IEA Bioenergy
Technology Collaboration Programme

BECCS & BECCUS

Net-Negative Emission Technologies| Glasgow, 12 May 2026

Workshop Report

IEA Bioenergy: Task 33: May 2026

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1. Executive summary

The Supergen Bioenergy Impact Hub and IEA Bioenergy Task 33 convened this workshop to examine how bioenergy with carbon capture and storage (BECCS), and bioenergy with carbon capture, utilisation and storage (BECCUS), can move from promising pathways to credible, scalable net-negative-emission systems. Researchers, technology developers, infrastructure specialists, policymakers and sustainability experts considered the full chain: sustainable biomass supply, conversion and products, CO_2 capture, transport and permanent storage, carbon utilisation, accounting, finance, regulation, environmental safeguards and workforce capability.

The discussion showed that no single BECCS or BECCUS configuration is inherently optimal. A project maximising durable carbon removal may differ from one intended to maximise renewable fuels, hydrogen, heat or fossil-carbon displacement. Gasification, pyrolysis, anaerobic digestion, sustainable aviation fuel production, green-gas manufacture and biochar can all contribute, but their climate value depends on feedstock counterfactuals, conversion efficiency, capture rate, energy inputs, co-products, storage permanence and residual emissions. Utilisation can improve resource efficiency and product yield, yet should not be described as removal when carbon returns rapidly to the atmosphere.

The strongest shared conclusion was that the principal bottleneck is not individual technologies but integrating proven and emerging components into dependable projects with shared infrastructure, long-term policy, credible measurement and bankable revenue. UK cluster development illustrates how CO_2 transport and geological storage can unlock capture projects across several sectors. Smaller and geographically dispersed biogenic sources require aggregation, intermediate storage and non-pipeline transport options if they are to participate. Modular conversion systems may reduce feedstock transport, construction and single-unit outage risks, whereas larger integrated plants can benefit from economies of scale and purpose-built product synthesis.

Speakers repeatedly returned to feedstock variability. Real biomass and waste streams vary in moisture, ash, particle size, minerals and contaminants, sometimes from one delivery to the next. This variability affects tar formation, slagging, catalyst performance, gas quality, biological inhibition and product specifications. The workshop therefore identified rapid feedstock characterisation, better sensing, large shared datasets, digital models and adaptive process control as high-impact research needs. Equally important are sustained pilot operation and transparent industrial data that demonstrate reliability outside tightly controlled laboratory conditions.

KEY MESSAGES

- Treat BECCS/BECCUS as a whole system: feedstock, conversion, products, capture, transport, storage, markets and sustainability must be designed together.
- Distinguish durable removal from temporary carbon utilisation, and define the accounting purpose, boundary and baseline before making claims or investment decisions.
- Build long-lived policy and shared infrastructure around an investable sequence of early projects, while creating connection routes for distributed biogenic sources.
- Prioritise feedstock intelligence, contaminant and tar management, catalyst durability, flexible operation and decision-grade pilot evidence.
- Use natural-capital and land-use safeguards so that biomass expansion delivers climate benefit without unacceptable effects on food, biodiversity, water or communities.
- Develop an interdisciplinary workforce through joint research, industrial placements, continuing professional development and access to shared demonstration facilities.
- For gasification, evaluate the trade-off between storing separated biogenic CO_2 and adding low-emission hydrogen to maximise product yield; carbon-removal value can reverse the preferred option.
- Treat biochar as a family of products whose stability, porosity, contaminants and suitable end uses depend on feedstock and conversion conditions.
- Separate announced, under-construction, commissioned and sustained operating capacity when assessing fast-growing green-fuel project pipelines.

The three Task 33 presentations sharpened three important decision areas. Prof. Joakim Lundgren showed that gasification normally creates a concentrated CO_2 separation point and that external low-emission hydrogen can substantially increase the fraction of biomass carbon converted into product, while a sufficiently high carbon-removal value can make permanent storage more attractive than utilisation. Dr Jitka Hrbek demonstrated that biochar is not a uniform product: reactor type and conversion severity affect porosity, chemical reactivity and carbon stability, so certification and end-use testing are central to credible removal. Assoc. Prof. Jian Li described a very large Chinese green-fuel project pipeline alongside a much smaller operating base, and presented research on coupled anaerobic digestion and gasification, hybrid process modelling and staged tar removal. Together, the contributions reinforced the need to distinguish technical potential, announced capacity, commissioned capacity and verified long-duration performance.

This report is written as a participant account of the workshop. It follows the sequence of the programme, summarises the presentations and discussions, and draws out the main technical, policy and deployment implications. The emphasis is on the principal evidence, viewpoints, areas of agreement and points of debate that emerged during the day. Quantitative values, project capacities and status dates are reported as presented during the workshop and have not been independently audited; they should therefore be read as information current to 12 May 2026.

2. Workshop context and approach

The workshop took place on 12 May 2026 in the Debates Chamber of Glasgow University Union, University of Glasgow. Its purpose was to critically assess technology pathways capable of delivering net-negative emissions, identify barriers to deployment, and identify research, collaboration and scale-up opportunities. The programme combined project overviews, a UK deployment keynote, technology and industry presentations, policy and sustainability contributions, panel questions and mixed industry-academia round tables. This structure was valuable because it connected detailed process questions with the policy, accounting and social conditions that determine whether a technically viable project can be delivered.

Table 1: *Workshop programme and thematic coverage*

Time / session	Chair and lead contributors	Focus
10:00-10:40 Welcome and framing	Prof. Manosh Paul; Dr Scott Banks; Prof. Mirjam Roeder; Dr Akshay Bagde; Dr Fabian Ejim	Workshop objectives, Supergen Bioenergy overview, Hydrogen-BECCUS and gasification project development.
10:40-11:15 Keynote	Chair: Prof. Michael Short Dr Chris Manson-Whitton, Progressive Energy Ltd	Making BECCS a reality in the UK: infrastructure, business models, clusters and deployment.
11:15-12:30 Technology pathways	Chair: Berend Vreugdenhil Prof. Joakim Lundgren; Paul Willacy; Sanjeev Gajjela; Dr Jitka Hrbek	Gasification, hydrogen, sustainable aviation fuel, biochar, carbon storage and utilisation choices.
13:30-14:30 Scale-up and deployment	Chair: Dr Jitka Hrbek PlusZero Ltd contribution; Assoc. Prof. Jian Li; Berend Vreugdenhil	Modular systems, Chinese green-fuel development, Dutch green gas and negative-emission potential.
14:30-15:30 Policy, regulation and sustainability	Chair: Dr Freya Horsfield John Kelly; Michael Goldsworthy; Dr Robert Holland	Commercial policy, accounting methods, standards, biomass sustainability and land-use choices.
15:45-17:00 Round tables and close	Chairs: Dr Scott Banks and Prof. Manosh Paul Closing: Prof. Mirjam Roeder	Research priorities, deployment barriers, industry-academia partnership, skills and capacity building.

Throughout the report, BECCS refers to systems in which biogenic carbon is captured and placed in durable storage, normally geological storage. BECCUS is used more broadly for systems that include utilisation as well as storage. The distinction matters: a fuel or short-lived product can displace fossil carbon and may be highly valuable, but it does not provide the same permanence as geological storage or suitably durable biochar. Net-negative performance therefore requires transparent lifecycle assessment and an explicit statement of what would otherwise have happened to the biomass, energy and carbon.

3. Opening framing and Supergen project development

3.1 SUPERGEN BIOENERGY IMPACT HUB: CONNECTING RESEARCH TO DEPLOYMENT

Prof. Manosh Paul and Dr Scott Banks opened the workshop by framing it as a practical examination of routes to deployment rather than a discussion of technology in isolation. Prof. Mirjam Roeder then introduced the Supergen Bioenergy Impact Hub as a UK-wide research consortium whose role extends from generating new concepts to creating an enabling environment for implementation. The Hub incubates research ideas, identifies commercial potential in bioenergy and bioproducts, supports knowledge exchange beyond academia and builds research capacity. Technology projects are accompanied by cross-cutting whole-system work on carbon, environmental, social and economic performance.

A central message was that technical success in a laboratory does not guarantee adoption. Projects must be designed around industrial operating conditions, regulatory requirements, finance, regional infrastructure and public value. The Hub therefore works with companies, policymakers, public bodies and early-career researchers, and uses international collaboration to accelerate learning and avoid duplication. A developing strand of work links bioenergy opportunities with regional economic strategies, skills and investable project pipelines. This emphasis on implementation established a recurring theme for the day: the value of research is greatest when it reduces a specific deployment risk or improves a real decision.

3.2 HYDROGEN-BECCUS PROJECT

Dr Akshay Bagde outlined an integrated Hydrogen-BECCUS concept combining biomass conversion, reforming or looping reactions and CO_2 capture to produce hydrogen and useful energy with very low or potentially negative lifecycle emissions. Modelling and early laboratory work examined pressure, feedstock blends, gas recycling, heat integration and reaction enhancement. Under the conditions studied, the project reported capture potential approaching 90 per cent. The figure was presented as an early result rather than a plant-wide commercial guarantee, and the next stage is to test a wider range of biomass mixtures and validate the model experimentally.

The project illustrates why integration is as important as the performance of an individual reactor. Increasing capture can alter heat demand, gas composition, hydrogen yield and equipment size; recycling streams can improve conversion but may also concentrate contaminants. A credible system must therefore optimise the complete mass and energy balance and account for the source and carbon intensity of auxiliary power. The planned combination of experiments and modelling should help determine which operating window remains effective when feedstock properties and process conditions vary.

3.3 GASIFICATION AND HYDROGEN PROJECT

Dr Fabian Ejim presented linked work on biomass gasification, water-gas shift and process intensification, catalyst development and carbon capture. A bespoke pressurised micro-gasifier enables experiments at pressures up to approximately 10 bar and temperatures in the range of roughly 650-850 degrees Celsius. Preliminary catalyst tests indicated that a nickel-based formulation promoted with tungsten increased the hydrogen fraction and reduced tar-related phenolic compounds under the conditions examined. These results were described as ongoing and unpublished, making continued validation and durability testing essential.

The project combines bench-scale evidence with computational fluid dynamics and other digital models, using feedback between simulation and experiment to refine operating conditions. The presentation highlighted feedstock variability, tar reduction and the need for pilot evidence that is representative of industrial operation. Gasification can produce a flexible synthesis gas, but downstream hydrogen production or fuel-cell use requires consistent quality and protection of catalysts and separation equipment. During questions, the speaker argued that the deployment gap remains partly technical: industry often lacks sufficiently long, integrated and transparent pilot campaigns to judge reliability, maintenance requirements and performance under real feedstock variation.

Taken together, the two Supergen projects demonstrate complementary research priorities. One focuses on integrated negative-emission hydrogen production and capture; the other develops the conversion, catalyst and modelling tools needed to control gasification. Both require early engagement with industrial users, realistic operating envelopes and a pathway from component results to complete-system evidence. They also provide a strong platform for training researchers who can work across reaction engineering, materials, modelling, carbon accounting and scale-up.

4. Keynote: making BECCS a reality in the UK

Dr Chris Manson-Whitton of Progressive Energy Ltd framed BECCS as delivering two services: useful energy or fuels and durable biogenic carbon removal. The preferred design depends on how these services are valued. Maximising storage may reduce renewable-product output, while using captured carbon to increase fuel yield may leave less for storage. Projects should state their objective and counterfactual rather than assume one pathway is universally best.

Geological storage offers high permanence and direct monitoring, but depends on coordinated transport and storage infrastructure. The UK cluster model addresses this by developing capture, transport and storage as an integrated chain. HyNet illustrates the approach: Liverpool Bay gas assets can be repurposed for CO_2 transport and storage, while hydrogen production and storage support industrial decarbonisation and dispatchable energy. Phased development allows projects to establish flows and capacity for later connections.

Energy-from-waste and cement were highlighted as promising early projects. Cement has process emissions that are difficult to eliminate without capture, while energy-from-waste can combine energy recovery with permanent storage of its biogenic carbon share. Early projects should be judged by CO_2-stream reliability, readiness and their ability to anchor shared infrastructure, as well as removal potential.

Smaller, dispersed sources such as anaerobic-digestion upgrading plants may produce concentrated CO_2 but be too small for dedicated pipelines. A hub-and-spoke model using purification or liquefaction, buffer storage and road, rail or ship transport could connect them to cluster networks. This requires common standards for composition, custody transfer and verification.

Concentrated biogenic CO_2 may be cheaper to capture than CO_2 from air, but projects still require revenue from removal contracts, emissions trading, voluntary markets, low-carbon fuels or combined products. Policy must reward verified net removal without double counting or weakening incentives to avoid emissions.

Discussion also emphasised trust, sequencing and collaboration. HyNet shows that companies must align data, assumptions, interfaces and schedules before commercial models are settled, often with public co-funding. CCS-enabled hydrogen can provide early flexible low-carbon supply, provided it does not justify unabated fossil-gas use and complements electrolytic hydrogen and variable renewables.

5. BECCS and BECCUS technology pathways

5.1 GASIFICATION AS A PLATFORM FOR PRODUCTS AND CARBON MANAGEMENT

5.1.1 Why gasification creates a natural carbon-management decision point

Prof. Joakim Lundgren, Co-leader of IEA Bioenergy Task 33, presented biomass gasification as a flexible platform rather than a single-product technology. Depending on gas composition, cleaning and synthesis, a gasifier can support heat, power, hydrogen, substitute natural gas, methanol, chemicals and transport fuels. This breadth is relevant to BECCU/S because synthesis-gas conditioning already includes separation of carbon dioxide to reach the composition required by downstream catalysts. In a well-integrated plant, therefore, a relatively high-purity biogenic CO_2 stream can be available at high capture efficiency without relying solely on dilute post-combustion capture.

The presentation distinguished three possible fates for that separated carbon. It can be released, which forfeits the opportunity for either removal or additional product; it can be transported to durable geological storage, creating BioCCS and potentially negative emissions; or it can be combined with hydrogen and returned to the product train, creating BioCCU and increasing renewable fuel or chemical output. This framing is useful because it locates the strategic decision at a real process interface rather than treating carbon capture as an isolated end-of-pipe addition.

5.1.2 The carbon-efficiency constraint and the role of low-emission hydrogen

A fundamental limitation arises from the elemental composition of the feedstock and desired products. The presentation represented biomass as having an approximate hydrogen-to-carbon ratio of one and a substantial oxygen content, while many target hydrocarbons or oxygen-free products have an effective hydrogen-to-carbon ratio closer to two. Biomass is also used both as a carbon source and as process energy, so some feedstock must be oxidised to supply heat. Carbon consequently leaves the main product route as CO_2 during gasification, reforming, shift conversion and gas conditioning. This is not necessarily evidence of poor reactor performance; it partly reflects stoichiometry and the energy balance of the overall plant.

Adding low-emission hydrogen changes that balance. Hydrogen can convert part of the separated CO_2 into additional methanol, methane or other products instead of allowing the carbon to leave the product chain. Lundgren reported that, in suitable configurations, the same biomass input could yield roughly twice or even three times as much product and that carbon efficiency could exceed 90 per cent. Oxygen co-produced by water electrolysis may also be valuable for oxygen-blown gasification. These gains are conditional, however: the hydrogen must be genuinely low-emission, and the extra electrolysers, power supply, synthesis capacity and heat integration must be included in both the lifecycle assessment and the investment case.

5.1.3 BECCS and BECCU as different optimisation objectives

The choice is therefore not simply between capture and no capture. BECCS and BECCU optimise different outcomes, as summarised in Table 2.

The alternatives are not necessarily mutually exclusive. A project could split the separated stream, store one fraction and use another, or alter the split as hydrogen, product and carbon-removal values change. Nevertheless, the accounting must remain explicit. Carbon embodied in methanol or another short-lived fuel will normally return to the atmosphere, so it should not be credited with the same permanence as geological storage, even when it provides valuable fossil displacement.

Table 2: Main characteristics of BECCS and BECCU in biomass gasification

Aspect	BECCS	BECCU
Fate of separated CO_2	Transported to permanent storage.	Converted into fuels, chemicals or materials.
Primary climate function	Durable carbon removal and negative emissions.	Additional renewable product and displacement of fossil counterparts.
Principal cost driver	CO_2 conditioning, transport and storage.	Low-emission hydrogen, electricity and additional synthesis equipment.
Principal revenue	Carbon-removal credits or policy support, alongside energy-product revenue.	Product sales and low-carbon-fuel or material value.

5.1.4 Carbon-removal value, regional economics and plant design

An illustrative methanol cost analysis showed how strongly the preferred option can depend on the price paid for carbon dioxide removal (CDR). Using a fossil-methanol reference price of EUR 560 per tonne, the presentation indicated that biomethanol including CO_2 transport and storage would reach that reference at an implied CDR value of approximately EUR 40 per tonne of CO_2 in China, EUR 70 in North America and EUR 170 in Europe. The underlying curves were based on a separate 2026 presentation cited in the slides and should not be read as bankable forecasts. Their value was to demonstrate sensitivity: regional capital and operating costs alter the level of support required, while increasing CDR value progressively improves the economics of storing biogenic CO_2.

At higher CDR values, storage can outperform utilisation because each tonne permanently stored receives increasing value, whereas converting the same CO_2 into methanol requires additional hydrogen and plant capacity and produces a carbon stream that is eventually re-emitted. Conversely, where storage access is costly or delayed, hydrogen and electricity are inexpensive, and products command a strong premium, utilisation may remain the more investable route. Policy design can therefore change not only project profitability but also the optimal physical configuration of a plant.

Lundgren used a further investment comparison to question whether capture should always be retrofitted to an existing asset. The figures presented compared a 320 MW fuel-input Repsol gasification-based concept, with an estimated investment of about EUR 900 million or EUR 2.8 million per MW, with the 420 MW Stockholm Exergi heat-and-power plant and CCS development, for which the cited boiler and CCS investments totalled about EUR 1.8 billion or EUR 4.3 million per MW of fuel input. The slides argued that even a 50 per cent increase in the former estimate would leave it below the latter specific investment, while converting the separated CO_2 into an equivalent e-methanol stream could add at least EUR 2 million per MW. These are not like-for-like projects and the figures were presented for strategic comparison, not procurement. The underlying question is nevertheless important: in some cases, reconstructing an integrated gasification, synthesis and capture system may create more value than adding capture and utilisation equipment to a legacy plant.

5.1.5 Implications for Task 33 and the BECCUS 3.0 work programme

The presentation concluded by introducing the IEA Bioenergy inter-task project BECCUS 3.0, which continues the 2022-2024 work on management of biogenic CO_2. Its proposed focus is to identify promising BECCU/S systems by comparing economics, emission reductions and infrastructure needs, and to develop governance frameworks and decision criteria for the role of BECCS in future energy systems. This agenda is well aligned with the workshop discussion because the technically feasible options are numerous, while infrastructure timing, market rules and accounting determine which combinations are credible in a particular region.

For project developers, the main implication is to test storage and utilisation at the front-end design stage rather than label a project as BECCS or BECCU too early. Scenario analysis should vary hydrogen carbon intensity and cost, CDR value, product price, CO_2 transport and storage access, capture rate, plant utilisation and the duration of carbon storage in products. A design that can redirect carbon between storage and production, while preserving clear measurement and verification, may be more robust than one optimised around a single policy or commodity-price assumption.

5.2 MODULAR GASIFICATION, HYDROGEN AND BIOCHAR

Paul Willacy of Compact Syngas Solutions Ltd made the case for modular, decentralised gasification located close to feedstock and energy demand. Modular units can be manufactured and replicated, reduce the distance over which bulky low-density biomass is transported, and limit the effect of a single unit being unavailable. They can also provide steady output independent of weather. The commercial proposition may combine several value streams: waste gate fees, synthesis gas for heat or power, hydrogen separated by pressure-swing adsorption, biochar and verified carbon value.

The company reported demonstration results with high CO_2 capture and hydrogen purity close to commercial product specifications. These were project-specific results rather than universal performance claims, but they indicated the potential of integrated modular systems. Containerised pilot and demonstration units were discussed, together with a Kenyan tea-processing case in which local residues could displace fossil energy and produce a potentially useful biochar. The presentation reinforced a general commercial lesson: a project that depends on one product price may be fragile, whereas a carefully governed product stack can make better use of the feedstock and provide resilience. The stack must still be assessed as a whole so that the same climate benefit is not claimed in more than one market.

5.3 SUSTAINABLE AVIATION FUEL PATHWAYS AND REFINERY INTEGRATION

Sanjeev Gajjela of PySAF discussed sustainable aviation fuel (SAF), which remains important for long-haul aviation because aircraft fleets are long-lived and few alternatives exist. Current supply is far below demand and largely relies on hydroprocessed oils and fats, whose feedstocks are limited. Future production will require routes including gasification with Fischer-Tropsch synthesis, alcohol-to-jet, power-to-liquid fuels and upgraded pyrolysis intermediates.

Each pathway faces scale-up barriers, including reliable syngas cleaning, catalyst performance, access to low-carbon hydrogen and electricity, high capital costs, fuel qualification and offtake. Certification can take years, so it must begin before commercial deployment.

PySAF aims to produce a stable, low-water, low-oxygen intermediate for co-processing in existing refinery units. This could use refinery assets and systems, but requires pre-upgrading, deoxygenation, contaminant control and demonstration at scale because untreated pyrolysis oil has limited blendability and can cause operational problems.

5.4 BIOCHAR FOR DURABLE CARBON STORAGE AND WIDER APPLICATIONS

5.4.1 Formation, structure and carbon residence time

Dr Jitka Hrbek of BOKU University Vienna, Chair of IEA Bioenergy Task 33, defined biochar as the carbon-rich solid produced during thermochemical conversion of biomass. During pyrolysis or gasification, hydrogen and oxygen are preferentially released in volatile compounds and the remaining solid becomes enriched in carbon. Much of the plant material's pore structure is retained and additional micropores can form, giving the product a high specific surface area and sorption capacity. At the same time, the carbon structure becomes increasingly condensed and aromatic, which makes an appropriately produced char more resistant to biological decomposition than the original biomass.

This change in residence time is the basis of the carbon-removal claim. Unconverted plant biomass, compostable residues and many organic wastes would normally decompose or be combusted, returning a large share of their carbon to the atmosphere over relatively short periods. Converting part of that carbon into a stable solid and placing it in a durable, monitored use can slow the return substantially. The climate benefit is not automatic: it depends on the feedstock counterfactual, process emissions, the fraction of carbon retained, measured stability, transport, end use and the treatment of energy co-products.

An illustrative mass balance in the presentation followed three tonnes of wood containing about 1.5 tonnes of carbon. The process yielded approximately one tonne of biochar containing 0.79 tonnes of carbon, 1.1 tonnes of pyrolysis oil containing 0.49 tonnes of carbon, and 0.67 tonnes of pyrolysis gas containing 0.22 tonnes of carbon. The solid fraction represented the potentially long-lived carbon store, while the oil and gas could provide thermal or electrical energy and displace fossil carbon. An accompanying indicative estimate associated the co-products with about 750 kWh of energy per tonne of CO_2 sequestered. Actual yields vary widely with moisture, feedstock composition, reactor type, temperature and residence time.

The presentation cited an indicative average carbon-removal cost of about US$179 per tonne of CO_2 for pyrolysis biochar, compared with US$388 per tonne for a broader set of removal technologies, and reviewed published estimates of global biochar potential ranging from roughly 0.1 to 6.6 Gt CO_2-equivalent per year. Both figures require caution. The cost values were drawn from market-oriented sources rather than a harmonised engineering comparison, and the very wide potential range reflects different assumptions about sustainable biomass, conversion yields, competing uses, permanence and deployment constraints. The defensible conclusion is not that biochar is uniformly low-cost or unlimited, but that it can make a material contribution within a portfolio of negative-emission technologies.

5.4.2 Feedstock quality, certification and carbon-removal assurance

Potential feedstocks include residues from agriculture, forestry, horticulture, food production and consumption, as well as selected composting inputs, anaerobic-digestion residues and sewage-derived materials. These streams differ substantially in nutrients, ash, salts, metals and organic contaminants. A clean woody char, a char from digestate and a char from sewage sludge cannot be assumed to have the same environmental behaviour or permitted applications. Feedstock acceptance, process control and product testing therefore determine whether the material is a useful soil amendment, an industrial sorbent, a construction additive or a waste requiring restricted management.

Hrbek highlighted several layers of assurance. The European Biochar Certificate is a voluntary scheme emphasising sustainable production, climate impact, contaminant limits and certification of production plants and process control. An Austrian national standard is more application-oriented, with particular attention to product quality for soil use and compliance with national environmental and waste requirements. At European level, the Carbon Removals and Carbon

Farming Certification (CRCF) framework provides an emerging basis for certifying carbon removals. These systems serve related but distinct purposes: product safety, process quality and carbon-credit integrity should not be treated as interchangeable.

A credible carbon-removal claim should therefore document chain of custody, feedstock eligibility, energy inputs, char yield, carbon content, stability, end-use location and the risk of reversal. It should also address additionality, leakage and double counting between the char product, renewable energy and any waste-management credit. Long-term field monitoring remains important because laboratory stability indicators cannot capture every soil, moisture and management condition. Certification can reduce transaction costs and support market trust, but it does not replace project-specific environmental assessment.

5.4.3 Product pathways and the distinction between pyrolysis and gasification char

The presentation grouped biochar uses into soil and agricultural applications and a growing range of industrial applications. The most relevant pathways include:

- soil amendment, horticultural substrates, composting and selected soil-remediation uses, where nutrient interactions, pH, water retention and crop response must be tested;
- wastewater treatment, adsorption, catalyst support and activated-carbon precursors, where surface area, pore-size distribution and surface chemistry are central;
- concrete and asphalt additives, where durability, leaching, mechanical performance and compatibility with standards determine acceptance; and
- functional industrial uses based on conductivity, thermal resistance or chemical stability, which may value properties different from those required in agriculture.

The comparison between slow-pyrolysis chars produced at 400 and 600 degrees Celsius and fluidised-bed gasification chars produced in air at 600 and 750 degrees Celsius illustrated why a single generic specification is insufficient. Pyrolysis-derived material commonly retains more surface functional groups and can have greater porosity and chemical reactivity, properties that can support soil, horticultural and adsorption applications. Gasification-derived char has normally experienced higher temperature and more severe reaction, producing a more carbon-condensed and thermally hardened solid that can offer enhanced stability and be attractive for industrial applications or long-term carbon storage. These are tendencies, not fixed rules: feedstock minerals, heating rate, oxidant, residence time and post-treatment can change the outcome.

A wastewater-treatment example from MCI Innsbruck demonstrated the value of matching char properties to a defined service. High sorption capacity can support pollutant removal, but spent material then has to be managed according to the contaminants accumulated. Similar end-of-life questions apply to char in construction products and activated carbon. Product development should therefore include the full life cycle, not only the initial carbon content and saleable application.

5.4.4 Role in climate action

The central conclusion was deliberately balanced. Biochar can provide durable carbon storage while producing useful energy and materials, and it may be deployable across a broad range of scales. It cannot compensate for unlimited ongoing emissions, nor can every char or application qualify as a removal. Its strongest role is as one element of a technology-open portfolio that also includes emissions reduction, geological storage and other negative-emission routes. For the workshop, this reinforced the broader message that carbon claims must follow measured performance, permanence and sustainable resource use rather than the name of the technology alone.

5.5 PATHWAY DISCUSSION: COMPLEMENTARITY RATHER THAN A SINGLE WINNER

The technology panel did not identify one universally preferred route. Refinery co-processing may provide a relatively rapid route to market for upgraded pyrolysis intermediates; Fischer-Tropsch and other synthesis pathways remain important for larger future volumes; gasification offers product flexibility and a natural point for CO_2 separation; biochar can provide durable storage while supporting selected material or soil applications. The practical decision should start with the local feedstock, infrastructure and product market, then test lifecycle carbon, technical readiness and scalability. The panel also discussed co-gasification and the effects of mineral-rich industrial residues, reinforcing the need to understand feedstock interactions rather than rely on a generic biomass specification.

6. Technology scale-up and deployment

6.1 INDUSTRIAL EXPERIENCE: DESIGN FOR REAL FEEDSTOCKS AND LONG POLICY CYCLES

The scheduled industry contribution on circular hydrogen and alternative fuel production drew on two decades of project-development experience, including projects that did not reach sustained commercial operation. The central warning was that technology development takes many years, while policy priorities and incentive programmes can change much faster. Inconsistent support can strand learning and supply chains just as a technology becomes ready for a larger demonstration. Durable policy should therefore reward outcomes and learning over a realistic development period rather than repeatedly restarting short competitions.

Industrial feedstocks are rarely as clean or uniform as early research materials. Developers are moving from highly processed wood towards heterogeneous residues, wastes and contaminated streams. These introduce tar, ash, alkali metals and other minerals that can melt or cause slagging, as well as variation in moisture and particle size. Plants designed around a narrow specification may achieve good tests but fail commercially when the supply chain cannot maintain it. The contribution advocated local supply chains, high-temperature oxy-steam gasification where appropriate, and modular fixed-bed or downdraft units operated in parallel. Parallel units can simplify maintenance and reduce the risk associated with one very large reactor, although they require standardised balance-of-plant and control systems.

6.2 CHINESE PROGRESS IN INTEGRATED GREEN-FUEL PRODUCTION

6.2.1 Resource, demand and policy context

Assoc. Prof. Jian Li of Tianjin University presented on behalf of Prof. Guanyi Chen and a collaboration involving Tianjin University of Commerce, Tianjin University and Tibet University. The presentation began with the scale and diversity of China's biomass resource. An indicative resource table assigned available-energy potentials of 4.43 x 10^8 tonnes of coal equivalent (tce) to domestic waste, 0.85 x 10^8 tce to sludge, 2.24 x 10^8 tce to agricultural stalks, 1.02 x 10^8 tce to forestry waste and 2.11 x 10^8 tce to livestock manure. The sum, approximately 1.065 billion tce, represents theoretical or available potential rather than an immediately recoverable fuel supply. The presentation also highlighted future resources such as dedicated energy plants, including Arundo donax, and other emerging solid-waste streams.

The industrial motivation was framed around energy security and rapidly developing demand for green liquid fuels. The presenter estimated that Chinese demand for green methanol could exceed 12 million tonnes by 2030, compared with a then-current supply below 300,000 tonnes, while sustainable aviation fuel demand was increasing from an almost negligible domestic production base. The presentation linked this activity to a 2025 National Energy Administration notice supporting research, development and industrial pilots for green liquid fuels made from agricultural and forestry residues through gasification, hydrogenation and catalytic synthesis, and to the March 2026 Government Work Report's emphasis on green fuels as a new growth area.

6.2.2 Green-methanol and sustainable-aviation-fuel project pipeline

By the end of December 2025, the presentation counted 173 signed, registered, pending-approval or planned green-methanol projects with a combined theoretical capacity of 53.46 million tonnes per year. Three projects had entered operation or partial operation, twelve were under construction with a stated combined capacity of 3.0672 million tonnes per year, and eight ports were shown as able to refuel green methanol. The scale of the pipeline demonstrates strong interest, but the categories are not equivalent: planned capacity can be delayed or cancelled, and commissioning does not by itself demonstrate sustained output, product quality or lifecycle performance.

The operating or partly operating examples highlighted were the 50,000 tonne-per-year first phase of Shanghai Electric's Taonan wind-power and biomass project, CIMC Green Energy's 50,000 tonne-per-year Zhanjiang biomass project, and the first phase of Goldwind's project in Hinggan League, listed at 250,000 tonnes per year and in partial operation. Table 3 summarises four projects for which more detailed process and timing information was presented.

Table 3: *Selected Chinese green-methanol projects described in the presentation (status and dates as reported in May 2026)*

Project and status	Route and nominal scale	Key presentation-reported features and timing
Shanghai Electric, Taonan, Jilin - first phase operating; wider build-out planned	Wind-power hydrogen coupled with straw gasification. First phase 50,000 t/year; full scheme 250,000 t/year.	680 MW renewable capacity; 800,000 t/year straw; fluidised-bed gasification; 8,000 Nm3/hour electrolysis; 10 t hydrogen storage. Construction began March 2024 and first production was reported for July 2025.
CIMC Green Energy, Zhanjiang, Guangdong - operating	Biomass gasification and synthesis coupled with biomass direct-combustion power; 50,000 t/year.	Circulating fluidised-bed gasification with mild gasification and char self-catalytic cracking; attention to particle fluidisation, in-situ tar cracking and alkali-metal corrosion. Commissioned 16 December 2025.
SPIC Jilin Electric Power, Lishu, Jilin - under construction	Wind-solar hydrogen coupled with entrained-bed biocarbon gasification; 197,200 t/year.	400 MW wind; hydrogen production 32,000 Nm3/hour; gasifier feed 43.94 t/hour biocarbon and 87.77 t/hour syngas output; 208,000 Nm3 hydrogen storage and 10 MW/20 MWh electricity storage. Expected production in the second half of 2028.
LANGE New Energy, Dafeng, Jiangsu - under construction	Agricultural-waste gasification without external green-hydrogen coupling; 300,000 t/year.	Combined fixed-bed/fluidised-bed gasification and 100,000 m3 methanol tank farm. Construction began May 2025; operation was planned for the end of 2026.

The presentation also described two announced biomass-gasification and Fischer-Tropsch sustainable-aviation-fuel projects. Lanze Energy's Luzhou project in Sichuan was presented as a 100,000 tonne-per-year route using distillery residues and wood, with construction starting in April 2026 and operation planned for 2028. China Energy Engineering Corporation's Shuangyashan project in Heilongjiang was presented as a first 100,000 tonne-per-year phase combining agricultural straw with wind-solar hydrogen, with construction beginning in September 2025 and operation planned for 2027. These projects indicate movement toward complete gasification-to-jet-fuel chains, but their schedules and performance remained to be demonstrated.

6.2.3 Coupling anaerobic digestion with gasification

The research programme sought to use wet and heterogeneous residues more completely by combining moderate anaerobic digestion with pyrolysis or gasification of the remaining solids. Anaerobic digestion first recovers a methane-rich biogas, while compression and separation can provide streams for reforming or synthesis; the digestate then enters thermochemical conversion to produce additional synthesis gas and char. Measurements of the solid and liquid phases showed that the largest changes occurred early in fermentation and that the degree of digestion approached saturation after approximately six to eight days. This supported the concept of stopping at a moderate stage rather than maximising digestion time before gasification.

Thermogravimetric and online FTIR analysis identified successive dehydration, volatile-release and residue-degradation stages, with characteristic temperatures around 252, 363, 569 and 727 degrees Celsius in the presented tests. Moderate digestion promoted the preferential release of characteristic functional groups and gases during subsequent heating, whereas full fermentation reduced the intensity of the released compounds. Methane production efficiency was highest in the early fermentation period, and carbon-hydrogen-oxygen diagrams showed the digestate shifting away from cellulose and hemicellulose toward a more lignin-rich composition. The team therefore proposed approximately day eight as a practical dividing point for high overall energy recovery.

Bench experiments on distillers' grains illustrated the influence of gasifying medium. At 800 degrees Celsius and a steam-to-biomass ratio of three, the reported gas yield was 72.33 per cent, tar yield 2.85 per cent and hydrogen-to-carbon-monoxide ratio 1.01, compared with a 56.73 per cent gas yield and 16.04 per cent tar yield in nitrogen pyrolysis at the same temperature. Steam gasification of digestate at the same ratio produced a higher hydrogen-to-carbon-monoxide ratio of 1.63 but a lower gas yield of 40.40 per cent and a higher solid-carbon yield. These results demonstrate that pre-treatment and gasification conditions can tune synthesis-gas quality, but also create trade-offs between gas, tar and residual solid.

In the system comparison, the coupled anaerobic-digestion and gasification route, described as Route 2 during the presentation, achieved a reported conversion efficiency of 16.72 per cent, compared with 11.04 per cent for the stand-alone alternative. The improvement was attributed to more complete use of hydrogen in the distillers' grains and to biogas reforming, which increased the hydrogen content of the synthesis gas. A simpler option retained advantages in footprint and system complexity. Under the study boundaries, both routes were calculated to reduce carbon emissions by more than 90 per cent because process energy was supplied from biomass. That result is model-dependent and should be re-tested with full feedstock, electricity, transport, methane-leakage and carbon-storage boundaries before being treated as a certified lifecycle claim.

6.2.4 Grey-box modelling and inverse process design

A second research strand combined classical process models with machine learning. Purely theoretical models can cover a wide operating range but may be inaccurate when kinetic or material parameters are uncertain, whereas empirical models can be accurate within their training range but extrapolate poorly. The proposed grey-box approach used the Anaerobic Digestion Model No. 1 as the fermentation framework while machine-learning models estimated difficult kinetic constants, improving reported accuracy by 5 per cent. For pyrolysis and gasification, a thermodynamic-equilibrium framework was supplemented by machine-learning estimation of effective reaction temperature, improving reported accuracy by 8 per cent.

Coupling the two models required more than connecting their outputs. Conventional digestion models emphasise gas production and provide limited detail on the composition of the residual solids needed by the gasifier model. Fermentation also evolves over days, while gasification occurs over minutes or seconds. The team introduced a macro-element-molecule representation based on elemental conservation to estimate solid-product properties, and a dimensionless time variable to reconcile the different time scales. Heuristic optimisation was then used to explore fermentation time, pH, temperature, catalyst, pressure and other variables in reverse design. The resulting design software was reported to improve system energy efficiency by 8.3 per cent compared with a traditional design approach.

6.2.5 Online monitoring and staged tar removal

The third research strand addressed gas quality. In-situ Raman spectroscopy was used to monitor hydrogen, carbon monoxide, carbon dioxide, methane, oxygen and nitrogen in the synthesis gas, while in-situ FTIR coupled with a fractional condenser was used to characterise tar components. The intention is to feed these measurements back to the gasifier so that operating conditions can respond to changing feedstock and tar formation rather than relying on delayed laboratory analysis.

Tar removal was divided into two stages. Microwave-assisted catalytic cracking targets heavy tar at high temperature. The presentation reported that metal-organic-framework-derived cobalt-on-carbon catalysts dispersed active metal sites effectively and showed greater activity and stability under microwave irradiation than under conventional heating. The proposed mechanism combined microwave electron focusing, enhanced water dissociation and exposure of cobalt sites, with carbon-deposit gasification proceeding faster than deposit formation. Nickel-cobalt variants were also being developed to tune active sites and resistance to deactivation.

A lower-temperature photothermal steam-reforming stage targets the remaining light tar. Lanthanum-manganese-nickel perovskite catalysts were screened for oxygen vacancies, light absorption and charge separation. The LM4N6 formulation maintained more than 95 per cent light-tar conversion for 24 hours at 400 degrees Celsius in the presented test. At pilot scale, the combined biomass-gasification and microwave-tar-removal equipment was reported to reduce tar to 28.4 mg/Nm3. The result is promising, but commercial relevance will depend on longer campaigns, energy consumption, catalyst replacement, contaminant tolerance and performance across real feedstock variation.

6.2.6 Assessment and implications for industrialisation

The Chinese contribution linked project development with research on feedstock conversion, digital design and gas cleaning. It showed why industrialisation cannot be judged by nominal capacity alone. Projects must secure large volumes of consistent biomass, integrate renewable power where relevant, maintain syngas quality, protect catalysts, certify methanol or aviation fuel and achieve high availability. The gap between 53.46 million tonnes per year of announced capacity and the much smaller operating base therefore indicates both opportunity and delivery risk.

The research programme addresses these risks through moderate digestion to broaden the resource base, grey-box models linking biological and thermochemical processes, online spectroscopy for adaptive control, and staged tar removal to protect synthesis. The next evidence threshold is integrated, long-duration operation supported by transparent mass and energy balances, catalyst-life data, start-stop performance and independently reviewable lifecycle results. Task 33 can help compare findings across European and Asian projects and distinguish transferable lessons from outcomes shaped by local policy, feedstocks and infrastructure.

6.3 DUTCH GREEN GAS AND NEGATIVE-EMISSION POTENTIAL

Berend Vreugdenhil of TNO described the Netherlands' developing market for green gas, supported by a blending obligation and an extensive gas network. An indirect-gasification route combined with OLGA tar removal, gas cleaning and methanation can convert varied biomass into grid-quality gas. The process requires CO_2 separation before grid injection, creating a concentrated stream that can be used or stored. With sustainable biogenic feedstock and durable storage, the gas supplied to the grid can be associated with strongly negative carbon intensity.

Demonstration at tens-of-megawatts scale and public support were discussed as steps towards commercial deployment. The talk argued that a carbon-intensity-based policy can distinguish between pathways more effectively than a simple volume mandate, because it rewards the additional value of capture and storage. At the same time, domestic biomass cannot replace all fossil gas. Green gas should be directed to uses where it has high system value, and decisions about imports must consider sustainability and security of supply. The Dutch example therefore combined technology, an existing network, market obligation and carbon accounting - the same elements identified elsewhere in the workshop as necessary for deployment.

6.4 SCALE-UP SYNTHESIS

Across the scale-up session, three principles stood out. First, scale should be matched to feedstock geography and project risk: modular systems and large integrated plants can both be appropriate. Second, long-duration operation with real feedstocks is more valuable than a short campaign that demonstrates only a peak efficiency. Third, deployment requires a repeatable commercial and regulatory package, not just a reactor design. International exchange through IEA Bioenergy Task 33 can accelerate this process by comparing operating data, standards and failure modes across countries while allowing for local resource and policy conditions.

7. Policy, regulation and sustainability

7.1 FROM CARBON REMOVAL TO COMMERCIAL REALITY

John Kelly of Ricardo opened with a challenging question: is BECCS genuinely carbon negative? The answer depends on the whole system. Biomass cultivation or collection, processing, transport, conversion, capture, compression, transport to storage, storage performance, co-products and residual emissions all shape outcomes. The biomass counterfactual is equally important. Capturing a tonne at the stack does not equal removing a net tonne from the atmosphere if upstream emissions are high or the feedstock would otherwise have retained carbon for a long period.

The presentation argued that deployment of engineered removals remains far below the levels envisaged in climate pathways. The constraint is not simply whether capture equipment works; it is whether governance, infrastructure, markets and public legitimacy can support a complete sector. CO_2 utilisation should be assessed carefully. A fuel or short-lived material can be valuable because it replaces fossil carbon, but the carbon is generally re-emitted and should not automatically receive a permanent-removal claim. Longer-lived products require evidence on lifetime, end-of-life and the likelihood that carbon remains out of the atmosphere.

Policy must also serve sources beyond major industrial clusters. Pipelines are efficient for large continuous flows, but distributed biogenic sources may need liquefaction, intermediate hubs, rail, road or shipping. Incentives should be stable enough to support capital investment yet flexible enough to avoid rewarding poor system design. The speaker cautioned against defining an idealised framework so complex that no projects proceed. A credible early system can be improved as evidence grows, provided its boundaries, uncertainties and safeguards are transparent.

International approaches differ. European and UK policy increasingly combines sustainability criteria, carbon pricing and targeted support, while North American tax-credit-style incentives can provide a more direct cash value for captured and stored CO_2. Harmonised principles for measurement, reporting and verification would help investors and buyers compare outcomes, but local implementation will still reflect national resources, regulations and infrastructure. The decisive point was that a BECCS project becomes negative because of how it is designed and operated, not because of its label.

7.2 ACCOUNTING PURPOSE, SYSTEM BOUNDARIES AND STANDARDS

Michael Goldsworthy of Drax focused on the methodologies used to quantify removals. This is commercially material because a project's revenue can depend heavily on the volume of credited removal and the price attached to it. Drax is considering both retrofit and new-build BECCS opportunities, making consistent decision rules important. The first question should be: what is the accounting for? National greenhouse-gas inventories, corporate reporting, project crediting and compliance-support schemes have different objectives and may legitimately use different boundaries and conventions.

National inventories generally follow agreed territorial categories. Project methodologies instead compare an intervention with a hypothetical baseline and must address additionality and leakage. That makes the baseline one of the most judgement-sensitive parts of the calculation. A plant-gate boundary can be useful for operations but cannot establish net removal on its own; a value-chain boundary must include feedstock production or collection, transport, energy, capture losses and storage. The assumed alternative fate of residues, forest material or energy crops can change the result substantially.

The presentation also distinguished measurement from claiming. A tonne may appear in a national inventory, a company disclosure and a carbon-credit transaction, but the right to claim the climate outcome must be allocated so that it is not sold or counted twice. Some regional consistency is desirable for investment and trade, yet one universal methodology may not be practical where sustainability rules, feedstocks and policy purposes differ. Voluntary and compliance systems are likely to retain differences. The recommended discipline is to state the use case and boundary before calculation, document material assumptions and expose sensitivity to the baseline rather than presenting one number as unquestionable.

7.3 BIOMASS SUSTAINABILITY, LAND USE AND NATURAL CAPITAL

Dr Robert Holland of the University of Southampton placed biomass supply within a natural-capital framework. Projections of future UK biomass demand vary widely, particularly for dedicated energy crops. Waste and residue streams are constrained by availability and the waste hierarchy, while energy crops can expand over a much broader range if policy and landowner decisions allow. The climate case must therefore be considered alongside biodiversity, ecosystem services, food production, water, soil and human wellbeing.

Dedicated perennial crops can provide co-benefits when they replace some intensive arable land, including reduced soil disturbance, improved water quality, flood mitigation, habitat and carbon storage. Outcomes are more ambiguous when grassland is converted and are generally poor when forest is replaced. National spatial modelling at one-kilometre resolution compared deployment driven mainly by market cost with deployment that also values natural capital and applies constraints for food and nature. Cost-only optimisation tended to concentrate crops on cheaper land and could create higher associated emissions. Including ecosystem services produced a different spatial pattern and substantial societal value, but tight food and environmental constraints could make very high biomass targets infeasible.

The modelling also demonstrated that a mathematically optimal national map will not appear automatically. Real deployment is local, patchy and path-dependent. Farmers respond to contract terms, risk, familiarity, machinery, neighbours and trusted advisers; environmental effects operate at catchment and landscape scale; and processing plants require a dependable radius of supply. Policy should therefore combine national sustainability limits with regional planning, local participation and long-term contracts. The best biomass strategy is not the one that maximises tonnes in isolation, but the one that delivers robust climate and public value within ecological limits.

7.4 POLICY-PANEL DISCUSSION

The panel questioned whether methodologies are sometimes treated as a compliance exercise rather than a tool for improving climate outcomes. Participants agreed that hypothetical baselines are particularly vulnerable to optimistic assumptions, and that transparency and scientific evidence are more important than superficial precision. Comparability will remain difficult because projects use different resources and operate under different rules. A practical framework should therefore identify a common minimum set of principles - lifecycle boundaries, permanence, leakage, uncertainty and double-counting control - while requiring project-specific evidence for the assumptions that drive the result.

8. Round-table outcomes

This concise summary is limited to the outcomes reported back to the wider workshop. Three priorities were highlighted: research on rapid feedstock characterisation, process monitoring and control, tar and contaminant prediction, integrated modelling and longer pilot campaigns; deployment through stronger industry-academia collaboration, shared testing, staged demonstration, and early planning for certification, logistics and community engagement; and workforce development through joint training, placements, continuing professional development and practical pilot-plant experience spanning technical, regulatory, financial and communication skills.

9. Conclusions and recommended actions

The workshop presented BECCS and BECCUS as a family of system choices rather than a single technology. Gasification can generate hydrogen, methane, methanol, heat, power and concentrated CO_2; pyrolysis can supply refinery intermediates and biochar; anaerobic digestion can contribute renewable gas and distributed biogenic CO_2; shared transport and geological storage can convert capture into durable removal. The strongest projects will combine these options according to local resources and infrastructure while remaining explicit about whether carbon is stored, recycled into a product or re-emitted.

Technical development remains necessary, particularly for feedstock sensing, tar and contaminant control, catalysts, product upgrading, integrated operation and long-duration pilots. However, the rate of deployment will be determined just as strongly by policy durability, accounting integrity, infrastructure sequencing, sustainable biomass limits, finance and skills. The workshop's closing perspective was therefore practical and collaborative: proceed with credible early projects, learn transparently, and build the institutions and workforce that allow successful configurations to be repeated.

The expanded Task 33 evidence also clarified that the preferred carbon-management route is conditional. In gasification, low-emission hydrogen can convert separated CO_2 into substantially more product, while a high and durable CDR value can favour geological storage. In biochar systems, retaining carbon in the solid must be balanced with energy co-products, contaminant control and product-specific standards. In the Chinese green-fuel sector, the scale of the announced pipeline is significant, but credibility will depend on commissioning, sustained operating hours, feedstock logistics, product certification and transparent lifecycle data. These are different manifestations of the same requirement: system claims should be tied to measured whole-chain performance.

***Table 4**: Recommended actions arising from the workshop*

Priority	Action and intended result
1. Policy certainty	Set durable carbon-removal, low-carbon-fuel and infrastructure signals that extend beyond individual funding rounds, creating a bankable pipeline from demonstration to replication.
2. Whole-chain infrastructure	Coordinate capture projects with shared CO_2 transport and storage, including practical routes for distributed sources, to lower connection risk and widen access to permanent storage.
3. Credible accounting	Define the purpose, boundary, baseline, permanence, leakage and double-counting rules before commercial decisions, so finance is linked to genuine net removals.
4. Feedstock intelligence	Develop rapid characterisation, sensing and data-driven control for variable biomass and waste streams, improving the robustness of conversion and upgrading.
5. Pilot evidence	Operate integrated pilots long enough to generate decision-grade data on reliability, contaminants, catalysts and product quality, thereby reducing scale-up uncertainty.
6. System optimisation	Assess storage and utilisation together, including co-products, hydrogen, oxygen, heat integration and alternative feedstock fates, to balance removal, displacement and resource efficiency.
7. Sustainability safeguards	Embed land-use, biodiversity, water, soil, food-system and local-value criteria in project screening, keeping expansion within defensible biomass and natural-capital limits.
8. Skills and collaboration	Expand joint PhDs, industrial placements, continuing professional development and shared pilots to build technical, commercial, regulatory and engagement capability.