The Role of Biomass in Achieving Net Zero

A joint response to the Department for Business, Energy and Industrial Strategy Call for Evidence on The Role of Biomass in Achieving Net Zero, submitted on behalf of the Supergen Bioenergy Hub, the Carbon Recycling Network, the Biomass Biorefinery Network, and the High Value Biorenewables Network.

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Supply

Question 2 - What is the potential size, location and makeup of the sustainable domestic biomass resource that could be derived from the a) waste, b) forestry, c) agricultural sectors, and d) from any other sources (including novel biomass feedstocks, such as algae) in the UK? How might this change as we reach 2050?

- The UK is projected to have high availability of biomass without food systems impacts to 2050, if appropriate strategies are put in place [1]. In the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report, Welfle *et al.* collated data on biomass resource based from notable modelling exercises which suggested that in 2025 the UK will use 825 – 1374 PJ primary energy from biomass, and this becomes 208 – 3528 PJ by 2050 [2].
- It is important to emphasise the complexity of modelling biomass resource availability. What is achievable in terms of biomass supply will be dependent primarily on the combination of policy and demand. Over the timeframe to 2050 there will likely be many changing dynamics in the demand for biomass resources as the demand from different sectors evolves. Demand is in some ways easier to predict policy than policy, and there is substantial variation depending on the underlying assumption of the scenario work. Furthermore, models can explore maximums that may actually be unrealistic. Given that one example required 60% of UK farmland to meet demand, are the models exploring a "realistic" set of figures or exploring a more theoretical maximum potential that would be unrealistic in the real world [3]? What determines the resource that will actually be available will be a variety of factors, including land, societal acceptance, and trade-offs in biodiversity and other ecosystem services [2].
- Modelling complexities aside, these tools are helpful to identify available land for bioenergy crops, and how much biomass and of what types can be accessed.

Resource from Forestry:

- The models collated in the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report estimated that in 2025 the UK will use 35 – 190 PJ primary energy from forestry biomass, and this becomes 39 – 511 PJ by 2050 [2]. The availability of forest residue for the UK is estimated to be 16.8 Mm^3 per annum over the 50-year period from 2013 to 2061 [4]. The use of waste-wood feedstock could support bioenergy-from-forestry production goals whilst involving minor impacts from land use change.

Resource from agricultural sectors:

- As a relatively mature technology, afforestation and sustainable woodland management can provide biomass feedstock. However, to upscale feedstock for domestic biomass supply, including for use in bioenergy with carbon capture and storage (BECCS) and the wider bioeconomy, requires the rapid planting of energy/ industrial crops that are fast growing and more suited to agricultural farming systems. The Climate Change Committee (CCC) have predicted that bioenergy crops will be needed to deliver on net zero targets through the generation of negative emissions. For example, in the CCC's Land use: Policies for a Net Zero UK (2020), the 'Further Ambition' scenario assumes bioenergy crops are grown on 0.7 million hectares of land by 2050 (23,000 hectares per year) to produce 15 oven-dried tonnes per hectare by 2050, after improvements in agronomic practice and breeding [5]. This compares to current deployment of around 12,000 hectares of Miscanthus and willow, and an annual increase of planted area of around 800 hectares in 2020.

- The models collated in the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report estimated that in 2025 the UK will use 44 – 146 PJ primary energy from biomass crops, and 33 – 1075 PJ by 2050 [2]. Ongoing Supergen Bioenergy Hub research utilising spatial modelling tools to develop opportunity maps for the deployment of bioenergy crops in the UK under current and future scenarios (i.e. 2050) will help to address the question of the potential resource from bioenergy crops in the UK.
- Marginal lands of UK have great potential to host biomass crops. Lovett *et al.* produced a Geographical Information System (GIS) constraint map based on preclusion factors covering biophysical, social, and environmental considerations, with a final constraint that only poorer quality land in agricultural land class grades 3 or 4 would be considered. Results suggested potential land availability for Miscanthus or Short Rotation Coppice (SRC) willow/ poplar, of 6.4 million hectares across England, Scotland, and Wales, and restricting planting to the very worst agricultural land grades 4 and 5 left 1.4 million hectares [6]. There are also crops such as reed canary grass that can perform well in locations where other energy crops may struggle, for example on contaminated or brown field sites [7]. There is also the potential for policy to support increased production of niche crops, such as hemp.
- In terms of current domestic biomass supply, whilst both the Supergen Bioenergy Hub and the CCC reports focus on second-generation perennial bioenergy crops due to their improved sustainability criteria compared to first-generation, it is maize for anaerobic digestion (AD) that has shown the greatest growth. The non-food datasets for 2019 showing for England alone there was 67,000 hectares of maize being purpose grown for AD compared to just 8,171 hectares Miscanthus and 2,233 hectares of SRC willow [8]. The expansion of AD and thus the increasing growth in maize production has been driven by incentives designed to reduce the cost of renewable energy production such as the Renewable Heat Incentive (RHI) [8]. In 2018 the legislation was updated to attempt to reduce the amount of a biogas being produced form food crops. However, this highlights how both the amount and the type of biomass crops grown will be directly influenced by policy. It also shows the need to consider the influence of incentives on the full supply chain if the UK government wishes to move to greater utilisation of second-generation crops.

Resource from waste:

- Research has identified a large potential waste biomass resource in the UK, as well as robust residue resource from ongoing activities [1]. The models collated in the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report estimated that in 2025 the UK will use 44 – 354 PJ primary energy from biomass from waste and 18 – 292 PJ primary energy from biomass from residues, and this will become 23 – 753 PJ and 14 - 1222 PJ respectively by 2050 [2].
- A recent study calculated that the UK generates 50 - 70 million tonnes dry mass of organic waste a year in the form of food waste, manure, agricultural residues, and sewage sludge [9]. All of these are potential biomass feedstocks, but not all of this is, or can be, collected.
- Another waste source is biomass that is generated from conservation management by land managers, for example rushes, grasses such as Molinia, and excess shrubby biomass on moorland that could represent a fire risk without management and also the removal of invasive species such as bracken, Japanese knotweed, and rhododendron. One study estimated that in Wales alone 1 million tonnes dry mass of biomass could be generated a year [10].

Resource from algae:

- Seaweed cultivation is an emerging sector in the UK, but it has the potential to be an important biomass source and to contribute towards net zero. There are a small number of commercial growers in Scotland, Northern Ireland, and the South Coast of England, but this is continually increasing. Currently a relatively few species are cultivated and there is a major need to further domestic other species for cultivation.
- We do not believe that there is a yet a comprehensive understanding of the full potential for sustainable seaweed production in the UK. However, significant academic expertise is available within our community and we can provide more information if needed.

Question 3 - What are the current and potential future costs of supplying these different biomass feedstock types, and the key environmental and land-use impacts (positive or negative) associated with supplying and utilising these different types of biomass, e.g. impacts on GHG emissions, air quality, water quality, soil health, biodiversity, food security, land availability, etc?

Upstream emissions:

- Upstream emissions depend on supply chain activities, in particular emissions rated to pre-treatment (biomass processing, like pelleting or drying) and transportation over long distances (e.g. imports). One challenge is that particular wastes are not accounted for in upstream emissions, while these are allocated to the main product. If such wastes/residues have currently no use (e.g. stay on processing site) and are not handled or are stored until utilisation, emissions that will then occur based on utilisation are not part of reporting framework. Although these can be low emissions compared to overall supply chain they can still generate an emission reporting gap [11-13].

Resource from forestry:

- The emissions impact of biomass sources will depend on timing/ length of biomass growth and biomass use. While currently biomass is considered as "carbon neutral" this concept does not work in the case of longer timeframes of biomass growth (e.g. forest-based biomass). A large point in time biogenic carbon release from biomass utilisation adds to the cumulative carbon budget in the form of carbon that has been previously and in a longer term removed from the atmosphere. This creates a carbon debt and is subject to high uncertainty in relation to future biomass regrowth and carbon uptake [14, 15].

Resource from agricultural sectors - ecosystem services:

- For second-generation bioenergy crop especially (due to their novelty) there is a discrepancy between the energy modelling community who work at highly aggregate spatial scales (national, regional, 50 km grid) and the level of detail needed to understand the implication of bioenergy crop deployment patterns at farm scale, and this makes understanding the environmental consequences of increased bioenergy crop production complex. Emerging evidence based on translation of energy system model outputs to fine spatial resolution data that is able to resolve patterns of biodiversity and ecosystem services distribution suggests that the costs to society (both economic and outside traditional markets) can vary from negative to positive depending on spatial configuration of the dedicated bioenergy crops [16].
- Despite the on-going research challenge of scaling down from current models to impacts at individual field/farm scale, we do have some understanding of the environmental

impacts of second-generation bioenergy crops. We know these impacts will be species dependent and thus field scale impacts need to consider current species distribution, especially any priority species, to avoid unintended impacts. However, the inclusion of perennial second-generation bioenergy crops on agricultural land, especially if these crops are integrated within intensively farmed landscapes, does have the potential to increase biodiversity and the delivery of ecosystem services [17]. This contrasts with first-generation food-based biomass crops which largely perpetuate the negative biodiversity and environmental impacts of current intensive agricultural systems. The delivery of ecosystem services from planting (even second-generation planting) is however also dependant on the scale of planting. Donnison *et al.* demonstrated that as demand for domestic supply of dedicated second-generation bioenergy crops increases, environmental benefits that initially accrue may be lost. The mechanism behind this is that below a certain level of demand land use change can be optimised to target areas where transitions (e.g. from wheat production to second-generation dedicated crops) would deliver environmental benefits such as for carbon sequestration or for water resources. However, above a certain inflection point there are potentially two mechanisms that begin to impact the environment: (i) spatial options become limited such that demand drives transitions in locations that have a negative impact on ecosystem services (e.g. driving location on high carbon soils); (ii) development of monocultures within the landscape leads to loss of services (e.g. homogenisations leads to loss of biodiversity) [16].

Resource from agricultural sectors – soil carbon:

- First-generation bioenergy crops for the most part will rely on conventional agricultural practices, including tillage and agrichemicals - practices that are largely detrimental to soil carbon stocks. In contrast, management of second-generation crops can protect or even enhance soil carbon stocks, with greatest gains in soil carbon achieved through targeting soil with low initial soil carbon stocks and taking steps to maximising bioenergy crops yields [18]. For example, planting on former arable land generally increases soil carbon stocks, with Miscanthus sequestering 0.7 – 2.2 Mg C4-C per hectare per year [19]. For perennial crops it is also key to maximize the lifetime of the crops as soil carbon gains take time to accumulate and may not persist once the crop is removed [20, 21]. This opens up the use of plant breeding to further increase this benefit for UK soils as a public good/ ecosystem service.
- For water use, catchment scale impacts are most important than individual fields, and modelling can predict these impacts. For example, in Welsh catchments it was found that unless planting is conducted on a very large scale within an individual catchment (>50% of land) impacts are likely to be minimal [22].

Resource from waste:

- Utilisation of wastes would provide a useful biomass resource and could enable the mitigation of potentially high greenhouse gas (GHG) emissions that occur through end of life incineration or decay. Biomass from wastes and residues currently managed utilising GHG intensive processes should be prioritised for use. This includes agricultural wastes (manures/slurries) currently stored in open tanks/lagoons where aeration, degradation and resulting emissions will occur, and food wastes that are currently sent to landfill where they degrade and release methane [23].
- It has also been demonstrated that agricultural residue harvest strategies should be implemented where 'sustainable levels' of resource are removed from the land. This provides a balance between the GHG impact of 'excess' residue being left on the land to degrade, and the GHG impact of having to apply synthetic fertilisers due to excess straw

(nutrient) removal [23].

Resource from algae:

- Increased demand for seaweed biomass for animal feed, human food, and as a feedstock in the production of chemicals and materials, led to growth in the UK seaweed industry, which was initially met through harvesting of wild stocks. This continually places wild populations under pressure and so there has been a focus on developing sustainable cultivation methods for high quality seaweed biomass [24, 25].
- Seaweed aquaculture can avoid the GHG emissions associated with fertiliser, pesticide and herbicide production and use, and does not compete with terrestrial agriculture for land [26]. It can also dampen wave energy and provide a biological habitat for marine species. Seaweed can be grown in combination with other species in Integrated Multi-trophic Aquaculture (IMTA) systems [25, 26].
- Blue Carbon (BC) strategies have been highlighted as an important toolset in offsetting CO_2 emissions in line with global climate targets such as the Paris Agreement [27, 28] . Seaweed aquaculture contributes to BC through the temporary storage of carbon in the seaweed biomass, the longer-term sequestration of carbon in sediments and deep-water, and the reduction in emissions caused by the replacement of fossil products with those derived from seaweed [26]. Although the contribution of seaweed habitats, including cultivated seaweed, remains unaccounted for in national and international assessments of BC, evidence supporting the contribution of macroalgae to BC has grown in recent years [27-29].

Question 4 - How do we account for the other (non-GHG) benefits, impacts and issues of increasing our access to, or production of domestic biomass (e.g., air quality, water quality, soil health, flooding, biodiversity)?

- Decision making relating to increased production of biomass should be holistic, and consider social, economic, and environmental implications to have a truly sustainable perspective. However, producing decision making tools or policy frameworks that take these things into account is complex. This is partly because many models of biomass resource consider the energy trilemma (decarbonisation, energy security, investment requirements and affordability) but do not incorporate other sustainability criteria, such as natural capital and ecosystem services. There is a need to incorporate wider sustainability criteria within bioenergy resource models and to create models that consider appropriate spatial scales to capture spatial heterogeneity. Such models will enable the identification of deployment patterns that address targets around the energy trilemma, but also benefit land managers through PES (Payment for Ecosystem Services) schemes, and society through the delivery of public goods [2].
- A recent study by Donnison *et al.* provided the first conceptual framework that integrates environmental and social impacts at a granular and site-specific level. This work indicated that integrating environmental values into land-use decision-making resulted in a higher net welfare value compared to a purely market-based decision. The study also demonstrated that a holistic appraisal can be quantitative, as is likely to be required by future land-use decision-making tools [16].
- Ongoing work by the FAB-GGR (Feasibility of Afforestation and Biomass Energy with Carbon Capture and Storage for Greenhouse Gas Removal) and ADVENT (ADdressing the Valuation of Energy and Nature Together) projects is also seeking to incorporate non-market costs and spatial data into our understanding of the implications of domestic dedicated bioenergy production. Work soon to be published will demonstrate that biomass

deployment strategies that are compatible with UK targets for net zero are substantially altered by the inclusion of ecosystem services valuations within modelling. A comparison of deployment strategies that takes into account both markets costs (e.g. land value etc) and non-market costs (e.g. flood attenuation, visual disamenity) demonstrates that the inclusion of the latter delivers important public goods to society that would be lost where only market costs are considered. If required, modelling outputs from these projects can be made available in advance of publication as part of this consultation.

- The Supergen Bioenergy Hub will soon publish a Bioenergy Sustainability Indicator Model that will allow assessment of more than a hundred indicators of sustainability, covering people, development, natural systems, and climate change.

Question 5 - How could the production of domestic biomass support rural employment, farm diversification, circular economy, industrial opportunities, and wider environmental benefits? This can include considerations around competition for land, development of infrastructure, skills, jobs, etc.

- Integrating bioenergy systems as part of agricultural and/or forest activities can add significant co-benefits to landowners, employees, and local communities. Biomass sourcing, production and utilisation can support diversification of agricultural/forest activities and create additional income from biomass-based activities, thus creating jobs and building capacity [14, 30]. In 2008 a study by Thornley *et al.* showed that power only bioenergy systems typically created 1.27 man-years of employment per GWh electricity produced. This included agricultural labour, transport, feedstock processing, staffing at the plant, employment within the equipment supply chain and the induced employment impact [31]. There is also a high potential for community and rural development if biomass production and technology deployment attract new businesses [30, 32]. An example given by our industrial partners was the local biomass for fuel supply chains that create and sustain jobs, not just in the UK but around the world.
- As explained in the previous questions, there is the potential for ecosystem services and wider sustainability benefits if these things are taken into account when making decisions about land use [16]. For example, in some locations second-generation bioenergy crops can improve soil quality and reduce flooding. Sustainable removal of residues can improve agricultural practices and reduce non-CO_2 emissions (N_2O, CH_4), and reduce risks of residue-based diseases and pests [33, 34]. A comprehensive review of the evidence for ecosystem service benefits is provided by Holland *et al.* [35].

Algae:

- A decline in the fishing industry and seaside tourism has deprived many coastal communities of economic prospects. The Department for Environment, Food & Rural Affairs (DEFRA) 25 Year Environment Plan (2018) [36] and Evidence Statement (2019) [37] on well-being and coastal environments had a notable focus on well-being in coastal communities in terms of physical and mental health, but less on the broader drivers of health and wellbeing such as employment, decent work, and quality of life. If deployed appropriately the sustainable development of new industries associated with seaweed cultivation and utilisation could lead to the revitalisation of coastal communities, and hence meet wider wellbeing imperatives.
- Algae cultivation can also be linked to wastewater treatment, including the treatment of agricultural runoff and landfill or industrial effluents, because algae are extractive species that can remove excess nutrients and pollutants from the environment as they grow. This can provide environmental benefits as well as a source of biomass, and there is potential

for nutrient recycling and waste recovery as part of a circular economy [38, 39].

Question 6- What are the main challenges and barriers to increasing our domestic supply of sustainable biomass from different sources?

- Done well, increasing domestic production of biomass crops could enable the UK to reap multiple benefits, but achieving this will only be possible with guidance [16] (also see the conclusion from the soon to be published ADVENT project). Economics will dictate which crops are favoured, but policy can be used to influence this. Landowners can be receptive to new cropping methods, as recent expansions of UK maize productions (for AD and animal feed) have shown, but a switch to perennial second-generation bioenergy crops would be a longer-term investment thus the economic case will need to be more attractive.
- Limited land resource and conflict with the provision of ecosystem goods and services are a barrier to biomass production. In the case of land use, increased biomass production will require full integration within the larger vision for the UK agricultural land (The 25 Year Environment Plan) and associated policy's and regulations. The Supergen Bioenergy Hub will soon publish report on marginal land assessment that will highlight alternative potential for bioenergy production in the face of limited land resources.
- Our industrial partners highlighted that one of the difficulties for producers and investors has been the changing views and policies relating to biomass supply and use. It is key that policy relating to biomass feedstocks and their role in achieving net zero is consistent across government departments and sectors, and that there is policy certainty in the medium to long term [2].

Algae:

- Seaweed cultivation requires a large level of space for operations to be economically feasible due to the dry weight of a harvested crop being approximately ten times less than that of its wet counterpart [40]. Available space in the marine environment is highly contested, with potential solutions for avoiding conflict including the combination of seaweed with other aquaculture or marine-related industries, or offshore operations (technology allowing) [25, 26, 41].
- There is a need to evaluate the wider ethical and moral challenges posed by the seaweed biorefinery technologies, where expansion of the industry must address societal reservations about large scale aquaculture. Although often viewed as an environmentally friendly and potentially high value alternative to finfish farming [42], societal views of seaweed cultivation are not always positive and have led to projects being scaled back. Given a clear need for public acceptance, stakeholder buy-in and an understanding of barriers to adoption; community engagement and the co-development of measures required for societal acceptance of seaweed cultivation are needed [43].

Waste:

- Waste resources are a large potential source of biomass, but there are clear barriers to increased waste utilisation. Plants utilising waste can run into issues with permits for using certain types of waste, particularly as they scale up. It is important that classifications are done on a feedstock by feedstock basis, with agricultural residues or 'green waste' from gardens being treated differently to municipal solid waste (MSW) or industrial waste.
- Waste is a distributed resource, and for it to be utilised as a biomass feedstock it must be collected. A report by WRAP suggested that in 2018 79% domestic food waste still ended

up in general waste [44]. There are also measures in place to reduce the amount of waste we produce and so when developing industries around waste feedstocks, it is important to consider that the feedstock may dwindle over time.

Question 7 - What is the potential biomass resource from imports compared to the levels we currently receive? What are the current and potential risks, opportunities, and barriers (e.g., sustainability, economic, etc) to increasing the volumes of imported biomass?

- Although the UK is projected to have significant indigenous biomass resources to meet its targets, current UK biomass strategies risk biomass deficit. One forecast suggested that the UK will need to import biomass to if biomass strategies are not altered to increase production sufficiently [1].
- The models collated in the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report predict that the UK will have greater reliance on its domestic bioenergy resource base in the future, but that there may be a significant role for imported biomass. The report suggested that in 2025 the UK could be using 92 – 136 PJ primary energy from imported biomass, and this becomes 19 – 662 PJ by 2050 [2].
- Key biomass rich countries, such as Brazil, are well placed to continue to be a dominant player in exporting resources for global trade in the future. However, it is possible that such countries may decide to utilise a greater proportion their renewable resources for domestic energy demands. Analysis focusing on Brazil found that biomass export could fall by up to 25.8% if it were to adopt and realise more ambitious energy strategies. This represents a strong caution for countries developing bioenergy strategies that will require large biomass resource imports to balance their future demands [45].
- If imports are coming from sources such as diseased timber or timber previously grown for paper pulping that has lost its market, then there can be opportunities for making good use of resources. Often though, the key challenge associated with importing biomass is ensuring that the supply chains are sustainable and avoiding offshoring of impacts. For example, work by Holland *et al.* demonstrated the impacts of the UK energy system mediated by international trade on water resources and biodiversity [46, 47]. These studies highlight that for certain energy technologies the UK is a net importer of environmental impacts – in other words UK demand for energy drives pressures on water resources and biodiversity in other regions of the world, primarily the least developed countries. This has important implications for the UK's ability to meet its target set out in the 25 Year Environment Plan that the UK will improve its own environment but not at the cost of the environment overseas.

End Use of Biomass

Question 8 - Considering other potential non-biomass options for decarbonisation (e.g. energy efficiency improvements, electrification, heat pumps), what do you consider as the main role and potential for biomass feedstocks derived from the a) waste, b) forestry, c) agricultural sectors, and d) from any other sources (including novel biomass feedstocks, such as algae)) to contribute towards the UK's decarbonisation targets, and specifically in the following sectors?: (i) Heat, (ii) Electricity, (iii) Transport, (iv) Agriculture, (v) Industry, (vi) Chemicals and materials, (vii) Other?

- As laid out in the 'Balanced Net Zero Pathway' described by the CCC in the Sixth Carbon Budget, fossil fuel use should be largely phased out by 2050, and where possible, non-carbon-based technologies should be adopted: solar and wind for electricity generation; electricity, green hydrogen and heat pumps for domestic heating; and electrification of road transport [48]. Biomass has a key role to play in reducing emissions from hard to decarbonise sectors, and in achieving carbon sequestration through negative emission technologies such as BECCS. By 2050 all biomass should be used to deliver net negative solutions via BECCS but the pathway to get there is not necessarily linear. We have today mobilized significant sustainable supply chains that need to be leveraged to maximize our impact on cumulative emissions in the next 30 years. That will require use in some non-BECCS applications in the short and medium terms to support our carbon budget commitments (e.g. in low carbon gas or liquids for heating).

Heat:

- Biomass has been used for heat provision for millennia and use of sustainably sourced biomass can provide low carbon heat. Previous work has shown that reductions in carbon intensity of up to 80% are possible for direct use of solid biomass [49]. However, this can have significant airborne emissions; particularly if wet wood is used or there is poor control of combustion air and conditions. In general, larger scale devices support better, cost-effective control of particulates and NO_x, which are harmful to health and eco-systems. Solid biomass should wherever possible be used as dried material in pellet or chip form, rather than logs and moisture contents above 10% should be avoided [50-52].
- The use of low carbon liquids derived from biomass can be used to readily deliver heat in existing boiler installations using kerosene heating fuel with significant (around 80%) reduction in carbon intensity. Low carbon liquids can be derived from pyrolysis or biomass to pyrolysis oils or fermentation to ethanol.
- Heating has a very significant temporal demand and there are often rapid surges in key winter periods. Biomass-derived liquids have the advantage that they are fungible, storable, pumpable (transportable) hydrocarbons and so can be rapidly deployed to match demand surges in a reliable manner.

Biomethane and biohydrogen:

- Methane can be produced from steam reforming of biomass-derived gases via AD or gasification. Biomethane can be used in existing infrastructure to reduce dependency on natural gas: it can be injected into the gas grid and used as a fuel for vehicles or for the generation of heat and power. It delivers significant carbon savings with a specification almost identical to that of current natural gas specification. However, greater carbon reductions could be used via direct use of low carbon gases of other specifications e.g.

closer to the syngas composition from biomass gasification. Since biomethane can be produced with high-TRL (Technology Readiness Level) technologies such as AD, it can be rapidly scaled as a near-term abatement option.

- Compared to fossil fuels, biomass has higher oxygen content and lower carbon to hydrogen ratio. The oxygen content is problematic and means that efforts to produce an exact drop-in replacement for existing fuels will require deoxygenation which can be expensive and energy intensive, but the carbon to hydrogen ratio is an opportunity. Converting biomass to a carbon intensive material requires removal of hydrogen atoms and that means that there is potential for release of hydrogen as a fuel, while retaining adequate carbon content for materials and other applications. The challenge is identification of the most appropriate processing pathways to transform the biomass material to a concentrated carbon source for materials use and liberate hydrogen for fuel use.
- Biohydrogen can be produced with technologies that are nearing the requisite technical maturity for full commercialisation (including gasification, dark fermentation and photocatalysis). With appropriate conditions this production can be even more carbon negative [53].
- Biomethane and biohydrogen can be substituted for their fossil equivalents in a wide range of roles but heating and electricity generation are notable in terms of the overall size of the current demands. A key strength of providing these near-term applications is that it enables a decoupling of the development and scale-up of the biomass supply chain and conversion infrastructure, from the development and scale-up of other applications that may be more appropriate in the longer term. Biomethane and biohydrogen may also play a key role in substituting fossil fuels in electricity generation for balancing and other grid services that non-dispatchable renewables, nuclear and power generation with Carbon Capture and Storage (CCS) are less suited to.

Off gas-grid dwellings:

- About 2 million dwellings (16%) in the UK are not connected to mains gas and are located in rural areas [54]. Rural areas often have limited options for their energy supply, high levels of fuel poverty and specific barriers to implementation of new technology. Around 48% of rural dwellings were built before 1919 (and therefore often not suitable for heat-pumps) and 80% are detached (with inherently higher heat losses than other housing types). Consequently 70% the least energy efficient housing (those rated F/G) are off gas-grid and 70% of those have expensive/hard to treat solid walls, not suitable for cavity insulation. Oil and liquid petroleum gas (LPG) are the default option for most rural communities, with over 3 billion litres of heating oil used by nearly 2 million UK households annually.
- This leads to triple disadvantage: households not connected to the gas grid are 1.5 times more likely to be in fuel poverty than those with a mains gas connection; decarbonisation of other households is progressing with heat networks and heat pumps but minimal research has addressed the challenges of decarbonisation in rural areas; and devolution of power to combined authorities and metro-mayors has arguably further marginalized the national visibility of rural decarbonisation.
- The challenge is of national, but also international importance: the UK has the fifth highest heating oil usage in Europe, but Germany, France, Switzerland, and Belgium consume more. Liquefied Petroleum Gas (LPG) has a global market of $125 billion/317 million tonnes in 2018, increased 3.6% over 2017 [55]. Without intervention 30 Gt CO_2 will be emitted globally from LPG and 270 Mt CO_2 from UK domestic heating oil use by 2050. Deployment of biomass derived low carbon liquids and gases could reduce UK GHG emissions by 200 Mt CO_2 over the period 2020 to 2050, but the impact of the technologies developed will achieve much more globally, via industries with UK bases.

Transport

- Biomass already plays a key role in UK transport fuel decarbonisation. Moving forward it is likely that more electric vehicles will be deployed, but it is worth nothing that the current level of biofuel deployment is 2 orders of magnitude higher than electric vehicle deployment. Coupled with the understanding that near term reductions in carbon are more valuable in a cumulative emissions context than longer term ones, there is a strong argument for maximizing biomass deployment to deliver near term carbon reductions in a way that requires minimal infrastructure investment. This can be done via production of renewable, low-carbon liquids or by conversion to lower carbon intensity renewable gas options e.g. renewable compressed natural gas. Prioritisation of "hard to decarbonise" sectors makes sense and that is likely to be the heavy freight sector in the short to medium term and/or other sectors with well-established fuel infrastructure and significant inertia (e.g. aviation and shipping).
- A long-term ambition in transport decarbonisation is hydrogen and fuel cell use. Production of hydrogen from biomass and/or waste is feasible via thermochemical and biological pathways though not commercially proven. This could deliver valuable near-term carbon reductions if appropriately developed.
- Routes for sustainable aviation fuel (SAF) production using a wide variety of biomass resources have been already discussed and approved for commercial aviation. Fischer-Tropsch Jet biomass-to-liquid (FTJ-BTL) can convert lignocellulosic-based biomass (woody and non-woody plants and residues) into jet fuel [56]. Lipid-based biomass (e.g. plant, waste, or algae oils) can be converted to blend stocks, with a maximum composition of 50%, using the hydrogenated esters and fatty acids (HEFA) process [57]. Sugar- and starch-rich biomass can be also fermented to farnesene intermediate that is latter upgraded to a certified jet-fuel blend by the Amyris process and although the low flash point of bioethanol has prevented its direct use to operate traditional jet engines, the alcohol-to-jet (ATJ) pathway has enabled its conversion to appropriate hydrocarbon blends approved by the ASTM [58]. By integrating CCS for capturing the CO_2 generated during the processes (i.e. from non-converted syngas in the FTJ-BTL pathway, from the decarboxylation step in HEFA process, or from the production of bioethanol (particularly when producing using second-generation crops)), a SAF production process with net-negative emission potential could be implemented.
- Further information on SAFs from biomass will be available in a briefing note titled "The decarbonisation of the aviation sector: bio-jet fuel production pathways, challenges and opportunities.", which will soon be published by the Energy and Bioproducts Research Institute (EBRI).

Chemicals and materials:

- Chemicals and materials cannot be decarbonised, they are fundamentally carbon-based compounds. Reducing the use of crude oil and natural gas in these products can only be achieved through a switch to an alternative renewable carbon source, such as biomass.
- Many high value chemicals and useful polymers can be directly extracted from biomass, for example high value compounds, such as fucoxanthin and sulphated polysaccharides can be extracted from Kelps (a type of seaweed). Furthermore, chemical, thermal, or biological conversion of biomass can yield a plethora of platform and high value chemicals depending on the type of biomass feedstock and the technology used. This includes chemicals like ethanol and organic acids, which can serve as routes into other parts of the chemicals sector [9, 59, 60].
- Ethanol has a large range of potential chemical applications the largest of which is the conversion to ethylene and polyethylene plastic. In fact, ethanol can serve as a platform intermediate for many of the olefin-derived sectors of the petrochemicals market providing

a potentially rapid route to reducing net emissions from the chemicals sector. Olefins in general represent the major class of petrochemicals used in industry and therefore bioethanol presents a clear entry point by which sustainable biomass can penetrate the petrochemicals olefin sector. Examples of this already exist at a commercial scale: Croda have opened a large scale bioethylene oxide plant in the US where they use corn ethanol to produce sustainable surfactants for companies such as Unilever [61]; and Braskem in Brazil has large scale facilities converting sugarcane bioethanol to bio-ethylene for use in sustainable polyethylene and PET production by companies such as Coca-Cola [62]. The UK has considerable potential to develop commercial waste to bioethanol plants. For example, Wilson BioChemical Ltd has signed a Memorandum of Understanding with Clariant for the use of Clariant second-generation bioethanol production from the biological component of municipal solid waste (BioMSW) having demonstrated the feasibility of this with a combination of Wilson and Clariant technologies.

- Plastics make up a large proportion of the UK chemicals sector. Bio-based plastics can be produced using polymers directly extracted from the biomass, or through the production of bio-based monomers which are then polymerised into novel or drop in materials, as was described for ethanol to polyethylene above [63].The UK also has an active world leading community of researchers in academia and industry, rapidly developing technologies to create high quality textile from biomass. Currently textile production and end of life are highly GHG emitting [64], and there is a clear opportunity to avoid this by using biomass to underpin a circular and sustainable fashion industry. Utilising biomass in the production of materials such as plastics or textiles can have the added benefit of storing carbon for longer lengths because often these products have longer lifetimes. However, great care must be taken to ensure that plastics derived from biomass are delivering carbon reductions. Some studies have demonstrated potential for this and others have shown disappointing results. At present there is not a good understanding of what is driving the variation and so care is needed with sustainability and assessment frameworks.

Question 9 - Out of the (i) Heat, (ii) Electricity, (iii) Transport, (iv) Agriculture, (v) Industry, (vi) Chemicals and materials, (vii) Other sectors, considering that there is a limited supply of sustainable biomass, what do you see as the priority application of biomass feedstocks to contribute towards the net zero target and how this might change as we reach 2050? Please provide evidence to support your view.

- Decisions around priority uses for biomass should take into account the carbon savings that can be achieved by transiting to a bio-based alternative, the potential for carbon sequestration (CCS or CCUS (Carbon Capture, Utilisation and Storage)), and the difficulty of decarbonising the sector in alternative ways. By 2050 the logic of net zero means that biomass will effectively provide the only usable carbon atoms on the planet, and it will be essential to shepherd those to uses for which there is no replacement. A framework for based on these principles is discussed further in Question 10.

Electricity:

- In the long term most electricity generation could potentially be provided through renewable energy sources such as wind and solar, and this should be used for heating via heat pumps. However, until these technologies have been deployed at levels that can meet demand, biomass will be important in providing renewable electricity. Using BECCS as a means of electricity production can allow for negative emission electricity production.

Transport fuels for shipping, heavy freight, and aviation:

- Although 78% of the UK demand for oil is consumed for transport purposes, the largest consumer of oil is road transport (56%). Domestic transport is amenable to electrification and demand from this sector can be expected to decrease in line with existing government policies on the decarbonisation of transport. The heavy freight, shipping, and aviation sectors are harder to decarbonise, and until technological developments allow electrification or the use of hydrogen fuel in these forms of transport, carbon-based fuels from biomass will be required to replace and reduce fossil fuels.

Chemicals and materials:

- The UK's chemical industry is an important part of the economy, but it is also based on the use of fossil feedstocks. In 2019 the UK non-energy consumption of oil accounted for around 6.5 million tonnes of UK oil demand representing around 10% of total UK demand for oil. The UK's chemical and pharmaceutical sectors add £18 billion of value to the UK economy every year and 500,000 UK jobs depend on the work of chemical and pharmaceutical businesses.
- Biomass represents the only readily available source of renewable carbon from which carbon-based chemicals and materials can be produced, and its use in the chemicals and materials sector is essential if we are to reduce the reliance of these sectors on fossil feedstocks. Using biomass feedstocks for the manufacture of chemicals and materials sequesters carbon for the lifetime of the product and reduces emissions from the end-of-life incineration or decomposition of displaced petroleum products. Targets for the best use of the biomass resource are the currently (or predicted) most carbon intense materials, with largest predicted markets and lowest production emissions (when a specific pathway is considered that actually delivers a replacement to the same not inferior specification).
- Unlike the bioenergy sector, there is not yet clear evidence on the magnitude of the carbon savings that could be achieved by transitioning to a bio-based chemicals and materials sector. There is also not a clear understanding of which the specific priority applications are for targeting biomass replacements within the sector to support decarbonisation targets. It is critical to not only consider the carbon intensity of the biomass production pathway and the carbon intensity of the incumbent, but how the carbon storage in the product changes over time. The permanency of the carbon sequestration is also difficult to predict because it varies not just by the chemical or material made, but the application it is used for and the potential for recycling. Despite this complexity we believe that some understanding of the potential of a bio-based chemicals and materials sector to contribute to net zero could be achieved by key groups of products that make up large parts of the sectors emissions. We intend to carry out this work and share the results over the next 12 months.
- As a precursor to this more detailed work we have carried out some initial scoping on the potential for biobased plastics to contribute to the UK's decarbonisation targets. In 2019, global plastics production reached nearly 370 million tonnes and European plastics production was a little under 58 million tonnes. Plastics make up a large proportion of the UK chemicals sector, and 60% of plastic products and parts have a use phase between 1 and 50 years thus giving them the potential to store carbon for long periods of time. A wide range of plastics can be produced from biomass, either using polymers directly extracted from the biomass, or through the production and subsequent polymerisation of bio-based monomers. Global bio-based plastic production capacity is currently around 2 million tonnes per year [65]. **Table 1** provides information on the highest demand plastics in Europe, their carbon intensity and lifetime, and the opportunities for producing them from biomass.
- The highest priority plastics for biomass use should be those that have a long life (meaning they store carbon for a long period of time), those that replace a petrochemical plastic that

has a very high carbon intensity, and those where a large carbon saving can be achieved by switching to the biobased alternative. The information in **Table 1** therefore implies that polyvinyl chloride (PVC), which makes up 10% of European plastic demand, would be an ideal target for biomass use: it is mainly used in long-life applications such as window frames and pipes, and initial studies have shown that the biobased alternative offer up to 90% GHG savings compared to fossil derived PVC [66]. Polyurethane and expanded polystyrene could also be priority targets for biomass use because both can be used in the production of building insultation. Not only is this an application that results in long term storage of carbon, but it is likely that demand for building insultation will increase due to the drive to create greener homes.

The importance of the biorefinery concept:

- The biorefinery concept is key to ensuring cost effective decarbonisation. In a biorefinery, optimum "value" is obtained from all fractions of the biomass feedstock, analogous to a conventional petrochemical refinery [67], where value can be defined as economic, environmental, social benefits or, as is more likely, a combination of these [68]. The economic sustainability of decarbonisation technologies will be ensured through gaining value from all fractions of the biomass, producing a range of products with high carbon conversion efficiency. Producing large quantities of bulk chemicals or fuels and competing in large markets often offers slim profit margins. Therefore, extracting additional value streams from biomass via innovative technology integration can produce smaller quantities of higher value products that can significantly impact economic sustainability [69]. Strategies to extract high value platform chemicals from biomass have a huge potential to positively impact the economic performance of decarbonisation processes. For example, it has been demonstrated that without a multi-product vision, the techno-economics of seaweed cultivation will be over-strained and if the industry is to grow, high value products and biochemicals will need to be part of the product portfolio alongside biofuels.
- Residues from the production of biofuels of biochemicals in a biorefinery can be used for the production of heat or electricity, and the CO_2 that is a by-product in the production of many biochemicals could be captured for CCS or used as a feedstock for further manufacturing to create an additional value stream.

BECCS:

- BECCS is a critically important technology for global decarbonisation. It is the only technology that can deliver net-negative emissions while supplying low carbon energy at the same time, thus helping to decarbonise the energy sector. This has led BECCS to have an essential role in most of the scenarios modelled by Intergovernmental Panel on Climate Change (IPCC) that limit global warming: over 100 of the 116 scenarios that limit average temperature rises to 2°C depend on BECCS; and 3 of the 4 pathways in the IPCC special report on 1.5°C involve BECCS removing 151 - 1191 billion tonnes CO_2 per year. Arguably it is even more significant for the UK, where it is envisaged that BECCS could deliver 20 to 70 million tonnes CO_2 per year negative emissions [70], reducing the cost of meeting our 2050 emissions target by up to 1% of GDP [71]. However, not all BECCS systems are equal, and the potential to increase carbon savings through the development of innovative BECCS technologies (such as pre-combustion gasification systems) is discussed in Questions 22 and 25.
- Another approach to BECCS is to utilise the near-pure stream of CO_2 that is produced as a by-product of biomass fermentation (for example in the production of bioethanol). This process, and the use of pre-combustion capture (gasification), links the production of fuels or chemicals to CCS allowing for the production of carbon negative products.
- For further information on BECCS, a briefing note titled "Opportunities and challenges for Bioenergy with Carbon Capture and Storage (BECCS) systems supporting net-zero

emission targets” will soon be available from EBRI.

Table 1. Plastic Demand and Carbon Footprint

Polymer	% European plastic demand	Applications	Carbon footprint	In use lifetime (years)*	Bio-based Status
Polypropylene	19.4	Food packaging, sweet and snack wrappers, hinged caps, microwave containers, pipes, automotive parts, bank notes, etc.	1.86 kg CO_2 eq / kg [72] (-2.2 kg CO_2 eq / kg of bio-attributed PP) [72]	Mainly short life non-durable packaging and household, leisure & sports but also durable applications in automotive and construction	Commercially available (mass balanced)
Polyethylene (Low-Density and Linear Low-Density)	17.4	Reusable bags, trays and containers, agricultural film, food packaging film, etc.	1.79-1.92 kg CO_2 eq / kg of LLDPE [72, 73] 2.25 kg CO_2 eq / kg LDPE [72] (-1.91 kg CO_2 eq / kg of bio-attributed LDPE) [72] (-2.2 kg CO_2 eq / kg of bio-attributed LLDPE) [72]	Predominantly short life non-durable packaging	Commercially available via steam cracking or via ethanol.
Polyethylene (High-Density and Mid-Density)	12.4	Toys, milk bottles, shampoo bottles, pipes, houseware, etc.	2.079 kg CO_2 eq / kg of HDPE [72] (-2.1 kg CO_2 eq / kg of bio-attributed HDPE) [72] (-3.09 kg CO_2 eq / kg of bio-based HDPE [74]	Mainly short life non-durable packaging but also durable construction	Commercially available via steam cracking or via ethanol.
Polyvinyl chloride (PVC)	10	Window frames, profiles, floor and wall covering, pipes, cable insulation, garden hoses, inflatable pools, etc.	1.6-1.8 kg CO_2 eq / kg [73, 75] Bio- attributed PVC GHG saving of over 90% compared to conventionally produced PVC [66]	Predominantly long-life durable applications in construction [76]	Commercially available via steam cracking
Polyurethane	7.9	Building insulation, pillows, and mattresses, insulating foams for fridges, etc	-	Long-life durable applications in construction and automotive	Various commercial polyurethane equivalents
Polyethylene Terephthalate (PET)	7.9	Bottles for water, soft drinks, juices, cleaners, etc	2.19kgCO_2eq per kg (bottle grade) [73]	Predominantly short-life non-durable packaging	Commercially available as partially bio-based. 100% bio-based production demonstrated at pilot scale
Polystyrene and Expanded polystyrene	6.2	Food packaging (dairy, fishery), building insulation, electrical & electronic equipment, inner liner for fridges, eyeglasses frames, etc	2.37 kg CO_2 eq / kg (EPS) [73] Bio-attributed PS produces 74% less GHG when compared to conventional grades	PS mainly short life non-durable packaging and EPS predominantly long-life durable applications in construction	Commercially available via steam cracking
Other thermoplastics	11.3	Hub caps (ABS); optical fibres (PBT); eyeglasses lenses, roofing sheets (PC); touch screens (PMMA); cable coating in telecommunications (PTFE); and many others in aerospace, medical implants, surgical devices, membranes, valves & seals, protective coatings, etc	-	Varied	Several polymers commercially available as partially or 100% bio-based including PTT PBS, PLA, PA PBAT, and thermoplastic starch.
Other thermoset plastics	7.5	Includes other thermosets such as phenolic resins, epoxide resins, melamine resins, urea resins and others	-	Varied	Epoxide resins commercially available based on glycerol derived epichlorohydrin.

*Plastic products can be classified as being either a durable or non-durable plastic good. Products with a useful life of three years or more are referred to as durables. They include appliances, furniture, consumer electronics, automobiles, and building and construction materials. Products with a useful life of less than three years are generally referred to as non-durables. Common applications include packaging, rubbish bags, cups, eating utensils, sporting and recreational equipment, toys, medical devices, and disposable diapers.

Question 10 - What principles/framework should be applied when determining what the priority uses of biomass should be to contribute to net zero? How does this vary by biomass type and how might this change over time?

- A framework that is applied when determining what the priority uses of biomass should be to contribute to net zero should consider the whole life cycle GHG intensity of both the displaced counterfactual and biomass alternative, and the carbon storage potential, as well as taking into account wider supply chain considerations and impacts. Policies and biomass GHG impact assessments should focus on the whole life cycle and specific steps of bioenergy pathways in order to promote and incentivise the use of specific biomass resources in end uses that cannot be easily be decarbonised in other ways, as well as uses that will result in the mitigation of high GHG impact activities [23].
- Through consideration of economic, environmental, and social indicators, research is required to map the sustainable uses for different categories of biomass so specific resource pathways can be prioritised/incentivised. Where potential impacts from increased competition for resources have been identified, it would be useful identify whether alternative resource solutions are available [2].
- A flexible system is needed that allows adjustments based on future market developments. The same sustainability criteria across all biomass using sectors would allow fair competition for biomass. A multi-level governance approach would then require a mechanism, where biomass user must provide evidence that they maximise GHG savings and that their activities supports the UK carbon budget (so not just emission reductions but minimising contribution to carbon budget or maximising negative emissions). As with time the carbon budget and the requirement for negative emissions will change, regular policy adjustments (e.g. in tandem with carbon budget reviews) would be required [77, 78].

Locking away carbon:

- The priority uses of biomass should be those that make the best use of the resource including for helping to achieve net zero targets. This therefore is to treat biomass as a feedstock for BECCS as well as for renewable heat and power. In addition, this can be as a feedstock for long lived and recyclable materials that ensure the carbon fixed through photosynthesis is not rapidly released again to the environment. For example, this could include uses in the wider bioeconomy for construction materials, long lived products through green manufacturing and platform chemicals.
- It is worth noting that there are many reasons why the priority for displacement would change over time and for this reason the framework that we have proposed in answer to Question 15 is capable of amendment for this. So, if priorities for target sector/use change because of e.g. varying carbon intensity over time or prioritisation due to lack of alternatives (aviation fuel) or social priorities (minimizing cost to vulnerable consumers) this can be accommodated e.g. by increasing the ranking of the “end-use” component of the assessment. This framework is being developed and further detail on this can be provided if required.

Question 13 - Are there any policy gaps, risks or barriers hindering the wider deployment of biomass in the sectors identified above?

Consistent policy:

- To ensure policies are developed that prioritize sustainable and cost-effective sectors it is important that policy is coordinated across sectors and different government departments, since bioenergy is so inextricably linked to land, people, industry processes and interactions between these as well as energy [2].

Displacing petrochemicals:

- The broad problem in realising biomass use in priority areas such as fuels, chemicals and materials is one of how to displace highly efficient global petrochemical supply. Industries producing fossil-based fuels, chemicals and materials have been developing over centuries, whereas bio-based alternatives in their technological infancy and are often of much smaller scale. Investment in research, innovation, and scale up facilities is needed to achieve more biomass-based technologies that are competitive in performance and cost with the current technologies based on fossil chemicals [79]. In addition, there should be a better pipeline of investment into commercialisation as private investment is less likely to support development of technologies between TRLs 3 and 6.

Deployment of small-scale or modular technologies:

- For the deployment of biomass utilising technologies, including BECCS, it is important that there is not a rush towards, or monopoly by, large scale plants. Smaller scale technologies can offer greater flexibility and more modular upscaling opportunities, and incremental scale up can allow technologies to be improved and costs reduced. Large plants also require greater amounts of feedstock, which is likely to overwhelm local regional supply chains [80].
- There are number of additional barriers and challenges to large-scale BECCS deployment, including CO_2 transportation and storage infrastructure deployment, lack of supportive regulatory framework and the need for investment incentives. A study by Donnison *et al.* suggested that rather than a few large BECCS deployments, an increased number of smaller deployments may be needed to ensure a win–win for energy, negative emissions, and ecosystem services [16]. A small-scale, decentralised vision might facilitate BECCS implementation in the short term, following a demand focused energy provision that would enable the use of regionally sourced biomass and residues. Small-to medium scale technologies commercially demonstrated, such as modular CHP systems or gasifiers, could be integrated in BECCS. The captured CO_2 could be distributed to other CO_2 utilising industries and generate potential revenues that might help attracting investment. This decentralised BECCS implementation could start to contribute decarbonising the energy sector and deliver negative emissions in the very short term, with the option of introducing centralised large-scale BECCS deployment in the longer term.
- For further information on the barriers to BECCS deployment, a briefing note titled “Opportunities and challenges for Bioenergy with Carbon Capture and Storage (BECCS) systems supporting net-zero emission targets” will soon be available from EBRI.

Question 14 - How should potential impacts on air quality of some end-uses of biomass shape how and where biomass is used?

Domestic heating:

- In recent years the trend of increasing wood combustion for domestic heating has resulted in high particulate and air pollution emissions within urban locations and has had detrimental effects on human health and climate forcing [52]. Modelling has predicted that UK residential wood combustion is going to increase [81]. Innovation and policy drivers in this sector must control fuel type, enforce smokeless zones in urban areas, and develop heating stoves fitted with pollution control.

Sustainability and Accounting for Emissions

Question 15 - Are our existing sustainability criteria sufficient in ensuring that biomass can deliver the GHG emission savings needed to meet net zero without wider adverse impacts including on land use and biodiversity? How could they be amended to ensure biomass from all sources supports wider climate, environmental and societal goals?

- Existing mechanisms in the UK developed for the RO (Renewables Obligation), RTFO (Renewable Transport Fuel Obligation), and RHI are generally robust in terms of consideration of GHG emission savings. However, the key concerns lie around the extent to which these mechanisms are actually enabling low carbon fuels to be deployed. It is, of course, important to consider the whole life cycle and to include consideration of land-use, land-use change and carbon stock change (for forests and soils). However, it is equally important to actually progress deployment that maximizes greenhouse gas benefits, and in some instances, detailed analysis of upstream emissions can be challenging, time-consuming and subject to high levels of uncertainty. The Supergen Bioenergy Hub has navigated this complex landscape by taking a pragmatic semi-quantitative approach to sustainability assessment that broadly allows us to distinguish between bioenergy systems that are strongly, moderately, or weakly positive or negative for a range of sustainability parameters. This approach has been under development for many years [82] and allows ranking of feedstock-process-use options using an environmental risk approach. We have also evaluated the impact of uncertainty and how this influences choice of policy mechanisms [77] as well as the impact of policy initiatives on deployment [13, 83].

  Our conclusions are that there is a need to quantify carbon savings from bioenergy system implementation to ensure there are no negative effects and efficient use of biomass resource that maximizes GHG savings is prioritized, but that this needs to be done in a manner consistent with the level of uncertainty associated with the system and calculation methods. This incorporates stochastic uncertainty related to decisions that may or may not be within the control of the bioenergy developer, but also non-stochastic uncertainty related to natural variability. We have also established that the counterfactual associated with the end energy vector and the sector where it is deployed (as well as the counterfactual land-use) will often dominate the carbon savings calculation, in a piece of work that concluded: *" Variations in GHG performance do not correlate with feedstocks or technologies, but are most sensitive to the inclusion of specific processing steps and the displacement of certain counterfactuals. This suggests that policies should be developed that target resources with high GHG intensity counterfactuals, and where possible avoid energy intensive processing steps."* [23]
- The policy objective of identifying and rewarding the system that maximizes carbon reductions from available biomass supply therefore needs to consider not just the embodied (and often uncertain) emissions associated with feedstock supply, but also the resource efficiency of the conversion mechanism (when deployed at scale with real feedstocks to deliver a standard specification output) and the carbon intensity or other prioritisation of the end-use vector/sector. Adoption of different mechanisms and calculation methodologies that incorporate different incentive approaches crates market distortions and unintended consequences that need to be addressed [78].
- The corollary is that GHG emissions from feedstock production should be minimized (but that this needs to be consistent with matching of the produced feedstock properties to the conversion technology e.g. high lipid content feedstocks often enjoy high conversion efficiencies via physiochemical routes as is the case for fermentation of high sugar

feedstocks; but both tend to have higher embodied GHG emissions than lingo-cellulosic feedstocks, which are likely to require more extreme conditions (higher temperatures) or additional pre-treatment to maximize conversion. So, there are strong links between feedstock and conversion, but allowing developers feedstock flexibility and market freedom to respond to commercial market signals is key to maintaining low costs (including to consumers).

- One way of achieving the objectives is to maintain a holistic perspective across feedstock, conversion and end-use for calculation/integration purposes, but to calculate the carbon performance associated with each of those steps separately. Effectively we consider: stage 1, which delivers a feedstock with a high, medium or low embodied carbon burden; then stage 2, where we make use of that feedstock to deliver a quantity of desired product at a high, medium or low efficiency; and then stage 3 where that product is delivered as an energy or product vector that displaces an incumbent that has a high, medium or low existing carbon burden. This allows the feedstock to change, and the end-use target to vary and its carbon burden to change over time while maintaining an overall assessment of the net carbon impact of delivering the bioenergy or a bioproduct.
- This concept is being developed in more detail by the Supergen Bioenergy Hub and we would be happy to provide further information in due course.

Beyond carbon:

- It is important to remember that sustainability goes well beyond just GHGs. The approach to these types of decisions must be holistic and consider social, economic, and environmental perspectives and indicators to be truly sustainable. The soon to be published Supergen Bioenergy Sustainability Indicator Model allows assessment of over one hundred indicators of sustainability, covering people, development, natural systems and climate change. This model is also based on the semi-quantitative approach to environmental risk that underpins the analysis described above.
- For domestic biomass supply it is important to consider how any sustainability criteria for end-users will map onto policy being developed for UK agricultural land-use sustainability [84].
- Sustainability criteria should also include consideration of land-use efficiency (e.g. KWh per hectare). Efficient and land-use has two outcomes, Firstly by maximising the energy yield per hectare we can seek to minimise indirect land use change, the second is that by considering the energy yield on an input to output ratio it is possible to select biomass crops with the greatest resource efficiency. Second-generation bioenergy crops for example have a much greater resource efficiency due to low input requirements and first-generation.
- Currently different sector policies have different standards for biomass production and sourcing should be treated the same cross all sectors. The focus should not be on carbon savings alone but the actual contribution to the carbon budget. While this is challenging as biomass can be used for different applications leading to different emission profiles of the full supply chain, biomass as such until the point of use, should have the same reporting standards and sustainability criteria across sectors. This would require a multi-level governance framework addressing issues at each level of supply chain processes (biomass production/sourcing; biomass use/conversion; final vector application) [78].
- Another challenge is that waste and residues are currently reported as zero upstream emissions, with increasing demand (for energy or other sectors) this is not justifiable once they become a commodity or an essential feedstock within a value chain.
- Biomass is currently treated independently and decoupled from the wider production system. Especially where biomass is residue-based, an assessment of the overall system (e.g. forest, agriculture) is important. With residues currently accounting for zero upstream

emissions, it is unclear how (un)sustainable the production/supply chain of the main product is. Providing minimum evidence for the whole product basket is key to also understand the overall impact of the supply chains biomass is part of [14].

Question 16 - How could we improve monitoring and reporting against sustainability requirements?

Transparency:

- Transparency is important. For example, understanding the location from which resources are being extracted provides an opportunity to integrate data from multiple sources to understand potential issues around sustainability.

Enforcement:

- When it comes to off grid heating applications, most of the feedstock is sourced domestically. Forestry schemes in the UK are heavily regulated, but industry experts have informed us that issues around inappropriate feedstock use (which can lead to air quality impacts) arise due to a lack of enforcement.

Soil carbon monitoring:

- There is increasing interest in incentivising landowners for increasing soil carbon stocks, however these increases will need to be monitored and validated. Cost is currently a barrier, but this may be reduced by the development of spectral approaches [85]. There is also not yet a clear protocol for the measurement of soil carbon stock changes, with discussion around sampling depth, methodology, and the use of equivalent mass approaches on going [18, 86, 87]. However, these technical challenges can be overcome. Care must also be taken in the development of any incentive for soil carbon storage to ensure that this does not penalise landowners who have already taken steps to increase their soil carbon stocks (soil does become carbon saturated thus storage is not infinite) or whose soil type will limit the sequestration possible [88]. One option would be to consider payments based on a percentage soil carbon stock reached compared to what would be feasible based on soil type and climate. In addition, to ensure the long-term maintenance of soil carbon stock and tackle the issue of reversibility it could be advisable for domestic supply that any soil carbon incentives are applied not only to biomass crops but across the agricultural sector [88].

Question 17 - What alternative mechanisms would ensure sustainability independent of current incentive schemes (e.g., x-sector legislation, voluntary schemes)?

- Voluntary schemes come at a cost and this hinders participation of small-scale producers. Mechanisms that allow reporting of trade-offs between different sustainability aspects, such as multicriteria assessment or “risk assessment”, would allow comparison and evaluation of synergies and trade-offs. Policy should set coherent standards and benchmarks that allow everyone to participate [78].

Question 19 - How do we improve global Governance to ensure biomass sustainability and what role does the UK play in achieving this?

- The UK has led significantly in development of carbon accounting and sustainability standards for biomass to date. Global governance is supported by continuing engagement with relevant bodies such as CORSIA, IEA Bioenergy, Roundtable on Sustainable Biofuels, and FSC. International co-ordination is important to prevent development of dual tier production systems in countries where some biomass may be allocated to UK export and other to national or other international uses with different standards. An agreed international labelling scheme that supported trading of biomass with a certified level of "embodied carbon" in accordance with an appropriate international standard would support this and could be led by the UK (e.g. at the COP26 meeting). This would help fulfil a key imperative of increasing transparency. The qualifying threshold for different countries, users or schemes could then be set independently if there were common agreement on an approved scope and methodology. This would help avoid the well-documented problem of offshoring of GHG emissions but also avoid the need to agree and adopt common standards on what does or does not constitute a "sustainable" biofuel or "sufficient" carbon reduction.
- The UK 25 Year Environment Plan included a commitment to not improve the UK environment at the expense of that overseas [36]. Failure to consider the wider sustainability impacts of UK biomass resource demand could undermine internationally agreed targets around sustainability, such as those in the United Nations (UN) Sustainable Development Goals [2].
- It is important that any development of biomass standards considers the implications of and is consistent with DEFRA's England Tree Strategy and that we address any potential gaps between the strategy (which does not cover SRC or SRF) and feedstocks that may be used for bioenergy or bioproduct purposes.

Question 20 - How should the full life cycle emissions of biomass be reflected in carbon pricing, UKETS, and within our reporting standards?

- It is important to ensure that biomass is sustainable across the whole supply chain so as not to undermine potential GHG savings resulting from its use. As soon as we accredit for biogenic carbon (e.g. in the case of BECCS) we need also include upstream emissions related to this carbon. While biomass use provides emissions reductions compared to other (high carbon) feedstocks, Emissions Trading Schemes (ETS) are usually based on the concept of an emission release, so biomass needs to be treated in the same way. While in the case of short production circles (e.g. annually grown/harvested biomass) the biogenic carbon impact in the biomass will be close to zero, the temporal impact of carbon sequestration and carbon release when using biomass with longer rotation should be acknowledged. There should be a clear carbon balance reporting on a mass, spatial and temporal basis [14, 89].
- We have future work planned to better understand the issues presented in this question and will present this evidence when it is available. The outline is described in our response to Question 15.
- It is also important to highlight the need for consistency. Accounting for lifetime emissions from fossil resources should be consistent with the accounting for emissions from biomass, and where possible UK carbon pricing and ETS should reflect standard international practices.

Question 21 - How should BECCS be treated for domestic and international GHG emissions accounting and reporting? What are the implications of existing reporting rules on our ability to deliver negative emissions, when for instance, land use change emissions and stored CO_2 are being accounted for in different countries?

- This is a critical question with profound implications. Research contrasting production and consumption based GHG emissions demonstrates that the choice of accounting fundamentally alters our understanding of whether our policies support or undermine UN Sustainable Development Goals [90].
- Emissions accounting and reporting should be based on the United Nations Framework Convention on Climate Change (UNFCCC)'s emission accounting framework, which provides a comprehensive methodology to measure, report and verify emissions from bioenergy. The framework addresses the potential for flux of emissions to and from the atmosphere at each stage within biomass resource supply chains and bioenergy process by accounting for carbon uptake and carbon release where it happens. If biomass is grown abroad and used in the UK for BECCS the UK has produced low emission energy, but the producing nation reports the carbon sequestration. Such supply chains could be supported with a premium, which could also make sustainable biomass production attractive in potential producer countries [91].

Innovation

Question 22 - Given the nature and diversity of the biomass feedstock supply, what specific technologies are best positioned to deliver the priority end uses (discussed in earlier questions), and how might these change as we reach 2050?

- A number of technologies have been developed for utilising biomass feedstocks, and different technologies can be better suited to certain feedstocks or products. Variations in biomass supply from waste, or due to seasonal and regional variations in crops, mean that there is a need for technologies capable of feedstock agnostic processing. When considering the production of fuels, chemicals and materials, variations in the feedstock can result in inconsistent products that are unsuitable for use in downstream processes. This leads to two innovation needs: development of processes that are feedstock agnostic; and development of adequate pre-treatment steps to improve the feedstocks. This is particularly acute when utilising contaminated waste streams (often the most economic biomass source) but it can be problematic for many feedstocks. There is a need to carefully consider what the energy vector or product is being used for and what constraints attend that, as the purity requirements differ for different applications.
- Multiple technologies may need to be used in tandem to create economically viable processes through biorefining. Biorefineries, like oil refineries, should produce multiple products to extract maximum value from a biomass resource. Downstream processing can also be used to add value to chemicals from biomass, and here synthetic chemistry, engineering biology and bio-catalysis will be important.
- For many biomass technologies further research and innovation are needed to make them cost and performance competitive with the established fossil-based technologies and products. In addition to the funding given to lab-scale research, investment should support scale up and commercialisation of priority biomass technologies with representative feedstocks. The UK would greatly benefit from more open access scale up facilities to speed up and de-risk the move to demonstration scales, and this should include facilities that can look at how different technologies work together. This could be accelerated by placing scale up facilities within existing petrochemical infrastructure.
- Thermochemical processes are generally the most resilient conversion mechanisms in the face of biomass and waste feedstock variation, since they rely only on proximate/chemical composition and calorific value within a fairly wide band. Combustion is well proven but certain feedstock characteristics can lead to higher level of airborne emissions on combustion. This can put constraints on feedstock compositions, for example maximum moisture content or reduction in the level of volatile organic compound and aerosol pre-cursors. Biological processes such as digestion and fermentation may be inhibited by the presence of specific species, and very small levels of sulphur and other elements can be poisonous to catalytic conversion processes like those used for aviation fuel or hydrogen production. There is good knowledge of conversion performance under laboratory conditions with ideal feedstocks, but understanding of how this varies with real feedstocks, and increasing levels and combinations of contaminants is often poor. This can lead to significant performance issues when technologies are scaled up.

Thermochemical processing of biomass – pyrolysis:

- Pyrolysis involves heating organic matter (such as biomass) to high temperatures in the absence of oxygen. It produces solid, liquid, and gaseous fractions that can be used in many different ways. There is increasing interest in production of biochar via pyrolysis.

Biochar contains valuable soil nutrients as well as stable carbon, and its production and use acts as a mechanism for transfer of CO_2 from the atmosphere to biosphere. This is being trailed in several locations with commercial interest in securing the carbon sequestration benefits, but there is a need to be confident of their permanency, to quantify the additionality, and to evaluate any unintended consequences via trials.

- The bio-oil fraction from pyrolysis can be used as a liquid fuel and this has significant potential for short term decarbonisation especially in rural areas reliant on oil-fired heating. Concerns about settling and the potential impact of trace components on system performance (e.g. seals, gaskets, and material corrosion) still need to be addressed for the full variety of potential feedstock compositions.
- Bio-oil can be upgraded via catalytic deoxygenation to provide drop-in substitutes for existing hydrocarbon products such as aviation fuels. This is a significant potential market in a hard to decarbonize sector. Various studies have been performed and some fuels approved. To date these have generally been the more straightforward (e.g. HEFA) pathways that actually have lower carbon saving potential than more advanced options such as gasification/Fischer-Troph pathways. Common across all pathways is the need to demonstrate compliance with relevant fuel standards at a scale sufficient to account for feedstock variability and to evaluate the achievable carbon savings. To date carbon savings have mostly been optimistically evaluated via computer models with limited consideration of real feedstocks and experimental performance.
- The gas fraction produced in many pyrolysis systems is often used for internal energy provision within the system, but excess may be used as fuel.

Thermochemical processing of biomass –gasification:

- In view of the recalcitrant nature of lignocellulosic biomass, gasification of biomass into synthesis gas (syngas) presents a universal, standardised route to gas production from biomass. Using gasification, syngas (a mixture of H_2, CO, CO_2, and water) can be produced from any biomass or carbonaceous waste. The ratios of the syngas components depend on the process conditions, which is linked to feedstock and reactor. Industrial catalytic technologies can be used to convert syngas to other chemicals or fuels, including hydrogen and methanol.

Biological processing:

- Engineering Biology and Industrial Biotechnology (IB) (the use of biological systems, including enzymes, micro-organisms, cells, or whole organisms, to produce desirable products at industrial scale) will be important for enabling the production of bio-based chemicals, materials, and fuels. IB has great potential to produce novel products from biomass and it utilises lower temperatures and pressures than other biomass technologies, meaning that although it is slower, it enables transformations that retain the embedded energy and structure of such materials for subsequent use.
- AD is used to produce biomethane, but it also results in a solid residue called digestate, which can be used as a fertiliser. AD is a well-understood process with around 100 plants scattered throughout the UK. Many of these plants are used for the conversion of food or agricultural waste into valuable products, and in general AD is more suitable for wet biomass resources. Innovation needs focus around feedstock pre-treatment to maximize gas yield, and characterisation of digestate. Current research being carried out in the Supergen Bioenergy Hub is investigating the potential to process the biomethane from AD via pyrolysis. This would convert the biomethane to a hydrogen-rich gas and a solid carbon-rich material, with potential for decarbonising the agricultural sector and sequestering carbon in soils.
- Traditional biomass fermentation processes produce CO_2 as a biproduct, but the CO_2

emitted may be used as a feedstock in secondary fermentation by autotrophic microbes able to recycle this carbon into further products. Syngas produced by gasification can also be used as a feedstock for microbial fermentation. The conversion of syngas into chemical products by microbial catalysts has several advantages over thermochemical conversion such as Fischer-Troph synthesis. The operating and production costs of gas fermentation are reduced as they do not require the high temperatures or pressures associated with Fischer-Troph. Biocatalysts also offer greater flexibility as microorganisms are less sensitive to impurities in gas mixtures and require no specific ratio of the syngas components. Accordingly, gas fermentation does not require the complex gas conditioning needed by Fischer-Troph, just a simple gas purification step. Syngas fermentation by autotrophs typified by acetogenic bacteria produce acetic acid, ethanol or other organic compounds and solvents. Using syngas as a feedstock for microbial fermentation permits a regular, sustainable, feedstock supply to be produced from a variety of sources thus ensuring consistency of product.

BECCS:

- BECCS can deliver effective greenhouse gas removal (GGR) at a significant level, resulting in a unique capability to remove carbon from the atmosphere while simultaneously providing energy, products, and other services. However, the GGR potential of different BECCS supply chains varies considerably, depending on the technology and the operational performance. While large scale electricity can deliver high GGR, this is down to a technology with low efficiency. In other words, lots of biomass is used to generate electricity and hence lots of carbon can be captured and stored/used, but this is not an efficient way of using biomass. More efficient technologies like combined heat and power (CHP) and gasification (pre-combustion) require less biomass per unit of energy and have often a higher carbon capture efficiency due to the increased purity of the flue gas stream. Studies have indicated that post-combustion systems might only achieve -700 g CO_2/kWh; more than 20% less than the -850 g CO_2/kWh that can be achieved with pre-combustion (gasification) systems. In addition, pre-combustion carbon capture offers the opportunity to produce hydrogen. While CHP and gasification have limits on upscaling in plant size, they offer greater flexibility and more modular upscaling opportunities [80]. The most appropriate choice of technology is determined by which greenhouse gas reduction measure/parameter is prioritized by policy focus [49].
- Gasification has long been of interest in the UK with 130 “advanced thermal conversion” plant proposals in the UK since 1995. In 2019, 15 UK plants were registered as operational, most of which have had significant operational issues and consequently, low capacity factors. In the absence of a GGR incentive and support for low-carbon electricity, commercial operators favour waste feedstocks (limiting the opportunity for GGR) and established electricity markets.
- In academia, gasification has attracted increasing attention since 2000. Around 3% of published bioenergy papers focus on gasification, with over half of these having been published since 2014. The dominant focus is on fluidised bed technology. UKRI has funded 23 gasification projects since 2002 across 17 universities. These projects often focused on the challenge of tar management and contaminant control within an integrated system.
- Another approach to BECCS is to utilise the near-pure stream of CO_2 that is produced as a by-product of fermentation of biomass to produce fuels or chemicals. The capture of carbon from fermentation processes offers a relatively low-cost option for carbon abatement through BECCS taking advantage of the high purity CO_2 gas produced at existing ethanol facilities and therefore avoids the costly separation of CO_2 associated with combustion processes.
- In 2019, 5 BECCS facilities were operating globally (4 in the US and 1 in Canada) all linked to corn to ethanol production; with 3 in progress in Japan, Norway, and the UK pilot facility

at Drax (Supergen Bioenergy Hub Industrial partner). None of these plants utilise gasification. To improve the economic viability of BECCS systems it makes sense to move away from an approach of “storing” carbon; instead making use of the carbon atoms as valuable sources of materials and products. This makes environmental sense to shepherd carbon atoms to useful material products and adds value to the BECCS system by integrating additional value-added product opportunities. These could include applications such as synthesis of synthetic fuels/hydrocarbons, polymers, synthetic textiles etc.

Question 23- What are the barriers and risks to increasing the deployment of advanced technologies (e.g., gasification, pyrolysis, biocatalysis) and what end use sectors do you see these being applied to?

Policy certainty and consistency:

- Our industrial partners highlighted that one of the difficulties for producers and investors has been the changing views and policies relating to biomass supply and use. It is key that policy relating to biomass feedstocks and their role in achieving net zero is consistent across government departments and sectors, and that there is policy certainty in the medium to long term.

Question 24 - In what regions of the UK are we best placed to focus on technological innovation and scale up of feedstock supply chains that utilise UK-based biomass resources?

- While it is always advisable to carry out process, life cycle and techno-economic analysis it also makes economic sense to match feedstock arisings to end use demands, and these often coincide in rural areas. For example significant agricultural and arboricultural residues in part of the South West, Yorkshire, Scotland and Wales, and significant manure and animal residues in the west Midlands and Northern Ireland are natural fit with production of low carbon liquids and gases via thermochemical and biological pathways to service off-grid demands in rural regions of the UK.

Question 25 - Post-combustion capture on biomass electricity generation is one method in which BECCS can be deployed to deliver net-zero. Specifically, how could innovation support be targeted to develop the maturity of other BECCS applications, such as biomass gasification?

- Gasification has significant technical potential based on several reports by Supergen Bioenergy Hub [92]. However, innovation needs persist. For gasification, syngas clean-up (tar removal in particular) remains a technical challenge. There is significant UK expertise on thermocatalytic, catalytic, and low and high temperature plasma approaches to gas upgrading that need to be characterized and pursued. This can include the use of biomass ash, process optimisation, investigation of economies of scale, efficiency improvements, process compatibility and automation [93]. Small or modular deployments may be favourable to minimize feedstock costs, reduce scale-up and investment risk and address location/acceptability issues. A chronic problem in the UK has been attempts to deploy technology by small, less well-resourced companies with high levels of specific but less breadth of expertise. When problems are encountered this quickly gives rise to financial and other difficulties with (sometimes premature) termination of projects before learning points have been fully extracted and potentially addressed. Better mechanisms are needed for academic-industrial collaboration through TRLs 3-6.

Question 26 - What other innovation needs to take place in order to reduce life cycle GHG emissions and impacts on air quality in biomass supply chains? Are all these easily achievable, and if not, what are the barriers?

Innovations for biomass crops:

- Delivering the necessary upscaling in bioenergy crop deployment demands new crop varieties and increased diversity to provide resilience and allow different land types to be used. Significant progress has been made in recent years and reported in the literature [94, 95]. Moreover, genomic sequencing of energy crops and tools such as genomic prediction will enable an acceleration of the rate at which new varieties can be developed [96, 97]. Seed based hybrids offer advantages for upscaling and reduction in establishment costs and in the energy used in planting compared to the lifting and transport of rhizomes [98, 99].
- As well as the innovations in plant biology that are needed to improve yields and reduce costs, there should also be a focusing on producing biomass feedstocks that serve multiple purposes, including acting as a source of high value chemicals.
- As with terrestrial plants, increased production of algae for use as a biomass resource requires innovation. There is the need to domesticate more seaweed species to match the species grown to the site selected for production.

Fuel upgrading:

- There is a need to focus on minimizing the energy and carbon intensity of fuel upgrading in order to meet incumbent standards for fossil liquids and gases. This upgrading is possible but adds significant GHG burdens to the overall process.

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The Carbon Recycling Network, the High Value Biorenewables Network and the Biomass Biorefinery Network are three of the phase II Networks in Industrial Biotechnology & Bioenergy funded by the BBSRC (BBSRC-NIBB) to encourage the growth of Industrial Biotechnology in the UK.

The aim of the Biomass Biorefinery Network is to act as a focal point to build and sustain a dynamic community of industrial and academic practitioners who will work together to develop new and improved processes for the conversion of non-food biomass into sustainable fuels, chemicals and materials.

The Carbon Recycling Network promotes those aspects of carbon recycling that support the re-use and exploitation of single carbon (C1) greenhouse gases, CO, CO_2 and CH_4. The focus is on gas fermentation, primarily using chemoautotrophs, and seeks to explore the potential of anaerobic digestion (AD) as a gas fermentation feedstock generator. The Network provides events and activities to foster and enhance collaboration between industry and academia; inform policy makers; train the next generation of scientists and educate the public.

The High Value Biorenewables Network actively promotes and facilitates collaboration between academia and industry in the Biorenewables sector, and works to promote discovery, development and application of bio-based chemicals, tools and platform technologies, facilitate partnership and knowledge transfer between UK academia and industry, and provide inspirational leadership to the Industrial Biotechnology community in the UK.

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The Supergen Bioenergy Hub works with academia, industry, government, and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future.

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