BB-REG-NET

# Making the most of biomass

## Guiding Principles for Biomass Utilisation in Policy Development

Lead Author: Dr Adrian Higson*

Contributing Authors: Ms Polly-Ann Hanson*, Dr Gail Shuttleworth*, Dr Jen Vanderhoven**

Organisation: Alder BioInsights*, BBIA**

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# List of Abbreviations

| | |
|---|---|
| AD | Anaerobic Digestion |
| BECCS | Bioenergy with Carbon Capture and Storage |
| BPT | Biomass Priority Tower |
| CCS | Carbon Capture and Storage/Sequestration |
| $CO_2$ | Carbon Dioxide |
| DEFRA | Department for the Environment, Food and Rural Affairs |
| DESNZ | Department for Energy Security and Net Zero |
| DfT | Department for Transport |
| DST | Decision Support Tool |
| EJ | Exajoule |
| EU | European Union |
| GGR | Greenhouse Gas Removals |
| GHG | Greenhouse Gas |
| Gt | Gigatonnes |
| IEA | International Energy Agency |
| IPPC | Intergovernmental Panel on Climate Change |
| LCA | Life Cycle Analysis |
| Mt | Million tonnes |
| NGO | Non-Governmental Organisation |
| NZE | Net Zero Emissions |
| TWh | Terawatt-hours |

# Executive Summary

The transition to a sustainable, climate-aligned and growing economy requires a fundamental shift in how society sources and uses carbon. Today, nearly all chemicals and materials rely on fossil feedstocks, locking the global economy into emissions-intensive production and continued resource extraction. Biomass - together with captured $CO_2$ and recycled carbon - offers a renewable alternative, but it is a finite resource under increasing pressure from climate impacts, land-use competition, and growing global demand for food, materials, and energy.

This report examines how limited sustainable biomass can be most effectively used in the UK and globally. It reviews the scale of biomass availability, its competing applications, the evolving UK and EU policy landscape, and the environmental and socio-economic factors that must underpin biomass governance.

Drawing on conceptual frameworks such as Moerman's Ladder, the biomass value triangle, principles of cascading use, and the distinction between defossilisation and decarbonisation, the report develops a Decision Support Tool (DST) and proposes an illustrative Biomass Priority Tower (BPT) to inform strategic biomass allocation.

Four core insights emerge:

**1. Biomass is essential but limited.**
Global net primary production is vast, but only a small, uncertain fraction can be harvested sustainably. Even optimistic estimates fall far short of the potential demand from energy, chemicals, materials, aviation, shipping, and land-based carbon sequestration. Electrification and renewable power can displace many biomass-for-energy applications, but unavoidable carbon demand remains in sectors such as chemicals, plastics, aviation fuel, and certain industrial processes.

**2. Competing demands require clear prioritisation.**
Without guidance, biomass deployment risks repeating the extractive patterns of the fossil-based economy. Food production and ecosystem services must remain the highest priorities due to their foundational social value. Beyond these, the optimal uses of biomass are those where no viable low-carbon alternatives exist, where biomass can deliver significant greenhouse-gas reductions, and where its molecular complexity provides unique functional or material advantages. Conversely, technologies where electrification, recycling, or renewable hydrogen can provide the same service should not rely on biomass.

**3. Legitimacy and sustainability are prerequisites for policy and investment.**
The UK's emerging *Common Biomass Sustainability Framework* and the EU Bioeconomy Strategy signal growing policymaker attention to land-use constraints, carbon accounting, and biodiversity protection. Yet stakeholder confidence remains fragile. Effective governance must include enforceable sustainability criteria, transparent supply-chain monitoring, and a prioritisation framework that directs biomass first to high-value, high-impact applications.

**4. A structured hierarchy can guide coherent decision-making.**
Through stakeholder workshops and analysis, BB-REG-NET has developed a Decision Support Tool that evaluates biomass end uses based on social necessity, environmental benefit, substitution potential, technology readiness, and alignment with net-zero pathways. The resulting Biomass Priority Tower ranks applications from high-value "penthouse" uses - food, biodiversity, ecosystem carbon storage, pharmaceuticals - to "basement" uses that can be electrified or satisfied through non-biological renewables, such as domestic road fuels or biomass-fired electricity without carbon capture.

Overall, the report demonstrates that biomass is a critical but constrained resource, and that strategic prioritisation is essential to achieving both defossilisation and net-zero objectives. The BPT and DST offer a practical foundation for aligning industrial strategy, sustainability governance, and innovation policy. They do not prescribe a definitive hierarchy, but they establish a transparent, evidence-based framework for the difficult choices ahead. Achieving consensus on these priorities will be central to unlocking a credible, sustainable, and socially legitimate bio-based economy.

# Introduction

Manufactured chemicals underpin virtually every aspect of modern life: plastics, food production systems, textiles, energy technologies, batteries, defence products, telecommunications devices, and pharmaceuticals. They are indispensable to ensuring food security, enabling clothing and shelter, maintaining national security, facilitating global communication, and providing essential medical treatments.

At present, however, nearly all industrial chemicals are derived from fossil oil and gas, a dependency responsible for approximately 10% of global greenhouse gas emissions[1]. As global temperatures continue to rise, the transition to an environmentally sustainable economy is no longer discretionary but imperative. Continued extraction of fossil resources and the consequent release of carbon dioxide into the atmosphere is fundamentally incompatible with climate-stabilisation goals. A sustainable chemical and materials sector must instead prioritise the utilisation of carbon that is already circulating above ground—whether in biomass, captured carbon dioxide, or recycled feedstocks.

In this context, the UK bio-based sector has articulated an ambitious pathway. Bio-based chemicals and materials—derived from renewable biological resources such as plants, algae, mycelium, and organic wastes collectively termed *biomass*—offer a route to reducing dependence on fossil carbon. The UK chemicals industry aims to double in size by 2050 while sourcing 30% of its carbon feedstock from biomass[2]. With appropriate policy and investment, bio-based chemicals and materials could generate more than £204 billion in annual revenue by 2050[2] and make a substantial contribution to the UK's Net Zero commitments. Evidence indicates that the adoption of just fifteen high-potential bio-based chemicals could deliver greenhouse-gas reductions exceeding 5.2 million tonnes of $CO^3_2$-equivalent each year—surpassing the savings achieved under the 2021 Renewable Transport Fuel Obligation[4].

Yet a chemical and materials industry reliant on geologically derived fossil inputs is inherently unsustainable and structurally incapable of reaching true net-zero emissions. A transition to alternative carbon sources is therefore essential. Crucially, however, this transition cannot be envisioned as a simple substitution of one raw material for another. Biomass is finite, multifunctional, and subject to competing demands from energy, agriculture, materials, and ecosystem services. Without a strategic framework, increasing biomass use risks reproducing the same extractive patterns that have characterised fossil-based production.

This is why a biomass utilisation hierarchy is necessary. Such a hierarchy provides a structured decision-making framework that prioritises biomass for the highest-value and highest-impact applications—those where no viable low-carbon substitutes exist and where biomass can deliver genuine climate and resource-efficiency benefits. Applying this hierarchy ensures that the shift to bio-based manufacturing is not merely a change in feedstock but a broader re-engineering of production systems, consumption patterns, and value chains. In doing so, it supports a transition towards a resilient, circular, and climate-aligned chemicals and materials economy.

For a bio-based economy to flourish, it must contend with two central challenges: cost and societal acceptance. From the perspective of consumers, cost remains the most immediate and

[1] Bauer, F., Kulionis, V., Oberschelp, C., Pfister, S., Tilsted, J. P., Finkill, G., Fjäll, S., 2022, Petrochemicals and Climate Change: Tracing globally growing emissions and key blind spots in a fossil-based industry, https://lup.lub.lu.se/search/files/117494791/Petrochemicals_climate_change_review_web.pdf

[2] Higson, A., Hobson, J., Mason, S., Vanderhoven, J., 2024, Innovate UK: Sustainable carbon ambition for the UK chemicals industry, https://iuk-business-connect.org.uk/perspectives/sustainable-carbon-ambition-for-the-uk-chemicals-industry/

[3] DESNZ: Project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223) 2024, unpublished

[4] DfT, 2025, The Renewable Transport Fuel Obligation – an essential guide Road Traffic Fuel Obligation https://assets.publishing.service.gov.uk/media/65a8113db2f3c60013e5d4ce/rtfo-essential-guide-2024.pdf

influential barrier. Bio-based products must achieve price parity—or demonstrate clearly superior performance—to overcome entrenched preferences for cheaper, fossil-derived alternatives.

For policymakers, however, acceptance and legitimacy are the more decisive concerns. Policy support will not be mobilised solely on the basis of cost; rather, it depends on whether bio-based production is perceived as environmentally credible, socially just, and aligned with long-term resource constraints. This is especially pressing given a fundamental structural reality: there is not enough sustainable biomass to meet all potential demands from energy, chemicals, materials, food, and ecosystem services. Consequently, questions raised by NGOs and the academic community about land-use competition, carbon neutrality claims, and biodiversity impacts—initially levelled at biofuels—extend to the broader suite of bio-based products.

Policymakers must therefore be confident that biomass will be directed to its highest-value and most appropriate uses, rather than reproducing the extractive dynamics that have characterised fossil-based systems. Establishing this legitimacy is essential for securing the policy frameworks, investment signals, and public trust needed to enable a cost-competitive and sustainable bio-based economy.

The 2012 Green Europe Foundation report *A Strategy for a Bio-based Economy* laid out the challenges facing the sustainable use of biomass, presenting the major concerns, many of which, remain as challenges to development in 2025.

- **Carbon Balance:** When land is converted for biomass production, it can release carbon stored in soil and vegetation, creating a "carbon debt." This needs to be weighed against the carbon savings gained by manufacturing bio-based products instead of fossil-based ones.
- **Food Supply:** As demand grows for both industrial biomass and energy crops, more land is used for these purposes. This can affect the availability and affordability of food by competing with agricultural land needed to feed people.
- **Land Scarcity:** There may not be enough suitable land to meet all demands—from food production to bioenergy, conservation, and urban development. This competition can force changes in land use that have broad social impacts.
- **Resource Scarcity:** Producing biomass can require significant water and nutrients. In many regions, these resources are limited, creating sustainability concerns and competition with other essential uses.
- **Limited Focus on High-Value Bio-based Products:** Current policies largely incentivise the use of biomass for low-value outputs like biofuels and bioenergy, rather than promoting higher-value bio-based materials and chemicals that could deliver greater economic and environmental benefits.
- **Lack of Governance Structures:** The bioeconomy spans many policy sectors—energy, agriculture, industry, biodiversity, and more. Without coordinated and consistent governance across these areas, development of a sustainable bioeconomy is slowed or fragmented.

Thirteen years on questions over biodiversity impacts, concerns around food security and continuing questions on the potential for greenhouse gas emission reductions, serve to reduce the acceptance of bio-based products as a positive change for good.

This position has resulted in the discrepancy seen between positive policy statements, recognising the need to reduce fossil-based feedstocks into chemicals and material production, and the inertia in the actual practical implementation of policy.

Therefore, unlocking the full potential of the bio-based economy rests on achieving a consensus between stakeholders on what a transition could look like and how it should be managed.

It is not disputed that biomass availability is finite, and indeed the supply of sustainably sourced biomass is already insufficient to meet the current economy's demand for virgin fossil-based resources. But this scarcity will only worsen, due to two intersecting pressures:

Climate change threatens the availability of land suitable for biomass production — through desertification, sea-level rise, changing rainfall patterns, or other ecosystem impacts.

Meanwhile, increasing global population and demand for food, plus land being set aside for nature protection and biodiversity, create competing pressures on the same land base that biomass depends on.

**Policy and planning must recognise these constraints**

In the UK, the government launched a consultation on what will become a *Common Biomass Sustainability Framework* (December 2025)[5]. This aims to set minimum sustainability criteria for biomass feedstocks (both domestic and imported), covering land use / land-criteria (including forest carbon stocks, biodiversity, legal harvesting, ecosystem protection) and greenhouse-gas criteria (full life-cycle emissions, carbon savings compared to fossil-based resources).

The framework will, however, apply initially to biomass used in government-incentivised sectors (power, heat, transport, industry), and may later be adopted more broadly for feedstocks for the chemicals and materials sector — helping to enforce sustainability across the biomass supply chain.

Recognising the interplay with land use, the consultation on a *UK Land Use Framework* (2025)[6] also addresses the difficulty in meeting simultaneously climate, food security, conservation, and biomass demand. As argued by the Supergen Bioenergy Hub, the scale and complexity of land use change needed may be underestimated, and simply allocating land for biomass without careful planning risks undermining food production, ecosystem integrity, and carbon-sequestration potential[7].

Moreover, at the European Commission's *Strategic Framework for a Competitive and Sustainable EU Bioeconomy*[8] calls for ensuring the "sustainable supply of biomass" — both from within the EU and through responsible imports. It emphasises a shift from volume-driven bioenergy to a more circular, resource-efficient, and high-value bioeconomy: prioritising biomass for materials, bioproducts, and bio-based manufacturing — not just energy.

However, critics point out that while the Strategy maps biomass availability and calls for "efficient use," it falls short of establishing a robust, enforceable hierarchy that would guarantee the scarce bioresources are directed first to highest-value, low-impact uses (e.g. materials, circular economy) rather than lower-value, high-pressure uses like large-scale bioenergy[9].

In short: the finite and already stretched supply of sustainable biomass — made scarcer by climate impacts, land-use competition, and biodiversity needs — means that any large-scale substitution of fossil resources with biomass must be handled very carefully. The new UK and EU policy instruments (the Common Biomass Sustainability Framework and the EU Bioeconomy Strategy 2025) acknowledge this — but their effectiveness will depend on translating broad goals into strict,

[5] DESNZ, 2025, Common biomass sustainability frameworkhttps://www.gov.uk/government/consultations/common-biomass-sustainability-framework
[6] DEFRA, 2025, Land Use Consultation, https://consult.defra.gov.uk/land-use-framework/land-use-consultation/
[7] Supergen Bioenergy Hub, 2015, Supergen Bioenergy Hub response to UK Government consultation on land use framework, https://www.supergen-bioenergy.net/wp-content/uploads/2025/04/Land-use-consultation_20250430_branded.pdf
[8] European Commission, 2025, Commission presents new Bioeconomy Strategy to drive green growth, competitiveness and resilience across Europe, https://ec.europa.eu/commission/presscorner/detail/en/ip_25_2819
[9] European Environmental Bureau, 2025, Commission's Bioeconomy Strategy falls short of curbing Europe's resource crisis https://eeb.org/de/commissions-bioeconomy-strategy-falls-short-of-curbing-europes-resource-crisis

enforceable criteria, careful land-use planning, transparent supply-chain monitoring, and a hierarchy of biomass uses prioritising high-value, low-impact applications over simple high-volume bioenergy.

In developing a sustainable bioeconomy, decisions will need to be made on how and for what we use our valuable land and biomass resource.

In support of these important decisions, BB-REG-NET has reviewed existing thinking and conceptual frameworks on how to prioritise biomass use and has developed a Decision-Support Tool (DST) to inform the assessment of different biomass applications. This tool is intended to act as a foundation for exploring how a biomass use hierarchy could be structured. The aim is not to prescribe a definitive hierarchy, but rather to stimulate informed discussion and collective reflection on how best to ensure that scarce biomass resources are used optimally and equitably. By encouraging dialogue across stakeholders, the framework seeks to promote decision-making that delivers sustainable outcomes for industry, society, and the environment.

Accordingly, the subsequent Biomass Priority Tower (BPT) should be taken as an example of biomass use rankings rather than a definitive ranking – since how the user of the DTS views the technology readiness, feasibility of deployment and the availability of alternative approaches for the particular biomass application, will influence its position in the tower.

# Background

## Biomass availability

The total mass of biomass on the Earth is estimated to be approximately 550 Gt carbon (Figure 1), of which, around 80% is plant biomass[10] - of which ≈70% is stems and tree trunks, which are mostly woody. Whereas plant biomass is predominantly terrestrial, animal biomass is dominated by arthropods found in the marine environment. The second largest source of biomass is bacteria, representing approximately 70 Gt carbon of biomass.

Above ground biomass equates to around 320 Gt carbon representing around 60% of global biomass, with below ground biomass composed mainly of plant roots (~130 Gt carbon) and, soil and deep subsurface microbes represent around 100 Gt carbon.[10]

In regard to annual global biomass production, the global net primary production (NPP) of biomass has been estimated at 105 Gt of carbon per year, with roughly equal contributions coming from land and oceans.[11,12] Yearly above ground biomass production represents 30-32 Gt carbon of the NPP, this translates to approximately 1,100 EJ (1 EJ = $10^{18}$ joules) and can be considered the biospheres maximum annual land production capacity[13,14]. To give perspective, 1 EJ is equivalent to the annual electricity consumption of ~25 million UK households, and the global primary energy use today is roughly 600–700 EJ/year.

[10] Bar-On, Y. M., Phillips, R., Milo, R., 2018, The biomass distribution on Earth, Proc. Natl. Acad. Sci. U.S.A. 115 (25) 6506-6511, https://doi.org/10.1073/pnas.1711842115.
[11] ITO, A., 2011, A historical meta-analysis of global terrestrial net primary productivity: are estimates converging? Global Change Biology, 17: 3161-3175. https://doi.org/10.1111/j.1365-2486.2011.02450.x
[12] Field C. B., Behrenfeld M. J., Randerson J. T., Falkowski P., 1989, Primary production of the biosphere: integrating terrestrial and oceanic components. *Science*. 281(5374) 237-240, doi:10.1126/science.281.5374.237
[13] Sertolli, A.; Gabnai, Z.; Lengyel, P.; Bai, A. Biomass Potential and Utilization in Worldwide Research Trends—A Bibliometric Analysis. Sustainability, 2022, 14, 5515. https://doi.org/10.3390/su14095515
[14] Haberl, H., Erb, K-H., Krausmann, F., Running, S., Searchinger, T. D., Smith, W. K., 2013 Environ. Res. Lett. 8 031004. https://doi.org/10.1088/1748-9326/8/3/031004

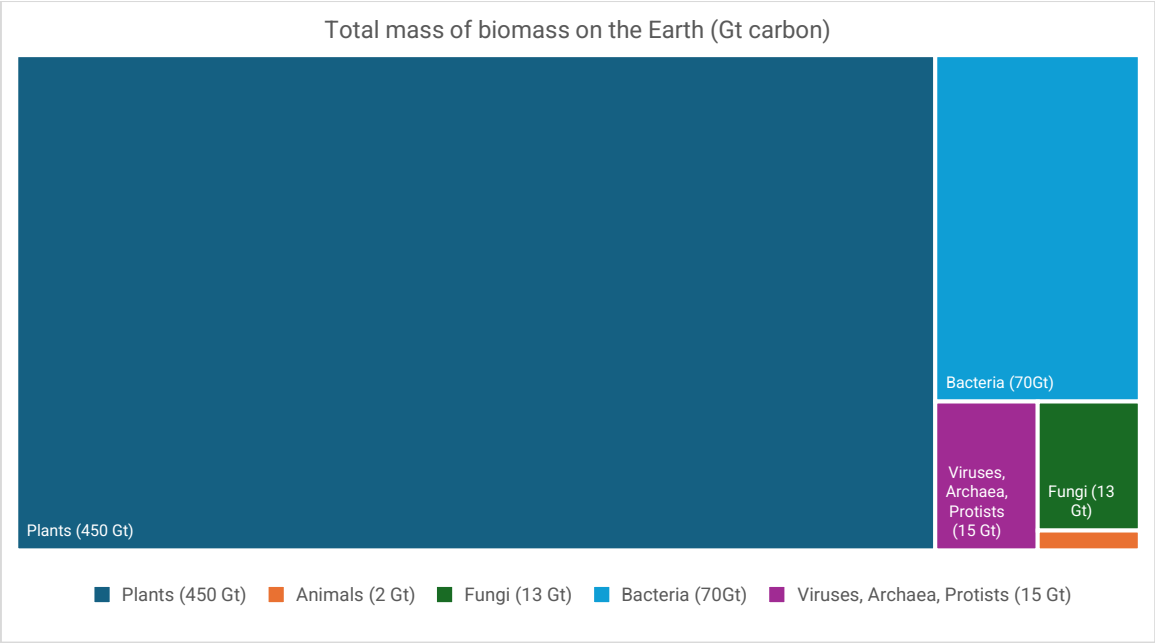



**Figure 1. Total mass of biomass on the Earth (Gt carbon)**

*Sustainable production potential*

While around 30 Gt carbon represents the biospheres maximum production of harvestable biomass, there is a wide debate and considerable variation around what volume of biomass could be sustainably harvested. The theoretical maximum bioenergy potential has been estimated at 20 Gt carbon while the biospheric land capacity has been assessed as 18 Gt carbon[15,16].

Many studies have assessed the global availability of biomass for bioenergy.[17,18,19] These potential biomass availability studies have returned a large range of results reflecting the authors views on what would/could be accepted as the conditions for the biomass to be regarded as sustainable.

Biomass availability assessment can be broadly divided into two types, those that test the boundaries of what might be physically possible and those that explore the boundaries of what might be socially or environmentally responsible. Because many of the most important factors affecting biomass potentials cannot be predicted with certainty and depend on a range of value judgements, all estimates of availability should be considered 'what if' scenarios rather than predictions.[20]

Key variables in estimating potential biomass availability include.

- The rate of improvements in crop yields.
- The extent to which productive agricultural land is used for biomass crop cultivation.
- The level of intensive farming practices used (e.g. plant protection products, fertiliser use rates, and rain fed versus irrigated cultivation), or vice-versa, the use of regenerative farming practices.
- Judgements of the size of the future global population, and energy and food needs.
- Changes in diet (i.e. moves to plant-based diets).

[15] Netherlands Environmental Assessment Agency, 2014, Integrated analysis of global biomass flows in search of the sustainable potential for bioenergy production, https://www.pbl.nl/uploads/default/downloads/pbl-2014-integrated-analysis-of-global-biomass-flows-in-search-of-the-sustainable-potential-for-bioenergy-production-1509.pdf
[16] Mensah, T., N., O., Solomon, O., Breyer, C., 2025, The global sustainable bioenergy potential until 2050 in global-national resolution. Applied Energy. 400. 10.1016/j.apenergy.2025.126464. (PDF) The global sustainable bioenergy potential until 2050 in global-national resolution
[17] Black, M., Richter, G. M., Mapping out global biomass projections, technological developments and policy innovations. 2010, International Institute for Environment and Development (IIED), https://www.iied.org/sites/default/files/pdfs/migrate/G02986.pdf
[18] Slade. R., Energy from biomass: the size of the global resource, 2010, https://ukerc.ac.uk/project/energy-from-biomass/
[19] Fuss. S., et al, 2018, Environ. Res. Lett. **13** 063002, **DOI** 10.1088/1748-9326/aabf9f
[20] UK Energy Research Centre, Energy from biomass: the size of the global resource, UK Energy Research Centre, https://ukerc.ac.uk/project/energy-from-biomass

At the lower end of the availability estimates are studies where cultivated biomass volumes are limited, either by restricting land availability by allocating land to ecosystem or cultural functions i.e. national parks, or through limiting the cultivation of biomass crops to degraded or marginal lands. Other estimates at the lower end of availability are based solely on the use of currently available biomass residues or in line with 2050 availability estimates.

Studies with less restrictive constraints on land availability e.g. more productive cropland land is used to cultivate biomass crops or less land reserved for nature conservation, show higher biomass availability values. Availability estimates from these studies typically lie in the 7-15 billion tonne biomass range. This equates to around 3-7 billion tonnes of carbon.

Other assessments have produced higher estimates for availability. Estimates increase on the basis on inclusion of more biomass sources, e.g. algal biomass, more intensive farming techniques e.g. increase fertiliser use and irrigation, positive assumptions on biomass crop yield improvements and the increasing use of productive grass lands for biomass crop cultivation. These more optimistic assessments suggest biomass availabilities in the range of 19-83 billion tonnes, equating to around 8-33 billion tonnes of carbon, with upper estimates representing theoretical potential rather than practical or sustainable realities.

## Current and future biomass demand

Biomass can be used in a vast variety of applications, these can be categorised as food, animal feed, materials, chemicals, liquid/gaseous fuels or solid energy products.

Each year approximately 5.8 Gt of carbon (230 EJ) of biomass is harvested for human use, including food, livestock feed, materials, and energy (Figure 2).[21] It is estimated that in order to produce this volume of harvested biomass a further 1.8 Gt (70 EJ) of biomass is either left in the field or burned in vegetations fires.[19] The volume of biomass harvested annually for energy purposes is around 1.4Gt carbon (55 EJ).[22]

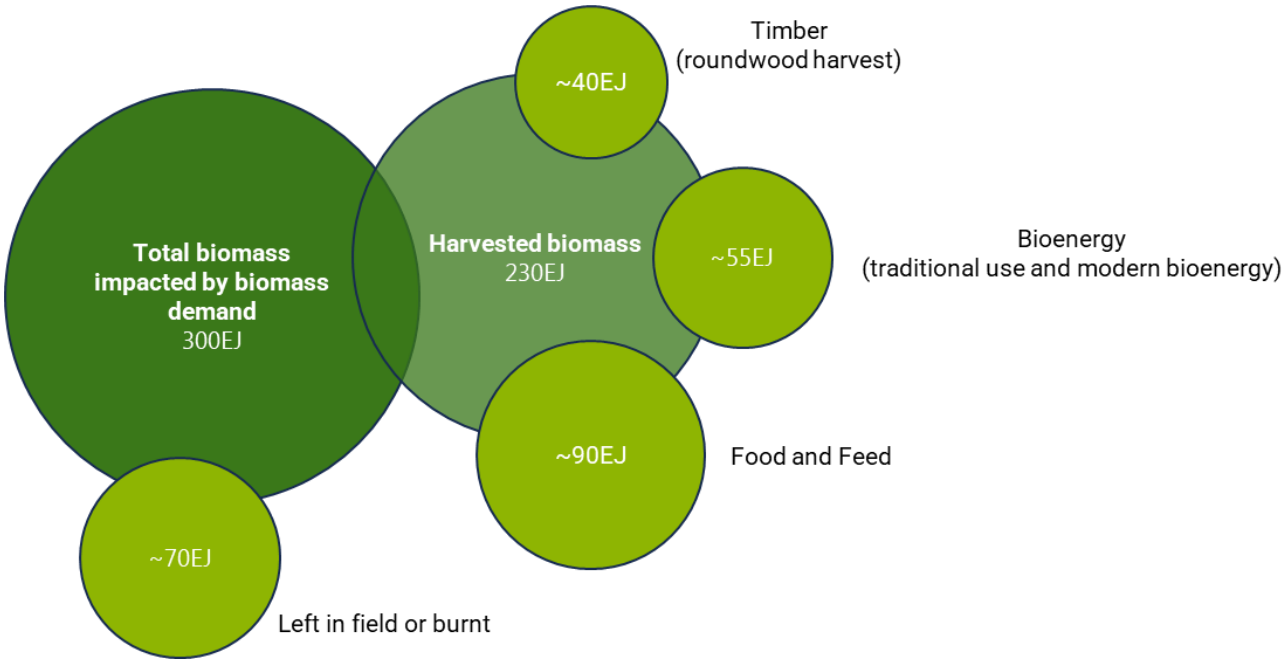



**Figure 2. Estimation of how globally harvested biomass is utilised in 2025**
BB-REG-NET estimation based on multiple sources.

[21] Haberl, H., Erb, K-H., Krausmann, F., Running, S., Searchinger, T. D., Smith, W. K., 2013 Environ. Res. Lett. 8 031004. https://doi.org/10.1088/1748-9326/8/3/031004
[22] IPCC, 2012, Special Report on Renewable Energy Sources and Climate Change Mitigation (Cambridge: Cambridge University Press)

In contrast, as of 2024, the global total annual energy demand stood at 650 EJ.[23] Industry and transport represent the largest consuming sectors, accounting for 30% and 20% of final energy demand respectively.[24] The residential sector is also a large consumer of energy accounting for 20% of energy consumption.

In 2023, the energy demand from global aviation was 13 EJ.[25] This equates to 10% of the world's transport-related energy consumption and 3% of total global energy consumption. In the same year energy consumption in the shipping sector reached 11 EJ.[26] However the demand for aviation could double by 2050 with projections indicating a demand for 500 Mt of aviation fuel.[27]

Under future net zero scenarios which account for food supply and environmental considerations, estimates of the future demand for biomass to supply bioenergy, range from 85 – 250 EJ per year[28,29,30.]

The IEA's Net-Zero Emissions by 2050 (NZE) Scenario is modelled on a total primary bioenergy demand of 100 EJ. This level of demand, which includes losses from the conversion of biomass into useful fuels, falls within lower estimates of biomass potential.[31] Equivalent scenarios produced by the Intergovernmental Panel on Climate Change (IPCC) aligned at limiting global warming to an average of 1.5°C above pre-industrial levels, use a median 2050 demand of 200 EJ of bioenergy.[32] Table 1shows the various biomass for bioenergy demand scenarios shown in EJ, Gt of biomass and Gt of carbon.

**Table 1. Biomass for bioenergy demand scenarios**

| | Energy (EJ) | Biomass (Gt) | Carbon (Gt) |
|---|---|---|---|
| Current bioenergy | 55 | 3.1 | 1.4 |
| IEA Net Zero 2050 (bioenergy demand) | 100 | 5.6 | 2.5 |
| IPPC scenarios (median bioenergy demand) | 200 | 11 | 5.0 |

In the IEA's 100 EJ scenario, roughly 60% of delivered energy is expected to be solid bioenergy, around 24% from liquid biofuels, and 16% from biogases. Of solid bioenergy demand, around 35 EJ is consumed in electricity generation. Although this is only 5% of total electricity generation it is considered an important complement to variable generation from renewables like solar PV and wind. A further 20 EJ of solid bioenergy is considered necessary to meet the need for high temperature heat that cannot be easily electrified such as in paper and cement production. Half of total biogas use is in the industry sector, where biomethane replaces natural gas as a source of high temperature process heat. A further 20% goes to each of the buildings and transport sectors.

However, biomass is more than a feedstock for the production of bioenergy. Biomass is a key source of renewable carbon, which, alongside atmospheric and recycled carbon, represents the

[23] IEA, 2025, Global Energy Review 2025, https://www.iea.org/reports/global-energy-review-2025/global-trends
[24] IEA, 2025, Word energy supply, https://www.iea.org/world/energy-mix
[25] IRENA, Aviation, https://www.irena.org/Decarbonising-hard-to-abate-sectors-with-renewables-Enablers-and-recommendations/Transport-sector/Aviation?utm, (accessed Dec 2025)
[26] IRENA, Shipping, https://www.irena.org/Decarbonising-hard-to-abate-sectors-with-renewables-Enablers-and-recommendations/Transport-sector/Shipping?utm, (accessed Dec 2025)
[27] IATA, 2025, Global Feedstock Assessment for SAF Production Outlook to 2050, https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf
[28] IEA Bioenergy, 2009, https://www.ieabioenergy.com/wp-content/uploads/2013/10/MAIN-REPORT-Bioenergy-a-sustainable-and-reliable-energy-source.-A-review-of-status-and-prospects.pdf
[29] Haberl, H., Beringer, T., Bhattacharya, S. C., Erb, K-H., Hoogwijk, M., 2010, The global technical potential of bio-energy in 2050 considering sustainability constraints, Current Opinion in Environmental Sustainability, Volume 2, Issues 5–6, Pages 394-403, https://doi.org/10.1016/j.cosust.2010.10.007.
[30] https://www.sciencedirect.com/science/article/pii/S1364032114000677
[31] IEA, 2021, What does net-zero emissions by 2050 mean for bioenergy and land use? https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use
[32] IEA, 2021, A closer look at the modelling behind our global Roadmap to Net Zero Emissions by 2050, https://www.iea.org/commentaries/a-closer-look-at-the-modelling-behind-our-global-roadmap-to-net-zero-emissions-by-2050

only sustainable alternatives to the use of fossil resources for the production of chemicals and materials.

As of 2012 the chemical industry was estimated to account for 10% of global energy demand. This annual demand for 42 EJ of fossil resources is comprised of 15 EJ for process energy and a further demand of 27EJ as process feedstock.[33] The equates to a carbon demand of 0.68 Gt. A more recent estimate of final energy use, including feedstock was put as 48 EJ/year in 2020, of which 50% (24 EJ) of demand was considered to be used as process feedstock.[34]

The chemical industry is estimated to use a total 1.2 billion tons of fossil derived hydrocarbons (natural gas, petroleum and coal) as process fuel and feedstocks. Around 70% of hydrocarbons are considered feedstock which equates to a carbon demand of approximately 0.7 Gt of carbon.[35] The Renewable Carbon Initiative calculates that 0.55 Gt of carbon is embedded in chemicals and derived materials.[36]

Clearly, with an annual energy demand of 650 EJ and a sustainable biomass supply in the range of 100 to 250EJ, biomass cannot simply act as a replacement for fossil fuels. Fortunately, this transition is unnecessary, many energy applications can be electrified with the majority of renewable electricity being generated through wind and solar technology avoiding the need to burn biomass.

However, just considering the hard to decarbonise sectors of aviation and marine transport, plus the impossible to decarbonise need for carbon as a feedstock in the chemical sector, this represents a current but growing demand of 24 EJ of liquid fuel demand in the aviation and marine sectors plus a demand for 0.55 Gt of carbon in chemicals and their derived products.

Allowing for conversion losses, the volume of biomass required to serve these three markets is in the order of 72 EJ.[37] Furthermore without significant efforts to curb growing consumptions this demand could potentially double by 2050.

Additionally, current policies place further demands on biomass to supply road transport fuel or generate electricity – particularly with carbon capture and storage. Further demand arises from the need to raise industrial heat and a variety of other uses.

Therefore, even with an extensive electrification of the global energy system, the demand for biomass will outstrip sustainable supply and decisions on how limited biomass should be used will be required considerably earlier than 2050.

## Biomass in the UK

The UK's utilised agricultural area is 16.8 million hectares accounting for 69% of the total area of the UK.[38] The total croppable area is 6.2 million hectares. The area of woodland in the United Kingdom is around 3.3 million hectares.[39] Additionally the UK has an extensive coastline and the potential to increase marine biomass production.[40]

[33] ICCA, 2013, Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes, https://icca-chem.org/wp-content/uploads/2020/05/Technology-Roadmap.pdf
[34] Ünlü, G., Maczek, F., Min, J., Frank, S., Glatter, F., Natsuo Kishimoto, P., Streeck, J., Eisenmenger, N., Krey, V., & Wiedenhofer, D., 2024, MESSAGEix-Materials v1.0.0: Representation of Material Flows and Stocks in an Integrated Assessment Model, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-3035
[35] Eryazici, I., Ramesh, N. & Villa, C., 2021, Electrification of the chemical industry—materials innovations for a lower carbon future. *MRS Bulletin* 46, 1197–1204. https://doi.org/10.1557/s43577-021-00243-9
[36] Renewable Carbon Initiative, 2023, RCI carbon flows report – Compilation of supply and demand of fossil and renewable carbon on a global and European level, https://renewable-carbon.eu/publications/product/the-renewable-carbon-initiatives-carbon-flows-report-pdf/
[37] Based on an average 20% mass yield of SAF from biomass (https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/safr-1-2015.pdf), and an average 45% carbon conversion mass yield for chemical production.
[38] DEFRA, 2024, Agricultural Land Use in United Kingdom at 1 June 2024, https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom/agricultural-land-use-in-united-kingdom-at-1-june-2023
[39] Forest Research, 202), Forestry Statistics 2024, https://www.forestresearch.gov.uk/tools-and-resources/statistics/publications/forestry-statistics/forestry-statistics-2024/
[40] CEFAS, 2016, Seaweed in the UK and abroad – status, products, limitations, gaps and Cefas role, https://assets.publishing.service.gov.uk/media/5a804b31ed915d74e33f9981/FC002I__Cefas_Seaweed_industry_report_2016_Capuzzo_and_McKie.pdf

In recent years the UK has operated a trade deficit in cereals and is heavily dependent on the import of biomass to fulfil its wood product and bioenergy demand.

In 2023 the UK harvested 10 million cubic meters of wood, however imports accounted for 80% of all wood (production and imports) consumed.[41] Imports included 6.2 million cubic metres of sawn wood, 3.1 million cubic metres of wood-based panels, 6.4 million tonnes of wood pellets and 4.8 million tonnes of paper.

For bioenergy applications, domestic production provides 66% of the biomass used, with the remainder derived from international sources.[42] The USDA ranks the UK as the largest global consumer of wood pellets. Their data shows total consumption reaching nearly 9.85 million tonnes, primarily driven by the biomass energy sector.[43] DRAX power station is the UK's largest consumer of wood pellets, in 2024 it generated 15 TWh in 2024 by burning 7.6 million tonnes of pellets, of which 99% was imported.[44]

The *UK Bioenergy Strategy*[45], published in 2012 by the Department of Energy & Climate Change (DECC), HM Treasury, and the Department for Transport, set out the government's long-term vision for the sustainable use of bioenergy. The strategy recognised bioenergy as an important component of the UK's pathway to decarbonisation, while stressing the need for strict sustainability controls. It introduced a set of principles designed to guide government policies on bioenergy. The strategy specified that bioenergy should deliver genuine greenhouse gas (GHG) reductions, make a cost-effective contribution to UK GHG emission objectives, and any increased production should consider the impact on food security and biodiversity, amongst others.

These principles continue to guide strategy and are reflected the 2023 *Biomass Strategy*[46]. While the Biomass Strategy is focussed on the use of biomass in energy applications it does highlight the role of land and biomass in providing ecosystems services as well as wider social and food security considerations.

## How to use limited biomass

As discussed, biomass can be used in a vast variety of applications, and it is this flexibility which results in unsustainable demands and the need to prioritise its use.

The key considerations for prioritising biomass use, are 1) meeting human 'needs' for a safe and healthy life, 2) the protection of the environment, climate, ecosystem services and biodiversity and 3) enabling humans 'wants', delivering economic value and ensuring sustainable businesses. These three pillars of sustainability – social, environmental and economic – require equal consideration in within frameworks guiding biomass use.

While the economic and environmental impacts of biomass use - such as those assessed through carbon footprinting or life-cycle analysis (LCA) - can be measured and rigorously quantified, the process of balancing these impacts within or between the pillars of sustainability is often an ethical or value-based judgement. Such decisions reflect the differing perspectives and priorities of stakeholder groups, including communities, businesses, and non-governmental organisations (NGOs) [47].

As a key recommendation the IEA states that *'increased bioenergy production must not create negative impacts on biodiversity, freshwater systems, food availability or human quality of life'*.[48] It

[41] Forest Research, 2024, Forestry Statistics 2024, https://www.forestresearch.gov.uk/tools-and-resources/statistics/publications/forestry-statistics/forestry-statistics-2024/
[42] DESNZ, 2023, Biomass Strategy, https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf
[43] USDA, 2025, Wood Pellets Annual, United Kingdom, https://www.fas.usda.gov/data/united-kingdom-wood-pellets-annual-0#
[44] EMBER, 2025, Drax is still the UK's largest emitter, https://ember-energy.org/latest-insights/drax-is-still-the-uks-largest-emitter/
[45] DECC, 2012, UK Bioenergy Strategy, https://assets.publishing.service.gov.uk/media/5a79806340f0b642860d8a1a/5142-bioenergy-strategy-.pdf
[46] DESNZ, 2023, Biomass Strategy 2023. https://www.gov.uk/government/publications/biomass-strategy
[47] OECD, 2023, Carbon Management: Bioeconomy and Beyond, OECD Publishing, Paris, https://doi.org/10.1787/b5ace135-en.
[48] IEA, 2024, Bioenergy, https://www.iea.org/energy-system/renewables/bioenergy (accessed December 2025).

goes on to say that *'only bioenergy that reduces lifecycle greenhouse gas emissions while avoiding unacceptable social, environmental and economic impacts should receive policy support'* and concludes that '*sustainability frameworks can help to phase out the traditional use of biomass [for energy] and help scale up a variety of sustainable feedstock supplies'*.

Specifically in regard to the use of biomass in addressing climate change and reducing greenhouse gas emissions, three key questions present themselves.[49]

1) What applications provide the greatest reduction in emissions from a unit of biomass?
2) Could GHG emissions be reduced through the use alternative non-carbon-based approaches?
3) Can biomass-based applications deliver negative GHG emissions?

The following sections of the report introduce conceptual frameworks commonly used to provide guidance around the use of limited biomass resources and consider alternative approaches to climate change mitigation either by targeting a reduction in fossil resource use or through the management of GHG emissions.

## Food First

A reliable and affordable supply of nutritious food is essential to public health and social stability. Because food production is a fundamental component of social sustainability, the use of land and crop biomass for food must be prioritised. Effective food systems are therefore critical for human welfare, ensuring access to adequate, safe, and nutritious food—an underpinning requirement for public health, social cohesion, and national security.

However, the UK Government does not currently have a plan for how the agri-food system will contribute to its 'net zero by 2050' commitment, even though the sector accounts for around 25% of the UK's greenhouse gas emissions. There is also no consensus around a vision for a sustainable UK agri-food system. With a growing population and the pressure of climate change impacting agriculture and the marine environment, it is clear that strengthening food systems is essential.

One of the most contentious topics within the bioeconomy is the use of cereal grains and oilseeds for biofuels production instead of their consumption as human food or animal feed. It is argued that converting edible crops to non-food uses—particularly biofuels—can reduce food availability, elevate prices, and increase market volatility. These effects would disproportionately harm low-income populations and import-dependent countries.[50] [51]

This ethical debate, widely referred to as the 'food versus fuel' debate has been central to biofuel policy development over the last 20 years.[52] The 'food versus fuel' issue has also significantly influenced biofuel research programmes, guiding funding towards the conversion on non-food materials such as lignocellulosic biomass into biofuels.[53]

[49] Supergen Bioenergy Hub, 2024, Carbon for Chemicals -How can biomass contribute to the defossilisation of the chemicals sector? https://www.supergen-bioenergy.net/output/carbon-for-chemicals-how-can-biomass-contribute-to-the-defossilisation-of-the-chemicals-sector/
[50] Monbiot, G.; Feeding Cars, Not People, https://www.monbiot.com/2004/11/23/feeding-cars-not-people/
[51] Tomei, J., Helliwell, R., 2016, Food versus fuel? Going beyond biofuels, Land Use Policy, Volume 56, Pages 320-326, https://doi.org/10.1016/j.landusepol.2015.11.015.
[52] IFPRI, Food versus Fuel v2.0: Biofuel policies and the current food crisis, https://www.ifpri.org/blog/food-versus-fuel-v20-biofuel-policies-and-current-food-crisis/
[53] BBSRC Sustainable Bioenergy Centre (BSBEC): Perennial Bioenergy Crops Programme, https://www.biomassconnect.org/directory/the-bbsrc-sustainable-bioenergy-centre-bsbec-perennial-bioenergy-crops-programme/#

However, this viewpoint is contested, other researchers argue that the development of industrial and energy markets for food crops could enhance agricultural resilience and increase food security.[54,55]

While recognising the urgent need to tackle global hunger, it is argued that utilizing food and feed crops for chemicals and materials does not automatically exacerbate food insecurity. On the contrary, the report concludes that such applications can offer multiple benefits, including enhancements to local and global food security, climate mitigation, and broader sustainability outcomes.

The authors contend that using first-generation biomass in non-food applications increases food security by increasing the overall availability of feedstocks and contributing to more stable markets, these uses support a more resilient food system. Importantly, many industrial processes generate valuable protein-rich co-products that help meet critical nutritional needs for both humans and livestock. The flexibility to shift crops between food, feed, and industrial markets allows the market actors to respond quickly to fluctuations in demand and to buffer against supply chain disruptions. Crucially, utilising first-generation biomass for non-food purposes can provide a rapid and cost-effective route to establishing emergency food reserves when needed. Furthermore, by creating additional and diversified markets for agricultural output, non-food uses of first-generation biomass help stabilise farm incomes and improve economic resilience. This market diversification strengthens the competitiveness of agriculture and encourages continued investment in rural communities.

The authors point to advances in precision agriculture, plant breeding, and biotechnology and the potential to further improve yields, resource efficiency, and environmental performance. High-tech agricultural practices amplify the benefits of arable agriculture by enabling more efficient land use, reducing crop inputs, and strengthening value chain sustainability.

Additionally, sustainable cultivation practices, improved crop rotations, and diversification of land use associated with arable agriculture can help maintain soil health, reduce erosion, and support landscape-level biodiversity. When integrated into well-designed agricultural systems, crops can complement conservation goals.

In summary, the use of arable crops can provide:

- Climate benefits – Bio-based materials can play a key role in mitigating climate change.
- Land productivity benefits – The real competition lies not in the type of crop grown but in how land is used and managed.
- Environmental benefits – Greater resource efficiency and higher productivity in food and feed crops can reduce environmental pressures.
- Farmer benefits – Farmers gain more market flexibility and income opportunities by being able to sell into diverse value chains.
- Market stability benefits – Increased global availability of food and feed crops can contribute to more stable markets.
- Feed security benefits – Protein-rich co-products generated alongside bio-based materials support livestock nutrition.
- Food security benefits – Higher overall availability of edible crops, which can be stored and distributed more flexibly, strengthens food security.

[54] Renewable Carbon Initiative, 2023, The use of food and feed crops for bio-based materials and the related effects on food security – Promoting evidence-based debates and recognising potential benefits, https://renewable-carbon.eu/publications/product/rci-paper-on-the-use-of-food-and-feed-crops-for-bio-based-materials-and-the-related-effects-on-food-security-recognising-potential-benefits-long-version-pdf/

[55] Renewable Carbon Initiative, 2025, Benefits of Using First-Generation Biomass for Food, Fuels, Chemicals and Derived Materials in Europe, https://renewable-carbon.eu/publications/product/benefits-of-using-first-generation-biomass-for-food-fuels-chemicals-and-derived-materials-in-europe-pdf/

## Feed for Food

The production of animal feed is inextricably linked to human food production. Livestock systems remain central to global food supply, particularly for protein and micronutrients. Feed also competes directly with food for land and crops, especially cereals. However, the production of animal protein is an inefficient use of biomass since, animals convert plant calories into edible meat with relatively low efficiency.[56] Producing 1 kg of beef, for example, requires several kilograms of feed, much of which is grown on arable cropland. Globally around one-third of arable land is used for animal feed production and about a third of global cereal production is fed to animals.[57]

In a UK context, annual feed requirements for livestock are estimated at 292 million tonnes of forage (predominantly grazed) which is supplemented with approximately 5.3 million tonnes of cereals and 3.6 million tonnes of oilseed and associated by-products.[58]

This creates a 'food versus feed competition' i.e. land that could be used to crops directly for human food is instead used to grow crops for animals, leading to higher land demand per unit of protein or calorie produced. Alleviating this issue can be approached by reducing the consumption of animal products as food (moving towards more plant-based diets) or increasing the efficiency in livestock production.

A third approach has been proposed based on eliminating the use of use of human edible feedstock in the rearing of livestock i.e. restricting animal feed to grazing and the use of food production by-products. An examination of this approach showed that such a strategy could provide sufficient food (equal energy and protein/calorie ratio) while reducing environmental impacts including a 18% reduction in GHG emissions, 26% reduction in arable land use, and reductions in the need for nitrogen, phosphorous, pesticides and water.[59] However, it should be recognised that this approach reduces the efficiency of livestock production and is therefore accompanied by a necessary and significant reduction in the consumption of animal products as food.

There is a broad consensus that non-human-edible biomass such as crop residues, processing wastes, and grassland resources should be prioritised for feed whenever possible. This aligns with broader aims of increasing resource efficiency in agri-food systems.

## Moerman's Ladder

Originating in the Netherlands and widely adopted in European circular-economy policy, Moerman's Ladder (Figure 3) is a hierarchical framework used to guide the optimal utilisation of biomass and food resources. The ladder aligns with principles of the waste hierarchy (Figure 3) but has a specific focus on food production.

The ladder ranks the possible uses of food and biomass from most to least desirable according to economic value, resource efficiency, and societal benefit. Its guiding principles are the prevention of food waste and maximum value creation.

[56] Aiking, H., (2014) Protein production: planet, profit, plus people?1234, The American Journal of Clinical Nutrition, Volume 100, Supplement 1,Pages 483S-489S, https://doi.org/10.3945/ajcn.113.071209.
[57] Christian Schader, Adrian Muller, Nadia El-Hage Scialabba, Judith Hecht, Anne Isensee, Karl-Heinz Erb, Pete Smith, Harinder P. S. Makkar, Peter Klocke, Florian Leiber, Patrizia Schwegler, Matthias Stolze, Urs Niggli; Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *J R Soc Interface* 1 December 2015; 12 (113): 20150891. https://doi.org/10.1098/rsif.2015.0891
[58] A C Jamie Newbold and Kirsty Dougal. (2016) Agriculture & Forestry climate change report card technical paper 4. Climate change and ruminant agriculture in the UK, https://www.ukri.org/wp-content/uploads/2021/12/131221-NERC-LWEC-AgricultureForestrySource4-Ruminant.pdf?utm_source=chatgpt.com
[59] Schader, C., Muller, A., Scialabba, N., E-H., Hecht, J., Isensee, A., Erb, K-H., Smith, P., Makkar, H. P. S., Klocke, P., Leiber, F., Schwegler, P.,Stolze, M., Niggli, U., 2015, Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J R Soc Interface; 12 (113): 20150891. https://doi.org/10.1098/rsif.2015.0891

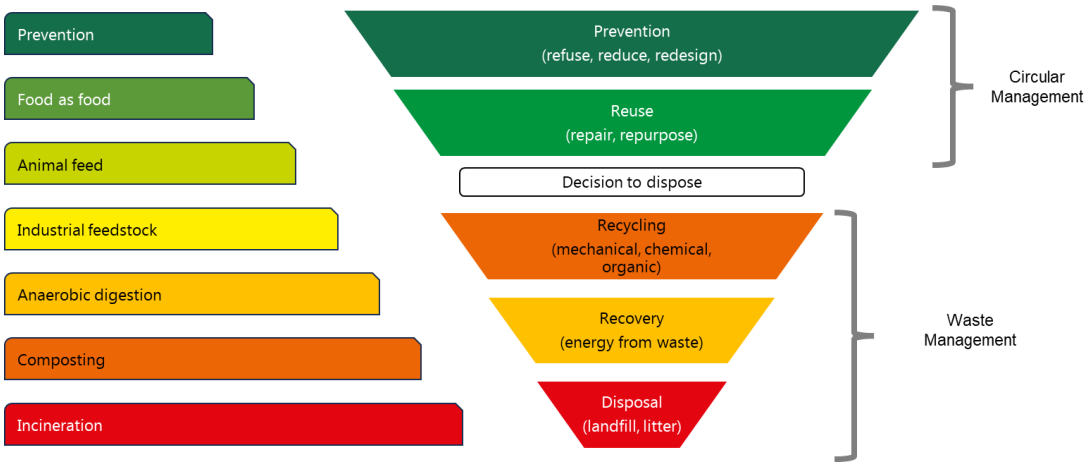



**Figure 3. Moerman's Ladder (left) and the Waste Hierarchy (right)**

Avoiding the production of surplus or unused food sits at the top of the ladder. This is considered the highest-value action as preventing waste conserves all of the land, water, energy, labour, and emissions embodied in food production.

The next preferred use is considered to human consumption; surplus food should be redirected to feed people wherever safe and feasible. Reuse for human food retains the greatest share of nutritional and economic value that would otherwise be lost. If direct human consumption is not possible, the next choice is animal feed. Converting food surplus into livestock feed keeps biomass within the food system and prevents the need for cultivating additional feed crops.

The ladder goes on to follow the concept of the waste hierarchy in the recycling of biomass into material and industrial uses. Further down the ladder is organics recycling with energy recovery, such as anaerobic digestion for biogas or the recycling of carbon and soil nutrients through composting.

A food first strategy places a focus on the use of non-edible crop residues as animal feed and aligns with the concepts of the biomass value triangle (Figure 4) and the cascading approach to biomass utilisation (Figure 5), expanded on below.

## Prioritising high value applications

The biomass "value triangle" is a guiding concept for biomass utilisation.[60,61] The principle behind the triangle is the use of biomass to create the highest economic, environmental, and societal value.

The triangle stems from the focus on the production of high value, low volume products as a priority - with high volume, low value applications appearing at the bottom of the triangle. This approach ensures that the most value is derived from limited volumes of biomass.

Food represents the highest societal value of biomass ensuring human health and wellbeing, placing it high in the triangle despite its large production volume and its often-low relative value.

[60] Green European Foundation, 2012, A strategy for a bio-based economy, https://gef.eu/wp-content/uploads/2017/01/A_strategy_for_a_bio-based_economy.pdf
[61] Sirkin, T., Houten, M., 1994, The cascade chain: A theory and tool for achieving resource sustainability with applications for product design, Resources, Conservation and Recycling, Volume 10, Issue 3, Pages 213-276,https://doi.org/10.1016/0921-3449(94)90016-7.

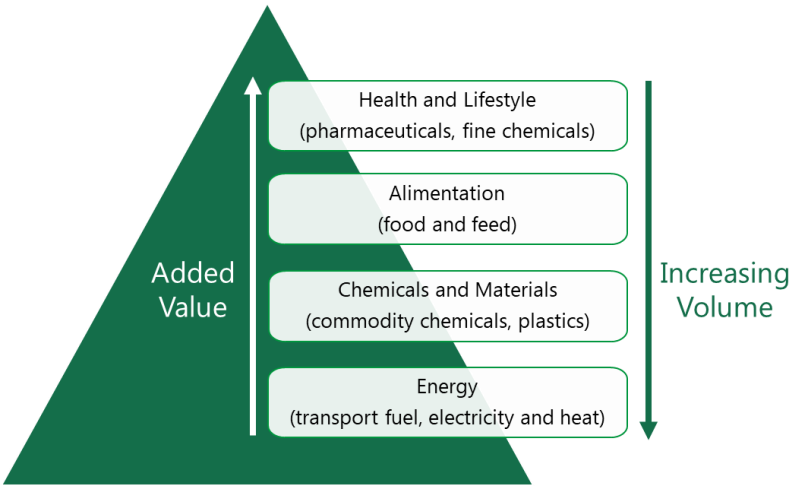



**Figure 4. Biomass Value Triangle**

Above food sits a small number of very high value applications often related to health and wellbeing such as pharmaceuticals, nutraceuticals and fine chemical food ingredients. These products create the highest economic value per unit of biomass and given their low volume of production do not create competition with the supply of food.

Beyond these high economic or societal applications, the remaining biomass should be directed to mid-value applications that create moderate value but use larger volumes. Ideally biomass is converted into durable materials or products where carbon can be stored and then recycled at end-of-life (see cascading use, Figure 5). This middle band of applications includes, building materials, paper/card, polymers and plastics.

At the bottom of the triangle sits energy applications, using the largest volume of biomass, but creating lowest value per unit of biomass. Additionally, energy applications result in the irreversible combustion of biomass preventing material reuse and emitting significant GHGs.

## Cascading Use

Cascading use is a resource-efficiency principle that aims to maximise the value obtained from biomass over time (Figure 5). Rather than using biomass once and then discarding it — as is typically the case with bioenergy — the cascading approach involves using the same material in a sequence of applications. At each stage, value is extracted while preserving as much of the material's functional integrity as possible. Only when higher-value uses are exhausted should the biomass be directed to lower-value applications, with energy recovery serving as the final step in the cascade.

The concept of cascading use stems from circular-economy principles and the waste hierarchy, by ranking biomass applications from highest to lowest in terms of their societal and economic value.[62]

The hierarchy reflects that different uses deliver different levels of value, efficiency, and carbon benefits. High-value material uses preserve biomass's chemical complexity for repeated or long-lived applications, while energy uses break it down and release carbon immediately.

[62] European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2018, Guidance on cascading use of biomass with selected good practice examples on woody biomass, Publications Office, https://data.europa.eu/doi/10.2873/68553

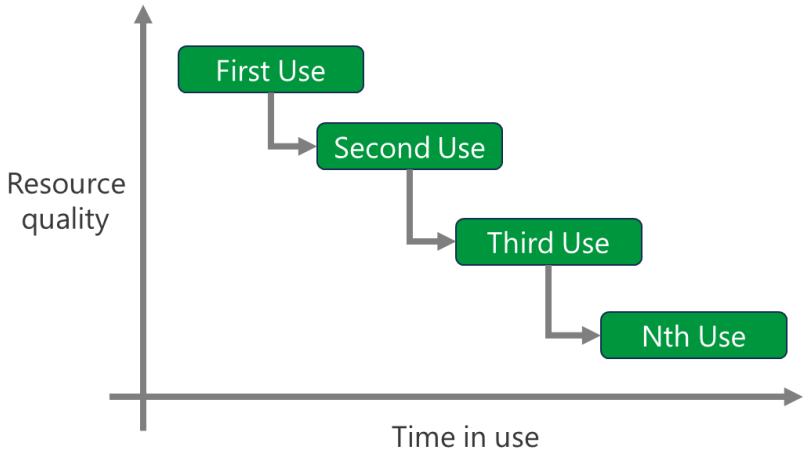



**Figure 5. Principle of Cascading Use**

Cascading systems also promote the utilisation of by-products, co-products, and residues. For instance, food-processing waste can be converted into animal feed; remaining fibres can be used to produce bio-based plastics or textiles; and only the final, non-reusable fractions should be directed toward energy recovery.

The European Commission includes the cascading principle in respect to the use of woody biomass in its Renewable Energy Directive (RED III).[63]

Under the RED, support schemes for bioenergy must ensure that the use of woody biomass follows the order of priority:

- wood-based products.
- extending the service life of wood-based products.
- re-use; recycling.
- bioenergy; and finally,
- disposal.

Ultimately, cascading use is about doing more with less, extending the useful life, utility and exploiting the environmental benefits of biological resources through intelligent, sequential use.

## Defossilisation versus decarbonisation

The act of reducing GHG emissions is commonly referred to as decarbonisation with the technologies deployed considered low or zero carbon. While this is justified in the energy sector, as wind and solar are literally zero-carbon technologies,[64] decarbonisation can be a misleading term in other sectors. In many key industries there is no alternative to carbon e.g., food and feed, organic chemicals, fibres, plastics, and cement – since carbon molecules make up the backbone of these products.

The terms defossilisation and decarbonisation are sometimes used interchangeably, but they describe two distinct strategies for addressing GHG emissions and climate change impacts[65]. Both aim to limit global warming, yet they differ in scope, mechanisms, and implications for energy systems, materials, and industrial transformation.

[63] European Commissions, 2023, Renewable Energy Directive, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
[64] At the point of electricity generation.
[65] Vanderhoven, J., 2023, Defossilisation versus decarbonisation, https://resource.co/article/defossilisation-versus-decarbonisation

Decarbonisation traditionally relates to reducing or eliminating carbon dioxide emissions from human activities. It focuses on the GHG emissions, particularly $CO_2$, and generally from the use of energy. The decarbonisation agenda revolves around reducing energy demand, improving energy efficiency, and importantly switching from fossil fuels to low-carbon energy sources (such as solar wind and bioenergy), or capturing or offsetting emissions through carbon capture and storage (CCS) or land-based sequestration.

Importantly, decarbonisation does not necessarily eliminate fossil resources; it looks to neutralise or off set the carbon emitted from them. Defossilisation, by contrast, concerns the phase-out of (virgin) fossil carbon itself, not just the emissions it generates. It targets the fossil carbon entering the economy—coal, oil, and gas—and aims to replace them with renewable carbon sources (biogenic carbon, captured atmospheric carbon, or recycled carbon). The goal is to stop introducing virgin fossil carbon into the economy and therefore addressing the root cause of anthropogenic climate change (Figure 6).

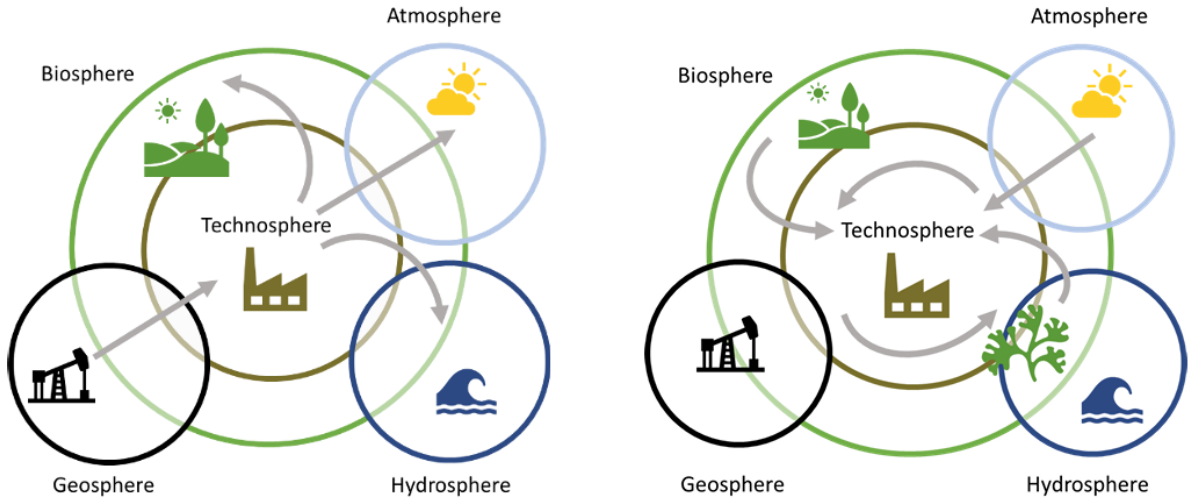



**Figure 6. Current and future carbon flows[66]**

The distinction between decarbonisation and defossilisation is especially important in the production of chemicals and materials. Products such as plastics, solvents and pharmaceuticals contain carbon, and therefore decarbonisation in the context of the material requirements is impossible i.e. decarbonising energy systems does not address the embedded fossil carbon in these products, which returns to the atmosphere when burned or degraded.

An example of the need for defossilisation is for plastics – which are made from chemicals, which inherently contain carbon. This carbon usually comes from fossil resources, and this means that these materials account for 10% of $CO_2$ emitted globally annually[67] and 3 gigatonnes of GHG emissions. With these emissions being almost entirely Scope 3[68], being generated in the extraction and conversion of virgin-fossil resources, the only currently feasible way to reduce these is to change the source material. Since feedstock needs to be carbon-based, this means plastic cannot be decarbonised but instead needs to be defossilised. The key challenge with defossilisation of

[66] Higson, A., Mason, S., Vanderhoven., A Sustainability Journey: A Perspective on Best Available Carbon (BAC) as Feedstock for the Chemical Industry, https://www.frey-consulting.co.uk/_files/ugd/677e00_88dee4c1c8e34b419e8a91dfd98cc789.pdf
[67] The Guardian, 2021, How the chemicals industry's pollution slipped under the radar | Environment, https://www.theguardian.com/environment/2021/nov/22/chemicals-industry-pollution-emissions-climate
[68] McKinsey and Company, What are Scope 1, 2, and 3 emissions? https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-are-scope-1-2-and-3-emissions

the chemical and plastics industry is, therefore, the requirement for carbon-based feedstocks, but from renewable sources.

In energy systems, the two strategies overlap: renewable electricity, green hydrogen, and energy efficiency all contribute to both decarbonisation and defossilisation. However, defossilisation adds an extra condition — no new virgin-fossil carbon inputs, even if resulting emissions are later captured.

The unavoidable need for carbon and the imperative to reduce fossil carbon emissions means that specific applications such as chemicals, plastics, and energy applications reliant of carbon fuels e.g. aviation, are priority uses for limited biomass.

Finally, in a defossilised economy, carbon capture and storage (CCS) becomes a mechanism for removing legacy carbon from atmosphere, delivering negative emissions, rather than enabling the continued use of fossil resources.

## Going Negative – Carbon Capture and Storage

The use of biomass to deliver negative GHG emissions, compensating for residual emissions system is seen as critical in many policies targeting net zero emission systems.[69,70]

In its 2023 Biomass Strategy the UK Government made a commitment *'to transition away from unabated uses of biomass where possible to uses such as bioenergy with carbon capture and storage (BECCS), which are critical to meeting net zero.'*

In doing so the Biomass Strategy places the emphasis for biomass use on hard to abate sectors and application with the potential to deliver negative emissions.

The Government recognises three approaches to deliver negative emissions:

- Post-combustion $CO_2$ capture e.g. from the use of wood, agricultural residues, wastes, etc in the generation of electricity, coupled with carbon capture and storage (CCS).
- Capturing $CO_2$ streams arising from advanced conversion processes such as gasification or steam reformation to produce fuels such as sustainable aviation fuels and hydrogen.
- Capturing the $CO_2$ emitted via biological processes such as fermentation or anaerobic digestion (AD) to generate biogas.

The technologies needed for carbon capture and the subsequent storage of $CO_2$ are well established. However, in practice, much of the $CO_2$ captured today is used primarily for enhanced oil recovery (EOR) — a process in which injected $CO_2$ helps extract additional oil from depleted reservoirs.[71] While this does store some $CO_2$ underground, it also facilitates further fossil resource production, which ultimately leads to additional emissions when that oil is burned.

Post-combustion capture of $CO_2$ involves the integration of carbon capture technology into biomass combustion facilities, typically associated with power generation, or for example, cement manufacturing. Although some commercial or large-scale demonstration projects exist, they're not yet widespread. Post-combustion CCS suffers from high costs associated with capturing dilute and contaminated $CO_2$ streams, the energy penalties incurred during capture, and the commercial risks associated with sector.[72,73]

[69] DESNZ, 2022, Net Zero Strategy: Build Back Greener, https://www.gov.uk/government/publications/net-zero-strategy
[70] Climate Change Committee, (2019) Net Zero – The UK's contribution to stopping global warming, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/
[71] Carbon Capture's Publicly Funded Failure - Oil Change International
[72] Raganati, F.; Ammendola, P.; CO2 Post-combustion Capture: A Critical Review of Current Technologies and Future Directions *Energy & Fuels* **2024** *38* (15), 13858-13905, DOI: 10.1021/acs.energyfuels.4c02513
[73] Marques, L.; Monteiro, M.; Cenci, C.; Mateus, M.; Condeço, J. Review of Post-Combustion Carbon Capture in Europe: Current Technologies and Future Strategies for Largest $CO_2$-Emitting Industries. *Energies* **2025**, *18*, 3539. https://doi.org/10.3390/en18133539

A range of precombustion technology have also been explored in an attempt to improve the efficiency of carbon capture and reduce its impact on the combustion process.[74] In a variety of technologies the production of clean $CO_2$ steams is an inherent part of the process.

Biological processes including fermentation and anaerobic digestion result in clean concentrated $CO_2$ streams. Several high-profile CCS projects are associated with ethanol production[75],[76] and the capture of $CO_2$ during the upgrading of biogas to biomethane post AD is becoming increasingly common.[77,78] The large-scale production of bio-based ethanol is a result of the demand for biofuel as a means to reduce the GHG emissions from road transport. However, the long-term demand for ethanol will likely be driven by its use in producing sustainable aviation fuel through the alcohol-to-jet (AtJ) process or for the production of ethylene as a feedstock to produce chemicals and plastic. Both aviation and the chemical industry are hard to abate sectors requiring carbon feedstocks and therefore represent long term CCS opportunities.[79]

This shift toward biogenic $CO_2$ capture aligns with broader changes in industrial carbon supply. Traditionally, industrial $CO_2$ has been produced through steam methane reforming to generate hydrogen for ammonia fertiliser production. Substituting natural gas with biomethane allows this established process to deliver *negative emissions* while maintaining compatibility with existing infrastructure. Similarly, biomethane can replace natural gas in the production of methanol or acetic acid, both of which rely on gasification to create synthesis gas and generate a clean $CO_2$ off gas. These pathways illustrate how mature industrial systems can transition from fossil-derived to biogenic carbon while contributing directly to carbon removal goals.

Beyond fuels and chemicals, carbon also plays a critical role in materials such as concrete and steel. In steelmaking, carbon functions as a reductant, and its incorporation into the steel matrix determines key material properties. The emerging potential to use biochar in steel and concrete production provides an additional route to sequester biogenic carbon in long-lived materials.[80,81] These applications extend the CCS value chain by linking biogenic carbon sources to durable end products, offering further opportunities for permanent carbon storage.

## Stakeholder views on biomass use

In order to understand how bio-based economy stakeholders would prioritise various biomass uses and explore the reasons behind the choices several round table discussions were undertaken. In total four stakeholder workshops (2 in York on 1st July, and 2 in Sheffield on 2nd September 2025) were held exploring the theme of priority uses for biomass and what a biomass hierarchy might look like. Participants at the workshops were self-selecting and would be regarded as knowledgeable in various areas of the bioeconomy and biomass use, without being experts in biomass availability, the wider area of renewable energy or a detailed understanding of competing use issues. During these workshops, participants were encouraged to think about the options for best use of limited biomass and explore rationale behind that decision-making.

[74] Vaziri, P., Rasaei, M., R., Seyfoori, S., Zamani, S., Mahmoodi, M., Sedaee, B, Advancing carbon capture technologies in CCS: A comprehensive review of pre-combustion processes, Gas Science and Engineering, Volume 131, 2024, 205481, ISSN 2949-9089, https://doi.org/10.1016/j.jgsce.2024.205481.
[75] ADM, ADM, Tallgrass Celebrate Opening of World's Largest Bioethanol Carbon Capture Facility in Columbus, Nebraska, 2025, https://investors.adm.com/news/news-details/2025/ADM-Tallgrass-Celebrate-Opening-of-Worlds-Largest-Bioethanol-Carbon-Capture-Facility-in-Columbus-Nebraska/default.aspx
[76] IEA Bioenergy Task 39, Case studies of CO2 utilization in the production of ethanol, 2024, https://www.ieabioenergy.com/wp-content/uploads/2025/02/Case-studies-of-CO2-utilization-in-the-production-of-ethanol.pdf
[77] Future Biogas, Carbon Capture and Storage, https://www.futurebiogas.com/our-business/carbon-capture-storage/
[78] Gueterbock, R.; Engineered Removal of Carbon is Creating Opportunities for the Biogas Sector, https://adbioresources.org/newsroom/engineered-removal-of-carbon-is-creating-opportunities-for-the-biogas-sector/
[79] Barnard, M.; The Realistic Future Of Carbon Capture: Pure Streams, Right Locations, Smart Uses, https://cleantechnica.com/2025/11/06/the-realistic-future-of-carbon-capture-pure-streams-right-locations-smart-uses/
[80] Salim Barbhuiya, Bibhuti Bhusan Das, Fragkoulis Kanavaris, (2024), Biochar-concrete: A comprehensive review of properties, production and sustainability, Case Studies in Construction Materials, Volume 20,
e02859, ISSN 2214-5095,https://doi.org/10.1016/j.cscm.2024.e02859
[81] Sarker, T.R., Ethen, D.Z. and Nanda, S. (2024), Decarbonization of Metallurgy and Steelmaking Industries Using Biochar: A Review. Chem. Eng. Technol., 47: e202400217. https://doi.org/10.1002/ceat.202400217

In the first part of the workshop, participants were tasked to record as many biomass applications as possible. These ideas were supplemented with a pre-pared list of applications containing the main uses for biomass (such as food, timber, road transport fuel, electricity, etc). Stakeholder groups were then asked to rank the applications from most to least important based on the group's perception and knowledge.

The results were analysed and individual applications grouped into categories.

- **Ecosystem**: Food, animal feed, biodiversity, carbon storage, ecosystem services
- **Healthcare**: Functional molecules (healthcare) and biopharmaceuticals such as antibiotics recombinant proteins and vaccines.
- **Chemicals**: Functional molecules for industrial use, biomass as a feedstock to produce hydrogen as a chemical feedstock and biomass and source of carbon for chemical production.
- **Heat**: Domestic heat, industrial heat, off-grid domestic heat and portable heat (LPG equivalent).
- **Power:** Electricity with CCS, electricity without CCS, emergency back-up power systems and Dunkelflaute[82] applications.
- **Transport Fuel**: Domestic road transport, road haulage, rail, hydrogen (fuel), aviation, marine fuel, portable fuel (LPG equivalent)

The general picture of the priority list for each of the workshop groups is shown in Table 2.

All groups valued food production and ecosystem services (food, biodiversity, natural carbon storage) the most as basic human needs and therefore the priority application for biomass, however beyond that view the results were varied. For example, there was a difference between groups that valued chemicals and materials over energy production, reflective of differences in perspective (or limited knowledge of production systems).

**Table 2: Generalised output of biomass hierarchy workshops.**

| Group A | Group B | Group C | Group D | Group E | Group F |
|---|---|---|---|---|---|
| Ecosystem | Ecosystem | Ecosystem | Ecosystem | Ecosystem | Ecosystem |
| Healthcare | Fuel | Materials | Power | Power | Chemical |
| Chemical | Healthcare | Heat | Materials | Healthcare | Heat |
| Materials | Chemical | Power | Healthcare | Heat | Fuel |
| Heat | Materials | Fuel | Heat | Materials | Power |
| Fuel | Heat | Chemical | Chemical | Chemical | Materials |
| Power | Power | Healthcare | Fuel | Fuel | Healthcare |

Group A and B are from the Sheffield workshop. Group C and D are from the first session in the York workshop and group E, and F are from the second session in the York workshop. Top represents the most important application allocated by each group and bottom the least important. Weighted scoring: Ecosystems = 42, materials = 23, health = 22, heating = 22, chemicals = 21, power =21, fuel = 17.

The groups which ranked electricity production relatively high (Group D and E) viewed electricity as a basic human need, more important than chemicals and fuel. However, those who ranked it at the bottom (Group A and B) went beyond the importance and use of electricity to explore how electricity can be generated; concluding that electricity generation was something easily achieved by non-biomass sources, such as wind and solar.

[82] Dunkelflaute is a term used in the energy sector to describe a prolonged period when there is little or no electricity generation from wind and solar power due to calm, dark, or heavily overcast weather conditions.

The reasonings behind the rankings were discussed further in the second part of the workshop. Participants were encouraged to think about what questions should be asked to determine the importance of each use for biomass, particularly considering both environmental, social or economic perspectives. Key themes that emerged were:

- Availability of alternative technologies
- How sustainable is using biomass in this way
- Wider impacts (of the specific feedstock, competition, long term-effects, etc)
- Whether the use is needed, can consumption/reliance be reduced
- How costly is the use of biomass and transition to biomass
- Technology readiness and scalability

After a period of further consideration, the groups were asked to choose their three most important questions.

The questions which were overall considered the most important by all groups related to:

- whether the biomass application was required to meet a basic human need,
- what the environmental impact and sustainability credentials of the application, e.g. the GHG emissions savings, water consumption, biodiversity impacts,
- and the availability or potential for the development of alternative non biomass technologies.

# Biomass priority applications

## Decision Support Tool

The increasing demand for biomass coupled with its finite and limited availability means there is an immediate need for a biomass hierarchy to both guide bioeconomy development and to ensure the numerous government policies impacting its development are aligned.[83,84]

Here we take the various concepts used, and described above, to guide the best use of biomass to produce a decision support tool (DST) and present what a biomass utilisation hierarchy could look like. We have used a number of principles to guide the design of the DST.

1) The social value of maintaining health and wellbeing, ecosystem services and biodiversity represent widely agreed biomass priority applications.
2) Limited biomass resource should be directed towards applications without alternative technology solutions.
3) The role of biomass in delivering negative emissions for net-zero should prioritise pathways where the production of clean $CO_2$ streams is an inherent part of the process, rather than relying on secondary or retrofit adaptations.

In Figure 7, we provide an example of what a decision support tree underpinning a biomass hierarchy could look like – with the result being a classification level for the biomass use withing a priority tower (Figure 8), between 1 and 7 – where 7 is the highest value use and 1 is the lowest value.

[83] OECD (2023), Carbon Management: Bioeconomy and Beyond, OECD Publishing, Paris, https://doi.org/10.1787/b5ace135-en.
[84] Green Alliance, (2025), The need for a biomass hierarchy, https://green-alliance.org.uk/wp-content/uploads/2025/07/The-need-for-a-biomass-hierarchy.pdf

The DST consists of a set of filter questions grounded in the core principles and research findings presented throughout this report. Its purpose is to evaluate biomass-based end-use applications—that is, the service, utility, or product delivered to the final consumer. Key points include:

- Focus on end-use, not specific commodities: The DST is not designed to assess individual fuels, chemicals, or polymers. For example, biomethane can provide heat, generate electricity, power vehicles, or serve as a chemical feedstock. Likewise, paper can be used for a birthday card or a writing pad. The DST therefore evaluates the *end-use application*, not the material itself.
- End-use specificity increases the precision of the hierarchy: The more clearly the end use is defined, the more granular and meaningful the biomass-use hierarchy becomes. Because sustainable biomass is limited and potential demand is high, this level of detail is essential. For instance, assessing '*biomass for transport fuel*' is too broad—the benefits and trade-offs differ significantly between road transport, aviation, and marine sectors, and even within these (e.g., domestic cars vs. light or heavy freight).
- Consideration of systems context: In some cases, the service, utility, or product may need to be understood as part of a broader system. Here, a biomass application may complement alternative supply options rather than directly compete with them.

## Background to DST questions

To elaborate on the logic behind the DTS, and its application, each question is briefly discussed below.

Q1. Addressing the current use of biomass to provide the service/utility/product. In respect to 'current use' biomass should be the dominant source of supply e.g. human food, or a significant source of supply e.g. textiles, with the supply not supported by direct or indirect Government polices providing financial support e.g. bioenergy.

Q2. This question reflects on the roles that biomass plays in meeting essential social and environmental needs. For example, the production of food relies on edible biomass production through the cultivation of crops and the raising of animals. Similarly, ensuring biodiversity and maintaining the environment we live in requires biomass. While other solutions may exist, such as the production of single cell protein from natural gas, these are niche edge cases with limited influence on the overall biomass system. Some social needs may be considered essential, such as heat or shelter but these needs could be met through means other than biomass.

Q3. A key driver behind the growing demand for biomass is the desire to avoid the use of fossil resource in the supply of services/utilities/products. This question reflects that although biomass could be widely used to provide services/utilities/products there may be alternative approaches which provide non fossil non biomass solutions e.g. the use of ceramics, glass or metals, particularly when applied to circular reuse systems.

Q4. As discussed earlier in the report, the potential demand for biomass outstrips it possible supply. It is therefore necessary to consider if the service/utility/product could be supplied through other renewable solutions avoiding the use of fossil resources. Renewables such as wind and solar provide a ready source of electricity with electricity being an attractive way to provide utilities such as motion (i.e. some forms of transport) and heat.

Q5 & 7. Greenhouse Gas Removal (GGR) is regarded as an important mechanism in achieving net zero emission policies. GGR such as bioenergy with carbon capture and storage (BECCS) provides a secondary function to the generation of electricity using biomass which can't be supplied by other electricity generating renewables.

Q6. Although non biomass renewable electricity is increasingly available the electrification of some service/utility/product remains to be fully demonstrated or widely commercialised. However, it is reasonable to believe that the carbon benefits (i.e. GHG emissions reduction) electrification will drive electrification in the foreseeable future.

Q8. Unlike other renewable technologies (wind, solar etc), biomass provides a source of molecules capable of directly fulfilling a function (chemical or physical), acting as feedstock to synthesise other molecules and polymers or as a source of chemical energy.[85] Chemical energy reliably stores large amounts of energy for long periods and offers far higher energy density than other storage forms. This makes it essential for applications needing high power from limited space, such as transportation. However, electrification may replace chemical energy in some uses, including high-grade industrial heat or heavy-goods transport. Conversely, molecules remain fundamentally necessary for chemical and physical functions and for producing materials.

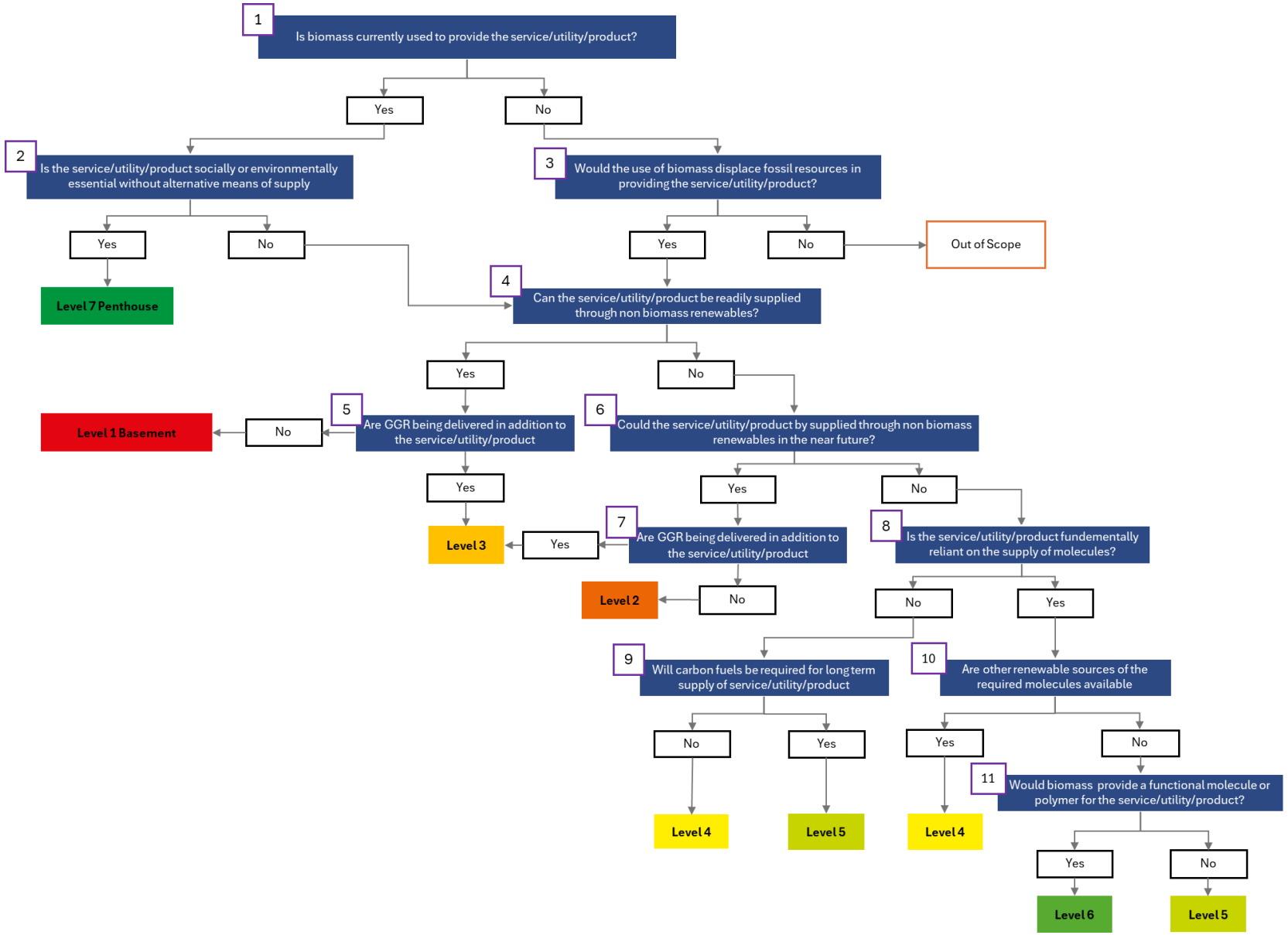
Q9. This question considers the feasibility of electrifying applications currently reliant on chemical energy such as high-grade industrial heat, fuel for heavy good vehicles or in aviation.

Q10. Alternative source of molecules may be available which avoids the need to use limited biomass. For example, the annual demand for hydrogen as a chemical is around 100 million tonnes[86] and represents a large source of GHG emissions. Although several biomass routes to hydrogen exist e.g. biomethane reforming, gasification or dark fermentation, it can also be produced via water electrolysis which avoids the need to consume biomass.

Q11. Biomass provides an array of molecules capable of directly fulfilling a function (chemical or physical). Biomass provides active molecules used as pesticides or herbicides, or functional molecules such as surfactants or lubricants. The physical structure of biomass molecules is used in the form or timber in construction or as cellulose in paper and card. These molecules and polymers are more valuable than the use of biomass as a raw material to synthesis new molecules and polymers.

[85] The energy within molecules is primarily called chemical energy, a form of potential energy stored in the bonds between atoms.
[86] IEA, (2025), Global hydrogen review 2025, https://www.iea.org/reports/global-hydrogen-review-2025/executive-summary

## Figure 7. Decision Support Tree



# Biomass Hierarchy – A Priority Tower

An assessment of various biomass end use applications using the DST resulted in the biomass use hierarchy depicted in Figure 8 – the Priority Tower.

The Priority Tower represents an 'if you can, you should' ranking for the use of biomass. It should be used alongside the concept of 'cascading use' and recognises there are technical, economic, geographic and market limitations in the use of specific biomass in some applications. The hierarchy is not intended to be rigid, as with the implementation of the waste hierarchy it is recognised that deviations from the hierarchy could be justified on environmental or economic grounds, as justified by further analysis (e.g. life cycle analysis or technoeconomic analysis), in order to deliver the best environmental outcome.

'Penthouse', Level 7 applications reflect the importance of food production and the important role of biomass in providing ecosystem services such as clean air and water. Other penthouse applications include the maintenance of biodiversity, nature-based carbon sequestration and the importance of natural products as active pharmaceutical ingredients e.g. antibiotics.

'Basement', Level 1 applications represent use cases where alternative technologies already exist which negate the need consume limited biomass. Examples include the use of biomass to generate electricity where solar, wind and other non-combustion technologies offer cheaper and more effective means of decarbonising power, and the production of liquid biofuels for domestic road transport.

The Priority Tower reflects a future point in time. It should be recognised that current biomass applications may be important today but will undergo a gradual phase out as alternative technologies are developed and increasingly deployed.

Examples of this transition include,

- as the uptake of battery electric vehicles increases there will be a decreasing role for biomass in the production of road transport biofuels,
- the need to use biomethane in the supply of domestic heat would be expected to decrease as heat is increasingly electrified through the use of heat pumps.

Additionally, some current applications have the potential to evolve as new technologies evolve and are deployed, these examples may be considered useful technologies during this transitional period. A case in point may be the use of biomass in power generation which with time could form part of BECCS system providing negative emissions.

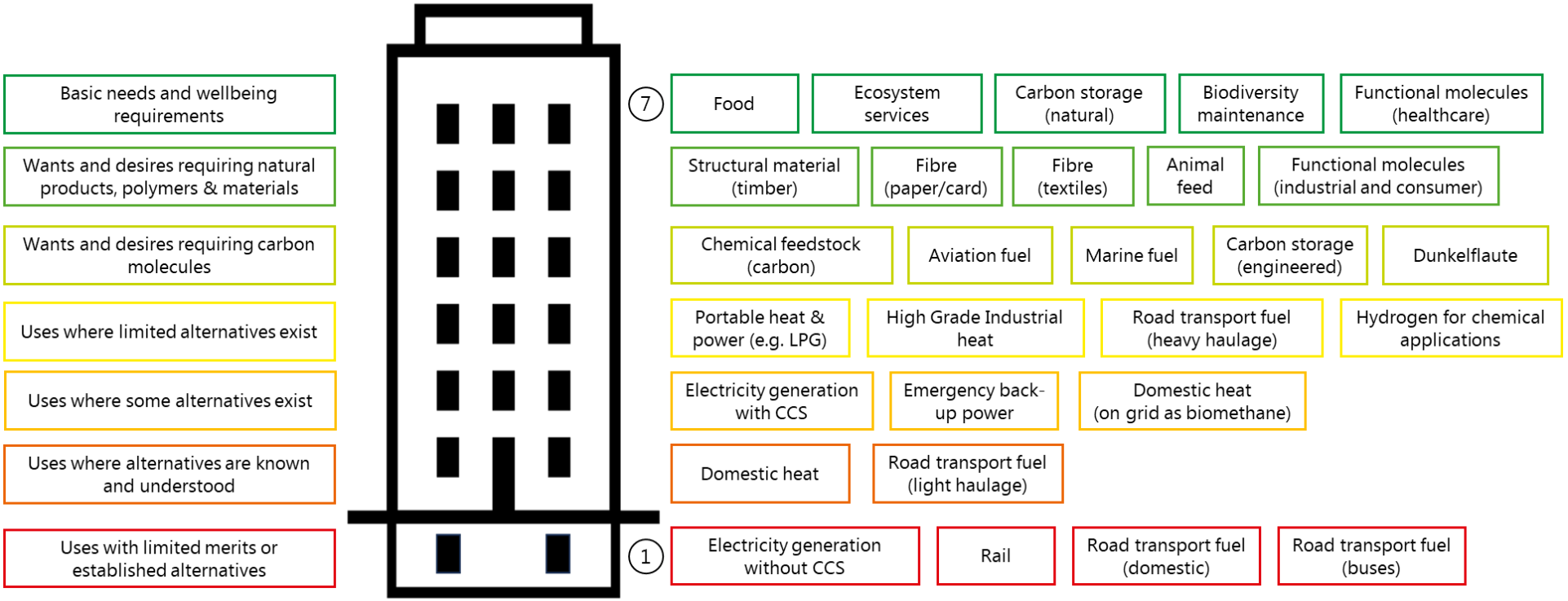



**Figure 8. Example biomass Priority Tower showing priority applications**

# Other important considerations

## Products, Residues and Wastes

The hierarchy applies equally to the use of primary products, residues and wastes, following the principles of the waste hierarchy and cascading use.

For example, the cultivation of arable crops results in the production of crop residues e.g. straw, a proportion of which after harvest, is left on the land to decompose. The decomposition of crop residues in the field can improve soil quality and therefore maintains ecosystem services and biodiversity and acts as natural carbon store. These services rank at the top of the use hierarchy and therefore care is required to avoid any excessive removal of residues for industrial or bioenergy applications lower in the hierarchy.

## Effectiveness and Environmental impacts

The DST considers the use of biomass at the level of the service/utility/product it ultimately provides. However, it does not assess the effectiveness or the efficiency of the delivery of service/utility/product and therefore there is a need for further analysis to assess the efficiency of individual production pathways[87] and projects[88].

In relation to the development of priorities for biomass uses, the hierarchy sits at the level of strategy[89] development with more detailed production efficiency analysis required at policy and regulatory levels; policy considering the effectiveness and efficiency of biomass production pathways and regulations requiring project level determination of efficiency fundamentally linked to location specific impacts from feedstock sourcing and energy consumption.

The concept of process or pathway efficiency is often restricted to measures of how efficiently energy is used or conserved in the conversion of biomass into energy products such as liquid biofuels or the mass yield of a biomass to chemical process. However, more broadly the efficient use of biomass can be considered as a balance between yield or technical efficiency (the amount of product produced from a given volume of biomass), the process economics (resource productivity) and the emissions intensity (considering GHGs and other emissions), as shown in Figure 9.[90]

Optimising efficiency may require the balancing of yield, the maximisation of which may not align with environmental impact and depending on the commercial/policy environment will determine the economic added value.

The environmental impacts incorporate both the impact of biomass sourcing and the impacts of the conversion technologies. A prerequisite for using biomass for any service/utility/product is ensuring its supply is sustainable. However, there is no single internationally accepted definition of ‘sustainable’ biomass (however, see earlier on in the report about the recently launched UK Government consultation on sustainable biomass). The wide array of feedstocks and diverse applications mean that sustainability needs to be considered in the relation to the unique characteristics of each feedstock, its supply chain and geography (reflecting the environmental conditions under which it’s produced e.g. water availability, nutrient requirements).

[87] Production pathways consider the type of feedstock, the conversion technologies, the produced material and the use of consumer product.
[88] Considering a production pathway at a specific facility in a specific geography.
[89] High level biomass strategies guide policy development which in turn determine regulatory requirements.
[90] Stegmann, P., Londo, M., Junginger, M., (2020), The circular bioeconomy: Its elements and role in European bioeconomy clusters, Resources, Conservation & Recycling: X, Volume 6, 2020, 100029, https://doi.org/10.1016/j.rcrx.2019.100029.

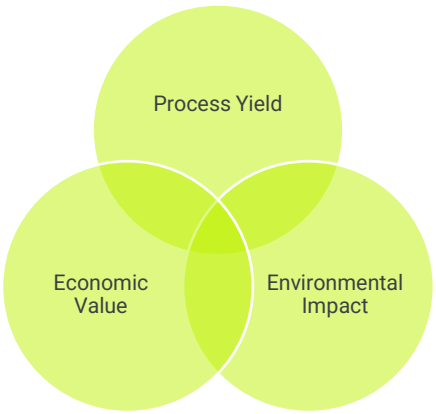



**Figure 9. Elements determining the efficiency of biomass use**

In summary while the DST guides high level priorities for biomass use, it does not determine if any particular process pathway should be considered sustainable or be favoured over any another process pathway regardless of application.

## Biorefineries

This basic decision tree only considers single biomass applications, however processes targeting specific products will inevitably produce one or more by-products. How these secondary products are valorised and the applications they serve will influence the overall process sustainability.

Biorefining is considered a means to optimise the conversion of all biomass components into value added products. With the biorefinery principal representing a facility where biomass is processed into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat).[91]

Biorefineries should follow the biomass hierarchy which both primary products and any by-product streams following the hierarchy in line with cascading use principles. It may however be necessary to assess the biorefinery operation as whole as opposed to the sum of its product outputs in order to ensure the optimal output.

Another important aspect of biorefinery operation is the on-site utilisation of process residues to serve the energy requirements of biorefinery processes and optimise its economic performance. The growing ability to electrify these demands using electricity from non-biomass renewables may create the opportunity to utilise these resources for applications higher up the biomass hierarchy. It is therefore important that policy environment in which the biorefinery sits recognises the full value of biomass utilisation and not just take an economic perspective.

An example of maximising biomass utilisation is the production of propane and naphtha as by-products in the conversion of vegetable oils to hydrogenated vegetable oil (HVO) diesel and Hydroprocessed Esters and Fatty Acids (HEFA) aviation fuel. The right policy environment could maximise the use of propane and naphtha in hard to defossilise sectors such chemicals manufacture or portable heating applications.[92] However without support, the costs of placing these valuable biomass derived resources on the market may be prohibitive and they may continue to be used as biorefinery fuel.

[91] De Jong, E, Higson, A, Walsh, P., Wellisch. M., 2012, Bio-based Chemicals: Value Added Products from Biorefineries, https://www.ieabioenergy.com/blog/publications/bio-based-chemicals-value-added-products-from-biorefineries/
[92] Liquid Gas Europe, 2025, Outlook for renewable liquid gas in Europe – Supply scenarios for 2040 and 2050.

# Conclusions

Biomass is both wide ranging in type and in its applications. It serves important social, environmental and economic functions, delivering food and shelter, providing ecosystem services and protecting biodiversity, and providing the basis for a wide range of industries.

In this report we have reviewed the potential supply of biomass and what volume of demand exists today and could exist in the future.

This potential demand for biomass is far in excess of its annual supply. Based on strict environmental protection and land use criteria, the availability of biomass beyond food, feed and current industrial uses, is extremely limited. Taking a more balanced view of biomass supply would allow more industrial and energy applications to be served but would still be limited.

It is therefore necessary to understand how biomass could and should be used and subsequently determine where the use of limited resources could best be used.

Various frameworks have been developed and are used to prioritise the use of biomass. We have summarised these frameworks and used them as the basis of Decision Support Tool which can be used to rank different biomass applications considering their social, environmental and economic value.

The resulting biomass Priority Tower provides a view of where biomass provides value (penthouse applications) in the supply essential services and products such as food and ecosystem services. Conversely many potential biomass applications could be readily served through alternative means such as electrification (basement applications) or the supply of renewable hydrogen via water hydrolysis rather biomass reforming or gasification.

However the biomass Priority Tower represents the ranking of applications, it doesn't consider the social or environmental impacts of different pathways to deliver the applications. Additionally, the techno-economics of pathways may prevent their use. Therefore, as with the widely used waste hierarchy, deviations from biomass Priority Tower hierarchy could be expected.

Finaly, the biomass tower is not intended to provide a definitive ranking but does serve as means to start a wider conversation on how limited biomass should be used.