation of the following low carbon heat technologies. [150]

- Biomethane injection into the gas grid through the Green Gas Support Scheme (GGSS).
- Building technology (heat pumps and limited cases of biogas) through "Clean Heat Grants" known as the Boiler Upgrade Scheme (BUS).

7.1.9.1 Green Gas Support Scheme

The Green Gas Support Scheme (GGSS) provides financial incentives for investment in new anaerobic digestion biomethane plants to help increase the proportion of green gas in the gas grid.[151] The scheme went into effect on 30th November 2021 and is open to applications for four years. The participants in the scheme will receive quarterly payments over a period of 15 years based on the amount of eligible biomethane that the participant injects into the gas grid. The scheme will be supported by the Green Gas Levy (GGL) which will oblige gas suppliers with quarterly payments to fund the GGSS.

7.1.9.2 The Boiler Upgrade Scheme

The Boiler Upgrade Scheme (BUS) is aimed at decarbonisation of heat in buildings by providing upfront grants in support of installing heat pumps and biomass boilers both in domestic and non-domestic buildings.[152] However, the BUS scheme is only open to domestic and small non-domestic properties, so will not support CEA. For example, the scheme pays up to £5,000 towards the cost of a biomass boiler, whereas the boiler cost for a "small" CEA operation may be £500,000.

Impact on horticulture industry

CEA operations cannot directly benefit from the GGSS, because the scheme only applies to biomethane injected into the grid. If biogas is used directly from an owned/co-located AD it is ineligible for support payments, and if a CEA operator buys from the grid it would be at market prices. Moreover, uptake of GGSS is currently constrained by planning restrictions, and requirements for large scale, adjacency to a reliable, economical feedstock source, and adjacency to gas grid nodes. There is also a need for longer-term tariff schemes that can support large investments with longer payback times.

7.1.10 Sustainable Farming Incentive

The Sustainable Farming Incentive (SFI) is one of three new environmental schemes the government is introducing under the Agricultural Transition Plan.[153,154] The focus of the scheme is on helping farmers manage land better to improve food production, care for the environment and become more sustainable. Essentially the scheme funds sustainable land management actions with some elements of advise to support the delivery of these actions. The SFI pilot opened in 2021 and the first elements became available to all land managers in 2022.

Impact on the CEA sector

The scheme does not exclude horticulture but is not necessarily useful to the sector due to structural differences between outdoor agriculture and indoor horticulture.

7.1.11 Farming Innovation Programme

The scheme went into effect on 20th October 2021 aimed at supporting farmers, growers, foresters, and other businesses to adopt innovations towards maximising productivity and sustainability.[155] It particularly states that this long-term support scheme is aiming to support ambitious projects to transform productivity and enhance environmental sustainability in England's agriculture and horticulture sectors helping them towards achieving net zero operations. The scheme will contain a number of different initiatives including Farming Futures R&D Fund.

Impact on horticulture industry

This program is beneficial with some impact mainly in updating operations and control systems for smaller growers and potentially enabling smaller R&D projects.

7.1.12 Net Zero Innovation Portfolio

The Net Zero Innovation Portfolio (NZIP), announced in March 2021, is a £1 billion fund to accelerate the commercialisation of low-carbon technologies, systems and business models in power, buildings, and industry.[156]. The portfolio covers ten priority areas: future offshore wind, nuclear advanced modular reactors, energy storage and flexibility, bioenergy, hydrogen, homes, direct air capture and greenhouse gas removal (GGR), advanced carbon capture, usage and storage (CCUS), industrial fuel switching, and disruptive technologies.

Impact on horticulture industry

The programme isn't directly aimed at horticulture, but several of the priority areas may have relevance for the future development of CEA. For example, the support for BECCS and CCUS will create new alternative sources of CO_2 (see section 5.6), and support for bioenergy will bring down the costs and barriers to use of biomass, biomethane, and green hydrogen making these more viable fuels for CEA in the future (e.g., see section 5.3.3 for details on various hydrogen initiatives within the NZIP).

7.2 Overall impact of the current policy landscape

The picture emerging is of a complex relationship between several different policies and schemes that have been utilised by the CEA sector to build the currently predominant business model, namely securing long term regular income through a combination of tariff payments and sales of excess electricity generated to the grid, to subsidise growing operations and to provide a long-term stable revenue stream to attract investment. At present, March 2023, the sector finds itself in a challenging situation because this very business model is now threatened due to discontinuation of key policies, notably NDRHI, which formed the backbone of commercial viability, high energy prices, and policy uncertainty, creating not only difficulties for existing operations, but also preventing further large-scale investments.

7.3 The Netherlands – A potential benchmark for the UK's CEA sector

In this section we present a brief overview of policy approaches to CEA in the Netherlands as a potential benchmark for future UK policymakers. CEA in the Netherlands is a key industry, with the Netherlands being a top three global food exporter with well-established infrastructure and support mechanisms. They are also global technology leaders in the CEA sector, and large UK glasshouses mostly use Dutch technology and expertise. The Dutch CEA sector uses 9% of total natural gas demand in the Netherlands mainly for CHP.[157,158] At the same time there has been a strong drive to specifically accelerate the decarbonisation of the sector through government policies for a number of years, aiming to have the sector climate neutral by 2040.[159]

7.3.1 Policy

From a policy perspective, energy savings are a major priority for the industrial horticulture sector, with energy being 30% of the costs for most crops even before recent energy price increases.[160]

The Netherlands has a broad energy tax that applies to the consumption of gas, electricity and district heating. Consumers also pay a Surcharge for Sustainable Energy Act levy on top, which provides funding to support schemes for renewables and emissions reductions. There are considerably lower rates for large consumers and an overall discount for gas used to heat glasshouses in the CEA sector.[161]

The "Greenhouse as Source of Energy" programme (in Dutch "Kas als energiebron"): is a collaborative initiative between the government, the Horticulture Product Board and the Dutch Confederation of Agriculture and Horticulture.[162] It is focused on bringing growers and researchers together to work on innovation and implementation of diverse energy research in glasshouses. The program is financed by the Dutch government together with major sector players. By November 2020, 70% of growers were members of the platform and nearly 10% of energy used in glasshouses was renewable. A successful example of this collaboration has been the TerLaak glasshouse operator, specialising in orchid/*Phalaenopsis* plants. Working with the University of Wageningen, they managed to set up a 6-hectare glasshouse with energy savings of 40% to 50%. Implementing this concept however took six years from inception, starting out from a $1m^2$ test greenhouse moving to a $400m^2$ pilot before building large-scale operations.[163]

Overall, the Dutch government is looking to reach net zero by 2050 and currently about 26% of national power generation is from renewables.[164] The low carbon energy sources in consideration are solar, onshore and offshore wind, biomass, geothermal and hydropower. The energy transition is encouraged by a series of grants as incentives for businesses to invest in sustainable energy:

- The Renewable energy Grant Scheme (SED+): supports large energy projects focused on geothermal and solar:[165] There is a transition from SDE+ to SDE++ over the coming years, which will see a strong increase of financial support for biogas and biomethane projects. SDE++ will be the main support mechanism for such projects with added support for targeted RD&D and pilot projects.[161]
- Renewable energy grants for smart technologies combines production and storage to contribute to smart grid.
- The energy investment tax credit: supports energy efficient environmentally friendly technologies.[166]
- Sustainable energy investment grants (ISDE): supports heat pumps, solar water heating systems, biomass boilers and biomass burners.[167]
- Geothermal projects are supported by the government through underwriting the drilling risk, investing in operational software support systems and the 'energy-production greenhouse' programme. Both the SIDE+ and grants for fixed geothermal heat pumps feed into promoting geothermal solutions.[168]

7.3.2 Agricultural cooperatives

Another key element for success in rallying the agricultural industry including the horticulture sector in the Netherlands around emission reduction is the strong presence of agricultural cooperatives and their close collaboration with the government.[169]

After the 2014 EU Rural Development Regulation introduced the option of group applications for agri-environment-climate measures (Regulation (EU) No 1305/2013, Article 28), the Dutch government decided to implement the measure for joint applications only. Hence, only projects involving a number of local cooperating stakeholders will be considered with the aim to realise more benefits for the wider ecosystem. This approach fits well with the long Dutch tradition of agricultural cooperatives. Cooperatives are considered the only vehicle that can address biodiversity decline, enable farmers/growers to have a say on the content of conservation activities and reduce the error rate and inefficiencies inherent in individual applications. By making cooperatives the final beneficiaries of agri-environmental support leads to simpler policy scheme designs with room for local fine-tuning allowing groups of farmers/growers to own their projects while substantially reducing the implementation cost for the government. Similar cooperative models for developing larger projects are increasingly becoming prevalent across the EU.[170]

The success of agricultural cooperatives is attributed to:[171]

1. an enabling cooperative legislation
2. innovations in internal governance
3. low membership heterogeneity
4. pragmatic approach to federative cooperative structures
5. focus on explicit strategies to their position in the food chain

A recent trend emerging from these initiatives is the enabling of cooperatives to become investment vehicles. Horticoop, a horticulture cooperative is one of such outfits. This means the member growers will buy from the companies in which the cooperative invests, helping companies where Horticoop has a participating interest and those companies in turn help the members. The members will also receive dividends from the success of the member companies.[172] This creates a new revenue stream for growers potentially mitigating some of the challenges they face resulting from energy transition.

7.3.3 Access to finance

The Dutch horticulture sector, including CEA, has historically invested in sector growth using bank loans provided by specialist banks with a high degree of expertise in the specific requirements of the agriculture and horticulture sectors. Only four such banks provide almost all loans to the Dutch horticulture sector. These are ABN AMRO, ING, Triodos and Coöperatieve Rabobank which is by far the largest and in 2017 held 85% of the total loan portfolio in Dutch agriculture. The agricultural expertise in the specific risks of the sector in tandem with sector specific government support mechanisms to de-risk investments for example by providing guarantees for exploratory drilling for geothermal wells[123] (see Section 6.3.1) have supported sector growth for many decades. Another example is the Agricultural Loan Guarantee Fund, which dates back to the 1950s and was established with the explicit goal to support lending to farming operations with insufficient collateral. Although now abolished in its original form as a non-departmental public body, its function is today carried out by an agricultural guarantee scheme (EU authorised state aid), which provides 80% guarantees for three types of agricultural loans: Basic (up to €600,000), Young Farmers (up to €1,200,000) and Investments in Sustainability (up to €2,500,000). Despite this strong support from the banking sector and government, more recently other sources of capital are now contributing to a smaller extent to the financing of expansion and technology upgrades of the sector, mainly through credit unions and crowd funding for smaller loans.[144]

More recently private equity investors have also started investing specifically in the high-tech glasshouse/CEA sector in the Netherlands as press reporting on its growth potential globally, and the possibilities for using renewable energy sources made it appear more attractive to investors, a trend also seen in the UK, where for example Greencoat Capital has invested in three large new builds of high-tech glasshouses (see also Annex A, Low Carbon Farming case study). From expert consultations carried out for this study as well as from analysis of activities of private equity investors in the Netherlands it is however apparent that very good alignment between project developers, growers, and long-term guaranteed financing and operational models have to be in place for private equity investment to be viable.[173]

7.3.4 Industrial Infrastructure

The Dutch CEA/horticulture infrastructure is more advanced and interconnected than the UK sector as the result of concerted long term support policies and collaboration with world-class home-grown research centres with a focus on CEA/horticulture and agri-tech, such as Wageningen University. Moreover, a characteristic of the CEA sector in the Netherlands are 'greenports'. These are areas where the entire horticulture chain, from propagation and breeding, nurseries, technology suppliers, auction houses and trading companies are concentrated. Research institutes are also often situated nearby creating 'golden triangles', whereby, with all parties closely situated, there can be intensive interchange of knowhow and cooperation.[174]

Heat supply for Dutch glasshouses, similar to the UK, is currently mainly through gas-fired CHP. Its dominance, as in the UK has been due to cheap natural gas prices helped by the fact that the Netherlands possess large domestic natural gas fields. With the sharp increase in natural gas prices this picture is also changing rapidly for the Dutch CEA sector.

Geothermal heat generation is well developed in the Netherlands, partly due to favourable geological conditions, and the cost of drilling a site at ~€5M is supported by government practically underwriting the risk of failure of exploratory drilling (in case there is not enough heat or flow rate) which attracts investors to large-scale projects involving geothermal heat energy. Currently ~10% of energy in the CEA sector is renewable, most of this is geothermal (numbers and detail from interview with Dutch experts).

Another well-established technology is seasonal heat storage in shallow aquifers**.** The technology has already been in use by Orchid growers for the past 20 years although it has not spread much into the wider sector due to cheap natural gas running CHPs.

Industrial waste heat is not widely used due to the need for substantial insulated heat pipe networks requiring large capital investments. There is currently only one large operation that uses district heating from an Energy from Waste plant (EfW) through a heat pipe network near Wageningen. Glasshouses are mostly too far away from industrial waste heat producers to make this source a viable option.

The dominant source of supplementary CO_2 for the CEA sector in the Netherlands, like the UK, is still currently CHP. However, the Linde Group owned OCAP (Organic CO_2 for Assimilation by Plants) operates a CO_2 distribution pipeline and network in the western part of the country, supplying CO_2 to CEA operations from Rotterdam to Amsterdam. The network consists of a main grid, local distribution networks, and supply stations, supplying CO_2 captured from industrial hydrogen and bioethanol refineries in the Rotterdam port area. OCAP currently supplies about 500,000 tonnes of CO_2 per year to approximately 600 glasshouse operators (representing 2,500 hectares).[175] Future expansion plans include extraction and supply of CO_2 from other industrial sources including AD plants. Since 2017, OCAP has been a leading player in a coalition of industry, government, and research institutions, working on the "CO_2 smart Grid", supported with EU approved state aid, with the aim to develop projects for further reducing the overall CO_2 emissions of the CEA sector and move towards net zero by 2040.[176] This includes a project to build a network of pipelines and storage facilities throughout the Netherlands.[175]

7.3.5 R&D contributing to energy efficiency of the sector

The Wageningen University Scenario Research is aiming to reduce fossil fuel energy use to zero in the horticulture sector with the project 'Horticulture Without Fossil Energy' conducted in collaboration with ABB, a technology solutions provider. The report was published in 2019 (in Dutch language [177]) and according to a presentation made at the Green Tech 2019 exhibition in Amsterdam, a researcher on the project from Wageningen University explained that during the research several carbon reduction options were considered, including:[178]

- lowering the glasshouses' set points (such as for temperature, light, and humidity)
- using renewable energy sources like green electricity, geothermal waste/heat, and surplus heat extracted from the greenhouse
- better energy conversion (LED lighting, smart dehumidification)
- better insulation through the deployment of screens, coated glass, double glazing, etc.

As the result of the research, they ruled out the utility of lowering glasshouses 'set points' concluding that the main lever for a carbon reduction option to become relevant is not its technical properties but its economic viability. Although overall energy costs (including cost of renewable sources) will rise, adopting energy efficiency technologies and new ways of heating can limit these cost increases for new builds when implemented from the start. Other findings pointed at:

- Using renewable energy sources like green electricity, geothermal waste/heat through involvement in municipal or regional infrastructure projects will be beneficial to access these kinds of heat sources, as they are often linked to regional heat networks and distribution systems.
- Harvesting and storage of and surplus heat extracted from the greenhouse to meet demands for winter heat.
- better energy conversion (LED lighting, smart dehumidification)
- better insulation through the deployment of screens, coated glass, double glazing, etc.

The report foresees that horticulture/CEA will move from an electricity producer, which is currently the case, to become a major electricity user, in part because lower renewables' costs will undermine the current economic model for CHP, and due to increasing flexibility of when heating and lighting is used through storage solutions, will be able to assist in balancing the renewables-based grid.[179]

7.3.6 Data collection and monitoring

In the Netherlands the government collects baseline data on energy use in the horticulture industry through the "Dutch Energy Monitor Programme" from the growers.

This is executed through the Wageningen Economic Research centre since 1990 under the project "energy-monitor greenhouse horticulture". The programme quantifies the energy-balance, development of physical production, CO_2 emissions and the share of renewable energy and share of energy-sources without CO_2 emissions in a time series, alongside analysis and explanation of background developments. The project is financed by the ministry of agriculture, nature and food-quality and Glastuinbouw Netherlands, the leading Dutch entrepreneurial network for glasshouse growers.[169,180]

7.4 Comparison of UK and Netherlands CEA sectors

Building on insights gathered through our expert interviews in the UK and the above insights into the Netherlands CEA sector, Table 2 presents a summary of the differences identified between the UK and the Netherlands on key dimensions of the sector, including policy approaches, infrastructure, cooperatives, financing and data availability.

Table 2 Comparison of policy contexts in the UK and the Netherlands

Factor	UK CEA edibles context	Dutch CEA edibles context
Industry scale and consolidation	Fairly small sector, dominated by a few large players. Will possibly undergo continuing consolidation in coming years (see Section 2.2). Geographically fragmented operations. Largest single site: one operator 91 hectares, but few are more than 20 hectares per site, and the majority are less than 5-10 hectares (research and expert interviews carried out for this study).	Large industry dominated by large players. Already an export industry for many decades, and now one of the top three global horticultural food exporters. Of the available cultivated land in the Netherlands, 0.5% is under glass.[181] Over the past two decades the industry has seen significant consolidation, with the number of edibles glasshouse operators continuously declining from 2,511 in the year 2000 to 822 in 2021 while the average size of glasshouses per farm has increased from 1.47 hectares to 6.1 hectares.[15] Many single-site glasshouse complexes well over 20 hectares and as large as 97 hectares.[182]
Dominant energy source	Natural gas-fired CHP is currently the main heat generation source (see Sections 3.2).	Natural gas-fired CHP is currently the main heat generation source (as of 2017 approximately two-thirds of the industry was heated with CHP)[157], with the industry, until the recent gas price increases, using almost 9% of the Netherlands' natural gas, and supplying about 10% of electricity in the Netherlands.[158]

Factor	UK CEA edibles context	Dutch CEA edibles context
		Geothermal heat and ATES are also in use, and in 2017 there were 55 geothermal projects covering about 7% of the sector.[157] (see Sections 4.4.2, 5.5.2 and 6.3.4)
CO_2 supply	CO_2 for yield increase is strongly dependent on use of gas-fired CHP and boilers. Where bottled liquefied CO_2 is required, it is supplied from only a small number of UK suppliers and in case of shortages imported from the Netherlands (see Sections 3.3, 5.6 and 7.4.2).	Much of the industry is still dependent on gas CHP or boilers for CO_2 supply at present, but about 25% of the sector obtains CO_2 from industrial supply networks, and there are plans to greatly expand this by 2040 (see Section 6.3.4).
Technology supply	Majority of glasshouse technology is imported from the Netherlands.	Netherlands is a global leader and major exporter of glasshouse technologies.
Policy support	If CEA growers are part of Producer Organisations in the Fruit and Vegetables Aid Scheme (EU Scheme since late 1990s, now retained in the UK since leaving the European Union), they can receive match-funded support to enhance competitiveness.[133,134] In terms of energy, the sector has utilised general energy incentives and policies quite successfully in the past, but few supporting polices available at present (see Sections 6.1, 7.4.1 and expert consultations). Various industry consultations have been undertaken, and funding competitions have been recently announced by BEIS on broader energy systems innovation that may influence the sector in the longer-term (e.g., see Sections 5.3.3 and 5.3.4).	Continuous directed policy support for the horticulture sector including CEA exists over many decades (see Sections 6.3.1 to 6.3.6).
Access to finance	No horticulture specific banking providers. No sector specific government guarantees for investments. However, as internationally, private equity investors perceive CEA more attractive recently (see Sections 2.5.2, 7.4.4 and expert consultations).	Traditionally financing through banks specialised in the horticulture and agriculture sectors for many decades. Additional, continuous government support mechanisms to de-risk financing in the horticulture sector for at least since the 1950s. Recent trends see an increase in alternative forms of investments, such as crowd funding, credit unions and private equity (see Section 6.3.3).

Factor	UK CEA edibles context	Dutch CEA edibles context
R&D support	Pockets of research around the country receive some funding, such as for example the Vegetable Genetic Improvement Network[183], but there has been limited specific national-level R&D and commercialisation support for the sector (see also expert consultations).[184,185] That said, UKRI, have recently announced providing funding (total fund of £5m) to support research focused on protected and controlled environment (PACE) horticulture.[186]	Strong directed R&D support by national policies and universities (see Section 6.3.5).
Role of cooperatives	Besides collaborations as part of the Fruit and Vegetables Aid Scheme, encompassing around 30% of growers, limited evidence of a strong cooperative culture in the UK horticulture/CEA sector was found, in particular for implementing new multi-stakeholder projects. Various growers associations, such as British Growers association[187], British Tomato Growers Association[188], and other crop associations, producer organisations, and marketing groups and professional membership groups exist. Role of cooperatives for infrastructure and project development is not well developed and explored (see Section 7.4.9 based on expert consultations regarding difficulties with multi-stakeholder projects in the UK).	Strong tradition of co-operatives in Dutch Agriculture extends to horticulture and enables smaller growers to access investment and policy schemes that are more relevant to larger players. Strong use of cooperatives and new models of collaborative project development (see Section 6.3.2).
Data availability	No directed long-term energy use data collection program with specific endpoints for the sector. There are pockets of data on energy use/emissions collated annually for the horticulture sector under the voluntary CCA scheme, which is the best industry data available at present, but the data is not widely shared due to confidentiality concerns (see Section 6.1.2.1). The sector administrator, NFU sets and monitors improvement targets for scheme	Long-term energy use data in the sector available through the ‘Energy Monitor Greenhouse Horticulture’ programme of Wageningen University & Research since 1990, with specific efficiency improvements targets and incentive scheme to drive sector-wide improvement. Has successfully improved performance of the sector (see Section 6.3.6).[169,189]

Factor	UK CEA edibles context	Dutch CEA edibles context
	members over a period of years (see also Section 7.4.7).	

8 Future development and challenges

Previous chapters have presented the current state of the CEA sector mainly with a focus on energy, the key trends and drivers in the sector, and an exploration of the key technologies currently available and viable for application to the sector within the coming decade to assist in energy efficiency and decarbonisation. An overview of the relevant policy initiatives supporting this transition have also been presented. In this chapter we bring these findings together and examine the implications for potential future development, and the main overall challenges the sector faces at present, including challenges not directly related to energy use as interdependencies between challenges need to be considered when designing solutions. This is relevant in particular when considering sector growth in the context of the UKs commitment to decarbonisation.

8.1 UK CEA sector at a critical crossroads

Overall, it is observed that energy-intensive CEA is barely viable in the UK without supplementary energy generation revenues using CHP or subsidy schemes, and this was the case even before the current energy crisis. The prospect of UK consumers willingly paying a premium for domestically grown produce to cover higher energy costs and profitability in support of expansion of the sector seems low, particularly in the current economic climate. Government intervention to subsidise food prices seems even more remote. Therefore, the industry has to be financially viable in its own right going forward. The carbon footprint of UK growers should change as the nation's energy system decarbonises, and there is a realistic potential for this sector to decarbonise ahead of the national grid, but cost competitiveness may remain an issue for UK growers. A partial solution could be focusing on non-intensive (in season only) CEA in the UK, but this is problematic due to the poor asset utilisation it implies which in turn is inadequate to attract large-scale investment to the sector.

With the prospect of longer-term steady income streams disrupted by fuel cost fluctuations and price increases and in the absence of long-term energy support schemes, financing large scale high-tech new CEA with low-carbon energy technologies that need high capital expenditure has become a challenge. Existing operations too find it challenging to remain commercially viable in the face of increasing energy prices, pressure to decarbonise, lack of supportive policies and increasingly eroding margins (see Annex A case study of Sterling Suffolk). Current concerns about seasonal labour availability are putting additional pressure on growers, and these factors combined have led many growers to reduce planting in the past two years, switch to low energy crops, or close their operations altogether. For example, the Lea Valley Growers Association (LVGA), representing the largest CEA hub in the UK, comprising 180 hectares of edibles glasshouses, has left 80 hectares unplanted in 2022, and a further 24 hectares have ceased trading in the past year.[27] An exodus from the sector is underway with some growers selling their land for more profitable redevelopment for residential housing or light industrial use. This means at this moment in time, the sector is not only unable to expand, but it is facing strong headwinds and contraction in at least the near future. The current precarious condition of CEA can at the same time be viewed as an opportunity for change to future-proof the sector while moving towards net zero.

8.2 Vision and ambition for UK CEA

Currently the CEA sector in the UK mainly sells to the domestic market, making up between 17% and 34% (depending on type of crop) of supply for certain produce.[14] Past growth of CEA has been mainly opportunistic rather than guided by a clear common vision by all stakeholders, including government.

The experts consulted for this study were all confident that an increase of CEA cultivation area of at least 100% of today's level in the UK, to a total of around 2000 hectares and moving toward becoming a significant exporter of horticultural produce is a realistic, viable aim for the UK to achieve by 2030 and beyond, given appropriate policy support. Such an ambition aims for global market leadership in low carbon food production as the result of a well-functioning horticulture ecosystem encompassing glasshouse installers, renewable energy use, advanced technology (AI, robotics, direct carbon capture etc.), as well as financing and policy mechanisms to grow the sector in the most sustainable way possible. The natural environment in many parts of the UK lends itself to glasshouse CEA and renewable energy, in particular electricity via wind farms and solar, is rapidly increasing. A common vision for the horticulture sector as a whole that would direct and focus efforts might help achieve the following:

- Increased domestic food security
- Enhanced international competitiveness in a sector increasingly essential for food security
- Implementation of innovations and advantages of other industries and R&D from the UK to bring horticulture specific innovation quicker to the market
- Increased exports of food and horticulture technology
- Production of low carbon food
- Creation of opportunities throughout the country by setting up horticultural hubs (both low and high skilled labour required)
- Developing local economies and helping the levelling-up agenda

8.3 Decarbonisation pathways for sector development

Given the energy intensity of the modern CEA sector, for the UK to be competitive, flourish and contribute more to national food security, and to address GHG emissions reduction targets, it needs to be part of an energy supply ecosystem which will enable its functioning. Future pathways, if they are to enable future sustainable growth of the sector, need specifically to address

i) Dependency on natural gas in a world of price volatility and supply constraints,
ii) Over-reliance on CO_2 from natural gas,
iii) Decarbonisation, and
iv) Competitiveness/profitability

From this research several parallel pathways for the sector might be envisaged. Figure 18 illustrates the trends and drivers of change ('Why?') that influence the transition from short to long term. To close the gap between the current state and future long-term opportunities for the CEA sector (on the right: 'Vision'), decarbonisation pathways are presented in the middle layer ('What?'). So, how can these pathways be implemented? The study has identified the key challenges for the transition as presented in the bottom layer, where policy can play an important supporting role (‘How?’).

These pathways consist of:

- Focus on low-energy farming
- Continuation with natural gas-powered CHP and fossil fuel-based CO_2
- Innovative energy efficiency measures
- Decarbonising the energy supply
- Geothermal and large-scale seasonal storage
- An end objective of 100% electrification?

Each of these pathways is discussed in detail in the following sections of the report (8.3.1 – 8.3.6).

It is anticipated that the transition pathways shown will apply more predominantly to new CEA builds. While it would certainly be desirable from the energy use and energy decarbonisation perspective to retrofit and upgrade existing operations with high efficiency glasshouses and zero-carbon power generation systems, the extent to which this is possible is likely limited. Retrofits are often costly and complicated and decommissioning equipment before its planned useful life can be financially challenging. It is also important to consider the embodied carbon in replacement equipment, which may offset the benefits of the transition. Overall, only the low-cost, short-payback efficiency improvement measures are likely to be adopted by most legacy operations unless there are significant incentives in place. Moreover, the low-carbon source energy solutions using waste heat sources and geothermal heat need to be co-located with the heat sink, and relocating existing glasshouses is not likely to be viable. As such, the transition is likely to be drawn out over an extended period of several decades.

Figure 18 Decarbonisation pathways for the UK CEA

Timeframe	Short-term (Present – 2025)	Medium-term (2025 – 2030)	Long-term (2030 – 2050)	VISION

Why? – Trends and drivers

1 (Present – 2025)
2 (Present – 2030)
3 (Present – 2050)

What? – Decarbonisation pathways

- Low energy farming (Short-term)
- Continuation with existing fossil fuel-based CHP and fossil fuel-based CO_2 (Short-term to Medium-term)
- Energy efficiency measures including optimisation measures through digital technologies (Short-term to Long-term)
- Tapping the potential for biogenic/carbon-neutral fuels and carbon-neutral CO_2 (Short-term to Long-term)
- Utilisation of industrial waste heat sources (Short-term to Long-term)
- Geothermal & large seasonal storages (Long-term)
- Build-out of renewable electrical energy generation systems (local and grid level) → 100% electrification
- CO_2 Supply: Natural gas CHP → Alt fossil-fuel based sources → Biogenic sources → DAC → Closed loop systems

How? – Top five priority challenges

- Lack of policy targeted to the sector
- CO2 supply
- Operating costs (particularly energy costs) and profit margins are affecting the growth potential
- Upfront capital expenditure barriers in the clean energy solutions
- Labour shortages (outside the scope of this study)

How? – Implications to support transition pathways

Short-term:

- Develop a clear policy and support for the sector
- Support legacy part of the industry to decarbonisation
- Investigate and develop potential support mechanisms for developing CO_2 generation technologies and infrastructure
- Replace the NDRHI and consider continuation of some taxation benefits of the CCA and UKETS to encourage investment
- Consider how the AHDB activities for horticulture sector might be financed in lieu of the levy or replaced
- Support for energy efficiency improvement measures
- Consider large scale CEA as national infrastructure
- Address the imbalance of power between growers and retailers
- Initiate exploration of the potential for technology innovation and commercialisation of low-carbon farming technologies
- Extend the CCA requirements to further set energy and carbon reduction targets for glasshouse operators

Medium- to long-term:

- Government-backed loans/low-cost capital to fulfil energy and CO_2 reduction goals
- Consideration of incentive schemes, or levy on industrial waste heat sources to encourage/facilitate greater reuse of waste heat
- Consideration of public funding of large-scale research and development in geothermal and long-term seasonal storage solutions
- Support R&D and technology commercialisation
- Support for education and training (both high- and semi-skilled)
- Create carbon capture pricing to help make DAC, and reuse of biogenic sources of CO_2 attractive and incentivise CEA to reduce CO_2 losses
- Explore opportunities within the retail/consumer level to better support domestic produce, and to encourage decarbonisation of supply chains

VISION

CEA sector long-term opportunities:

1. A growth of at least 100% from current levels
2. Becoming a significant exporter of CEA technology and produce
3. Net zero CEA energy supply
4. Integrated ecosystem

Subsequent opportunities:

- Enhanced international competitiveness
- Bring horticulture specific innovation more quickly to the market
- Increased domestic food security and quality
- Increased exports of food and horticulture technology
- Production of low carbon food
- Creation of opportunities throughout the country by setting up horticultural hubs
- Support the levelling up agenda

Trends and drivers (P: political; E: economic; S: societal; Env: environmental; T: technology; L: legal)

1. Short-term (Present – 2025)

- Energy costs 30% of operational costs, and rising steeply in 2022 (E)
- Growers moth-balling operations, and exiting the market
- Concerns about labour shortages by the industry

2. Short- to medium-term (Present – 2030)

- Ongoing issues of labour availability due to Brexit constraints (P)
- Increasing market value of fresh produce (E)
- Price of product is still the deciding factor for consumers (S)

3. Short- to long-term (Present – 2050)

- National and international obligatory legislation to reduce GHGs and fossil fuel use (P)
- National food security concerns (P)
- Increasing awareness that local food production is important for climate goals (S)
- Growing awareness around nutrition and public health (S)
- Rise of digital and automation technologies (T)
- Shift to sustainable energy sources, and energy efficiency initiatives (T)
- Emissions, and impact on and of climate change on CEA (Env)

8.3.1 Focus on low-energy farming

The large CEA operations in the UK are designed for extended-season and out-of-season growing, making use of extensive energy inputs for supplementary heating and lighting. Placing fresh produce on supermarket shelves earlier in the season brings significant commercial advantage and has contributed to an expansion in consumption of fresh produce in the UK and enables growers to maximise asset utilisation and returns on investment in what is typically a low-margin industry. Competition with imports from growers in southern Europe and North Africa has always been challenging, but with gas and electricity prices now at record levels, most growers in the UK cannot compete on cost for out-of-season produce, and with the ongoing cost-of-living crisis impacting UK consumers, the ability to charge a premium for locally grown produce, or even to pass on the energy costs, is minimal. The simplest solution, to which many growers have already resorted in 2022, is to scale back production to in-season growing only, or not plant at all for the year, and allow overseas producers to fill the demand, or perhaps for the consumer demand to reduce. This is certainly not a pathway to sector growth but may be the only option for the sector in the short-term for retrenchment and survival until energy prices restabilise.

8.3.2 Continuation with natural gas-powered CHP

The push to decarbonise the energy system in the UK has rightly raised questions over the continued use of natural gas-powered CHP. However, a closer look at the forecasts for the future energy mix in the UK suggests that even by 2050, natural gas may still represent more than 10% of the energy generation mix. Although this will be down considerably from the 36% share of today, a steep increase in overall generating capacity means that natural gas-powered electricity generation may only drop from 40GW today to 30GW by 2050.[190] This ongoing reliance on natural gas reflects the intermittency challenges associated with renewables, and the continued need for solutions to provide for peak demand. These forecasts may well change as new technologies emerge, but currently, retaining some gas-powered generating capacity looks unavoidable. Industrial CHP in 2021 provided about 7% of the national grid supply in the UK, and uses about 7.2% of the UK's natural gas[7], and given that CHP is far more efficient (if the heat is used productively) than a stand-alone power station, then the best option may be to retain this industrial CHP capacity as an integral part of the grid. In CEA particularly, as there is a direct need for CO_2, it may make even greater sense to retain gas-powered CHP as the preferred energy solution and CO_2 source for the foreseeable future. While seemingly at odds with net-zero plans this option needs consideration. This doesn't necessarily mean encouraging the build of new gas-powered CHP CEA operations, but at least allows the sector to take a balanced perspective on the urgency of the need to transition all legacy operations away from natural gas. In the short to medium term in the absence of low-cost alternative CO_2 supplies, CHP will remain essential to the sector. Integration of low-carbon technologies such as heat pumps with CHP is a viable partial solution, to provide the required CO_2 and still greatly reducing carbon footprint. The GHG emissions associated with natural-gas CHP in CEA could be mitigated in part through semi-closed/closed glasshouses to reduce losses, and CCS when CO_2 generation exceeds the levels needed for growing. As the grid decarbonises and power costs better reflect the true lower cost of renewables, the economics of gas-powered CHP will decline probably making CHP unviable in the longer-term.

8.3.3 Energy efficiency measures

Efficiency improvements are the first place to start for both existing operations and new builds and should therefore be a priority. Many of these technologies are well proven, readily deployed, and relatively low cost with short payback periods. Energy savings of 10% can be achievable with simple maintenance and monitoring improvements, with larger savings possible with investment in technologies such as thermal screens and advanced glass coating/materials (see Chapter 4). The savings generated from the improved energy efficiency can be used to finance the investments at larger scale such as on the energy supply side. However, with energy costs being so significant, most technically and financially viable energy efficiency measures have already been adopted, particularly in the larger-scale CEA operations. Some of the more complex efficiency options, notably closed/semi-closed glasshouse designs, cannot be retrofitted but would be relevant to new sites – albeit at present the economics don't justify investment. Closed/semi-closed glasshouses not only bring energy efficiency benefits, but also a potentially significant reduction in CO_2 use and emissions for the sector. To raise efficiency levels further, a national programme across the sector to support retrofit and upgrades may be necessary. In the longer-term this needs to be considered more fully as part of the net-zero transition.

8.3.4 Decarbonising the energy supply

This report has laid out in detail the energy sources and main technologies available to support efficiency improvements and decarbonisation of the sector. Options for decarbonisation of the energy supply system include using AD generated biogas to run boilers and CHP, using industrial waste heat streams, possibly geothermal in some locations, and moving towards full electrification solutions using heat pumps, and various combinations of these solutions with renewable energy generation. Most of these decarbonisation technologies are now proven and have been deployed widely. However, none of these solutions are economically viable in their own right for CEA in the UK at present – on the whole they have only been successfully deployed with the support of policy in the form of incentives. Until these policies are replaced, these technologies may not be deployed at scale despite the potential for cost savings in the face of high energy costs.

8.3.4.1 Tapping the potential of biogenic/low-carbon fuels and alternative CO_2 sources

Biomass and biogas boilers and CHP, possibly in combination with an AD, offer a proven decarbonised energy supply system for CEA, with a low-carbon CO_2 source, and a compelling solution for a circular economy model for the agriculture sector. The percentage of CHP running on renewable fuels in CEA is not available, but for the UK as a whole the figure is already 15%.[7] Running on biogas is also a relatively simple retrofit to existing CHP systems. However, sourcing adequate biomass feedstocks or biogas is a challenge. For biogas, CEA operators can buy biogas directly if they are directly co-located or consider installing AD plants themselves. However, AD plants are not a simple add-on nor natural diversification project for a grower but are generally significant high capital expenditure business operations in their own right. Also currently, the biogas/biomethane must be sold at market prices to pay for the initial investment even if the producers were to sell the gas directly to CEA. It is also important to note that if using the gas directly in CEA rather than exporting to the grid the operator is prevented from benefiting from the GGSS scheme, which would provide an additional income stream. These issues combined make biogas an expensive and complicated option for growers at present. Notwithstanding this, there are already many AD plants in operation in the UK (see Annex H for map of AD plants in the UK), and biomethane injection into the grid from third-party AD operators contributes to decarbonisation of the overall gas grid, which in turn does contribute to decarbonisation of CHP in CEA operations.

8.3.4.2 Utilisation of industrial waste heat sources

Solutions using waste industrial heat are intuitively appealing as a means to reduce waste and enhance efficiencies at the industrial system-level and they are technically feasible. However, most have significant economic and non-economic barriers and risks, for instance considerable geographic constraints, leading to much of the potential sources not actually being usable. Moreover, at present the waste heat is generated in most cases by processes using fossil-fuels, so strictly speaking might not actually be low-carbon solutions, although it is obviously environmentally beneficial to utilise the waste heat and to mitigate additional combustion of fossil fuels by CEA.

In discussion with industry experts, the most promising options are using heat pumps with waste heat from WTW and ambient heat from lakes, rivers and reservoirs. These sources are almost guaranteed to be in place 50 years from now, and it is estimated that about 40 sites with a total capacity of supplying heat to up to 1000 hectares of new glasshouses based on this system in the UK would be achievable by 2030, with opportunities distributed widely across the country (see Annex H for map of suitable WTW sites able to support at least 10 hectares of CEA).

Aside from these sources, most other industrial waste heat in the UK is currently considered unsuitable due to co-location challenges, and concerns over life span and commercial viability of the involved waste heat providing industry partner. For example, most EfW plants in the UK are likely to be unsuitable for co-located CEA due to their location in urban areas and zoning restrictions. Concerns over whether the source business will still be operational in 20 years' time are a significant barrier that makes most co-located waste heat recovery unfinanceable. Even gas-fired and biomass-fired power stations represent a risk as they may not be in use in the future as the grid decarbonises. Finally, perception issues such as co-location with nuclear power plants must also be considered.

Many industrial sources may include a CO_2 source (from fossil-fuel combustion or as by-product from their processes), but otherwise, these solutions may raise the need for an alternative CO_2 supply.

8.3.5 Geothermal and seasonal aquifer thermal energy storage (ATES)

Closed glasshouse operations in latitudes such as the UK have the potential to capture solar thermal energy of three times their annual energy demand. However, closed glasshouses are expensive and require complex climate control systems, but more affordable semi-closed glasshouses could still capture significant thermal energy. If this excess heat is captured and sequestered efficiently in seasonal storage such as ATES underground aquifers (see section 4.4.2), the CEA sector could dramatically reduce its supplementary heating demands. These solutions could also form an integral part of the energy grid, providing load balancing services in times of excess power generation.

Long-term storage technologies have been demonstrated in places like the Netherlands, combining solar thermal and geothermal sources, but although relatively simple technologies, they are expensive to install and are not currently economically attractive in the UK. Effectiveness of such systems is also dependent on geological conditions which may or may not be well aligned with CEA operations in the UK.

Geothermal could be included within this transition pathway, but unlike the Netherlands where geothermal is positioned as a major plank of the national strategy for CEA, in the UK the potential for significant exploitation of geothermal is considered lower and more dispersed, and no government support for geothermal exploration currently exists. The majority of CEA operations in the UK are concentrated in the Central, East and Southeast, while the best geothermal resources are in Cornwall, along the South Coast, and in the North (see Annex H for map of geothermal potential in the UK). Further research is required to explore suitability, but industry experts suggest 100 to possibly 200 hectares of glasshouse might be possible from geothermal by 2030. Greater use of geothermal might be feasible if integrated with district heating or power generation but these are far beyond the scope of any grower to develop themselves.

While conceptually these solutions are attractive using naturally occurring thermal energy, it is unclear whether they will ever be significant in the UK – high costs of installation and falling costs of electricity by 2050 may render these solutions unnecessary.

8.3.6 An end objective of 100% electrification?

The current electricity grid is still far from being 100% renewable energy, so electrification does not currently mean zero-carbon CEA operations. Additionally, a key barrier at present is that the cost of electricity is based on the price of natural gas-generated power, and the electricity to gas price ratio is too high to support the adoption of energy efficient heat pumps, much less, electric boilers. With the cost of renewable power generation rapidly falling, and the levelized cost of electricity (LCOE) of large-scale solar and offshore wind now lower than fossil fuels there is significant opportunity to change this dynamic, but this will require a major shift in energy wholesale market pricing.

This could ultimately transform the UK CEA sector and make off-season growing in the UK competitive even with unheated CEA operations elsewhere. In the meantime, direct connection to local renewable energy systems can offer a significantly lower cost of electrical energy and be attractive to generators due to the difference between the low feed-in prices paid to generators and the market rates, but this solution may not be practical due to land availability and planning constraints for much of the CEA sector. As the grid decarbonises and renewables drive down grid electricity costs, the economics of gas-fired CHP will become increasingly less attractive. A probable outcome, as anticipated in the Netherlands, is that the CEA sector will shift away from CHP, from being a net electricity generator, to increasingly become a major consumer of electricity. With this, the sector may play a larger role in being able to absorb excess grid power through electrified heating and lighting, and so an increasing role in grid services.

Opportunities in long-term renewable energy from a variety of new sources are evolving in the UK, including solar farms, on-shore and off-shore wind power, geothermal (including the Coal Authority and their focus on mine water heat and energy storage), and riparian and coastal tide turbine systems. Access to affordable local renewable energy sources could drive the evolution of CEA, with new operations following the energy sources, ultimately reshaping the location of future food production in the UK. Mapping of renewable resources in the UK, overlaid with water availability and possibly alternative sources of CO_2 would provide an indication of which potential geolocation shifts are advised and imminent. For example, see Annex H for maps of solar, geothermal, wind, and wastewater treatment locations for waste heat.

Electrification is the preferred decarbonisation pathway for many sectors, and it seems reasonable as an end objective for the CEA sector. However, a shift to electrification may present significant cost challenges associated with high capacity (MW) connections to the electricity grid – such distribution grid capacities and connection capacities are not readily available in rural locations where CEA is predominantly located. Moreover, provision of an alternative CO_2 source for CEA will remain an important consideration for the sector, which may mean that solutions based on AD biogas or combustion of other biogenic fuels remain important in the sector for the long-term, or ultimately perhaps a shift to electrically driven DAC.

8.4 Challenges for CEA on the way to net zero

The sector currently faces a set of challenges that are the result of rapidly changing external conditions and trends as outlined in Chapter 2 and the prevalent sector business model. Key challenges identified through this study and in consultation and the workshop with industry experts are discussed below with the intention to help inform policy design while outlining the interdependencies between factors impacting the sector.

8.4.1 Lack of policy targeted to the sector

The highest priority identified in the validation workshop was the current policy vacuum around CEA, and a recognition that resolving the policy issues would address many of the other identified challenges.

There is currently a lack of over-arching policy on the role and significance of CEA in the UK food system and the government's future goals and ambitions for the sector. There is a significant gap in policy support for encouraging or mandating energy efficiency improvements and retrofit in the sector to raise performance levels across the sector. There is also a lack of supportive policies targeted specifically at horticulture to mitigate many of the challenges faced by the sector such as high capital costs, low profitability, and currently unaffordable low-carbon technologies. The effect of this policy vacuum leads to a lack of decision-making ability and lack of support for low carbon technologies such as heat pumps, and innovative business models (e.g., energy storage to aid grid balancing).

Since the lapse of the NDRHI scheme there are currently no clear long-term follow-up policy directives to support long-term investments in renewable energy solutions at scale. This situation is further exacerbated because there is currently no single one ideal technology that can lead to energy efficiency and reduction of carbon emissions as became clear conducting this study. Energy systems are generally highly bespoke solutions dependent on local context, energy flows, growing requirements, etc making a one-size-fits-all approach not workable. There is therefore a requirement for flexibility of choice of different source energies and technologies working together. It is very likely that also in the future energy models for CEA will require operations to be well integrated with energy markets in order to remain viable. This integration requires targeted policy support. Key issues also remain around some of the technologies, particularly CO_2 supply in zero-carbon CEA, with no clear policy initiatives in place to support technology development for the transition.

8.4.2 CO_2 supply

As discussed in this report, supplementary CO_2 plays a critical role in modern intensive CEA operations. This has traditionally been supplied through on-site combustion of fossil-fuels in boilers or CHP plants. The anticipated shift away from natural gas-powered CHP and boilers leaves the industry with the challenge of how to supply CO_2, and at present much of the industry perceives this as a critical barrier to a net-zero transition. Any growth of the sector based on decarbonised energy supply will therefore be dependent on an economically viable alternative supply of supplementary CO_2 for yield enrichment.

The price for bottled CO_2 has increased considerably in 2022 due to closure of one of the main suppliers in the UK, adding to the financial pressures on the sector. Alternative biogenic supplies of CO_2 for growing are feasible, e.g., from AD plants, but are not widely available at present and cost is a significant issue. It is technically feasible to capture and pipe industrial waste CO_2 (as done at scale for example in the Netherlands), from many sectors directly to CEA, but there is currently no comparable infrastructure in the UK and the current scale and locally fragmented nature of the UK sector makes a dedicated network difficult. That said, as discussed in Section 5.6.4, the Drax UK CCS facility under construction in North Yorkshire and their proposed North Sea CO_2 sequestration pipeline could create opportunity for a large new CEA cluster in the region based on biogenic CO_2.[126,127]

In the longer-term direct air capture technology (DAC) for extracting CO_2 from air is perceived as the technology to help achieve net zero in glasshouses, but there are strongly divergent perspectives within the expert community on the potential role of DAC in the future of the sector. Changes in operating practices to move towards closed/semi-closed glasshouse operations, offers an effective method to greatly reduce CO_2 demand and CO_2 emissions, but such systems are currently not economically viable in the UK.

8.4.3 Operating costs and profit margins

One of the key longstanding challenges affecting the growth potential of the sector is low profitability. The sector has faced long-term erosion of margins making growers more dependable on other sources of income to compensate for rising operational costs. One prime example is the widespread use of natural gas fuelled CHP to generate and sell electricity to the grid as a supplementary revenue stream, a practice also prevalent in the Netherlands.

Growers are increasingly under pressure from all directions. Input costs are rising rapidly, particularly energy costs, while the disproportionate power of supermarkets to control price of produce combined with the cost-of-living squeeze on consumers limits the ability of growers to pass on increased costs. Consumer spending on out-of-season fresh produce is somewhat discretionary, and more likely to be scaled back as other costs rise. Based on current prices for gas and electricity and renewable heat alternatives much of the CEA sector in the UK is struggling to cover operating costs in 2022. Concurrently, the industry faces competition from imported cheaper produce from countries in Southern Europe and North Africa with more suitable climates for growing cheaply without supplementary heat and light, and from the

Netherlands with a larger horticulture sector with greater efficiencies of scale. It should be noted that even in the Netherlands many growers mothballed CEA operations in 2022 due to the extreme energy costs, so there is likely to be a significant shortage of salad produce on supermarket shelves by next spring.

As discussed through this report, decarbonisation and energy efficiency trends in the sector will help to reduce costs and emissions of UK domestic production and enhance competitiveness with imports, but this differential will likely remain a challenge for the sector in the near term.

8.4.4 Upfront capital expenditure barriers

The pressure on the industry to switch to renewable energy and heat generation technologies requires substantial investments and in many cases retrofitting of CHP or heat-pump based systems, etc would not be commercially viable. Available decarbonisation solutions may also not be as straightforward to implement as they seem. Installation costs for many of the potential decarbonisation pathways can be prohibitive at present (e.g., costs of drilling wells for geothermal, connection to co-located industrial heat source such as a power station, complex combinations of AD, CHP and heat pumps). Payback periods and return on investment (ROI) are often unattractive, and this is combined with some considerable risks, and hence projects currently struggle to attract financing. There is high risk associated with investment in the infrastructure required to leverage the potential for and opportunities from the usage of existing heat sources, e.g., heat pipes for transferring industrial waste heat between co-located operations or geothermal.

Moreover, the sector was traditionally not considered attractive by investors due to its perceived and real high risks and low returns. There are currently no financial risk mitigation structures in place (such as government guarantees for loans, or de-risking large investments into renewable source energies such as geothermal or AD which exist for example in the Netherlands) to attract investors. Moreover, with the closing of past energy policies such as the NDRHI and the FIT there is currently an environment of uncertainty regarding future energy models for new projects which places the sector in limbo due to inability to make long-term (20-30 years) investment decisions. There is currently a gap between infrastructure finance and finding cheap capital for large scale greenhouse projects. To reduce risk and attract investors a long-term view of revenue streams and a long-term sustainable energy model (at least 20 years) is essential.

Countries like the Netherlands have a tradition in providing long-term capital to CEA and has a finance sector that understands and focuses on the sector development. This makes it easier to attract investors to get major glasshouse developments off the ground, and there may be opportunities for UK policymakers to learn from this experience, as discussed in Section 7.3. Recent interest of pension funds and city financing in low carbon agriculture and more broadly in net-zero and ESG investment opportunities might help the sector given it is well aligned with many environmental and societal objectives.

8.4.5 Labour availability

Despite the focus of this report on energy, the availability of labour will remain important for the sector with potentially broader national and political solutions required. Labour availability is also important for energy systems, as higher labour costs and uncertainty about seasonal labour directly affect the ability of and attractiveness for farmers and financiers to invest in upgrading and low-carbon energy technologies, which in turn delays the net-zero transition.

Labour availability, especially the requirement for skilled and semi-skilled seasonal workers have been impacting the sector recently due to EU Exit and the Covid-19 pandemic, and have forced growers to scale back operations in 2021 and 2022.[27] Despite recent increases in visas for seasonal labour and a government-commissioned Independent Review into Labour Shortages in the Food Supply Chain[32,191], the concern of the industry about labour availability remains and that this will likely be a limiting factor for some considerable years to come, hampering growth and likely precipitating further decline of the sector. In the long run, over a 10–15-year horizon, automation and robotics may replace much of the labour requirements and reduce labour costs (although increase electrical energy requirements), but dependency of the sector on skilled and semi-skilled labour will remain high for the foreseeable future.

Separately, challenges resulting from the lack of high-skilled technical capabilities in the UK in the field of high efficiency, and low-carbon energy supply in CEA and the challenge of exchanging knowledge and experience / learning from other countries, were not considered significant by the industry experts. Technology providers from the Netherlands are readily providing technologies to the UK sector.

8.4.6 Lack of clarity on full environmental impact of solutions

Although considered by the expert panel as of less significance than the above challenges, there is a recognised need for improving the understanding of the actual environmental impact from mitigation measures (e.g., emissions allocation in use of waste heat streams – how to split them between the source and the grower). And in addition, there is a need in standardising methodologies for the social and environmental impact assessment in order to assess the trend and end consumer demand towards low carbon and regional food production. Greater clarity on these issues would enable growers and policy makers to make more informed decisions, and perhaps stimulate greater consumer engagement with the value of sustainably and locally grown produce.

8.4.7 Data availability and accessibility

Data availability and accessibility was not deemed a primary challenge for the sector by most experts consulted, but more (open source) data and an information platform that can be used by growers would be beneficial to more quickly access the potential for using industrial waste heat, geothermal etc. in their location. UK wide data collection would help enabling both the industry and policymakers in decision making.

Gaining a deeper quantitative understanding of the energy use and changing usage patterns throughout the year would be very helpful for designing policy support mechanisms. In the Netherlands the government collects baseline data and monitors efficiency improvements through the “Dutch Energy Monitor Programme” from growers. It provides insights into the changes in energy input, output and energy indicators agreed with the authorities. This has led to a year-on-year reduction of energy use and supports policy design (See section 6.3.6 for more details). The UK CCA scheme similarly collects data on energy use and emissions, and incentivises efficiency improvements, but participation in CCA is voluntary, and currently centralised CEA data collection is limited to energy used by target unit, and carbon emitted by target unit (see section 6.1.2).

8.4.8 Climate change impact on the CEA Sector

Among the challenges and risks facing the sector, industry participants were unanimous that climate change itself was not a significant challenge for the sector, but rather presented a significant opportunity. It is perhaps too soon to say what the longer-term impacts of climate change might be on the sector in the UK, but it seems that Europe and the UK will see hotter, drier summers, and also more extreme weather events. Growers in Southern Europe and North Africa are already seeing climate change effects such as extended droughts and extreme temperatures impacting on growing conditions, and the EU Commission Agricultural outlook published in 2020 predicts a permanent decline in Spanish tomato production of about 20% by 2030.[45]

Climate change is likely to bring positive as well as negative change for the UK CEA sector. UK CEA may benefit from:

- Increased demand for CEA to replace field agriculture to protect against adverse weather events, make more efficient use of water to protect against water shortages, protection against new invasive species and diseases, and more efficient use of land to meet calls for rewilding and reduced biodiversity impact associated with field agriculture.
- Decline of competition from South Europe/North Africa due to increasingly persistent heatwaves and drought, and public pressure to restrain the effective “exporting drought” from these regions. This presents a risk for UK consumers, but also a significant opportunity for UK growers to carve out a stronger competitive position.

Conversely, several potential threats are identified:

- Shifting weather and temperature patterns in the UK, are also a threat to CEA, potentially creating risks to assets, productivity decline, new invasive species and diseases necessitating more closed glasshouse designs or greater use of pesticides, yield losses, supply chain disruptions, etc.
- One likely risk is increased requirement for cooling/ventilation, which will increase energy costs.
- Warmer climate may support more field grown vegetables and soft fruit in the UK, undermining the viability of CEA.

8.4.9 Stakeholder engagement

A challenge identified during the course of this study is related to the need for bringing diverse stakeholders together to facilitate dialog in order to close the loop between horticulturists and different/novel energy streams (e.g., use of waste heat streams or opportunities for synergistic operations) and playing a more integral role in the UK net-zero energy transition (energy storage/grid balancing). In particular aligning multiple stakeholders for planning financing and implementing source energy solutions for wider regional supply has been identified as a major challenge in the UK already for some time.[192] From the perspective of stakeholder engagement, planning permission is perhaps one of the most prominent challenges. For any large-scale development planning processes are complex and expensive, and local opposition can be a deal-breaker. Addressing this challenge through national-level policy on CEA may be beneficial, as for example in Germany and Austria protected crop horticulture, including CEA, have “privileged” status in the planning application process.

Although our expert panel did not see other aspects of stakeholder engagement as a primary challenge, it is clear from case studies of capital-intensive CEA operations abroad, (The Netherlands, Germany, see Section 7.3 for specifics of the Dutch context) that deploying multiple renewable sources at scale is crucially dependent on well working, long-term cooperative stakeholder interaction models in order to be commercially viable.

8.4.10 Technology access and R&D

Finally, during workshop discussions, technology access and R&D capabilities were also highlighted as a challenge for the sector. The knowledge base and key research infrastructure in CEA is currently strongest in the Netherlands as the international leader of the sector. The proportion of research being carried out depends on sector size, which is much larger in the Netherlands, supported by decades of substantial policy mechanisms.

Technologies are readily available from the Netherlands to support the immediate needs of the UK sector, and so lack of R&D is not specifically a limiting factor to UK CEA growth. However, if the UK wants to increase its capacity for horticulture technologies, innovation support and initiatives with a focus on commercialising novel technologies specifically for the horticulture sector would be required. Expansion of R&D is undoubtedly an integral part of growth activities for the sector, particularly if there is an ambition to become globally competitive and gain a position of leadership. Besides fragmented funding of individual research projects of relevance for horticulture, such as the Vegetable Genetic Improvement Network[183] mentioned earlier, or the UKRI Horticulture and Potato Initiative managed by BBSRC and the Horticulture Innovation Partnership that ran from 2013-2019 [193], there appears to be a lack of national level policy to support scaling and implementation of innovation in line with growth requirements of the CEA sector, unlike in the Netherlands where such support has existed for decades. The UK would benefit from support for research, development, and deployment of technology aligned with specific goals and targets for the horticulture sector matching national policy support for research in other industrial sectors.

9 Conclusions

9.1 Summary of findings

The CEA sector is facing acute pressures from multiple directions, and this situation has deepened significantly over 2022 due to the current gas/energy crisis. Unaffordable energy costs have already caused shutdowns across the sector, and indications and reports from the industry identify reluctance to plant out produce and predict significant further closures over the coming years without action on energy costs. A variety of technologies and integrated energy solutions have been presented in this report that are proven and have potential to enhance energy efficiency, reduce operating costs, and decarbonise the energy supply of CEA, and some are already being used successfully in the sector in the UK and abroad.

9.1.1 Energy efficiency measures

The potential for energy efficiency measures may be a good starting point for both existing operations and new builds to reduce energy demand alongside investing in optimising energy generation systems. Energy efficiency measures are described in Chapter 4, outlining that the potential of some measures can be utilised at a low investment cost and can be retrofitted to existing CEA. Opportunities include improvements to routine maintenance and repairs, improved monitoring and control systems, and interventions such as thermal screens. Some of the more sophisticated options, such as advanced glazing materials and closed/semi-closed glasshouses, are unsuitable for retrofit but building new with these measures already integrated would make the greatest impact. At present costs of these initiatives are a barrier to adoption, and regulation on building efficiencies would probably be required to drive further adoption. However, with energy costs being so important, most technically and financially viable energy efficiency measures have already been adopted, particularly in the larger-scale CEA operations and new builds. Therefore, optimising energy generation systems and decarbonisation of energy sources will be the main source of impact.

9.1.2 Energy generation - transition

The design of an appropriate low-carbon energy system is strongly dependent on the local context, available local and regional resources, technical and ecosystem constraints, size of operation, and the energy demand profile of the horticulture farm and crop types. For example, for solutions based on industrial waste heat, planning consent and a supportive business ecosystem are key considerations, whereas for geothermal and seasonal storage, geological factors are important. It should also be recognised that use of industrial waste heat may not actually be a low carbon solution if it comes from fossil-fuel combustion in another sector, even so it is obviously better to reuse the heat. Hence, when it comes to optimising energy solutions for CEA operations a case-by-case consideration of requirements is key. Focus on decarbonising energy sources will reduce barriers and dependencies on context.

Underpinned by case studies, this report finds that neither internationally nor in the UK is there a single “one-size-fits-all” technical system design that is suitable for all growing operations. Therefore, the major difference from the current dominant energy system based on natural gas-fired CHP for power and thermal energy co-generation (as explained in Chapter 3) is that in the future a combination of different technologies and measures will be needed to decarbonise the electrical and thermal energy demand of CEA.

In the next decade, the following three example combinations of existing technologies are seen as most likely to be deployed in the sector in energy use type 1 and 2:

- Biofuel CHP/boiler and AD located on site or co-located,
- Electric heat pump sourcing from low-grade thermal energy (industrial, geothermal or ambient sources) and renewable electricity generation on site or co-located,
- Heat exchanger and heat pipes for waste heat recovery from industrial processes, and renewable electricity generation on site or co-located.

For energy use type 3 (fully electrical requirements) integration with fully renewable electricity is required.

When looking at a time horizon beyond ten years, there is still considerable uncertainty over the future evolution of energy technologies, step changes in hydrogen systems, fuel cells, and battery storage, and DAC are just some of the possible areas of change that may help to enable a cost-effective full transition to a zero-carbon economy based on 100% renewable/clean power generation and alternative CO_2 supplies. Technology readiness levels of these existing low carbon/renewable technologies varies, and successful, commercially viable implementation of some of them, for example hydrogen, requires first establishing of a new economy and market design. Hydrogen for example is therefore not anticipated to play a role in CEA even in the medium to long term. Geothermal energy and waste industrial heat is already playing a large role in CEA in some countries such as the Netherlands, Germany, Austria[194–196] and Italy. EU wide incentivisation of the use of industrial waste heat and cooling is fairly advanced, as outlined by the Renewable Energy Directive and the Energy Efficiency Directive, with many working systems being implemented at large scales across Europe.[197,198] However, the indications are that opportunities are somewhat limited in the UK across industries and with respect to CEA by the small scale and locally fragmented nature of the sector at present. These may grow in importance in the future if the sector expands significantly, or if CEA can be leveraged in a larger system such as district heating where CEA is one of the heat consumers within a network.

As energy generation moves away from fossil fuel-based technologies such as natural gas-fired CHP, the CO_2 they currently generate and use to enhance plant yields may have to be purchased separately. This report has outlined a range of options for alternative sources of CO_2, including biogenic processes such as AD, composting and fermentation, through to DAC further in the future.

The energy transition is changing the design of the energy system leading to its decentralisation and new paradigms where a consumer becomes a prosumer (producer and consumer). This is currently established practice in the sector through the use of CHP, but the future may create new opportunities for additional revenue streams, for example by providing grid services to electricity grid operators where a greenhouse serves as a load balancing provider and energy storage.

9.1.3 Policy context

Future planning and policy making needs to be undertaken within the context of transitioning UK CEA to build resilience in the face of climate change and geopolitical volatility, and also to capitalise on the opportunities that emerge from this transition. A key element to success for such transition is initiating and shaping a new culture of collaboration between growers and wider stakeholders to build closer ties between players in the sector, particularly the legacy parts of the industry and the high-tech large-scale horticulture operations. Not only when it comes to short-term decision making such as setting prices or lobbying for policies which will impact individual growers, but also for making collective decisions for infrastructure investments in their region where the local ecosystem can collectively benefit in the long run. This culture shift requires incentives for all stakeholders, including landowners, to invest long-term. This can also help changing business models and bring new revenue streams as seen in the example of the Dutch cooperative Horticoops (See Section 6.3.2).

The current energy crisis and the future energy transition also present a broader opportunity to fundamentally rethink the role of CEA in the UK. The consulted sector experts share the view that a concerted policy effort to make CEA a key part of the food system in the UK could feasibly see a doubling of CEA in the UK by 2030, with an opportunity to position the sector as a market leader in low-carbon/zero-carbon farming. There are already pockets of research and development in the UK, but there is the potential to develop a whole new eco-system based on low/zero-carbon horticulture, covering technology innovation and commercialisation, energy modelling services, crop genetics, export development, and so on. However, this needs to be initiated rapidly, as the Netherlands has already implemented ambitious policies for net-zero for their CEA sector and there is a high risk that UK CEA will be left far behind and rendered entirely uncompetitive if action is not taken quickly.

9.2 Commentary on potential role for Government

Considering the acute challenges the sector faces at present, and its potential and ambition, new policy mechanisms may be needed to help the sector survive the current energy and cost of living crisis in the short-term, and transition away from strong dependence on fossil fuels as its main energy source, and support the ambition to become a net-zero global industry in the longer-term. Taking into consideration the long time-horizons of CEA operations, with a minimum 20 years and possibly up to 40-50 years, action probably needs to be initiated now if the sector is to be net-zero by 2050.

Given the interdependent nature of the influencing factors, a holistic and tailored approach with consideration of these interdependencies is required. Three main considerations in any future policy development work are:

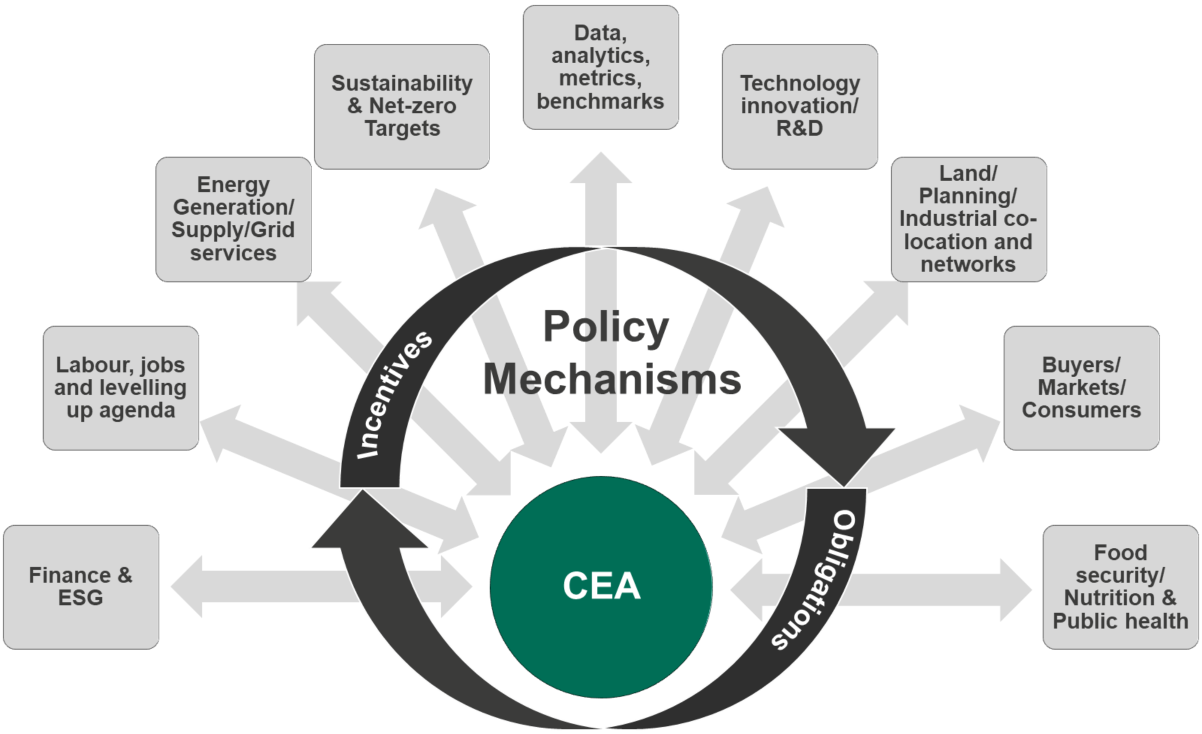
1. Any new energy model would need to allow for flexibility of choice of energy source because energy requirements in CEA are directly related to type of crop being cultivated as well as other locally specific factors for each CEA operation.

2. Incentives and obligations built into future policy mechanisms to encourage net-zero energy solutions and to discourage maintaining the status quo. A long-term view of revenue streams is essential in any support schemes and encouraging the future-proofing of new projects is important as retrofitting is usually not economical.

3. Creating horticulture specific policies to support the sector through the transition toward net-zero could support the sector's evolution and give government the ability to shape the emerging industry.

The challenges and aspirations of the sector are highly interdependent and would require a holistic approach for designing any interventions with consideration for the influencing factors discussed in this report. Figure 19 summarises these factors and shows the role of policy as an interconnected cycle of incentives and obligations to support the sector through its transition to net-zero. This necessitates involvement of multiple government departments in formulating future policy for CEA.

Figure 19 Influencing factors and the role of policy in supporting CEA sector



There are short-term, mid-term and long-term priorities for the sector that would help inform policy design as listed below. These suggestions below evolved from the validation workshop with industry experts, the full outputs of which can be seen in Annex E. However, it should be recognised that a full analysis and economic impact assessment of a range of options and the counterfactuals to deliver the intended outcomes was well beyond the scope of this study. As such the suggestions presented in the following sub-sections 9.2.1, 9.2.2 and 9.2.3, are intended for preliminary guidance only. There remains an important role for Defra and other HM Government departments to fully investigate and develop policy options in further depth to operationalise sector changes.

9.2.1 Key questions for consideration arising from the validation workshop:

- What role should CEA play within the future UK food security plan, including import/export policy, and should it be considered as key infrastructure?

- What role should CEA play in jobs creation and the levelling up agenda?
- What national objectives are realistic and appropriate for CEA going forward over the next decades and the sector growth, including technology leadership and export?
- How best can policy support the transition to net-zero within CEA, and what role should CEA play within the broader energy transition?
- To what extent does the UK government wish to, or is able to, support the development of the sector through incentives, investment, regulation?
- How best to create a joined-up CEA sector-specific approach to policy across government highlighting and connecting the sectors' impact on different agendas, such as food security and affordable food for the coming decades, decoupling of food prices from gas prices, net-zero and decarbonisation objectives, levelling-up, and export development.

9.2.2 Short-term priorities (1-2 years) proposed following the validation workshop

Short-term initiatives that might be considered, as suggested by the industry experts, and presented in perceived order of priority are shown in Table 3.

Table 3 Recommendations for short-term actions

Challenge/ problem to be addressed	Potential solution and rationale
Lack of clear strategy and overall direction for the sector	Appoint a sector "czar" or champion to act as a sectoral leader and conduit between industry and policymakers to drive the needed and urgent transition of the sector.
	Consider developing a clear growth strategy for the horticulture sector and link it to the wider UK future food security and energy security strategy, including an agricultural policy that specifically targets CEA for the longer term (environmental protection policies alone are probably not sufficient).
Lack of financial viability for new investment in the sector	Consider replacing the Non-Domestic Renewable Heat Incentive (NDRHI) with a follow-up policy as it seems to have worked well in the past and consider continuation of some taxation benefits of the Climate Change Agreement (CCA) (or any amendments thereof post 2025) for the horticulture sector to encourage investment in decarbonisation.
	Consider granting large scale CEA access to the Energy-Intensive Industries (EII) Exemption Scheme. This scheme excludes qualifying businesses from the higher energy costs associated with renewable schemes and has proven a valuable tool for energy-intensive businesses competing in the global marketplace.
Difficulties initiating new large-scale projects in much of the UK	Consider classifying large scale horticulture as UK Critical National Infrastructure (CNI) to simplify the planning application process at the national level to accelerate the approval and deployment of new projects.

Limited profitability of the sector discourages investment and expansion	Address the imbalance of power between growers and retailers (85% of all CEA product in the UK is sold through supermarkets so they control the market and what goes on in CEA). Industry experts raised the idea that supermarkets could be obliged to buy guaranteed volumes of UK produce, differential pricing/taxation for domestic produce vs. imports.
Lack of direction and support for industry on net-zero ambitions	Extend the CCA requirements to further set energy and carbon reduction targets for glasshouse operators, including national targets for efficiency improvement, ongoing monitoring, reward mechanisms for net-zero energy solutions, and penalising obligation mechanisms for maintaining the status quo.
	Support the legacy parts of the industry through decarbonisation, helping them adapt with a stepwise controlled phase out of older technologies and wide adoption of modern energy efficiency and decarbonisation technologies. This might include a well-controlled phase-out of CHP as the main energy generation model to make sure the legacy parts of the industry do not collapse, and recognition that many of the needed innovations are unsuitable and unaffordable at present for small scale growers.
Lack of R&D and innovation to support future low-carbon farming	Investigate and develop potential support mechanisms for developing CO_2 generation technologies and infrastructure at scale to provide a cost-effective alternative supply for growers in place of natural gas CHP, e.g., capture and purification of CO_2 from industrial applications and AD, incentivise infrastructure, recovery, and reuse of CO_2, and DAC. Until this is addressed CHP will remain important for the sector.
	Initiate exploration of the potential for technology innovation and commercialisation of low-carbon farming technologies in the UK – Explore the potential scale and scope for building a meaningful export sector.
	Several of the industry experts highlighted the impact of termination of the Agriculture and Horticulture Development Board (AHDB) activities for horticulture and potatoes sectors (statutory levy was discontinued in 2021 following levy payers' vote to discontinue funding, and HMG has publicly stated they will not fund the board, creating uncertainty over future support to the sector[199]). In the absence of the AHDB there is currently no sector-based approach to R&D. Consideration of what might replace the AHBD and be more attractive to the levy payers (the farming community) is recommended to provide the needed support for the CEA sector going forward, particularly for the smaller growers.

9.2.3 Medium to longer-term priorities (2-7 years) proposed following the validation workshop

Medium to longer-term initiatives that might be considered, as suggested by the industry expert panel, are presented in perceived order of priority are shown in Table 4.

Table 4 Recommendations for medium- to long-term actions

Challenge/problem to be addressed	Potential solution and rationale
Lack of access to capital to fund new projects, particularly for those using less-proven technologies	Provide government-backed loans/low-cost capital, or government underwriting of risk (e.g., consider the US Department of Agriculture (USDA) schemes that underwrite 80% of investment costs for the sector[200], making traditional bank financing more accessible to the sector, as is also the case in the Netherlands) to fulfil energy and carbon reduction targets in CEA. Perceived risk levels are expected to reduce as technologies such as heat pumps evolve and are deployed more widely.
	Consideration of further incentive schemes, or levy on industrial waste heat sources to encourage/facilitate greater reuse of waste heat. Examples from EU countries may be informative.
Lack of R&D and innovation to support ambitious future low-carbon farming	Consideration of public funding of large-scale research and development in geothermal and long-term seasonal storage solutions in the UK (similar to the Netherlands approach).[123] Specifically, this might include consideration of how to incentivise large-scale multi-actor initiatives such as district heating and geothermal power integration with CEA.
	Support R&D and technology commercialisation in the sector to drive transformational change, perhaps by incentivising horticulture specific technology incubators, or a technology catapult to accelerate technology adoption and/or support export development.
Limited access to highly skilled workers to support the highly technical nature of future of low-carbon farming.	Support for education and training, e.g., Local Enterprise Partnership (LEP) network, etc. to train the next generation of workers in the sector (both high- and semi-skilled).
Lack of a viable zero-carbon solution for the supply of CO_2	Create carbon capture pricing (per tonne) to help make DAC and capture and reuse of biogenic sources of CO_2 attractive and incentivise CEA to reduce CO_2 losses from glasshouses.
Limited public support for domestic production may be limiting the potential success of the sector	Explore opportunities within the retail/consumer level to better support the growing and promotion of domestic produce, and to encourage decarbonisation of supply chains. This could perhaps include carbon labelling to allow consumers to differentiate/choose low carbon produce, although there is little evidence that this will have impact.

9.3 Summary of proposed path to net-zero

Energy remains a central factor for the industry for the foreseeable future, either through on-site generation or becoming a net electricity consumer as the grid decarbonises. Any changes to the current energy generation models in the sector will have a decisive impact on business models which are crucial at least in the short to medium term until increasing margins from sales of produce might reduce importance of income from electricity generation, which has been the prevalent model so far. This in turn is only possible when the sector is able to increase efficiency and scale by adopting relevant technologies to reduce operating costs and can attract sufficient capital.

Access to capital underpins growth and scale. Therefore, de-risking the sector and making it economically viable to attract investors is a necessity. This connects directly with creating the right conditions for viable business models, particularly at the early stages of the sector's transition to net-zero when it is still dependent on income from energy generation alongside sales of produce. This is particularly so given that none of the current low-carbon solutions for thermal energy generation are economically viable at present without subsidies or other support. Support for business models that have scope for evolution as the sector moves through the transition to net-zero is an important factor in weathering the impact of changing external conditions such as volatility of energy costs, access to labour and changing consumer demands.

Given that the horticulture sector at present is not homogenously developed and contains a considerable level of legacy infrastructure which lags behind the large-scale, high-tech part of the sector it is crucial to encourage structured cooperation between players towards achieving scale and the creation of an industry ecosystem that drives the transition to net-zero.

9.4 Recommendations for future research

This study examined various technologies that have the potential to contribute to the decarbonisation of the energy systems used in CEA, and drew upon the expertise of a wide range of academic and industry practitioners. Despite a broad consensus among experts on most challenges and the pathway forward, there are also differing views on the potential of some solutions and the mechanisms of how to support their scale up. Thus, further research can be recommended in the following areas:

- A quantitative assessment of sustainability of the sector, to gather more complete data on current energy usages levels, emissions, levels of deployment of low-carbon technologies and efficiency levels, and other impacts of CEA. The current dataset, gathered through the CCA programme, while useful, only covers a part of the sector, so a broader study would give a clearer indication of the areas of the industry requiring greater attention.
- An evaluation of the overall industry picture through a quantitative analysis of energy source technologies and the economic case as the next step to this report, examining some of the most promising technologies in terms of their environmental and economic potential. This might better indicate what scale of incentives should be considered for future support schemes.
- A thorough investigation of data collection methodologies and their utilisation that give quantitative insights into the operational aspects of CEA as a whole would be very useful for targeting any future policy initiatives to the sector.
- Review and consideration of development of a uniform guidance on the application of the GHG emission quantification methodologies, for instance the allocation of emission in case of waste heat use from other industries.

- This study identified a range of energy efficiency and decarbonisation incentives (past, existing, and planned) such as CCA, CfD, NDRHI, etc. However, there are some conflicts between the schemes, for example NDHRI does not encourage efficiency, while CCA does not target emissions reduction. Moreover, arguably one of the most important programmes, CCA, captures rather limited sector data on technologies and performance, limiting its ability to provide guidance to the sector. An in-depth review of the effectiveness or otherwise of the various incentive schemes and exploration of what new incentives might be required for the sector is recommended.

- A comprehensive assessment of existing and possible technology development initiatives that can accelerate sector specific technology solutions is required to understand where UK horticulture technologies actually stand and compare internationally. Several relevant technology areas, such as in the PV fundamental sciences, or LED technologies as well as material sciences are represented with world leading academic research in the UK accompanied by a strong start-up sector. However, translation into horticulture specific applications is lagging well behind. Ways to support sector specific R&D and implementation need to be explored systematically, possibly in public private partnership models.

- Innovations are generally slow to be taken up in the CEA sector (although vertical farming is an exception) and there is a chance to identify the huge uplift in the digital sector and economy as a route forward to de-risk innovation. Enormous advances in computing capabilities and techniques such as digital twins and AI, have yielded the ability to better model, at scale, CEA in its many formats and to explore evolution in the process without the need for capital intervention. For example, the interface of digital twinning experts with crop scientists, engineers, energy experts offers a very attractive way forward for the industry and its infrastructure evolution and development. Further study is recommended to explore the potential in this area and how best Defra might support.

- Related to the above two points, this report has presented an overview comparison with the Netherlands, but a more in-depth assessment of the Netherlands and other leading markets is recommended to determine which policies, R&D strategies, and other initiatives may be most beneficial for the UK to emulate, and, or where the gaps and opportunities might be for the UK to develop new capabilities to compete at the global level.

- Analysis to explore how changes in other countries' national policies might impact the UK horticultural import/export balance and hence the pressure on national CEA. This needs to look at the impacts of climate change on growers in countries such as Spain and how this might shift the market dynamics.

- The need for a joined-up CEA sector-specific approach to policy across government has been identified in this study. A next step would be to explore the intricacies and identify consequences of alternative policy interventions, possibly through scenario analysis.

- A quantitative analysis of the sector specific effectiveness of current and past policy instrument options and best combinations between incentives and obligations. This may also include a detailed assessment of interactions and synergies between existing policy areas such as energy, labour, taxation mechanisms, levelling up initiatives, etc.

- This study was based on extensive desk research and consultation with industry experts to gain a deep understanding of the energy systems and opportunities in the CEA sector. While the output of the study is comprehensive, a broader study or survey to explore opinions, challenges, needs and priorities, across the sector including both large and smaller growers, investors, and retailers may be a beneficial extension of this work.

- Review of the past role of AHDB, NFU, and government departments in supporting the sector to identify what has worked well, what could be done better, and what specifically do the growers need greater help with. In particular, to explore the reasons for the votes against the AHDB levy, and understand how more cost effective, value-for-money services that strongly support the energy transition might be offered to the CEA sector in other ways.

- Planning permission has been identified in this study as a barrier to evolution of the sector and the associated new energy systems (generation and storage). The fragmented nature of the planning process, with 333 local authorities just in England, mean that a project may get planning permission approval in one but not another for the same project. Further study is recommended to explore potential resolution or routes to harmonisation of planning issues for the sector.

- Geothermal and ATES is a promising area of development and forms a key part of CEA policy in the Netherlands. However, development in the UK requires further data on the country's geology. Currently available data (as shown in Annex H) is largely based on 1950s data. A more comprehensive new survey using modern techniques may be beneficial to identify and unlock the potential for CEA and other sectors.

- This report touched upon some of the broader industrial ecosystem and societal aspects of the energy transition in CEA, but further study is recommended to build upon this report to explore the potential consequences of policy change and how best to engage stakeholder groups for positive effect. For example, in the Netherlands there was the well-publicised rebellion by farmers following the government drive to tackle nitrogen pollution through a major reduction in numbers of pigs, cattle and chickens.[201] Also, more recently the New Zealand Government's progress to tax agricultural emissions has been met with anger, bemusement and disagreement with the base modelling undertaken, by the industry.[202]

The expert consultations for this report highlighted that the contributions of CEA to UK society and prosperity today and in the future have several dimensions: the contribution to food security, the potential to take a leading role in research and development and export of sector-specific technologies as well as in developing sector specific policy instruments, and last but not least, the integration with other sectors to promote and accelerate the transition to a net zero future.

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11 Annex A: Case studies

This annex presents a series of deployment examples (case studies) illustrating the various decarbonisation pathways outlined within this report.

- British Sugar – Industrial waste heat use
- Dyson Farming – Anaerobic digestion
- Gemüsebau Steiner – District heat networks and geothermal
- Jones Food Company – Vertical farming
- Koppert Cress – Aquifer thermal energy storage
- Low Carbon Farming – Large-scale heat pump
- Sterling Suffolk – High efficiency semi-closed glasshouse

11.1 British Sugar – Industrial waste heat use

Website: https://www.britishsugar.co.uk/about-sugar/co-products

Source: Existing case study [203], and interview with retired technical director of British Sugar.

What: When launched in 2002 was a pioneering example of industrial symbiosis in the UK, a comprehensive example of a zero-waste factory, and an example of use of industrial waste heat from a sugar production factory for use in CEA. The heat and power sources for the sugar factory are generated by a CHP plant fed by large-scale AD biomethane. By 2016 it was the UK's largest tomato grower representing 20% of the UK domestic market. In 2016 the business abruptly exited the tomato sector and transitioned to higher-margin medicinal cannabis cultivation.

Where: Wissington, Bury St Edmunds, Norfolk

When: Commenced move into horticulture in 2002

Size: Operations expanded in three phases to a total of 18 hectares of glasshouses by 2016.

Investment: Internal investment by AB Foods.

Ownership: British Sugar (owned by AB Foods). British Sugar's ownership and operation of both the sugar production plant and the horticulture operations was a key enabler but this is unusual in these types of industrial heat transfers.

Jobs: 36 skilled jobs

Systems: Waste industrial heat from sugar production facilities is captured through heat exchangers and is piped to the co-located glasshouses for growing operations. The factory runs year-round and provides a waste heat source for all growing operations.

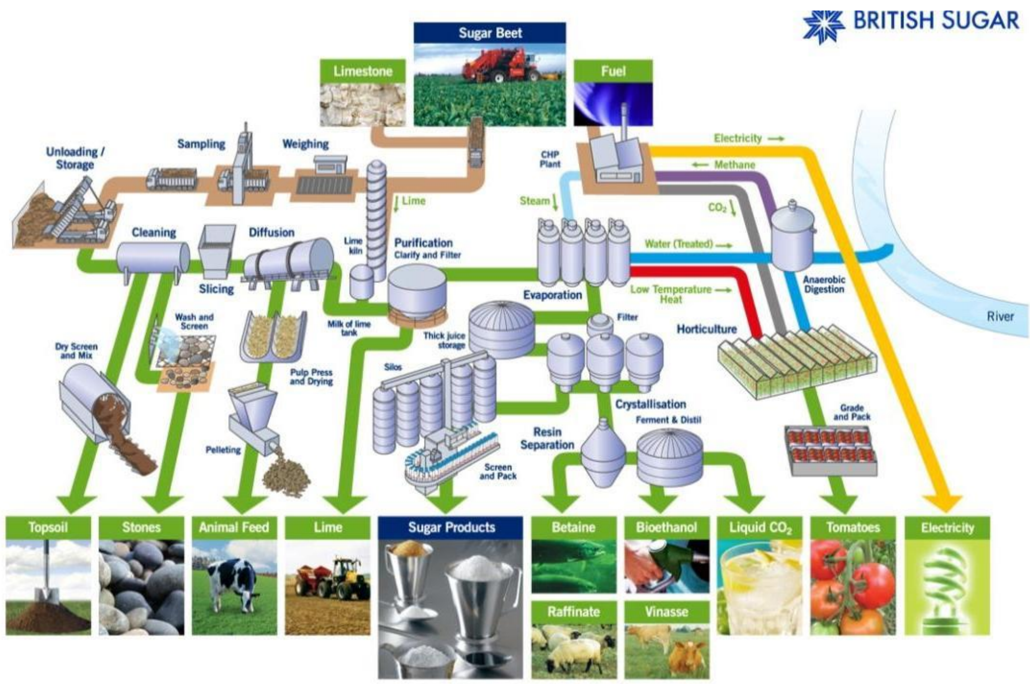
An on-site 66MWe CHP plant generates electricity and steam for the sugar factory processes. The plant participates fully in the electricity market as a generator with a committed day-ahead position and trades intra-day to maximise returns. Having a clear operating protocol covering plant flexibility, it also participates in the short-term operating reserve (STOR) service, providing additional active power from generation or demand reduction.

Electricity from the CHP is provided to the CEA for the glasshouse operation to drive 19,000 low-energy LED lights for extended season growing, irrigation, and ancillary requirements. Flue gases from the CHP are piped into the glasshouses to provide an enriched CO_2 atmosphere to enhance growing. High temperature heat from the CHP is also used for dehumidification activities.

The site uses rainwater harvesting from the roofs of the glasshouses to be almost self-sufficient in water. Automated climate control systems coupled with thermal screens monitor and adjust shading, temperature, and ventilation within the glasshouses to optimise growing conditions.

Figure 20 British sugar Wissington plant by-products reuse

Source: https://www.britishsugar.co.uk/about-sugar/co-products



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Another British Sugar site at Bury St Edmund's, although not involved in CEA, demonstrates the implementation of biogas CHP on a large scale. In 2016, British Sugar invested £15 million in a new anaerobic digestion plant which uses the pressed sugar beet pulp that results from the sugar making process to generate biomethane. This is fed into a CHP. An estimated 97,500 tonnes of pressed pulp will be processed in the AD each year, and export 38GWh of electricity to the national grid, contributing to the UK's renewable energy targets. (At the Wissington site, beet pulp is used to generate bioethanol instead which is used as a renewable fuel for transportation, rather than CHP).

11.2 Dyson Farming – Anaerobic digestion

Website: https://dysonfarming.com/strawberries

Source: Company website information, supplemented with information from website of installers, Cambridge HOK https://cambridgehok.co.uk/projects/dyson-farming

What: Illustration of a circular approach to farming combining CEA operations with open field farming, utilising large-scale AD fed with waste biomass and bioenergy crops, combined with a biogas CHP to provide thermal and electrical energy and CO_2 supply to glasshouses. Extended season operations from early spring to late autumn (9 months) are planned using LED lighting that will produce 750 tonnes of strawberries per year for domestic markets, reducing the need for imported fruit and their associated transportation footprint.

Where: Carrington, Lincolnshire, UK

When: 2020

Size: 6 hectares

Investment: Not known.

Ownership: Dyson Farming

Jobs: 169 total farming operations (details for CEA operation not known)

Systems: Dyson farming have 35,000 acres (14,000 hectares) of farmland, growing a range of crops, including 100,000 tonnes of energy crops per year (representing 60% by weight of annual crop production).

On-site anaerobic digesters use these energy crops to produce biogas to generate electrical power for the farming operations and surrounding homes (power equivalent to requirements for 10,000 homes), heat to warm the glasshouses, and digestate that is used as an organic fertilizer for field crops and may be used for CEA operations in the future. A biogas converter generates CO_2.

Glasshouse uses state-of-the-art climate control systems to maintain optimal growing conditions. An LED lighting system and flowering lamps will extend the growing season, combined with thermal/light pollution screens to optimise performance. A rainwater harvesting system provides water self-sufficiency.

Robotic picking systems are being considered for future use to enhance productivity.

11.3 Gemüsebau Steiner – District heat networks and geothermal

Website: https://www.gemuesebau-steiner.de

https://www.biohof-geinberg.at/

Source: Interview with company managing director and company website.

What: Example of CEA operations utilising a combination of heat sources, including geothermal for 95% of heat demand at one site, additional heat from municipal waste, AD, and solar PV power (see Figure 21). Producing year-round five varieties of tomatoes, peppers, and strawberries, some of these as organic produces, on 34 hectares of glasshouses over two sites in Bavaria, Germany and one site in Austria. All sites involved direct negotiations with local stakeholders, such as district councils, energy providers, and supermarkets leading to long-term (>20years) contracts. Given current CO_2 shortages also in Germany, the company is exploring sourcing CO_2 in the future from local industrial waste CO_2 sources, based on sharing investments in required infrastructure, such as purification and liquefaction installations.

Where: Bavaria, Germany (Two sites: Kirchweidach and Emmerting 5km apart) and Austria, Geinberg (20km from Emmerting).

When: 2013, 2020

Size: Overall 34 hectares at two sites in close proximity (5km) in Germany and 11ha in Austria. In 2020 the company opened Germany's then largest (4.5ha) tomato glasshouse fully equipped with LED lighting for winter tomatoes, producing ~1,800 t of tomatoes/year.

The Kirchweidach site used to be Germany's largest glasshouse heated with geothermal heat. In March 2022 the company opened a joint venture they have initiated with Perlinger BioHof in Geinberg, Austria, with a 11 hectare glasshouse heated by a local deep geothermal plant.

Investment: Kirchweidach: €45M; Emmerting: €15M; Geinberg: €20M. No subsidy schemes were used for setting up long-term financing for any of their sites. Land was leased on heritable, long-term leases. Planning regulation in Germany and Austria attributes privileged status to protected horticulture operations.

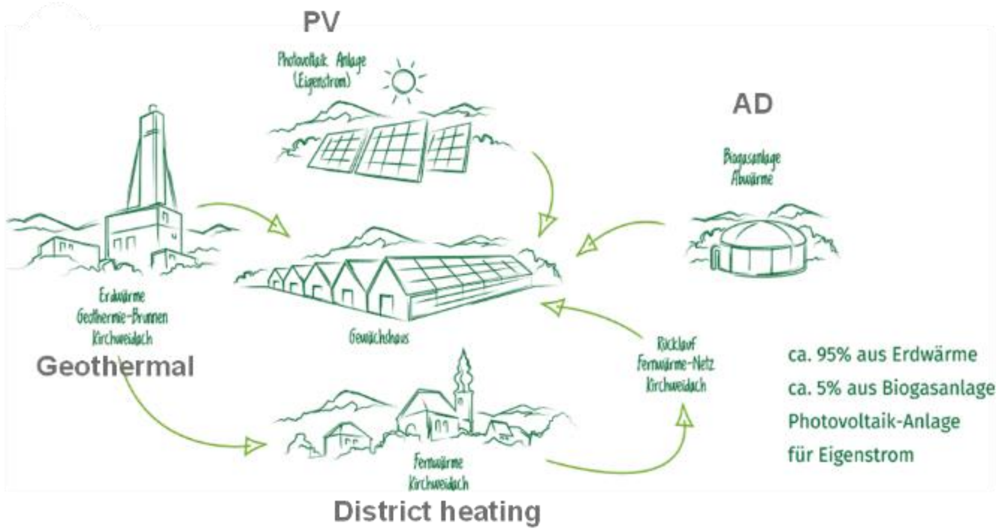
Ownership: Family ownership, Gemüsebau Steiner

Jobs: At their three sites: Kirchweidach 250, Emmerting: 30, Geinberg: 120

Systems: Their operations run on a mix of deep geothermal (over 5000m deep, provided since 2013 by a local geothermal energy provider in Kirchweidach that generates heat and electricity), waste heat from a local AD plant for biomethane production, and at the Emmerting site additional waste heat from an Energy from Waste plant using a short district heating network.

Figure 21 Gemüsebau Steiner schematic

Source: https://www.gemuesebau-steiner.de



Connecting heat pipes to waste heat suppliers and geothermal provider were paid for by Steiner Gemüsebau. At Kirchweidach 95% of heat is supplied from geothermal, 5% from waste heat of the local AD plant. All glasshouse technology and installations as well as energy modelling expertise were imported from the Netherlands. Gemüsebau Steiner are fully self-sufficient in terms of water supply using rainwater as well as condensation collection systems, recirculation of irrigation excess and storage reservoirs.

They use their own photovoltaic system for electricity and sell surplus to the grid.

They estimate that compared to fossil fuels, 16.5M kg of CO_2, and an estimated 1M produce transport km are saved due to long term contracts with large regional supermarket chains such as REWE within a 200km range.

11.4 Jones Food Company – Vertical farming

Website: https://www.jonesfoodcompany.co.uk

Source: Interview with company, supplemented with company website information.

What: State-of-the-art Vertical farming. Set up the farm with the intention to reduce food miles in the sector. 17-20 harvests/year of leafy greens and herbs. Recent focus on basil as it needs very specific requirements (settings), and currently produce 30-35% of UK retail basil, supplying Tesco, Sainsbury, etc. Now moving into strawberries, and a longer-term ambition to grow vine crops including grapes and tomatoes. Unlike many players in the vertical farming sector, JFC position themselves as a grower, not a technology provider.

Where: Scunthorpe, North Lincolnshire (JFC1)

When: JFC1 opened 2018.

Size: 5000m^2 (0.5 hectare) growing space (JFC1). JFC2 will be 1.5 hectare growing space.

Investment: Investment from Ocado and a private family wealth office (latest funding round in April 2021). Once JFC2 is up and running early 2023, anticipate it will become a viable institutional investment and more attractive for investment money more broadly, either pension fund money or other. In single digit ROI numbers at present but improving.

Ownership: Jones Food Company.

Jobs: Vertical farming does not provide seasonal labour, but long-term jobs. With respect to skilled labour, JFC1 had to source skilled labour mostly from outside the area.

Systems: Year-round lighting (using most efficient LEDs on market) and HVAC climate control systems, 100% electrification driven by grid electricity and solar PV energy. Currently JFC1 site receives 15% of energy requirements from PV with target to be 100% PV power by summer 2022. Future vertical farming operations plan direct link to wind/solar or AD plants to deliver low-carbon solution. Commercial viability dependent on maintaining low price per kWh of electricity/kg of produce, so energy efficiency is key and looking into more energy efficient HVAC.

Supplementary CO_2 is used during the main growth phase to increase yields, but technically it would not be needed for these crop types.

JFC has its own R&D site besides the growing operation, which is primarily for optimising JFC growing. Also have a joint venture with Berry Gardens to optimise growing of strawberries all year round in vertical farming conditions. Automation will certainly be a big area of innovation for the sector and will be an important focus of the JFC2 site. AI to optimise future growing conditions is also anticipated to be important – more so than the input technologies themselves.

11.5 Koppert Cress – Aquifer thermal energy storage

Website: https://www.koppertcress.com/en

Source: Company website and included case study.

What: An example of a heat and cold ATES seasonal storage system used with a semi-closed glasshouse to facilitate carbon neutral CEA for the growing of an assortment of freshly-sprouted seedlings (cresses) and other edible leaves and flowers (specialties) from 100% natural aromatic plants. The ATES system is estimated to have reduced gas consumption by almost 70% per m^2.

Where: Monster, Westland, Netherlands

When: Initiated in 2010

Size: 10 hectares

Investment: Not known

Ownership: Koppert Cress

Jobs: 200

Systems: The operation uses a semi-closed glasshouse, whereby the windows/vents are kept closed as much as possible to prevent loss of heat. During the summer months solar radiation warms the glasshouse and excess heat is "harvested" and stored in the ATES system.

Four pairs of sinks/sources are used at a depth of about 150m below the surface, containing cold water or low-grade heat at around 40ºC, which can be used for either cooling or warming of the glasshouse depending on the season. Heat pumps are used to step up the low-grade heat to temperatures required for the glasshouse operation. The operation also provides heating for neighbouring houses in a small district heating solution. Ground storage temperatures in the region are limited by law to 25ºC, but permission was granted to store at 40ºC through a Green Deal contract, a government scheme to support sustainable energy projects.[204]

An initial challenge with the system was balancing the heating and cooling needs, and initially they found they had a heat deficit. Therefore, additional heat sources were sought, including an LED cooling system (a water-cooled system connected with the ATES, with a back-up cooling system from local canals), table cooler/cold storage, and office space. Two notable additions were firstly, the construction of an 2000m^2 "energy roof" on top of their pack house – black panels through which water is circulated to harvest solar thermal energy. The system allowed them to raise the water temperature being fed into the aquifer by about 10ºC, and create capacity in the installation of up to 1 MW. Secondly, using the surrounding local canals, which function as effective solar collectors during the summer months, currently provide 15% of the annual heat requirement of Koppert Cress.

Electricity is provided from the grid. Due to low electricity costs and high installation costs for PV it was deemed to be more cost effective to use solar thermal collectors on the roof rather than PV panels.

11.6 Low Carbon Farming – Large-scale heat pumps

Website: https://www.lowcarbonfarming.co.uk

Source: Interview with Oasthouse Ventures, supplemented with website information

What: State-of-the-art glasshouses, and first large-scale use of heat pumps in CEA in the UK, with the aim to "*be a showcase for how renewable heating systems, and heat pumps in particular, can be deployed at a commercial scale*". 80-90% of heat comes from heat pumps, which enables a 75-80% reduction in carbon footprint compared to conventional natural gas-heated CEA. Estimated that conventional glasshouse setup of same size without heat pumps would need 5x the CHP capacity (30MWe to cover both sites).

Where: Two UK sites, Norwich and Bury St Edmunds

When: Commenced build of Norwich and Bury St Edmunds sites in 2019, growing operations commenced January 2021.

Size: 28 hectares of glasshouses across the two sites (16.1ha + 13.8ha), capacity to produce 12% of the UK's tomatoes. 10 month growing season.

Investment: £110m in total, funding from Greencoat Capital acting on behalf of UK pension funds. NDRHI scheme enabled both projects, providing inflation proof term that delivered long-term 30-40% of the income through a tariff guarantee. This enabled funding to be secured, but risk premiums were applied as a UK first for this type of operation.

Ownership: System design and technical support, Oasthouse Ventures; 100% owned by Greencoat Capital; facilities leased to growers on 20-year term with option to buy at lease-end.

Jobs: 360 full time jobs in total over two sites

Systems: Both sites are based on use of commercial-scale ground source heat pumps (GSHP) extracting waste heat from treated water output from wastewater (sewage) treatment works located 2km away. The heat pumps uprate the heat to about 50ºC to provide heat for the glasshouses. Known parameters of the heat source, flow rates and temperatures, defined design of heat pump and backup systems, heating profiles based principally around crop needs, e.g., treatment works discharging clean water at up to 1000 litres/second at up to 25ºC. Between the two CEA sites the heat pump systems generate 60 MWth, equivalent to requirements for heating 20,000 homes, providing 90% of the glasshouse heating requirements. (33.4MWth + 26.4MWth).

A natural gas-powered CHP plant provides 80+% of the required CO_2 (summer levels) to enrich the atmosphere within the glasshouses to enhance plant yields, and also high-grade heat for dehumidification and supplements growing operations. CHP peak electrical output of 6MWe across both sites (3.6MWe + 2.4MWe). Electricity for the heat pumps is provided by the on-site CHP plant and grid power. Gas boilers provide a back-up heat source of 15MWth and 12MWth for a total of 27MWth across both sites).

Operations software balances energy needs in real time depending on energy cost calculations. Controls energy import/export, and engine operations, and use of heat pumps vs. CHP. Two large water heat buffer tanks: 4-5m litres, low grade ~50ºC and higher-grade 75-80ºC to store CHP generated heat for overnight use. Venlo glasshouse specification includes 25% recycling of used water, rainwater reservoirs, and is largely water self-sufficient; hanging gutter hydroponics; diffuser glass; thermal screening; best-in-class climate control system.

11.7 Sterling Suffolk – High efficiency semi-closed glasshouse

Website: http://ambersidealp.com/

Source: Various news reports in the public domain

What: The UK's first industrial-scale semi-closed glasshouse for edibles production, producing more than 150 million tomatoes a year. "*Part of the ethos of this nursery was ecology*", Lewis, "*The land that we're on was very low agricultural land, it was poorly producing, not great soil. What we've done is taken that and built a high-tech glasshouse on it and moved it to being very intensive and very, very productive.*"[205] Using 25% less energy per tonne of tomatoes than other conventional glasshouses, while capturing and reusing at least 75% of the CO_2 generated from heating.

This case demonstrates the challenges of introducing innovation in the sector, including difficulties using initially planned waste heat streams, and high capital costs of semi-closed glasshouse, along with dependence on natural gas that forced the business to close.

Where: Blakenham Nursery, Bramford, Suffolk

When: Project initiated in 2014, commenced build 2018, growing operations commenced January 2019.

Size: 5.4 hectares glasshouse, with ambition to expand in three phases up to 17 hectares. (1.4 hectares lit with LEDs for extended out-of-season growing).

Investment: £15m initial phase, the project was funded by individual investors, with the lowest investment at £100 and the highest at £1.5 million from Amberside ALP. In 2021 a crowdfunding initiative was launched to raise an additional £6.75 million through Abundance, to support 2.8-hectare expansion.

The business has faced trading and cash flow challenges, and with significant increase and uncertainty in energy prices the business ceased operation in March 2022.[80]

Ownership: Purchased out of administration in April 2022 by the company's prime investor Amberside ALP, part of Amberside Capital, an investment fund focused on sustainable infrastructure.[206]

Jobs: 32 full-time jobs, could increase to 150 by the third phase of the project.

Systems: The greenhouse is a state-of-the-art, semi-closed design, built by leading Dutch firm Van der Hoeven. Initially, 25% of the greenhouse, 1.36 Ha, will be lit 100% with Hyperion 1750 LED top lights to provide over 200 micromole/s/m² of artificial light (measure of photosynthetic photon flux density)). Sterling Suffolk plans to extend the area lit with LEDs in subsequent years.[207]

Cooled air is piped in from the sides, instead of opening roof vents which wastes energy and carbon dioxide. Roof vents are occasionally opened to release air pressure and humidity, with levels monitored by an advanced computer system.

The project was initially proposed as a way of using spare heat generated by the Energy from Waste (EfW) incinerator at Great Blakenham - but eventually it was found to be uneconomic to use that.[80] Instead, the glasshouse is heated by 2 x 6MWth natural gas boilers, with hot water running through 62km of pipe on the ground which doubles as a rail track for trolleys used by workers tending plants. A computer monitors when plants need to be watered by weighing their growbags to see how much water they have used and by monitoring the amount of light, from UV lights and sunlight.

Crops are planted in a natural fibre extracted from coconut husk, instead of soil, and are irrigated with rainwater collected from the roof in a 61 million-litre reservoir.

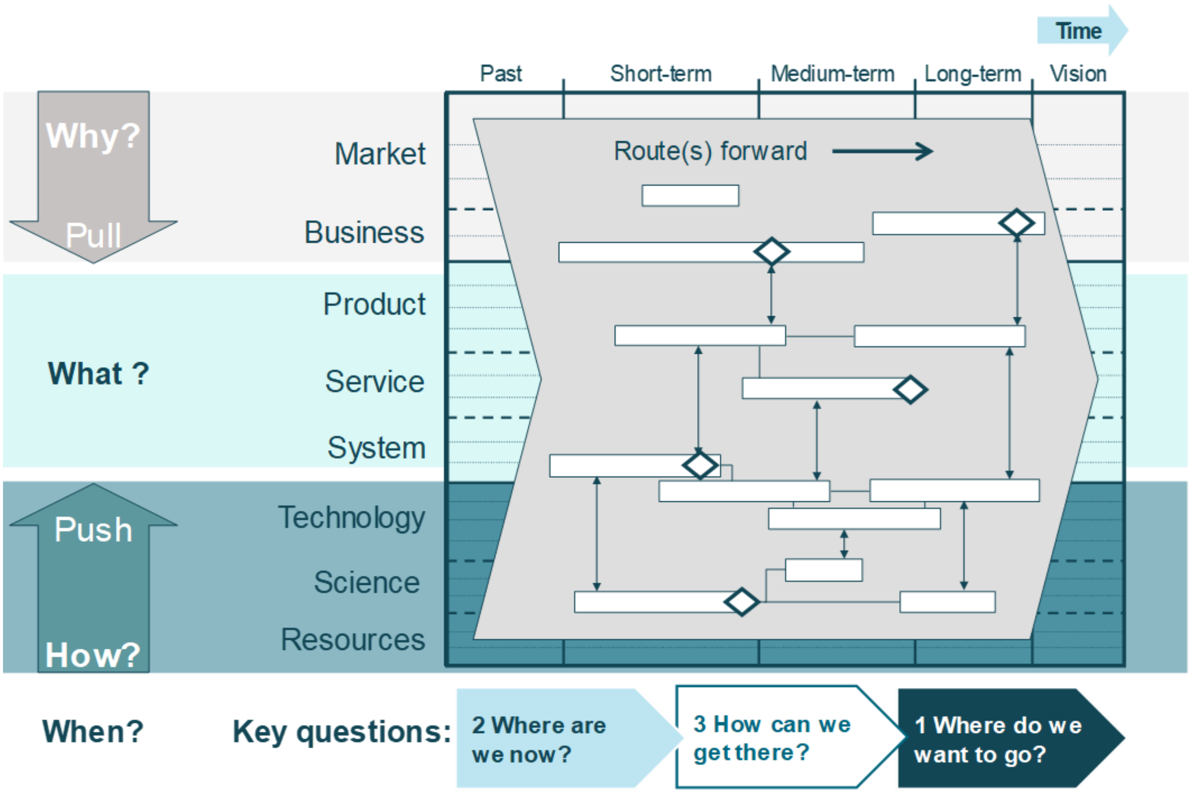
Bumble bees pollinate the plants, with 60 cardboard box hives and 9,000 bees in the glasshouse. Few can be seen at ground level as they focus on the flowers.

12 Annex B: Methodology

12.1 Data collection

To structure the data gathering through the interviews and desk research, which is an essential part of the assessment activity, the Strategic Roadmapping framework based on the IfM's fast-start approach was used. This conceptual approach provided structure to the identification process of relevant evidence and ensured coherence between the relevant areas of information and guided data collection and technology assessment as well as the deduction of implications for policy decision-makers. Roadmaps provide a structured visualisation of information for achieving specific strategic goals. Generally, this framework is particularly suitable for understanding and addressing issues at the 'front-end' of innovation, where decisions may have considerable long-term strategic implications.[8] The design and customisation of the roadmapping framework for this study was part of the scoping and design phase. Figure 22 shows the generic framework.

Figure 22 The generic Strategic Roadmapping framework



For this project, the *"Why?"* layer outlined the relevant trends and drivers of change affecting the UK CEA sector and the current energy needs of the growing operations. The *"What?"* layer described different technologies, solutions and approaches to decarbonising the energy demand of growing operations, as well as alternative supply routes for CO2. And the *"How?"* layer guided the data collection on enablers, focusing on policy as one of the most important enablers for the transition of the sector towards net zero and the definition of challenges faced by the sector.

The data gathering was conducted by collecting existing information from Defra and also reviewing any relevant publicly available documents e.g., academic literature, grey literature and industry reports. This helped to narrow down the priority technology areas that then were the focus of the assessment process.

12.2 Technology assessment

The assessment of the relevant technologies (models) comprised the identification of the areas for potential improvements for the specified industrial horticulture use cases and the state-of-the-art of technologies deployed, as well as existing low technology readiness level solutions and new emerging technologies and solutions that can help the sector's decarbonisation in the future.

Strengths and limitations of the selected technologies were assessed using the IfM's Innovation Velocity Analysis Tool[9] in combination with classical SWOT analysis. The assessment deployed seven factors as shown in Table 5. The performance of each technology concept was scored against each factor using a Likert scale as follows:

- "-2" for significantly lower than baseline technology concept
- "-1" for lower than baseline technology concept
- "0" for same as baseline technology concept
- "+1" for better than baseline technology concept
- "+2" for significantly better than baseline technology concept

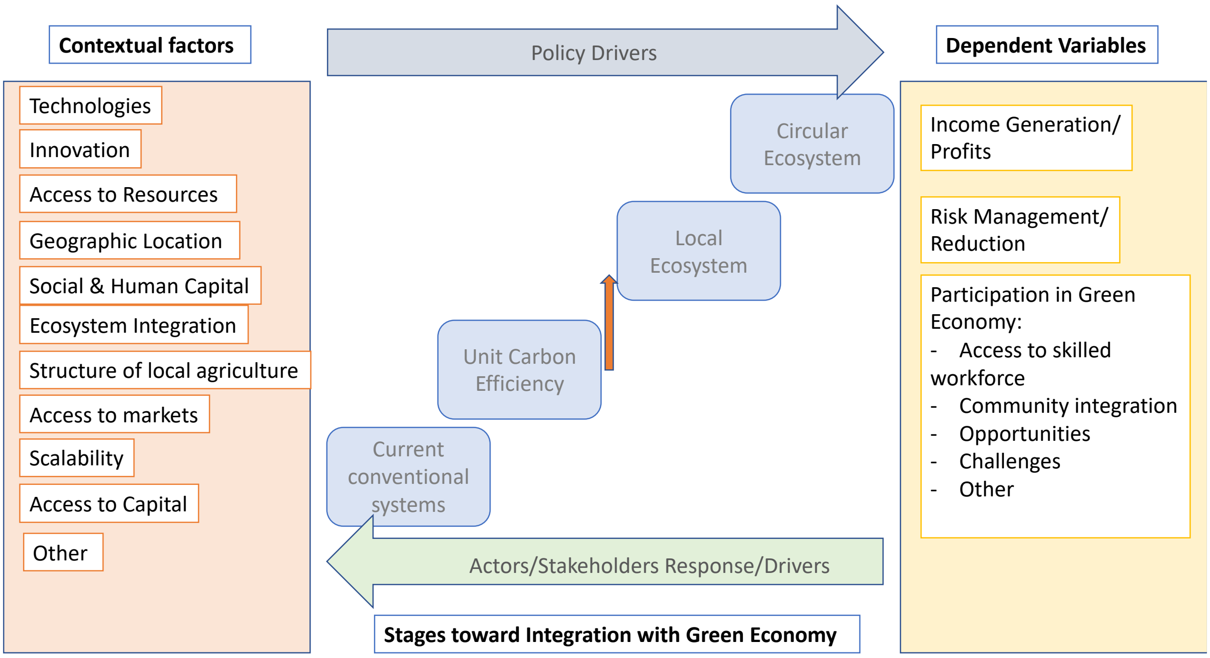
Table 5 Definition of factors for technology assessment

Factor	Definition
Technical feasibility	It indicates when it is safe to count on a technology and to demonstrate its conversion efficiencies, reliability, controllability, and complexity of deployment or feasibility of the retrofit as well as needs for the supporting infrastructure. Also, it includes how widely the technology is deployed globally and across different sectors and application cases.
Commercial feasibility	Investment required, its availability and ease of its acquisition, operational costs, which include energy source price volatility, maintenance and costs of co-dependence risks, cost of sourcing CO2. Difficulty level of the match between demand and generation.
Environmental performance	Contribution to the UK's GHG emissions or net-zero targets, reliance on and impact of decarbonisation of the network, and contribution to other environmental impact categories, e.g. eutrophication, water, land use, deforestation, biodiversity loss and other pollution, and reduction in waste disposal needs (e.g. energy generation from waste, use of waste biomass in biowaste treatment plants, etc.).
Organisational/ecosystem requirements and capacity	Availability of the market and ecosystem players, including specific skill sets, need and general availability of assets/capability. Also, skills (internally for deployment as well as in the UK) that support the implementation of the new technology.
Suitability of existing policy/regulatory/fiscal incentives	The UK' s policy initiatives and regulatory alignment to support technology adoption, covering legal frameworks, financial incentives (including taxation and subsidies), voluntary directives and mandatory regulation.
Societal value creation potential	Effects on social value creation and contribution to the UK's economy, including the creation of new jobs, IP, revenue creation e.g. through technology export, potential contribution to regional levelling up/import replacement potential/in-country manufacturing.
Societal/Consumer/Retailer acceptance	Perceived societal and customer/retailer legitimacy associated with contribution to net-zero, reduced environmental impact, and food safety and quality considerations.

12.3 Policy analysis

The data and insights gathered through the data collection phase were used to derive implications for policy as one of the main outcomes of the work. The policy development framework, designed by Camrosh Limited that was used to structure policy analysis is shown in Figure 23.

Figure 23 Policy development framework



The policy development framework summarises the generic trajectory towards the Green Economy for the next decade from a policy perspective. It is based on consideration for both a set of “contextual factors” that are independent of actors/stakeholders intent, and “dependent variables” which are defined by and dependent on the stakeholder intent. Both contextual and stakeholder-dependent variables will influence the trajectory of technology and market development for CEA in general. Strategic policy intervention or regulation has the potential to affect both the speed of moving from one stage to the next as well as the proportions of the technology and innovation mix, as far as constraints set by other factors such as geographic location and social and human capital would permit.

12.4 Findings validation and identification of the policy implications

Initial findings on policy affecting the CEA sector in the UK and the Netherlands were based on desk-based literature review, including government policy documents and analysis of individual expert interviews. These findings were validated through an validation workshop with Defra representatives and CEA experts participating. The workshop processes were designed based on the strategic roadmapping framework, in particular utilising so called topic roadmaps.[8] Topic roadmaps help to scope a topic and to map its development pathway. In this case, a customised template was designed to outline how a challenge faced by the CEA sector can be addressed and what the implications for policy are. A list of challenges was derived from the technology assessment and the analysis of the current policy landscape (reviewed by Defra and the industry experts at the start of the workshop). At the beginning of the interactive workshop session, the delegates voted in order to select and prioritise key challenges. These were then explored in individual discussion groups using the topic roadmap template to structure information gathering from the discussions. Outcomes of the group discussions were presented to all participants in a plenary session at the end of the workshop. The validation workshop outputs (see Annex E) were sent to the participants for their review and updated based on the feedback.

13 Annex C: Interviews

Interview Round 1: Understanding controlled environment horticulture (CEA) in the food sector

<u>The objectives for the interview:</u>

- Understand the contextual background to CEA in the UK and develop general understanding of the current status and future anticipated evolution of CEA in the UK and internationally
- Confirm CEA use-types classification
- Understand the role of energy supply in the CEA sector in the UK and how it might evolve over the coming decades for each use type
- Capture the main drivers, trends, enablers, and barriers for decarbonisation of the energy supply systems of the UK's CEA

Hypothesis to validate: Suggested classification of the use types of controlled environment horticulture for food production:

1. Large scale glasshouses
2. Vertical farming
3. Emerging use types: Indoor, shipping container-based, etc.

<u>Participant details</u>

- Tell us more about yourself, your role in the organisation and area of expertise.
- What is the role of your organisation in the ecosystem of CEA?

<u>Overview of CEA sector</u>

1. What is the current status of the CEA sector in the UK, the significance of the CEA sector in terms of food production, revenue, food security, and how important might it become over the coming decades?
2. Who are the most important actors / stakeholders in the CEA sector?
3. Which other countries are leading players in CEA from which the UK might learn, and how does the UK current state of development compare with these leaders?

<u>Trends and drivers of change in CEA</u>

4. What do you consider are the most important trends and drivers of change for the controlled environment horticulture sector in the UK? (e.g., Political including food security concerns, Economic, Social including changing consumer demands, Technology innovation, Environmental (decarbonisation, climate change impact, etc), Legislation)
5. What future innovations within the CEH sector are anticipated to support market growth and support the sustainability/net-zero transition, and over what timeframes?
6. What might the sector look like in the UK in 10-20 years' time (what is the long-term vision)?
7. How do you expect the market share between open-field horticulture, and the various forms of CEA to change in the future?

<u>CEA Use-types</u>

8. What alternative CEA use-types can be identified, and how might these best be categorised when considering energy supply systems. Potential categorisations might

include by operation – industrial-scale glasshouses, vertical farms, etc. / by crop type / growing system – soil-based, hydroponics, aquaponics, aeroponics)

Current CEA energy supply systems, and related ecosystem

9. For each use-type, what are the energy supply technologies and fuels currently in use?
10. What is the split between power and heat generation for each use-type, and the pros and cons of these current energy solutions?
11. To what extent is industrial symbiosis (co-located CEH operations exchanging energy with other industries), or exporting power to the grid, or other industrial ecosystems important in the CEA sector in the UK?

Future low-carbon energy systems for CEA

12. What and where are the leading examples in the horticulture industry for low-carbon energy supply? Who are the market and innovation leaders in this area in the sector? Exemplar cases in the UK, Europe and globally?
13. What role will new energy supply technologies play in the decarbonisation of CEA? How do you expect the energy supply for CEA to evolve in the future and what new technologies might be deployed? (if possible, identify for the individual use types)
14. Which of the horticulture use types are best suited to renewable/carbon neutral energy generation sources and why?
15. Which of the use types/aspects of the use types will be problematic to transition to renewables/zero-carbon and why?
16. What are the opportunities for upgrade/retrofit and improvement from carbon-intensive energy supply technology in use today (fuelled by fossil fuels)? (i.e., should upgrade/refit be an important focus, or is it better to focus on new operations?)
17. What are the primary technological and operational barriers to transition to zero-carbon energy systems in CEA?

Economic considerations for low carbon CEA

18. What are the potential timeframes for capital equipment upgrade cycles and how quickly might a transition to new systems and in particular, low-carbon energy supply systems in CEA occur? E.g., life cycle, payback period? What can be done to reduce long payback periods?
19. What is the share of energy-related operating costs in the total operating expenditure for the different use types?
20. Where CHP-powered CEA operations sell electricity back to the grid, how significant is this for their overall operating revenues?
21. What role do current incentives, grants, subsidies, tax breaks play in supporting innovation and investment in energy supply systems of the sector?
22. What are the main barriers for investing in the low-carbon energy system within the CEA sector?

Regulation and policy supporting investment in low-carbon energy systems

23. What are the regulations/policies that support net-zero transition of the sector?
24. What are the regulations/policies that are challenging to navigate, and, or barriers holding back wider adoption and change in the sector?
25. What regulation would you like to see implemented that would benefit the industry/sector, and why?
26. Do you foresee change in regulation? If yes, what is the direction?

Final wrap up

27. Any other comments or observations?
28. Can you recommend any specific reports, case studies, other sources of information, key contacts for the project?

Interview Round 2: Assessment of the low-carbon energy technologies

The objectives for the interview:

- Get a general understanding of low-carbon, clean energy technologies and solutions.
- Understand the potential pathways and timeframes for decarbonisation of energy supply of CEA sector in the UK within the broader context of the UK's net-zero objectives.
- Capture main advantages and potential for decarbonisation as well as barriers and enablers for implementation of different low-carbon, clean energy technologies and solutions.
- Understand how the energy mix in CEA and required policy might have to shift over time to best adapt to the changing UK grid over the coming decades.

Participant details

- Tell us more about yourself, your role in the organisation and area of expertise.

1. Technical feasibility

1. What are the TRL, maturity, conversion efficiencies, reliability, controllability, and complexity, retrofit feasibility/disruption, etc.?
2. How well spread is adoption of technology, will there be chasms in adoption?
3. What are the overall effects of national and international investments in development, plus tipping points that would influence the wide market adoption of the technology e.g. for H2 the required distribution infrastructure?
4. What is the progress in closely related technology clusters that support the deployment of this technology?
5. When is the technology likely to be appropriate for large-scale deployment in the UK?
6. What are the general pros and cons / technological and operational barriers and challenges for the large-scale uptake of this technology?
7. What technological innovations are anticipated/still required for the technology to become more viable, and how likely are these to be realised? What if any are the emerging innovations in this space?
8. What risks are there of technologies becoming prematurely obsolescent due to technological innovation?
9. What timeframes will these emerging technologies become available and technically viable?
10. Which countries are at the forefront of this technology?
11. If relevant, what are alternative fuels needed to operate this technology? What are the opportunities for upgrade/retrofit and improvement from carbon-intensive energy supply technology in use today?

2. Commercial feasibility, including energy source price volatility, maintenance

12. What are the operating costs, CAPEX, Cost and availability of capital, Payback period and ROI, maintenance costs, cost of sourcing CO_2, etc.?

13. What scale of investment is required for retrofitting or purchase of new assets incl. complementary assets and costs for the writing off the investment for current system?
14. What are the ease of raising the capital / cost of capital and availability in the market for required investments?
15. What are the additional existing or future opportunities for securing returns, larger market share or entering new market segments?
16. What is the share of energy-related operational costs in the total OPEX?
17. How do costs currently compare with contemporary gas-powered CHP or all electric operations, and what are the timeframes for the technology to become more commercially viable? In what areas does cost have to reduce, and what are the potential pathways to cost reduction?
18. What are the potential timeframes for capital equipment upgrade cycles and how quickly might a transition to the latest systems occur? E.g., 10-year life cycle, 5-year payback period?
19. What are the typical payback periods for investments into low-carbon energy supply systems in CEA? What can be done to help to reduce long investment payback periods?

3. Environmental performance

20. What are the CO_{2e} emissions (contribution to net-zero goal) can be expected from the deployment of this technology?
21. Is there any dependency on and impact of grid decarbonisation?
22. Can a contribution to any other environmental impact category, e. g. eutrophication, water, land use, deforestation, biodiversity loss, and other pollution be expected?
23. Can this technology contribute to a reduction in waste disposal (e.g., waste to energy, use of waste biomass in bio digesters, etc.)?
24. How might the technology's suitability in the energy mix shift over time? E.g., will it still be appropriate when the grid is 100% decarbonised, and why?
25. What are the carbon emissions profiles for relevant technologies?

4. Organisational/eco-system requirements and capacity

26. What is the availability of industrial eco-system players, capabilities, and skillsets?
27. What is the need and general availability of assets/capability as well as skills (internally as well as in the UK) that support the implementation of the new technology for energy supply?
28. What are the internal levels of capabilities and skills needed for the deployment?
29. How shifts in the UK power and natural gas/hydrogen grids might influence technology choices over time?
30. Co-dependencies on external non-horticulture partners/international suppliers
31. Geographic, co-stream proximity, planning permission challenges
32. Grid connection to high power electricity and maybe gas/hydrogen
33. How do these considerations impact on the potential for widespread deployment in the UK – which regional areas of the country would be most suitable, which areas of the country might be excluded from these innovations?
34. Where are the geothermal hotspots in the UK, availability of deep aquifers for seasonal storage?
35. What are the challenges and barriers of co-dependency associated with industrial symbiosis?
36. What are the costs associated with grid connection, and which areas of the country might be poorly served with power and natural gas connectivity so limiting applicability?

5. Societal value creation potential

37. What is the potential for including new co-stream jobs/IP and revenue creation/technology export potential/contribution to regional levelling up/import replacement potential/in-country manufacture?
38. What is the potential for contribution to grid load balancing and renewable energy storage and release of excess capacity?
39. What is the potential for contribution to the depth of experience and expertise of this sector segment in the UK and towards the level of their involvement - supporting or leading roles, need for development, training?

6. Societal/Consumer/Retailer acceptance

40. Perceived legitimacy associated with contribution to net-zero, and reduced environmental impact – are there any indications to date of potential problems with consumer or retailer/food processor acceptance?
41. What are the food safety and food quality considerations (real and perceived) that might constrain uptake?
42. Are there any further implications regarding food security?

7. Supply of CO_2

43. What change in requirement for additional CO_2 (bottled liquid CO_2) or other sources can be expected?

8. Alignment with existing policy/regulatory/fiscal incentives

44. Policy initiatives and regulatory alignment to support technology adoption, covering legal framework, financial incentives including taxation and subsidies, voluntary directives and mandatory regulation
45. What role do currently financial incentives, grants, subsidies, tax breaks play in supporting innovation and investment in energy supply systems of the sector in you UK? For non-UK based experts: Do you have examples from your country?
46. In what way might current regulation and policy be acting as a barrier to technology adoption?
47. What policy interventions might be suitable to drive technology development, cost reduction, and broader acceptance and adoption of low-carbon technologies in the sector?

Final wrap up

48. Any other comments or observations?
49. Can you recommend any specific reports, case studies, specific companies demonstrating class-leading performance or cutting-edge development, other sources of information, key contacts for the project?

14 Annex D: Validation workshop

The validation workshop took place as an online meeting on 21st July 2022. The agenda was as follows:

– Welcome and introductions	13.30 – 13.40
– Project objectives	13.40 – 13.45
– Workshop goals and process	13.45 – 13.50
– Brief presentation of our key findings	13.50 – 14.00
– Prioritisation of the key challenges and discussion	14.00 – 14.45
– Break	14.45 – 15.00
– Exploration of the key topics (in small groups)	15.00 – 16.30
– Carousel review of the group’s discussions	16.30 – 16.55
– Wrap-up and close	16.55 – 17.00

15 Annex E: Validation workshop outputs

In this annex the outputs from the validation workshop are shown. Each table describes the ideas of the workshop delegates on one of the key challenges that were selected for in-depth exploration as follows:

- Table 4 Policy vacuum
- Table 5 CO_2 supply in low carbon energy systems
- Table 6 Upfront capital costs and operating costs and pricing pressures

The outputs were reviewed by the participants post-workshop.

Table 6 Policy vacuum

Vision for the future
 	
- 30% is underwhelming. 60% or 100% or becoming an exporter is what we should be aiming for.
- Ambition is to be a global market leader in low carbon food production. This includes being the market leader in all units of the horticulture ecosystem e.g., policy, glass house design, renewable energy, AI, robotics. To grow the sector in the most sustainable way we can.
- We have the ability to be ambitious here. We have an atmospheric environment that is optimal, we have water, light, and other requirements. The natural inputs we get from light, heat, CO_2 and water we can source as far as policy conversation from a low carbon, or a carbon negative perspective is concerned. So, ambition needs to be high, and it has to be also aligned with other government targets that is to be net carbon zero by 2040. With technology and renewable energy from the North Sea the ability to harness new technology such as direct air capture (CO_2) and abundance of water, a local market, renewable forms of heat we can lead the world in carbon neutral or carbon negative (when you take out the food miles). We can be a leader globally.
 	
<u>What are the benefits to the UK's CEA sector?</u>
- UK can become a market leader in low carbon or carbon negative/neutral food production. This is dependent on policy, design, renewable energy, AI robotics and plant genetics creating a whole ecosystem to enable the industry into a leadership position. Benefit for the UK are:
    o Higher food security.
    o Low carbon to carbon negative (accounting for the food miles when it is imported) food.

- Job creation in different parts of the country by setting up horticultural hubs both in high skilled labour as well as lower skilled labour. This will also liven up the local economy and help the levelling up agenda.

Current situation and issues associated with the challenge

- Currently in the UK we are producing low carbon food because we are using low carbon energy.
- A key challenge of the current model is the disproportionate power of supermarkets to drive prices down. This forces growers to seek other sources of income to compensate for their operational costs; hence the widespread use of CHP burning natural gas to generate and sell electricity to the grid.
- The current model would not allow for increase in production (30% to 100%) without support for the growers
- The horticulture industry suffers from lack of direct and targeted support to enable its growth. In contrast with for example offshore wind receiving such direct support about 10 years ago.
- lack of supportive policies around CO_2 either using Direct Capture (DAC), CO_2 from AD plants and other non-fossil fuel-based CO_2 sources
- Any form of decarbonisation that would lead to reduction of CO_2 being available for yield enrichment will be a problem. For example, decarbonisation of the gas grid, if that is achieved with methane horticulture will not be affected however, if hydrogen is going to be the replacement, then there is not CO_2 by product to be used in horticulture and that has a critical effect on reduction of yield.

Scope of the challenge

The effect of this policy vacuum leads to lack of decision-making ability and support for low carbon technologies and innovative business models (e.g., energy storage to aid grid balancing), exacerbated by no clear ideal one technology solution. Since the expiration of the Renewable Heat Incentive, RHI, which enabled the emergence of CHP as the optimum technology solution for increasing energy efficiency in the industry there are not clear directives. This situation is further exacerbated because there is no clear ideal one technology that can lead to energy efficiency and reduction of carbon emissions. Systems are generally highly bespoke solutions dependent on local context, energy flows, growing requirements, etc making a one-size-fits-all approach less workable.

Ideas for potential solutions/initiatives/projects that can help to address this challenge

1. Inclusion of commercial greenhouses (not protected agriculture) as an Energy Intensive Industry (EII) which is a BEIS policy will be a big step forward. However, nuances of making such a move have to be taken in consideration e.g., being included in the UK Emissions Trading Scheme (ETS) and some other legislative concerns around paying for carbon emissions that are made alongside being recognised for being able to decarbonise emissions.

2. Support mechanisms for helping CO_2 generation technologies including direct air capture (despite its reputation for being far off commercialisation stage the technology is ready to scale but it requires support to do so). Other CO_2 generating technologies such as AD would need policy support to enable capturing and repurposing the CO_2 generated from AD. In general support for non-fossil fuel-based CO_2 technologies.
3. As part of the joined-up government policy design support for biomethane from AD can be increased through putting more domestic food waste into none landfill use. This both benefits biomethane production and when combined with policies for CO_2 capture from AD plants will also create CO_2 source for use in horticulture. However, this must come with considerations for intensive upfront capital investment of £2m to £3m per hectare which needs a payback time of up to 40 years.
4. Most of the CO_2 and heat leave the glass house through the walls and the vents, there is an opportunity to innovate methods to prevent this loss without impacting the amount of light coming into the glass house.
5. If we are going to decarbonise the rural economy and rural sectors of agriculture and we need an agriculturally specific policy not just a protected environment policy.
6. Make sure that energy efficiency and renewable energy policies are in tandem alongside well thought out economic cost benefit analysis of the energy principals involved.
7. Consider large scale horticulture as national infrastructure and simplification of planning permissions at a national level.
8. Continuation of some taxation benefits for CCA and UKETS.
9. Build reward mechanisms for doing the right things and penalising maintain the status quo.
10. Incentivise CO_2 infrastructure.
11. Controlled phase out of CHP to make sure the legacy parts of the industry would not implode.
12. Greater government policy integration.
13. Eclipse Dutch hegemony in the low carbon CEA sector and create a global leading horticulture ecosystem.
14. Support R&D in the sector to drive transformational change.
15. Transition of the industry will evolve and let the government own the breaks and accelerators.

Implications for policy and next steps that might be undertaken

<u>Immediate actions that policymakers could undertake to achieve 'quick wins' within 1 year</u>

- Consider large scale horticulture as national infrastructure and simplification of planning permissions at a national level.
- Greater government policy integration.
- Continuation of some taxation benefits for CCA and UKETS.
- Build reward mechanisms for doing the right things and penalising maintain the status quo.
- Incentivise CO_2 infrastructure.
- Controlled phase out of CHP to make sure the legacy parts of the industry would not implode.

<u>Medium- and long-term actions that policymakers could undertake</u> - Eclipse Dutch hegemony in the low carbon CEA sector and create a global leading horticulture ecosystem. - Support R&D in the sector to drive transformational change. - Transition of the industry will evolve and let the government own the breaks and accelerators.

Table 7 CO_2 supply in low carbon energy systems

Vision for the future
- Reduced reliance on CO_2. - Ideally, we will not burn fossil fuels to produce CO_2 at a greenhouse location. The CO_2 will be coming from e.g., CCS at a power station. - Suitable Carbon Capture mechanisms are in place. - CO_2 will be still produced at breweries, fertilizer industry, etc. But the amount will be limited, or the CO_2 will be captured from the atmosphere. - Efficient use of CO_2 within the growing operation. - More efficient structure will lead to less CO_2 being needed. - Organic waste / Biomass becoming an important source for CO_2. - More crops will move to glasshouses. - <u>What are the benefits to the UK's CEA sector?</u> - Lower operational costs, more competitive internationally, food prices. - Environmental: fewer emissions from another sector. - Solve the carbon credits, for not putting this carbon in the atmosphere but in the plants. - CEA can benefit from the innovations and advantages UK's research and other industries regarding carbon capture.
Current situation and issues associated with the challenge - CO_2 give 10% - 40% additional yield, most is produced through consumption of natural gas (gas boiler or CHP). It is a cheap and efficient way of getting CO_2 in the glasshouse. - The technology is there, but economically non-viable / expensive. - There are already examples of deployment of these technical solutions. - AD is used to supply CO_2.

- A lot of research was done in the UK on CEA and UK was leading, before Netherlands became the international leader. The sector size in Netherlands is much larger and therefore, more research is happening there. - Approx. 5% energy in CEA are from biomass / AD.
Scope of the challenge - Recovery of CO_2 reach streams, from AD, power station, biogas - existing industries. - Improved efficiency of utilisation of CO_2 / reduction of reliance on CO_2. - Awareness of using CO2 more efficient, e.g., plant biology - how can plant use absorb more CO_2? - As more crops move to high tech glasshouse, as more they will benefit from additional CO_2 and therefore, more efficiency is needed
Ideas for potential solutions/initiatives/projects that can help to address this challenge 1. Technology is there, investment costs are too high and natural gas are (still) low enough: Initiative of how to best harness and purify the CO_2 from biomass/biogas/AD. 2. Look at other industries in the UK e.g., creation of lime/CO_2 source and what is needed to make it available. 3. R&D Extraction of CO_2 from the air. There are two different perspectives within the community on the role of DAC. 1. It will not be economically viable in medium-term. 2. It is not possible to achieve a large-scale carbon negative food production without DAC. There are technologies being trailed and supported in glass in other countries (Norway a good example), but it needs to be scaled up for costs to come down (economy of scale). 4. Composting - big green waste composting sites produce a lot of CO_2, and other natural sources: how can this CO_2 be captured and transported to CEA. 5. Algae as a source for CO_2. 6. Storage of CO_2: If and how can we store CO_2? Can we use it as a seasonal storage? 7. CO_2 will need to be transported to CEA size, you will need therefore to liquefy and store it - it requires additional energy and releases additional emissions. 8. Structure that can use CO_2 more efficiently - closed greenhouses concepts, heat pumps are used to cool (not to heat), reduced need for ventilation resulting in lower leakage of CO_2 - examples in Netherlands. 9. Greenhouse as a prosumer - CEA producing energy and food, surplus of heat in summer - how can this heat be captured and used in winter? Seasonal storage is required. 10. Can we apply CO2 in a different form, e.g., CO_2 dissolved in water? Alternative CO_2 delivery systems to the plant? https://co2gro.ca/ 11. Hybridisation and co-location of different growing engineering systems across different types of growing facilities incl. CO_2 and energy use.

12. Incentives through policies that help to recover and reuse the CO_2 or exceptions from CO_2 taxation.
    - incentivising all measures that promote the efficient use of CO_2.
    - incentivising usage of existing CO_2 sources.
    - promotion of novel technologies (not only research but also in business).
13. Investigate the closed loop approaches (energy CO_2, water etc.).

Enabling conditions, key capabilities and resources required for the development of the solutions and initiatives

- Near market R&D work to show case "yes it works" - demonstrators, pilots.
- Clear targets from policy.
- Growers exchange with each other on regular basis, this can be used an enabler. There are technical tomato, cucumber etc. grower groups.
- Funding/capital grant/schemes for green investment.
- CEA is the only industry that can convert CO_2 to oxygen.

Actors to be involved

- CEA industry, growers.
- Key business/experts who are designing the energy/CO_2 supply systems.
- Investors / Funders.
- Retailers (also as representatives of consumers).
- Technology providers.
- Academia.

Implications for policy and next steps that might be undertaken

<u>Immediate actions that policymakers could undertake to achieve 'quick wins' within 1 year</u>

- Encourage the capture of CO_2:
    - Direct grant systems that do not need just be directed only on energy and not just on high-tech glasshouse, but also about water reservoirs, etc. The focus should be on more holistic combination of different technologies. You need to have technical restriction on what can and cannot come into this category. E.g., high tech alternative technologies.
    - Repurpose RHI system as it is already there. This will attract VC investors.
    - Penalty: paying for CO_2.

- A credit for any Tonne CO_2 purchased from a CO_2 source.
- Number one priority action: Technology demonstration.

Medium- and long-term actions that policymakers could undertake (2023 – 2030)

- Incentivise technology incubators.
- Develop a clear strategy and link it to the wider UK's future energy strategy.
- Support improving productivity and efficiency of glasshouses long-term for existing and other crops that are starting or will be moving to glasshouse area. "Produce more tonnes of tomatoes with the same amount of energy and CO_2" -> Incentivise high-tech horticulture.
- Support displacing the imports, this will also reduce dependencies on other countries, reduce the reliance on fossil fuels, on CO_2 etc. Less dependencies on second tier impact will contribute to food security and reassurance of supply chains (dangers from Ukraine War have been seen).

Table 8 Upfront capital costs and operating cost and pricing pressures

Vision for the future

- Summer crops require heat (Use type 1).
- Out-of-season require heat and electricity (use type 2).
- Vertical farming likely to remain a small fraction of overall scene.
- Target. What is the UK's vision for 2030 and beyond? 30% expansion;100% expansion; 200/300% expansion? 100% represents 1000 hectare increase which is considered doable based on technology, availability of sites, etc.
- Needs to be government backed sector.
- Over 20 years decouple food from energy price (i.e., not using fossil fuels).
- Low-carbon model - decarbonise not only source energy, but also reduce CO_2 wastage through CO_2 supply to plants. (Only 3% of CO_2 is sequestered by plants; 1500 tonnes CO_2 per hectare per year emitted from CHP, if only 3% of CO_2 is sequestered in glasshouse the rest contributes to CO_2 emissions).
- Have a carbon negative energy model by using direct air capture and renewable source energy.

What are the benefits to the UK's CEA sector?

- Enhanced competitiveness.
- Domestic food security.

- If your operating costs are low enough, the cap ex is there.
- Export potential of food and technologies.

Scope of the challenge

- Recovery of CO_2 reach streams.
- Capital expenditure costs.
- Energy input costs (heat & power).
- CO_2 supply.
- Labour.
- Water.

Out of scope

- Land is not a major challenge (can be leased/financed cheaply), although can be expensive to buy.

Ideas for potential solutions/initiatives/projects that can help to address this challenge

1. Force supermarkets to buy guaranteed volumes of produce - different pricing for domestic produce versus imports.
2. Growers won't take a long-term lease on new technology - someone else needs to take the risk or prove technology before growers will invest themselves. Typically, developer needs to take the risk.
3. Reduce the cap ex costs of traditional glasshouses - Lightweight ETFE polymer 3% weight of glass, 10% of steel structure, no need for concrete slab (also maybe benefits for plant health from UV transmission compared to glass).
4. Back-up systems are mandatory to ensure energy supply continuity to protect crops against cold damage (gas boilers, diesel generator are inexpensive, unless need to run them!) If the power system goes down and must use back-up gas supply the cost of gas and possibly carbon taxes in the future represent high additional operating costs.
5. Zero-carbon (summer application, no lighting): Renewable electric heat pumps with water treatment plants and ambient heat (from reservoirs, etc). 1000 hectares by 2030 is feasible using existing identified sources, (10-hectare minimum size per operation). Geothermal could deliver 100 hectares (200 ambitious) by 2030. All need CO2 supply such as direct air carbon capture support. AD plants as a source of CO_2 aren't financeable under current situation for glasshouses (FITs expiring).
6. For winter (out of season growing under artificial light - use case 2): need low-carbon electricity - offshore wind, existing wind farms - most wind energy generated in winter so a good fit with horticulture), direct connection desirable, 500-1000 hectares is viable by 2030 using air source heat pumps. EII exemption to eliminate electricity soft costs. (Solar generation timing poorly matched with CEA needs for lighting).
7. Industrial sources including municipal EfW not generally viable in the UK because in built-up areas, green belt, and also cleaning the CO_2 from EfW is expensive £80-100/tonne (600 tonnes per hectare per year). Waste heat providers expect to be paid-for waste heat, but

generally not competitive with CHP. Operator and owner not easy to coordinate. Few industrial sources that have 50+ year viability so represents a major risk to link with horticulture operation (excludes most industrial applications).

8. District heating low application in the UK.
9. Operating cost reduction through efficiency measures - tough to increase efficiency because a glasshouse with ventilation is inherently inefficient, and costs of dehumidification of closed/semi-closed systems are unavoidable. Many of the efficiency technologies, although improving operating costs pushes cap ex costs up making them unattractive. Vertical farm - addresses issues of efficiency, but at a high cost, and is niche market only (Jones produce 30% of basil, but vertical farming is only economically viable for non-flowering crops at present.
10. Labour costs were not discussed, but perhaps need to be discussed - potential for automation to reduce labour costs?
11. Energy and carbon reduction targets for greenhouses.

Enabling conditions, key capabilities and resources required for the development of the solutions and initiatives

- Financing support mechanism needs to be in one place - not multiple pots of funds - requires a high-level policy approach to allow easy access to grants/support.
- Grant mechanism required to support proof at scale and absorb development/setup risk.
- Need cheapest cost of capital possible (single digit IRR) - cannot use VC funding. However, lots of funds available for ESG from institutional investors such as pension funds - but obviously does require an economically viable business model.
- Policy to drive energy solutions and efficiency improvements (directives, mandatory requirements, incentives).
- Policy to support food production in the UK - Domestic percentage of production and food security.
- Requires government multi-department solution - currently multiple departments are involved in related policy.
- Netherlands - efficiency monitoring and performance improvement initiatives - drive standards through tax policy (40% reduction in carbon footprint in 10 years) - Established base, scale, but their starting point was very high based on CHP and gas boilers (built on cheap gas supply). Relevance to UK situation is not clear.
- Need to implement leap-frog technology rather than incremental efficiency improvements.
- Opportunity to engage untapped local labour resources for glasshouse production through appropriate policy and government support (e.g., providing childcare).
- Increased technical skills for advanced horticulture (courses, education).

Actors to be involved

- BEIS - energy policy, industrial strategy, net-zero.
- Defra - agriculture and food security policy.
- Cabinet office - strategic decisions on self-sufficiency, export potential, long term vision for UK grown food needs to be coordinated from higher up.

- Supermarkets.
- Technology providers - including emerging technologies (e.g., lighting solutions, pulsed modulation, demand management systems integration, next gen HVAC), research centres - all could be integrated into next gen of glasshouses.
- Energy and carbon reduction targets for greenhouses.

Implications for policy and next steps that might be undertaken

Immediate actions that policymakers could undertake to achieve 'quick wins' within 1 year

- Carbon price per tonne to make DAC attractive.
- Policy vacuum for carbon capture - needs support level from organisations such as Innovate UK.
- Needs a joined-up approach across government (levelling up, net-zero, export growth, food security).
- Set up a horticulture technology Catapult UK - bring diverse technologies together to tackle industry problems. Potentially great opportunity for UK to become a leader/exporter in the technology - including training of skilled labour.
- EII exemption for growers.
- Mandate supermarket to buy certain percentage of domestic produce, mandate supermarkets decarbonise their supply chain, introduce carbon labelling to allow consumers to differentiate/choose low carbon crops. (To achieve lower price, more needs to be produced in the UK).
- Government-backed loans (Cheap capital) USDA equivalent - Energy and carbon reduction targets for greenhouses.

Medium- and long-term actions that policymakers could undertake (2023 – 2030)

- Support for education and training (Local Enterprise Partnership, LEP network?) to train next generation.
- Many of the initiatives will certainly take more than one year to implement, but they ideally need to be kicked off immediately to address the current policy vacuum and provide direction and a vision for the sector.

16 Annex F: Marginal abatement cost curve (MACC)

This annex presents detailed data of the assumptions supporting the MACC analysis for energy efficiency initiatives as well as the results of the sensitivity analysis through parameter variation.

16.1 Key assumptions

- To differentiate between the use types, a specific thermal energy demand was applied as a threshold. All farms with >599 kWh(th)/m^2 demand are allocated to Use Type 2.
- Electricity generated through PV, Wind and CHP is partially sold to the grid. An assumption was made on %-share of the electricity exports for each use type as follows:
    - 25% of photovoltaic and wind power generated electricity for both use types
    - 100% of electricity generated by CHP for Use type 1
    - 50% of electricity generated by CHP for Use type 2

  When calculating the current emissions that can be reduced by the measures under consideration, only the self-consumed electricity was taken into account.
- The data set includes information about the farms with a CHP, however there is no information about the CHP sizes, or the natural gas needed for their operation. An assumption was made about a 80%-share of natural gas demand that is used for CHP for the sites with a CHP.
- Some of the measures considered focus only on reducing thermal energy or electricity demand. Therefore, the emissions and costs for the natural gas needed for CHP were allocated to the electricity and heat energy produced based on the average thermal and electrical efficiency of a CHP.

Table 9: Overview of measures and specific assumptions for MACC analysis

	Measure	Description	Specific assumptions
1	Routine maintenance & repair	General regular maintenance and repair activities including a regular sensor calibration.	
2	Intelligent solutions for optimisation of growing conditions (more sensors, etc)	Physical benefits of installing more sensors, software updates etc. for intelligent solutions for energy optimisation including thermostatic control, climate control computers and destratification, optimised airflow and temperature gradient control.	

3	Better use of the computer capabilities & Next generation growing (NGG)	This is the management element of the measures above describing a better use of the computer capabilities including next generation growing (NGG).	
4	Variable speed drives, improved efficiency of fans & motors	Upgrade to variable speed drives, improved efficiency of fans and motors.	An assumption was made of how much % of electricity demand is required for electric appliances (which include packhouse cooling and motors, fans, etc.) and about the split share between electricity for packhouse cooling and for motors, fans, etc.
5	High efficiency boilers & optimised boiler control	High efficiency boilers and optimised boiler control.	Sums of the fossil fuel-based emissions/costs excluding emissions/costs for natural gas for CHP
6	Biomass boilers & burners	A significant replacement of fossil fuels boilers with biomass boilers and burners to generate thermal energy.	The calculation refers to the fossil fuels used to generate thermal energy, which are to be partially replaced by biomass. To account for the fact that fossil fuels are not 100% replaced by biomass, a fuel mix with a higher share of biomass and a certain share of fossil fuels was considered in the calculation of emissions/costs; this also includes the amount of fossil fuels required for the peak load boilers and redundant system. The current use of biomass/biogas from the CCA data sample was not considered in the calculation of current emissions/costs. In the case of the sector part using CHP, the thermal energy generated by CHP was not considered. Thermal energy demand was calculated using typical boiler efficiencies. The delta of market penetration rates reflects the uptake potential of this measure by CEA utilising fossil fuels and is used to calculate how much thermal energy demand is generated by biomass boilers/burners.
7	Electric boilers for electrification of thermal energy generation	A significant replacement of fossil fuels boilers with electric boilers to generate thermal energy.	The calculation refers to the fossil fuels used to generate thermal energy, which are to be partially replaced by electricity. To account for the fact that fossil fuels are not 100% replaced by electricity, a fuel mix with a higher share of electricity and a certain share of fossil fuels was considered in the calculation of emissions/costs; this also includes the amount of fossil fuels required for the peak load boilers and redundant system. The current use of biomass/biogas from the CCA data sample was not considered in the calculation of current emissions/costs. In case of the sector part using CHP, the thermal energy generated by CHP has been excluded. Thermal energy demand was calculated using the typical efficiency rates of the boilers. The delta of market penetration rates reflects the uptake potential of this measure by CEA utilising fossil fuels and is used to calculate how much thermal energy demand is generated by electric boilers.

			Efficiency rate is used to calculate the additional electricity demand. The GWP for electricity in 2022 was used to calculate the emissions. The costs for electricity are calculated using current market price. This measure would require an alternative CO_2 source. These costs are not included in the calculation.
8	Heating with electric heat pumps	A significant replacement of fossil fuels boilers with electric heat pumps to generate thermal energy.	The calculation refers to the fossil fuels used to generate thermal energy, which are to be partially replaced by electricity. To account for the fact that fossil fuels are not 100% replaced by electricity, a fuel mix with a higher share of electricity and a certain share of fossil fuels was considered in the calculation of emissions/costs; this also includes the amount of fossil fuels required for the peak load boilers and redundant system. The current use of biomass/biogas from the CCA data sample was not considered in the calculation of current emissions/costs. In case of the sector part using CHP, the thermal energy generated by CHP has been excluded. Thermal energy demand was calculated using the typical efficiency rates of the boilers. The delta of market penetration rates reflects the uptake potential of this measure by CEA utilising fossil fuels and is used to calculate how much thermal energy demand is generated by electric heat pumps. COP is used to calculate the additional electricity demand. The energy costs are calculated using current electricity market price as well as an additional fee for the use of an industrial waste heat source. This measure would require an alternative CO_2 source. These costs are not included in the calculation.
9	Retrofit of natural gas CHP to biomethane	Retrofit of the existing CHP plants to biomethane.	Only existing CHP are considered. NFU data provides an overview of what farms operate a CHP. An assumption was made of how much % of natural gas demand is used to operate a CHP. An AD plant is considered as a separate project and therefore, the associated capital and operational costs are not included in the MACC calculation.
10	Geothermal heating with direct pumping of water	A significant replacement of fossil fuels boilers with geothermal energy. Reduced thermal demand but increased electrical power requirements for pumping and heat pumps to step up temperatures. Impact on fuel costs and emissions associated with the switch in source thermal energy.	Same as for the heat pump.
11	Improved cooling & refrigeration system	Improved cooling and refrigeration system, including free cooling usage.	An assumption was made of how much % of electricity demand is required for electric appliances (which include packhouse cooling and motors, fans, etc.) and about the split share between electricity

			for packhouse cooling and for motors, fans, etc. Further an assumption was made about % of industry that would be big enough to have a packhouse. Consequently, the ha was calculated to estimate the capital and operational costs.
12	Thermal screens upgrade from single to double & black screens	Thermal screens and upgrade from single to double screens and black screens.	Based on the calculation of the thermal energy demand and associated savings.
13	Advanced glazing including novel glass/polymer combinations	Advanced glazing incl. double glazing and glass/polymer combinations and air leakage minimisation related to vent ceiling.	This measure will realistically only be deployed for new builds. Market growth rate is not considered in the static analysis; therefore, the current market size is taken as a baseline. Based on the calculation of the thermal energy demand and associated savings.
14	Diffuse glass	Diffuse glass.	This measure will realistically only be deployed for new builds. Market growth rate is not considered in the static analysis; therefore, the current market size is taken as a baseline. Based on the calculation of the thermal energy demand and associated savings.
15	Semi-closed glasshouses	Semi closed glasshouse including frameless vented glasshouses and advanced dehumidification.	This measure will realistically only be deployed for new builds. Market growth rate is not considered in the static analysis; therefore, the current market size is taken as a baseline. Based on the calculation of the thermal energy demand and associated savings.
16	Closed glasshouses	Deployment of the closed glasshouse concept for new built CEA operations.	This measure will realistically only be deployed for new builds. Market growth rate is not considered in the static analysis; therefore, the current market size is taken as a baseline. Based on the calculation of the thermal energy demand and associated savings.
17	Daily & longer-term thermal storages for heat buffering	Daily and longer-term thermal storages to buffer the non-synchronized requirement for CO2 and heat.	
18	Closed glasshouse with seasonal thermal storage	Closed glasshouse with (underground) seasonal thermal energy storage for storing summer heat for winter use.	This measure will realistically only be deployed for new builds. Market growth rate is not considered in the static analysis; therefore, the current market size is taken as a baseline. Based on the calculation of the thermal energy demand and associated savings.
19	Energy efficient light sources (LEDs to replace HPS lamps)	Energy efficient light sources (LEDs to replace HPS lamps).	
20	Dynamic tuning of LED light sources & sophisticated	LEDs and lighting controls including dynamic LED system for photosynthetic colour spectrum tuning,	This measure can be only realised in combination with the above. Therefore, the savings are a sum of both measures.

	lighting controls	illumination intensity, and duration of lighting.	
21	Availing of CO_2 from other sources	See the report for further details on the alternative CO_2 sources, when fossil fuels are replaced. The associated costs require a dynamic scenario and sensitivity analysis to estimate the impact of carbon pricing. Thus, it was not considered in this MACC calculation.	

16.2 Data used in the MACC analysis

Table 10: Estimated costs, percentage energy savings, and market penetration

	Decarbonisation measure	Expected lifespan of measure (Years)	CAPEX costs (£/ha)	Annual additional operational/ maintenance costs (£/ha)	Annual energy savings (% kWh)	Current level of market penetration (%)	Forecast level of market penetration over 30-year duration
1	Routine maintenance and repair, including sensor calibration	1	£0	£5,000	5%	50%	85%
2	Physical benefits (more sensors, updates etc.) - Intelligent solutions for energy optimisation including thermostatic control, climate control computers and destratisfication, optimised airflow and temperature gradient control	1	£5,000	£1,000	5%	50%	85%
3	Management element - better use of the computer capabilities including Next generation growing (NGG) (Building on #2)	10	£35,000	£8,000	20%	0%	15%
4	Variable speed drives and improved efficiency of fans, motors	15	£8,000	£1,600	50% [1]	50% [7]	95% [7]
5	High Efficiency Boilers and optimised boiler control	25	£50,000	£0	10% [3]	75%	85%
6	Biomass Boilers/Burners (deployed up cover up to 50% of site thermal demand)	25	£1,000,000	£35,000	0% [3,4,5]	30% [8]	50% [8]
7	Electric boilers / Electrification of thermal energy generation	20	£100,000		0% [3,4,5]	0%	10%
8	Heating via heat pump (assumed COP of 4, deployed to cover up to 80% of site thermal demand)	20	£2,000,000	£35,000	75% [3,4]	8%	50%
9	Retrofit of natural gas CHP to biomethane (co-located with an AD, but excludes cost of AD)	20	£0	£1,875	0% [3,4,5]	0%	50%
10	Geothermal heating with direct pumping of water (assumed COP of 6.5)	30	£4,000,000	£100,000	85% [3,4]	0%	20%
11	Improved cooling and refrigeration system, including free cooling usage for packhouse operations	25	£15,000	£2,000	35% [2]	5%	18%
12	Thermal screens and upgrade from single to double screens and black screens	10	£80,000	£8,000	12.5% [3]	10%	50%

13	Advanced Glazing incl. double glazing and glass/polymer combinations and air leakage minimisation related to vent ceiling	30	£250,000	£0	15% [3]	0%	30%
14	Diffuse glass	20	£200,000	£0	7.5% [9]	5%	50%
15	Semi closed glasshouse including frameless vented glasshouses and advanced dehumidification	30	£3,000,000	£50,000	22.5%	1%	5%
16	Daily and longer-term thermal storages to buffer the non-synchronized requirement for CO2 and heat	35	£25,000	£0	5% [3]	80%	95%
17	Closed glasshouse with (underground) seasonal thermal energy storage for storing summer heat for winter use	30	£4,000,000	£80,000	40% [4]	0%	20%
18	Improved Light Sources – Upgrade from HPS to LED lamps	10	£1,000,000	£5,000	55% [6]	80% [6]	99% [6]
19	Improved Light Sources - LEDs and Lighting Controls including dynamic LED system for photosynthetic colour spectrum tuning, illumination intensity, and duration of lighting	10	£1,500,000	£6,000	13% [6, 9]	1% [6]	90% [6]

1. Applies only to electrical energy supply for pumps, ventilation, cooling.
2. Applies only to electrical energy use for refrigeration/packhouse cooling.
3. Applies only to thermal energy supply.
4. Energy system change including switch to alternative fuel or electricity.
5. No significant energy savings but emissions reductions associated with switch to alternative fuel.
6. Only applicable to type 2 operations with supplementary growing lighting.
7. Numbers are for protected edibles. For protected fruit CEA penetration currently 25%, forecast to rise to 85%.
8. Numbers are for protected edibles. For protected fruit CEA penetration currently 40%, forecast to rise to 60%.
9. Figure given is for increase in yields across operations, representing savings in all energy categories.

Table 11: Fuel parameters and assumptions for MACC (baseline)

Fuel type (Data from BEIS carbon intensity (greenhouse warming potential GWP), 2022 Q4 non-domestic fuel costs)	Price for unit (£/kWh)	Carbon intensity factors (gCO_2e/kWh)
Grid electricity	0.2373	193.00
Natural gas	0.066	183.87
Oil	0.0729	248.74
LPG	0.11	214.48
Coal	0.020	344.62
Biomethane & Biomass Mix total emissions 2022 (75% biomass)	0.058	30.75
Biomethane	0.060	63.00
Biomass (avg. between imported and domestic)	0.034	20.00
PV/Wind on site		50.00
Waste heat from industrial sources (EU range EUR0.05 – 0.30 depending on source)	0.01	Assumed 0.0
Geothermal heat (assumed no third-party fee for usage)	0	0

Table 12: Boiler efficiencies and COPs used for MACC

Boiler Efficiency ηth	Efficiency (%)
Electric	99%
Natural gas	95%
Oil	94%
LPG	95%
Coal	90%
Biomass/biogas	90%
Biomethane	95%
Coefficients of performance	**COP**
Low temperature heat pump	4.0
Medium temperature geothermal (70-90ºC)	6.5
High temperature geothermal (120ºC)	10.0

Table 13: Assumptions on energy split and power exports

Type 1 Heated CEA; Type 2 Heated and supplementary grow lamps

Assumptions on split of electrical energy use in type 1 and type 2 CEA operations	Percentage (%)
Use type 1 Electrical energy used for ancillaries and cooling	100%
Use type 2 Electrical energy used for ancillaries and cooling	25%
Split between packhouse cooling vs. electric ancillaries (pumps, ventilation, etc)	50%
Use type 1 Share of electricity used for supplementary lighting	0%
Use type 2 Share of electricity used for supplementary lighting	75%
CEA Self-generated electricity sales to the grid	
Sales of electricity from wind and PV (average):	25%

PV	10-15%
Wind	25-50%
CEA with CHP, Use type 1: Sales to the grid from power generated through CHP	100%
CEA with CHP, Use type 2: sales to the grid from power generated through CHP	50%
Percentage of natural gas used by CEA to operate CHP	
Percentage of total natural gas purchase	80%

Table 14: Market split between Use type 1 and type 2 CEA operations

- Use Type 1 are heated CEA; Use Type 2 heated and supplementary growing lamps.
- Based on Climate Change Levy – Climate Change Agreement (CCA) participants data TP4, Jan 2019 to Dec 2020.

Total CCA sector	Use type	Area hectares	Total energy use (GWh)	kWh/m2	Percentage share of energy use
Protected vegetables and herbs	**Sub-total**	**284.3**	**877.2**	**309**	**85%**
Protected vegetables and herbs	Use Type 1	216.7	580.3	268	**56%**
Protected vegetables and herbs	Use Type 2	67.7	296.8	439	**29%**
Protected soft fruits	**Sub-total**	**86.1**	**154.0**	**179**	**15%**
Protected soft fruits	Use Type 1	56.9	105.7	186	**10%**
Protected soft fruits	Use Type 2	29.2	48.4	166	**5%**
TOTAL		**370.4**	**1,031**	**278**	**100%**

16.3 Uncertainty and mutual exclusivity of measures

Figure 24 provides a qualitative indication of the uncertainty of the final MAC outcome for each measure. Low and medium confidence is based on access to and/or availability of data on each measure (efficiency, current and future potential deployment rates, costs, etc.). All three measures rated low confidence are concepts that are not yet in use in the UK CEA sector. Their deployment will depend on a variety of technical and economic factors, as well as the political decision to support them as described in the report.

Further, for the interpretation of the MACC results is it important to consider that some measures are mutually exclusive, for instance investment in a biomass or electric boiler will be either one or the other. Therefore, their emission saving potential cannot be aggregated. Other measures are complementary, which means that they can implemented in one project or in a staged series of projects. The relationships between the measures is shown in Figure 25.

Figure 24 Assessment of the confidence about MAC of the measure

Assessment of the confidence about MAC of the measure (H=high confidence; M=medium confidence; L=low confidence)		
ID	**Measure**	
1	Routine maintenance and repair, including sensor calibration	**H**
2	Physical benefits (more sensors, updates etc.) - Intelligent solutions for energy optimisation including thermostatic control, climate control computers and destratisfication, optimised airflow and temperature gradient control	**H**
3	Management element - better use of the computer capabilities including Next generation growing (NGG) (Building up on #2)	**M**
4	Variable speed drives and improved efficiency of fans, motors	**H**
5	High Efficiency Boilers and optimised boiler control (without CHP)	**H**
6	Biomass Boilers/Burners (biomethane for CHP is not included)	**H**
7	Electric boilers / Electrification of thermal energy generation	**H**
8	Lower level of temperature water via heat pump	**M**
9	Retrofit of natural gas CHP to biomethane	**M**
10	Geothermal heating with direct pumping of water	**L**
11	Improved cooling and refrigeration system, including free cooling usage	**H**
12	Thermal screens and upgrade from single to double screens and black screens	**H**
13	Advanced Glazing incl. double glazing and glass/polymer combinations and air leakage minimisation related to vent ceiling	**M**
14	Diffuse glass	**M**
15	Semi closed glasshouse including frameless vented glasshouses and advanced dehumidifcation	**L**
16	Daily and longer-term thermal storages to buffer the non-synchronized requirement for CO_2 and heat	**H**
17	Closed glasshouse with (underground) seasonal thermal energy storage for storing summ	**L**
18	Improved Light Sources - LEDs	**H**
19	Improved Light Sources - LEDs and Lighting Controls including dynamic LED system for photosynthetic colour spectrum tuning, illumination intensity, and duration of lighting	**M**

Figure 25 Mutual exclusivity of intervention measures

Assessment of measure mutual exclusivity in respect to GHG emission savings (x: mutually exclusive; o: complementary)		Measure																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ID	Measure	Routine maintenance and	Physical benefits (more sensors,	Management element - better use	Variable speed drives and	High Efficiency Boilers and	Biomass Boilers/Burners	Electric boilers / Electrification of	Lower level of temperature water	Retrofit of natural gas CHP to	Geothermal heating with direct pumping	Improved cooling and refrigeration	Thermal screens and upgrade from	Advanced Glazing incl. double glazing	Diffuse glass	Semi closed glasshouse	Daily and longer-tern	Closed glasshouse v	Improved Light Sour	Improved Light Sour
1	Routine maintenance and repair, including sensor calibration		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
2	Physical benefits (more sensors, updates etc.) - Intelligent solutions for energy optimisation including thermostatic control, climate control computers and destratisfication, optimised airflow and temperature gradient control	o		o	o	o	o	o	o	o	o	o	o	o	o	x	o	x	o	o
3	Management element - better use of the computer capabilities including Next generation growing (NGG) (Building up on #2)	o	o		o	o	o	o	o	o	o	o	o	o	o	x	o	x	o	o
4	Variable speed drives and improved efficiency of fans, motors	o	o	o		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
5	High Efficiency Boilers and optimised boiler control (without CHP)	o	o	o	o		o	x	x	o	x	o	o	o	o	o	o	x	o	o
6	Biomass Boilers/Burners (biomethane for CHP is not included)	o	o	o	o	o		x	x	x	x	o	o	o	o	o	o	x	o	o
7	Electric boilers / Electrification of thermal energy generation	o	o	o	o	x	x		x	x	x	o	o	o	o	o	o	x	o	o
8	Lower level of temperature water via heat pump	o	o	o	o	x	x	x		x	x	o	o	o	o	o	o	x	o	o
9	Retrofit of natural gas CHP to biomethane	o	o	o	o	o	x	x	x		x	o	o	o	o	o	o	x	o	o
10	Geothermal heating with direct pumping of water	o	o	o	o	x	x	x	x	x		o	o	o	o	o	o	x	o	o
11	Improved cooling and refrigeration system, including free cooling usage	o	o	o	o	o	o	o	o	o	o		o	o	o	o	o	x	o	o
12	Thermal screens and upgrade from single to double screens and black screens	o	o	o	o	o	o	o	o	o	o	o		o	o	o	o	o	o	o
13	Advanced Glazing incl. double glazing and glass/polymer combinations and air leakage minimisation related to vent ceiling	o	o	o	o	o	o	o	o	o	o	o	o		o	x	o	x	o	o
14	Diffuse glass	o	o	o	o	o	o	o	o	o	o	o	o	o		x	o	x	o	o
15	Semi closed glasshouse including frameless vented glasshouses and advanced dehumidifcation	o	x	x	o	o	o	o	o	o	o	o	o	x	x		o	x	o	o
16	Daily and longer-term thermal storages to buffer the non-synchronized requirement for CO2 and he	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o		x	o	o
17	Closed glasshouse with (underground) seasonal thermal energy storage for storing summer heat for	o	x	x	o	x	x	x	x	x	x	x	o	x	x	x	x		o	o
18	Improved Light Sources - LEDs	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o		x
19	Improved Light Sources - LEDs and Lighting Controls including dynamic LED system for photosynthetic colour spectrum tuning, illumination intensity, and duration of lighting	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	x	

o Measures can be applied together so their emissions abatements can be aggregated in the MACC.

x Measures are mutually exclusive, they cannot be combined.

16.4 Sensitivity analysis

In addition to the baseline scenario, where all parameters were set based on current data (Q3, 2022), a sensitivity analysis was carried out by varying the parameters. Table 15 summarises the parameter setting across the considered scenarios. The resulting MACC figures are shown in following from Figure 26 to Figure 31.

Table 15: Parameter settings for MACC scenarios

Parameter		**Scenarios**					
		1	**2**	**3**	**4**	**5**	**6**
		Baseline settings (Q3 2022)	**"Pre-Covid/ Ukraine" prices" (Q1 2020)**	**Partially decarbonised grid at today's power to gas price ratio**	**Decarbonised low-cost power grid**	**Decarbonised grid and high gas prices**	**High biomass prices**
1	**Financial Discount rate**	5%	4%	5%	5%	5%	5%
2	**Emissions discount rate**	2%	2%	2%	2%	2%	2%
3	**Emissions intensity of grid power (gCO2 /kWh)**	193	193	90	50	50	193
4	**Market price for grid electricity (£/kWh)**	0.2373	0.1444	0.2373	0.0400	0.0400	0.2373
5	**Market price for natural gas (£/kWh)**	0.0660	0.0268	0.0660	0.0660	0.2000	0.0660
6	**Market price for biomass pellets (£/kWh)**	0.0340	0.0340	0.0340	0.0340	0.0340	0.0340
7	**Market price for biomethane (£/kWh)**	0.060	0.060	0.060	0.060	0.060	0.030
8	**Gas to electricity price ratio**	3.595	5.39	3.595	0.62	0.21	3.595

Figure 26 Scenario one: Baseline settings (based on Q3 2022 prices)

(Note: The measure "Electric boilers for electrification of thermal energy generation" is cut off on the vertical axis)

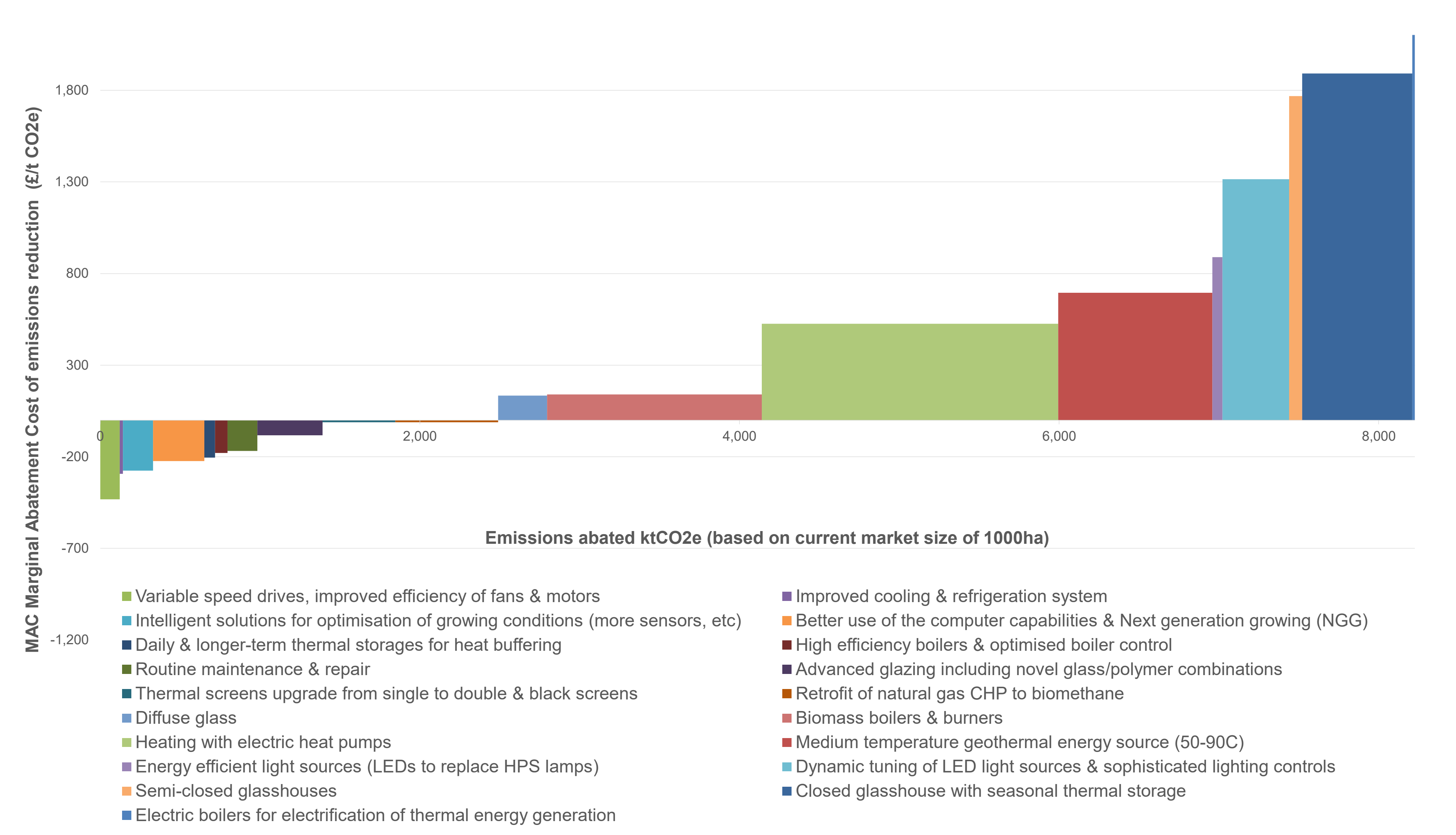


Figure 27 Scenario two: "Pre-Covid/ Ukraine" (based on Q1 2020 prices)

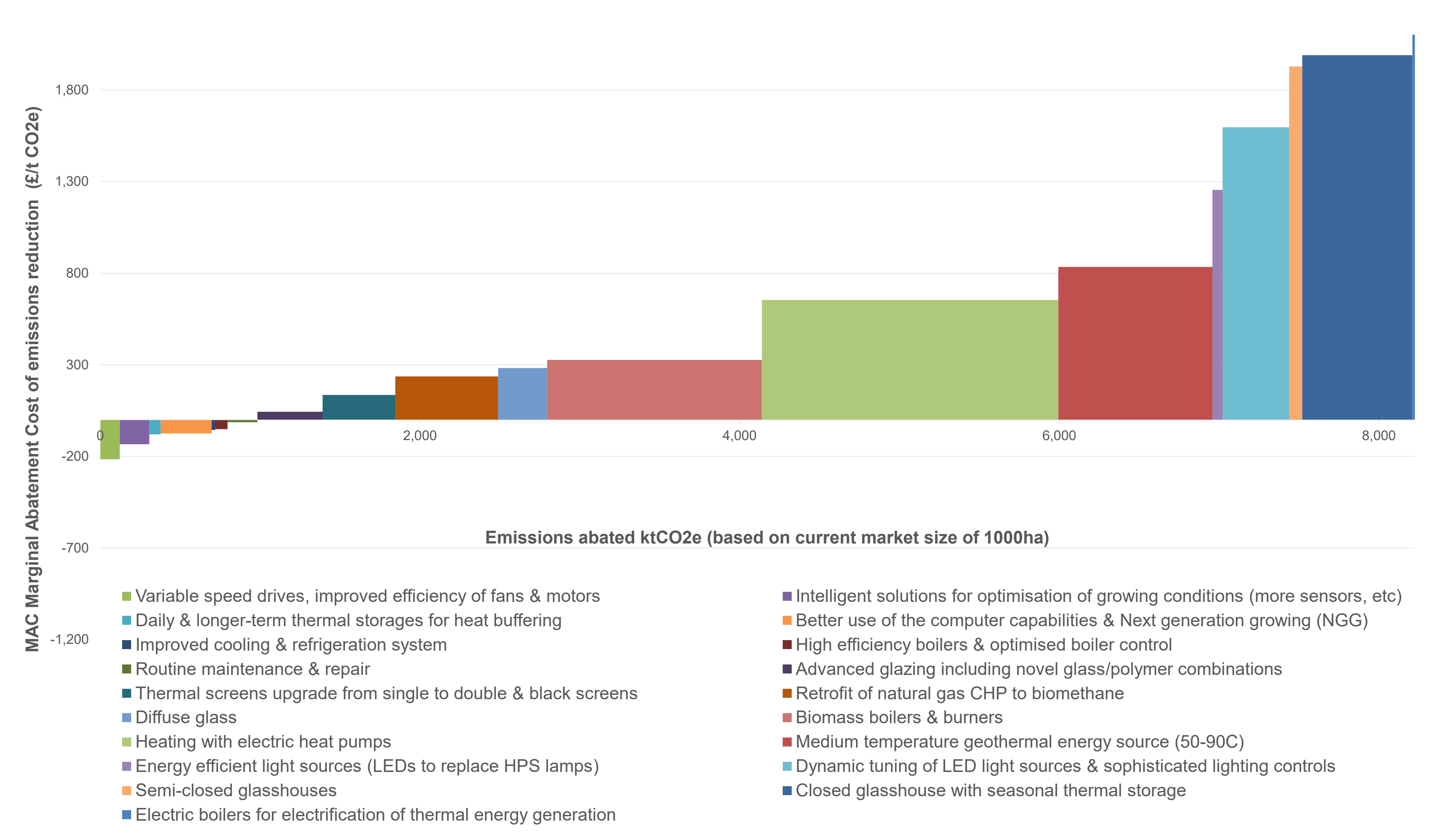


Figure 28 Scenario three: Decarbonised grid, unchanged power/gas price ratio

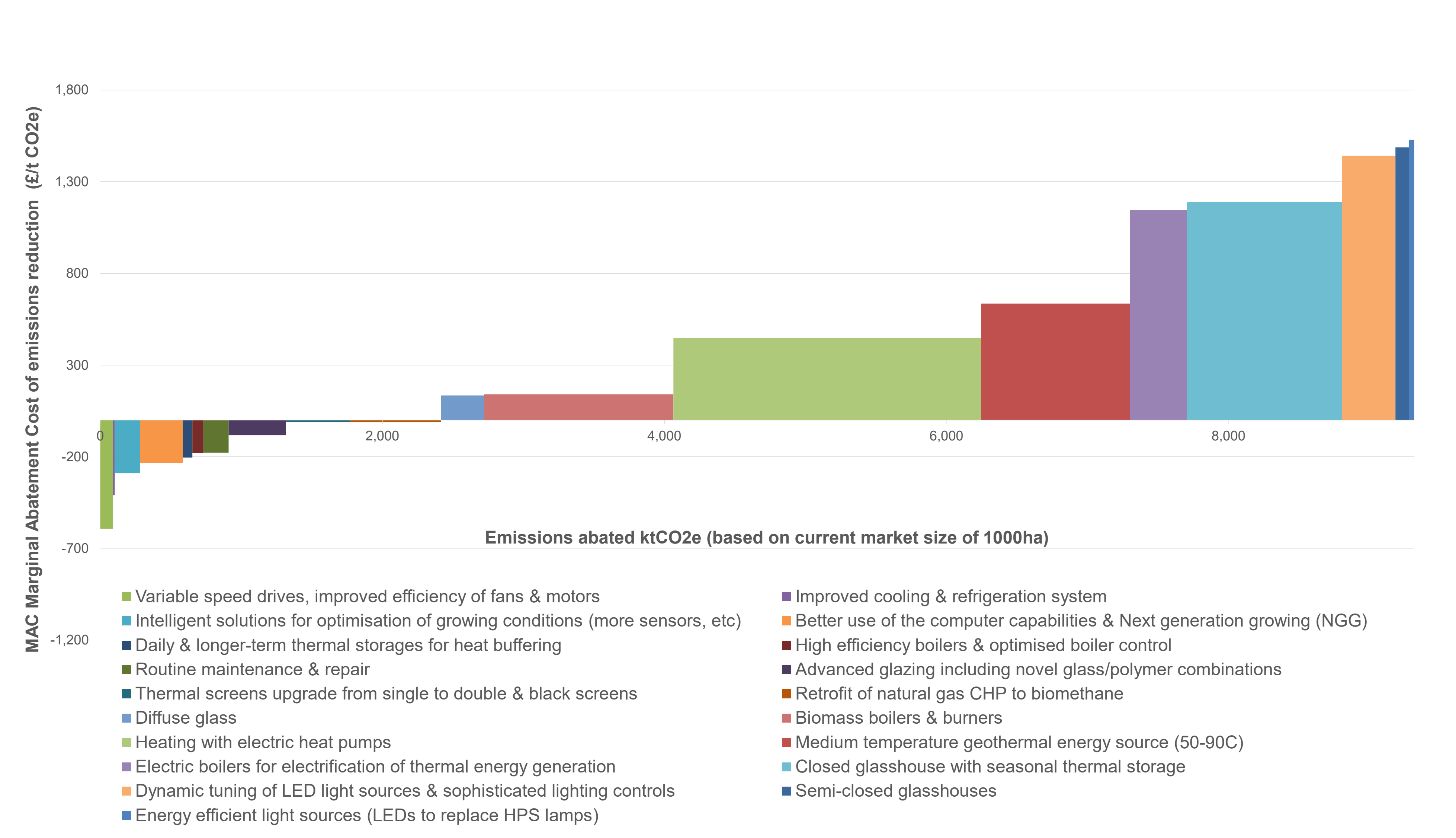


Figure 29 Scenario four: Decarbonised low-cost electricity grid

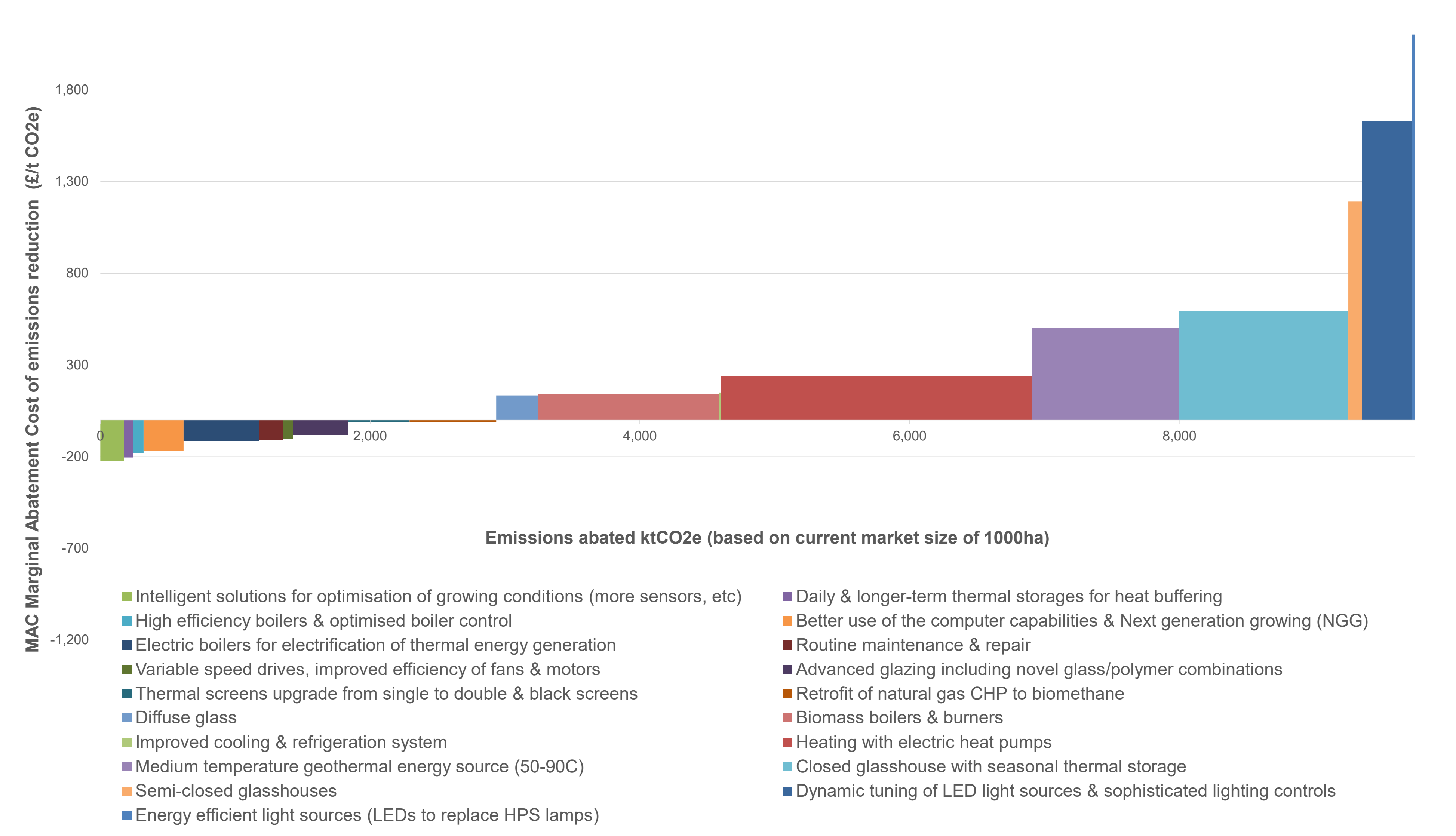


Figure 30 Scenario five: Decarbonised electricity grid and high gas prices

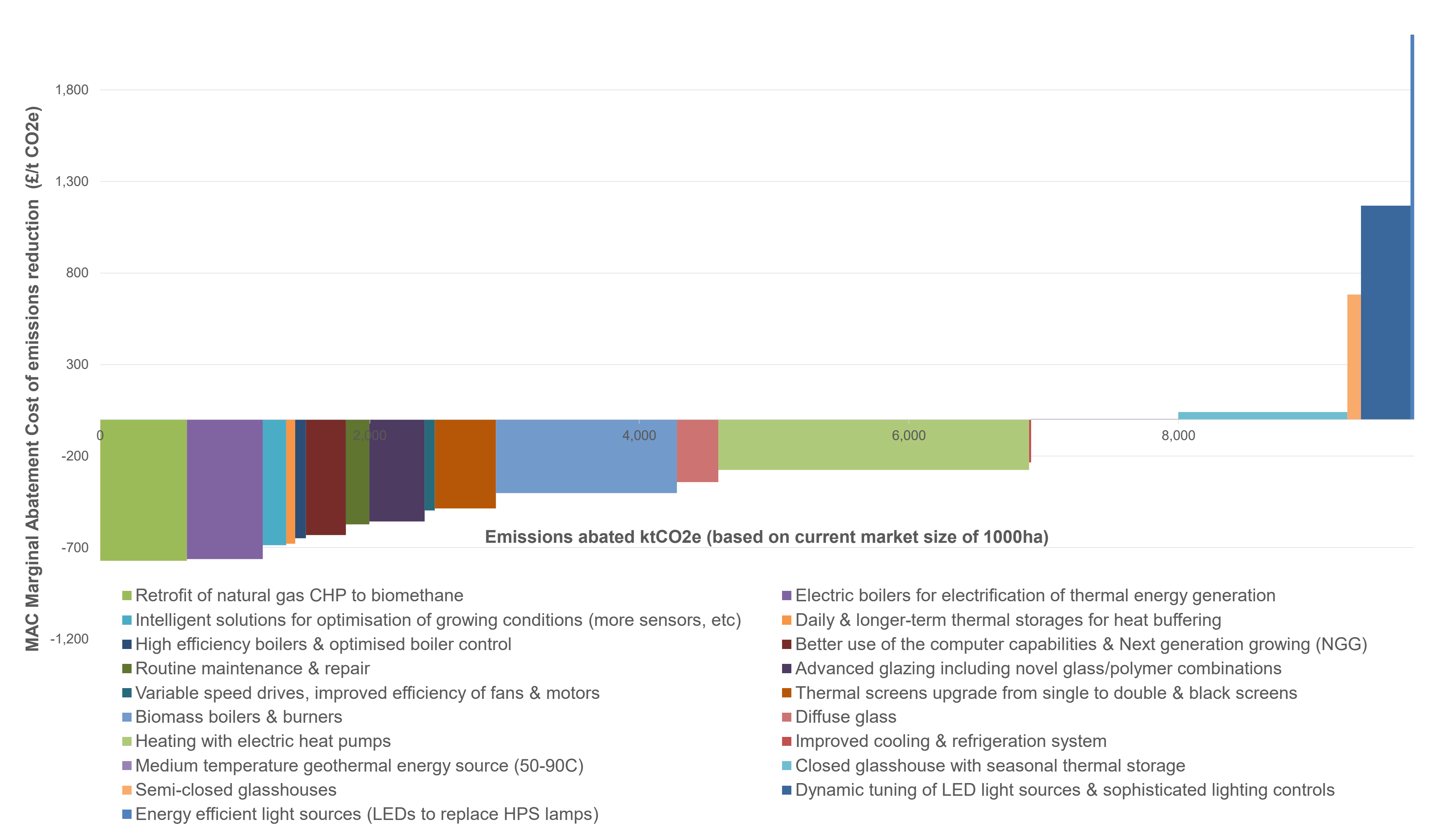
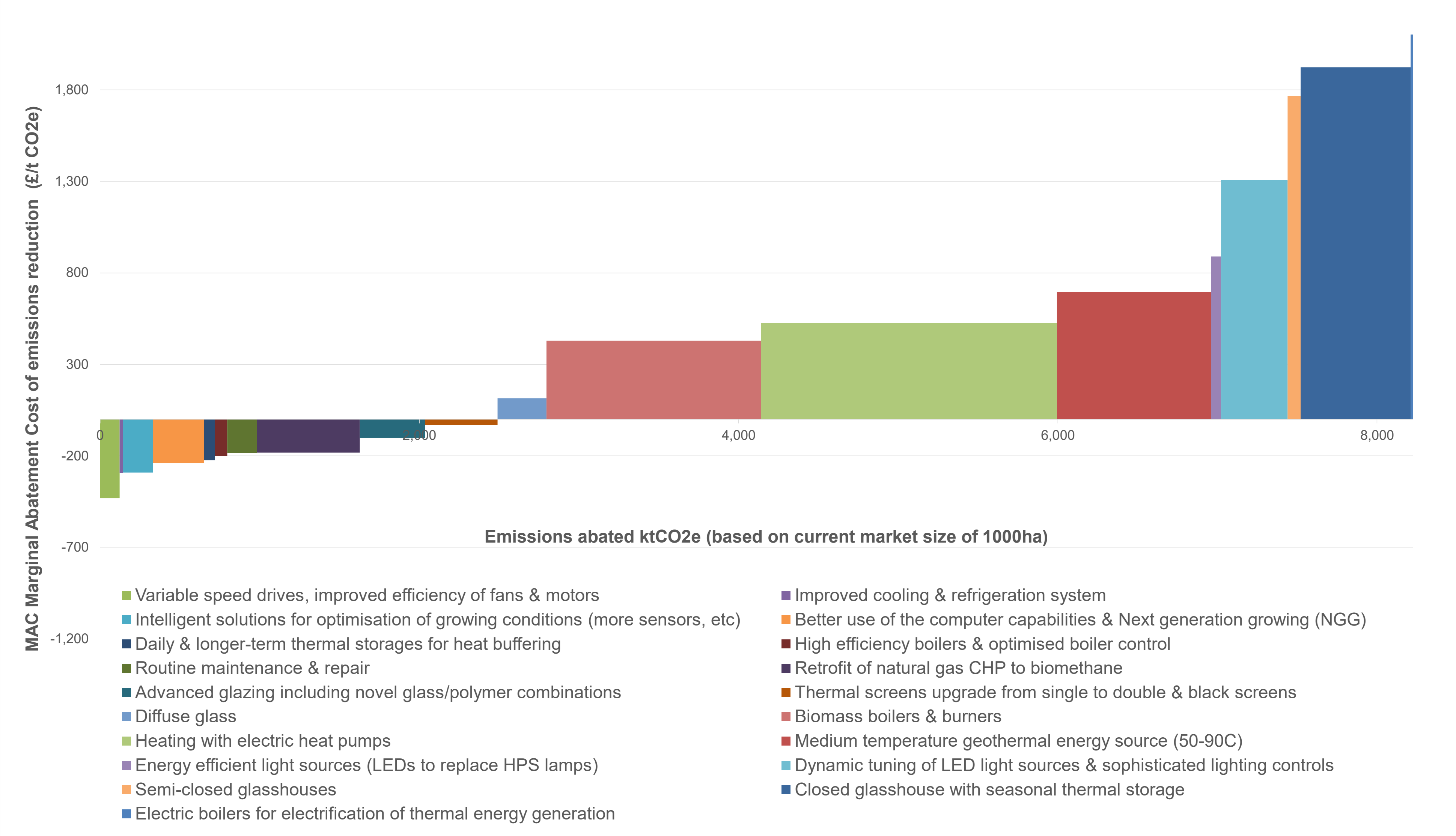


Figure 31 Scenario six: Low biomethane price

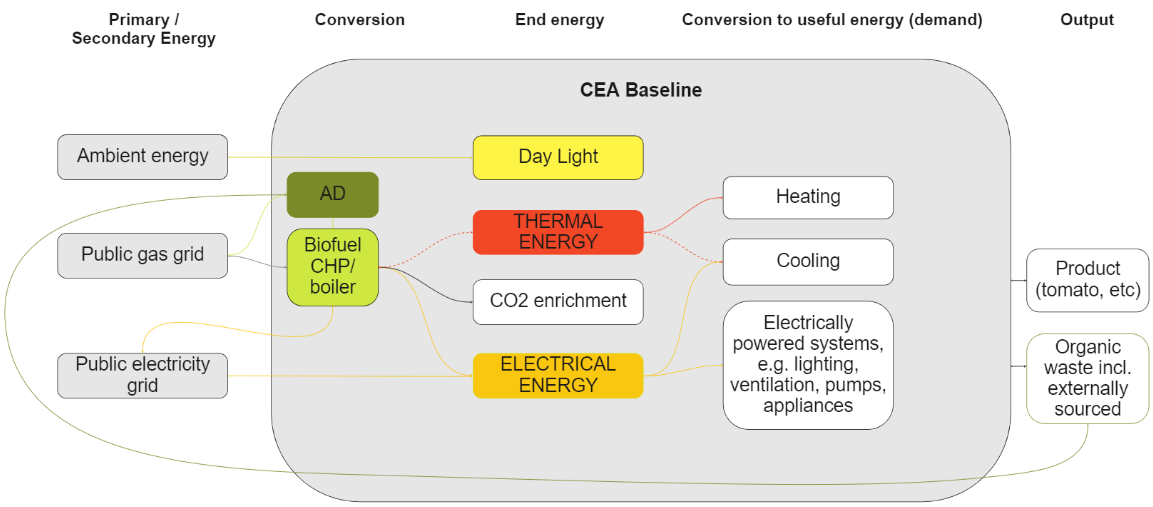


17 Annex G: Technical system maps for technology combinations

This annex presents the technical systems maps for deployment of the three alternative technology combinations described in Section 6.1. Each visual shows the energy flow and the sequence of its conversion.

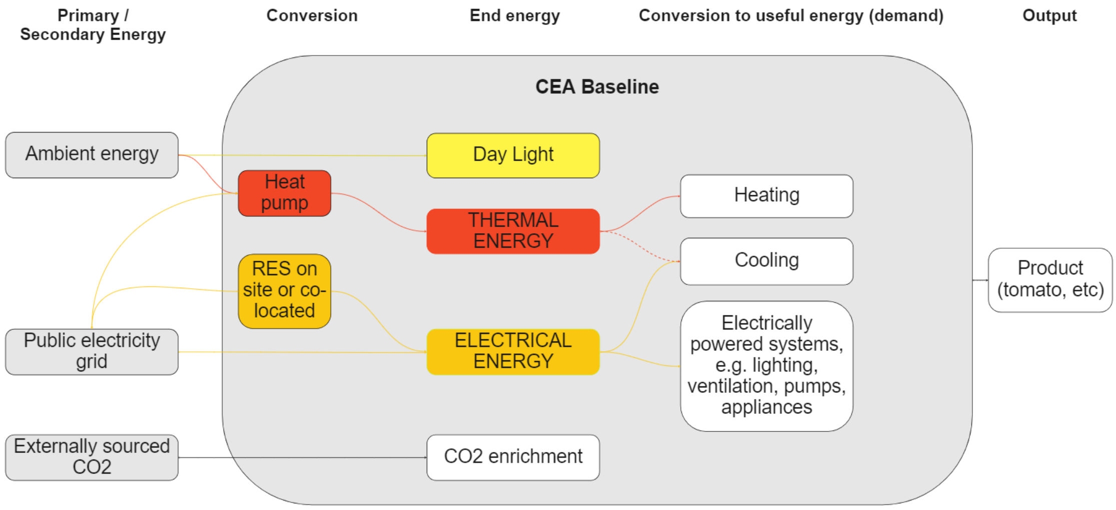
In the first case "CHP and AD" in Figure 32 it is assumed that the CHP is fired with a biogenic fuel produced by AD. The AD can be operated on the CEA site or at another co-located site and fed with organic waste. If an AD plant is operated at a CEA site, additional feedstock must be procured for its operation. The gas produced can then be used in impurified or purified form for CHP. Surplus gas could also be fed into the public gas grid but must first “upgraded” to pure bio-methane in a biogas upgrading plant. Similarly, surplus electrical energy can be fed into the public electricity grid. As shown in the report, the thermal energy generated can in most cases be consumed by the growers themselves, but it can also be fed into a public district heating network if this makes economic sense, and the infrastructure is available. The CO_2 can be extracted from the exhaust gases of the combustion process.

Figure 32 Biofuel CHP/boiler and Anaerobic Digestor



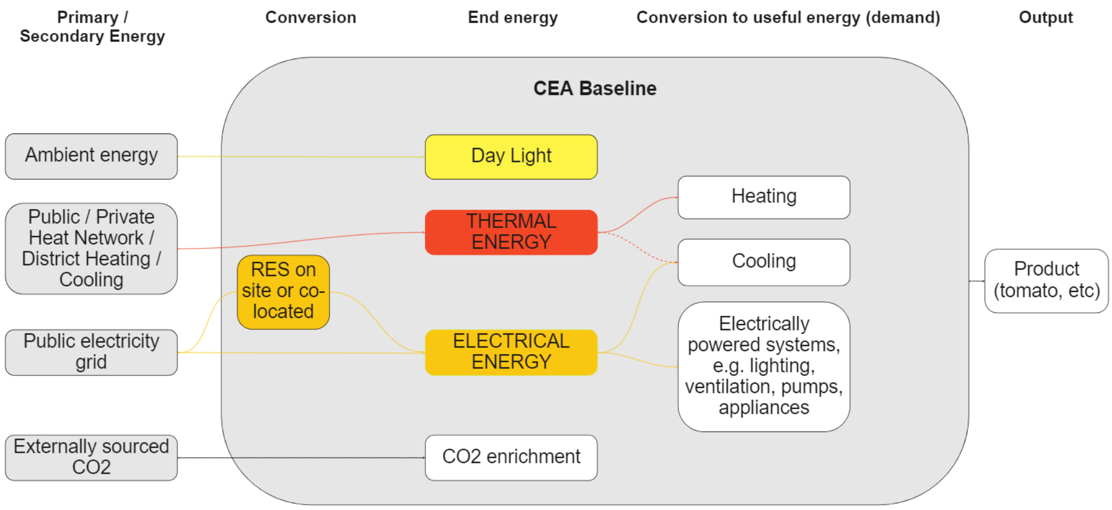
The use of an electric heat pump is an alternative for thermal energy supply that requires electricity and ambient energy such as air (which is less efficient option), water (including lakes, rivers, reservoirs) and ground source or low-grade industrial waste heat, as shown in Figure 33. A heat pump can be used for both heating and cooling (in particular relevant for use type 3 operations, indoor and vertical farms). However, a system based on an electric heat pump also leads to an increase in electricity demand. Therefore, a combination with electricity generation from renewable energy sources on site or co-located is currently often a chosen option due to economic benefits. As long as the public electricity grid is not decarbonised, it is also likely to be the low-emissions option. In this case, an alternative CO_2 source is required.

Figure 33 Heat pump and renewable energy system (on site or co-located)



Finally, Figure 34 shows the use of waste heat. The difference to the above case is that here only a heat pipe network and heat exchangers are considered to use an external waste heat source. This source can be a private heat network, e.g. from an industrial site, a waste water treatment plant or a power plant, or a public network such as a district heating system. In this case, a match between the temperature levels required at the CEA and those available at the source is crucial. Options to cover electricity and CO_2 demand are similar to the previous case.

Figure 34 Waste heat and renewable energy system (on site or co-located)

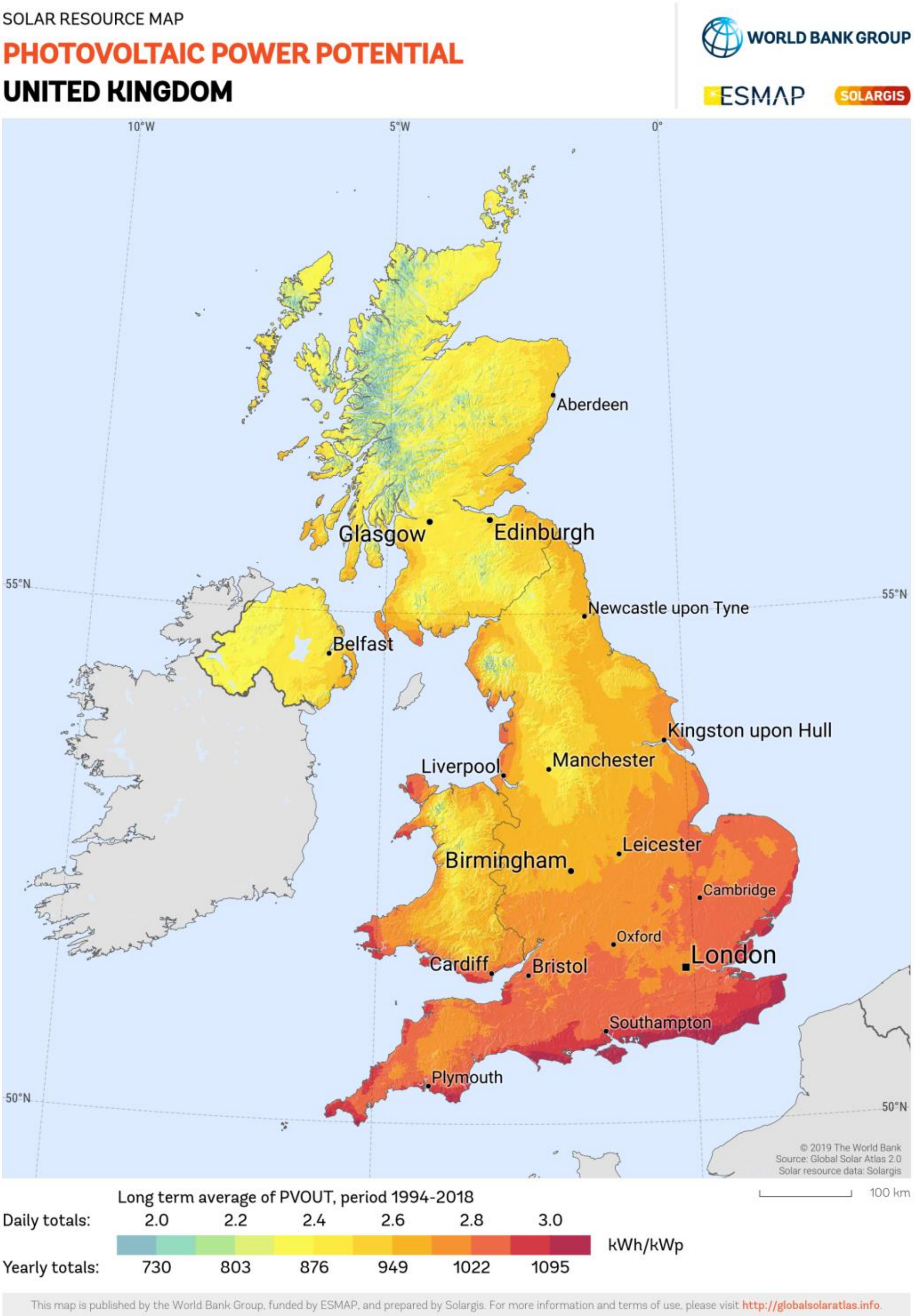


18 Annex H: Supplementary data

18.1 UK Solar Radiation Map

Figure 35 Map of solar power generation potential in the UK

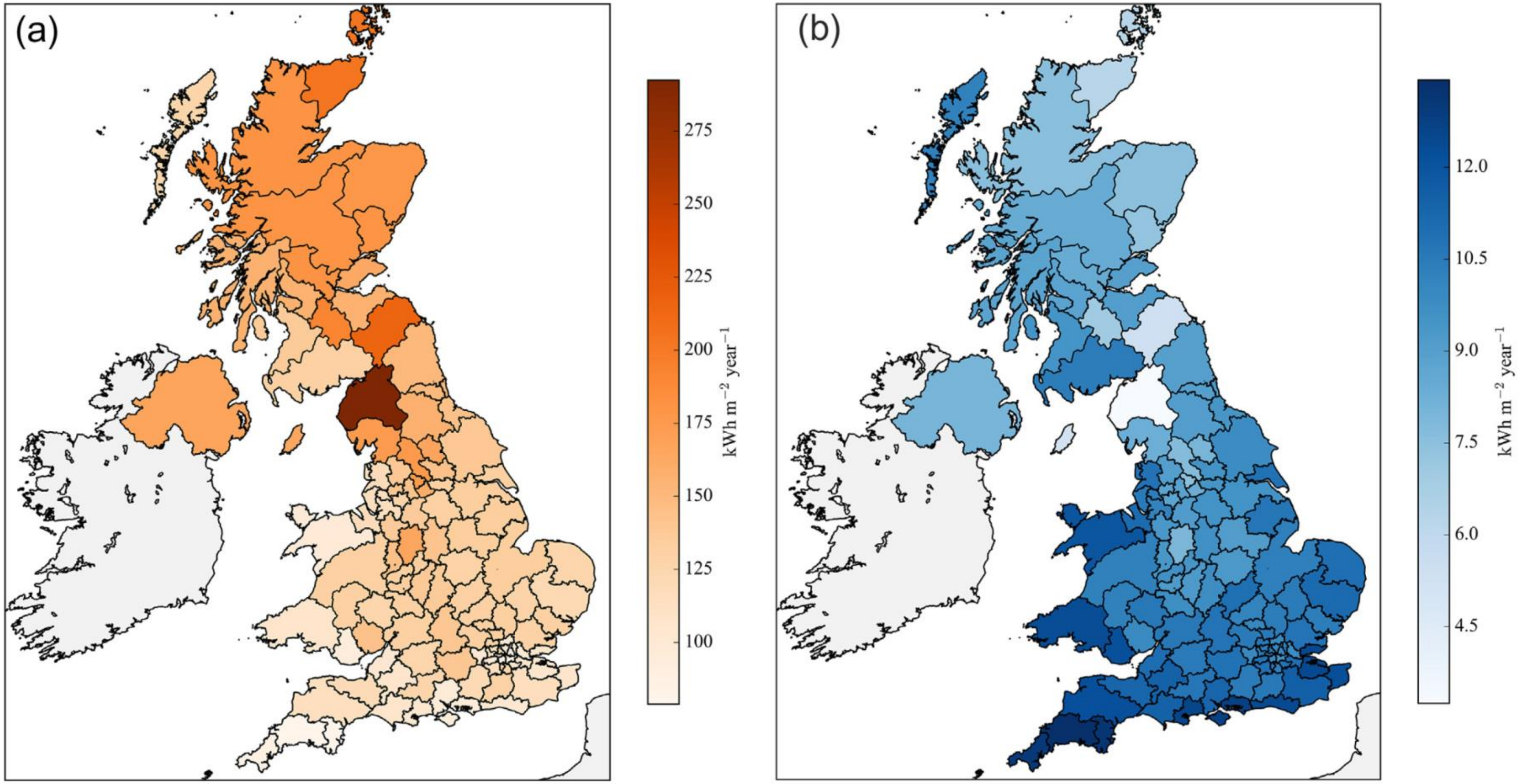
Source: Solargis, 2020 [208]



18.2 Annual heating and cooling requirements per unit area maps in the UK

Figure 36 21-year daily simulation of (a) annual heating and (b) cooling requirements per unit area maps in the UK for glasshouse

Source:, Simulation model, Georgiou et al. (2018). [54]



18.3 Wastewater treatment works as a source of thermal energy

Figure 37 Wastewater treatment works suitable for CEA co-location

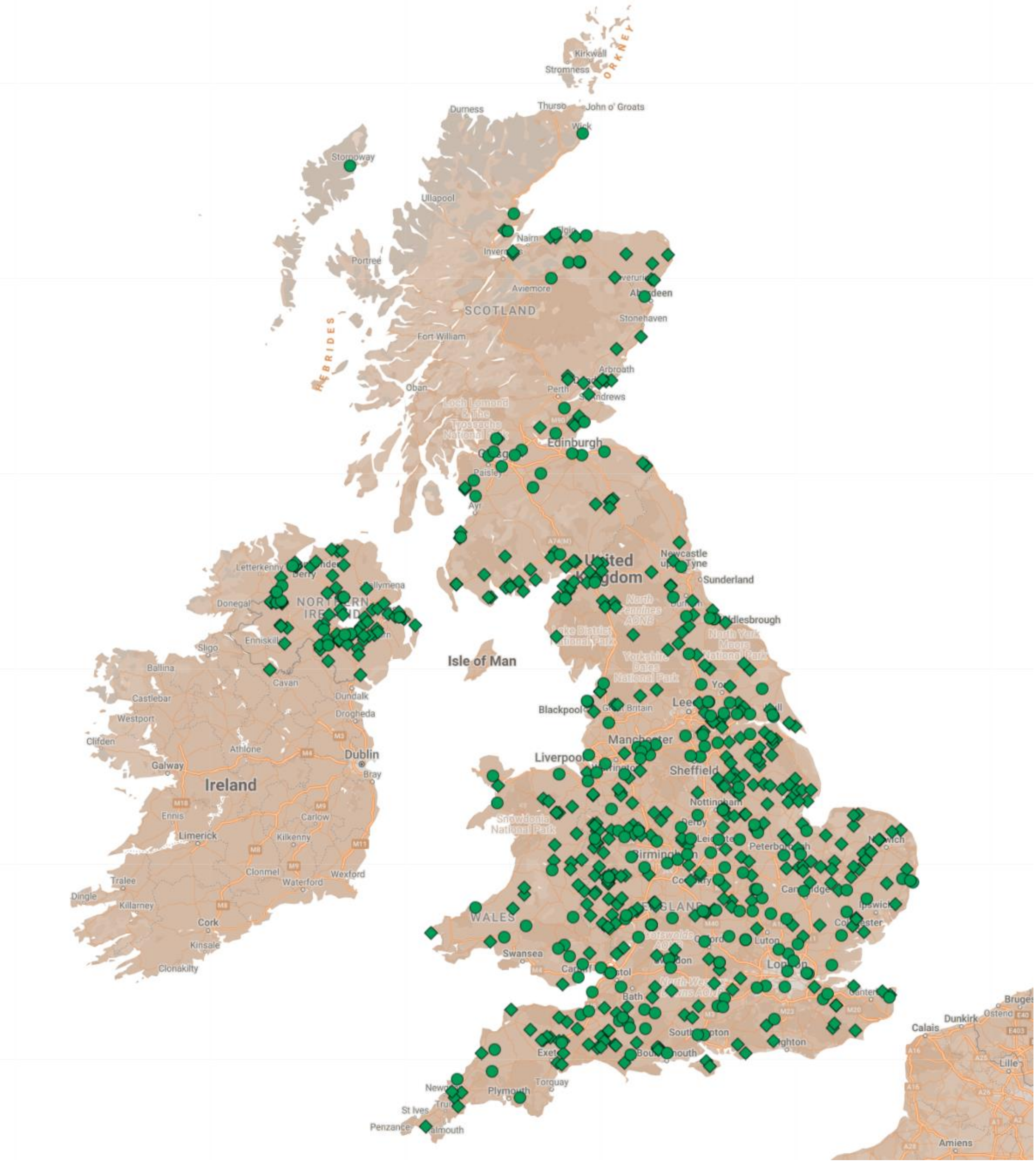
Source: Oasthouse Ventures, 2022

18.4 Anaerobic digestion plants in the UK as of 2021

Figure 38 Map of Anaerobic Digestion plants in the UK

Source: The Official Portal on Anaerobic Digestion [209]

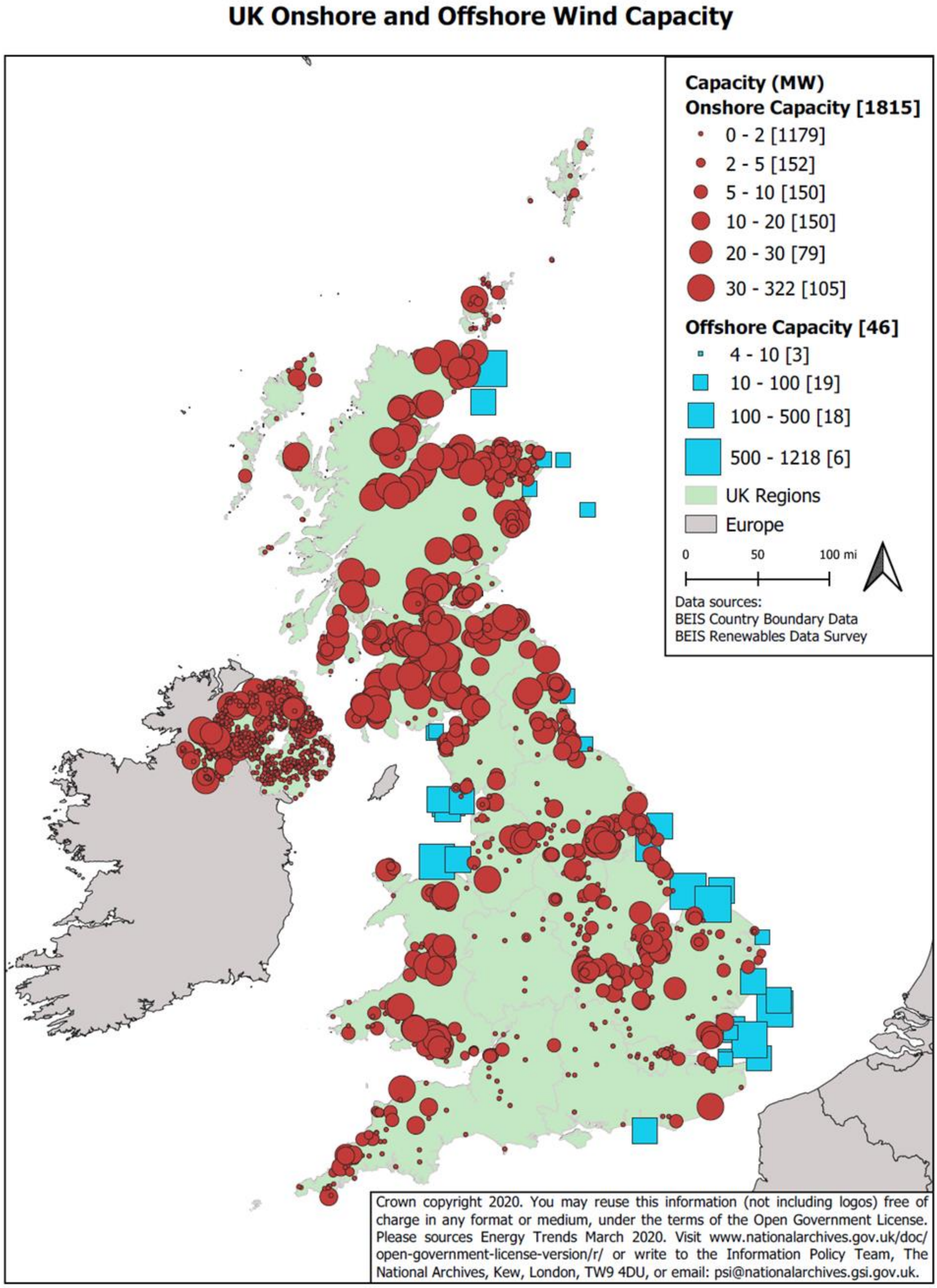
- Farm fed
- Waste fed



18.1 Wind power capacity in the UK, 2020

Figure 39 Map of wind power capacity in the UK

Source: BEIS, 2020 [210]



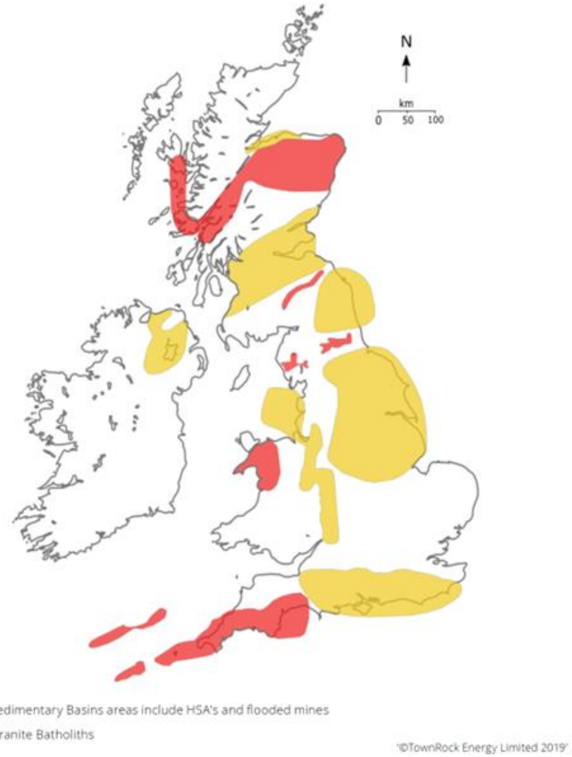
18.2 Geothermal resources in the UK

Figure 40 Geothermal resources in the UK based on 2011 survey data

Source: Townrock Energy, 2020 [211]

Where are geothermal resources available?

Ground-source heat pumps can be installed nearly everywhere in the UK. This map highlights the areas of greatest geothermal energy potential. Aquifer and minewater resources are found in the sedimentary basins and granite 'Hot Dry Rock' resources are found in the granite batholiths.



What is the temperature at 1 km depth?

The flow of heat from deep underground to the surface of the planet also varies from place to place, which in turn affects the temperature of the rocks. Extensive datasets have been collected from boreholes, wells and mines, and this dataset has been interpreted across the UK, showing the temperature at 1 km depth.