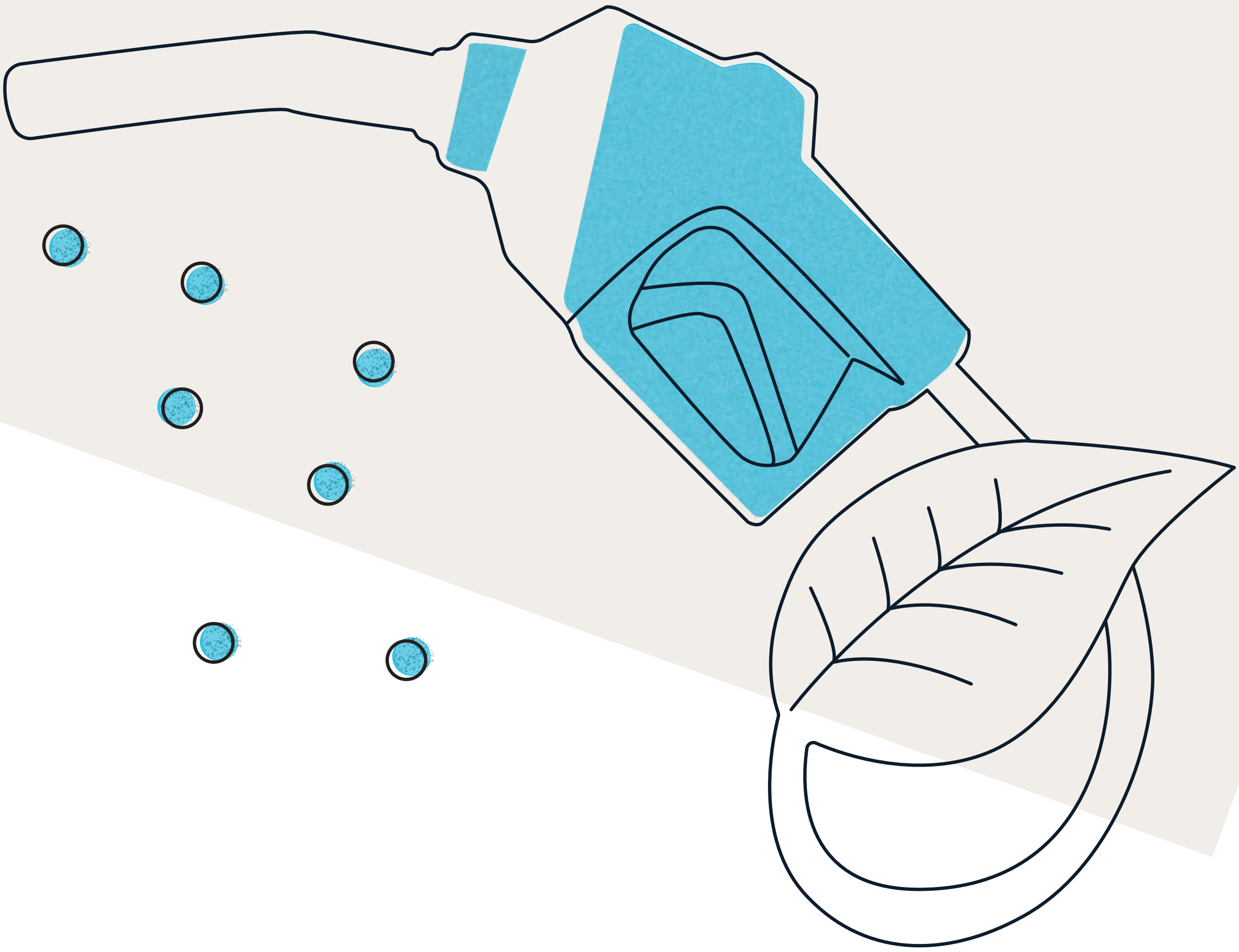
Commissioned by the University of Cambridge Decarbonisation Network

Decarbonising Fuels

Workshop Summary

Bringing together academia and industry with a shared interest in how to decarbonise fuels to achieve a net zero future

June 2023



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Introduction

Low-carbon, alternative fuels are critical to achieving the energy transition to meet net zero targets by 2050. Fuels play a vital role in the global energy ecosystem and cannot be simply eliminated by a one-size-fits-all solution. Replacing dependence on fossil fuels demands a combination of fundamental and applied research to address the spectrum, depth and speed of decarbonisation necessary to limit climate change.

It is not realistic to assume one solution, such as electrification, will be able to replace all fossil fuels in all applications in the short-term. There will be many use cases that require interim or hybrid solutions to fully decarbonise. Road freight is one such area. In his presentation Professor David Cebon highlighted where,

" in the short-term, biofuels are being used to support decarbonisation while electrification infrastructure is being rolled-out. Even with improved electrification for the very long-haul use case, a hybrid approach of electrification and biofuels will still be needed in some countries."

A huge range of fuels are derived from fossil fuels (oil, gas, coal). Each has been optimised for its corresponding set of applications and the applications have been optimised to the fuel. There is equal, if not more, variety in chemical complexity and production methods across alternative fuels, which adds further difficulty in matching which decarbonised fuel should replace which fossil fuel derivative across the wide variety of applications.

Understanding the best options for replacement across the whole value chain of each application is necessary for building a compelling business case that will direct investment into development, scaling, optimisation and deployment of new solutions.

Alongside the technical understanding, clear and confident policy is required to unlock the business case. At present political uncertainty caused by changing governments, weak policy and lack of international agreements is contributing to the gap between stated policies, announced pledges and the final commitments needed to meet net zero. Despite this, all future energy scenarios rely on widespread adoption of decarbonised fuels and in his presentation Dr Ilkka Hannula from IEA stated,

" for the first time, today's pledges, if implemented on time and in full, would keep the rise in global average temperatures in 2100 to below 2°C."

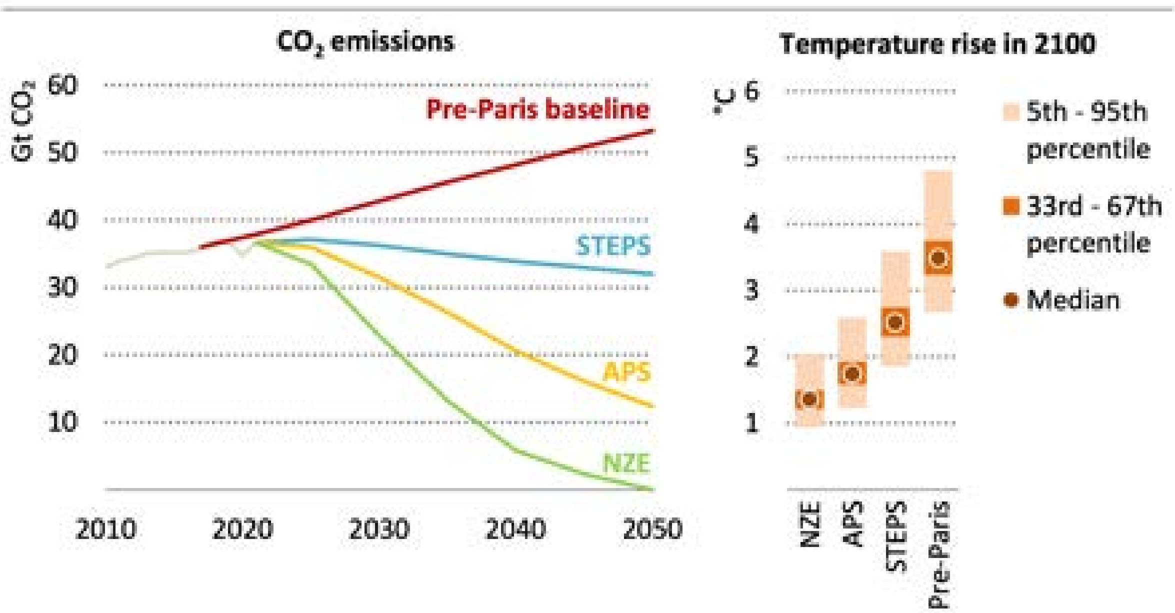
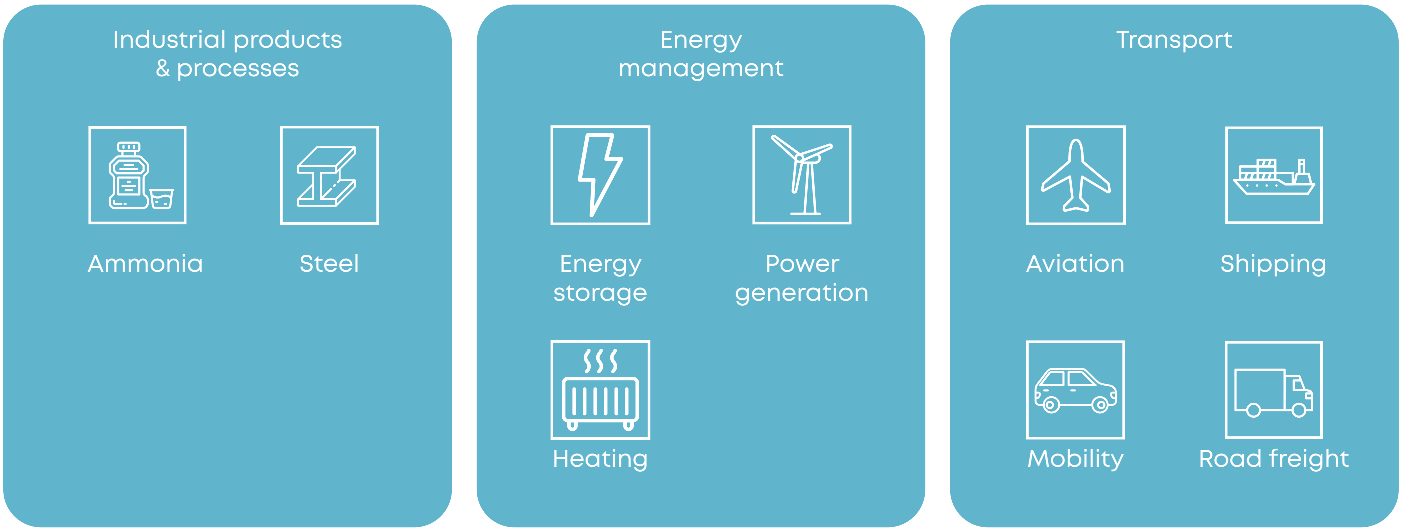


Figure 1.
Energy-related and process CO2 emissions, 2010-2050 and temperature rise in 2100 by scenario, World Energy Outlook 2022, IEA. Stated Policies Scenario (STEPS) shows the trajectory implied by today's policy settings. Announced Pledges Scenario (APS) assumes that all aspirational targets announced by governments are met on time and in full, including their long-term net zero and energy access goals. The Net Zero Emissions by 2050 (NZE) Scenario maps out a way to achieve a 1.5 °C stabilisation in the rise in global average temperatures, alongside universal access to modern energy by 2030. [1]

[1] IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

Example applications of decarbonised fuels



Academic institutions are a powerhouse of research and expertise. Their breadth of domain knowledge, state-of-the-art facilities, ability to create, test, analyse and demonstrate radical ideas makes them a powerful asset to industry. Professor Simone Hochgreb highlighted that,

"over 250 academic researchers work in energy research at the University of Cambridge[2]"

including one of her own research topics in modelling hydrogen turbulent flames.

So how can academic institutions better support industry to overcome the challenges associated with transitioning to decarbonised fuels to ensure the 2050 targets are fulfilled?

The Decarbonising Fuels Workshop is a prime example of how a university can leverage its global reputation, connections and influence across academia and industry to bring people together in a particular focus area to

"plant seeds for collaboration."

For many attendees, a key aim of attending the workshop was to make connections with individuals facing similar problems in their industry areas, understand the wider challenges, and find ways to work together. The workshop succeeded in this aim by providing plenty of time for information sharing across a variety of topics and capturing the spectrum of experiences and opinions.

The day was structured into two halves. The morning session identified current and future industry challenges across the value chain from production to end-use for four alternative fuels: hydrogen, ammonia, e-fuels and biofuels. A series of presentations by the policy and industry representatives set the scene prior to the break-out session. The afternoon began with quick-fire presentations to showcase research at the University of Cambridge. This was followed by a second breakout session to identify collaboration opportunities and research topics relevant to academia and different parts of the value chain of the four alternative fuel types.

The following pages summarise the industry challenges and opportunities for research identified by the workshop participants.

[2] https://www.energy.cam.ac.uk

Ammonia

Ammonia (NH3) is a carbon-free fuel. Ammonia is produced by the Haber Bosch process, which combines hydrogen and nitrogen in a high temperature, high pressure, catalysed reaction. Annual global production is >200 million tonnes and a staggering 1.8% of global CO2 emissions is attributed to this process.[3] The majority of these emissions come from the hydrogen feedstock, which is produced by steam methane reforming of natural gas. Today, 80% of the ammonia produced is used to make fertilisers, which are essential for feeding the global population. There is growing interest in ammonia as a promising alternative fuel and as a hydrogen carrier. Green ammonia is made from using a decarbonised hydrogen feedstock produced by electrolysis of water powered by renewable electricity.

Professor Laura Torrente Murciano believes

"green ammonia can unlock a new trade system of renewable energy and describes green ammonia as sunshine/wind in a bottle."

Despite the existing know-how and infrastructure for (brown/grey) ammonia production, distribution and use, there are still a number of challenges to overcome before green ammonia can become a widespread alternative fuel.

Highlighted industry challenges

The required scale of green ammonia production and speed of deployment to abate existing industrial processes as well as provide an alternative decarbonised fuel is vast. Major and rapid infrastructure development is required to meet these targets.

The availability and competition for renewable energy and decarbonised hydrogen could slow development and deployment. These two factors also contribute to the higher price of green ammonia compared to the price of conventional ammonia, which could limit market uptake.

Ammonia is a toxic chemical that causes severe irritation if inhaled or in contact with the skin and is very toxic to aquatic ecosystems. This toxicity prevents it from being directly used in consumer applications in the way traditional fuels are used today.

Combustion of ammonia produces NOx emissions, which are harmful to health and the environment.

The Haber Bosch process is highly optimised for today's production parameters and must be re-optimised to enable alternative production scenarios. For example, smaller-scale production plants to enable widespread, distributed ammonia production close to the source of decarbonised hydrogen and that are resilient to fluctuating feedstock levels.

Opportunities for research

Optimise the Haber Bosch process to a) cope with fluctuating feedstock availability due to the intermittent nature of renewable energy; b) produce green ammonia at smaller-scale. Opportunities to develop and use novel optimisation tools, such as using AI to engineer new processes and develop new catalyst chemistry.

Development of high yield ammonia cracking to separate the hydrogen from the nitrogen will demonstrate capability of ammonia as a hydrogen carrier.

Research and development into emissions control technologies to eliminate, or reduce to a safe level, the production of NOx in ammonia combustion.

Develop health and safety technologies and procedures to enable safe and widespread use of ammonia in consumer applications.

[3] https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Hydrogen

Decarbonised hydrogen is produced by water electrolysis powered by renewable electricity or by steam methane reforming with carbon capture. Not only does decarbonised hydrogen offer a vital solution to difficult to decarbonise sectors, such as industrial processes, industrial and domestic heat and hard-to-electrify transport, its production by electrolysis offers a solution to storing surplus renewable electricity and transporting that energy from the site of production to the site of use.

Today, annual global production of hydrogen stands at ~75 million tonnes as pure hydrogen and an additional 45 million tonnes as part of a mix of gases.[4] It is a critical feedstock in the chemical industry and in refineries, for example in steel production and ammonia production. The majority of hydrogen is produced from fossil fuels with no carbon capture.

Not only does hydrogen production need to decarbonise in order to decarbonise the value chain of industrial products, but growth in hydrogen production from the equivalent of 3% of global final energy demand today to 12% of final energy demand in 2050 could contribute 10% of the mitigation needed to achieve the IRENA 1.5°C Scenario.[5]

Highlighted industry challenges

The case for producing hydrogen by electrolysis in an offshore location is challenging due to the space and weight required for the electrolysers and associated equipment, including the supply of water to split into hydrogen and oxygen. Offshore operation and maintenance also carry safety risk and impact operating costs. Ernie Lamza, NSTA, described how solving these problems could enable more windpower sites that operate independent of a grid connection.

"Conversion to hydrogen onsite versus taking generated electricity to shore could help maximise the amount of wind power converted to hydrogen supporting energy storage and export opportunities."

Hydrogen is a leaky and explosive gas with its own global warming potential. Safety and environmental concerns must be addressed before large-scale production, storage and transport can come online.

There are not enough pilot scale demonstrations of hydrogen production, storage and distribution to inform technology investors about the lifetime cost of running the equipment, which weakens the business case for investing in the construction of this infrastructure on a large scale.

Cost effective storage solutions and distribution infrastructure is missing for hydrogen and oxygen. This is particularly relevant when the gases are not used at the site of production, and this can block a business case for investment in hydrogen production infrastructure.

The hydrogen economy can only be successful when every position of the value chain is filled. Without end users for the hydrogen it is not practical to produce it at scale. But before you can use hydrogen you need to be confident that you will be able to procure enough. To combat the challenges and risks of entering the hydrogen economy more hubs are being built with the aim to grow the UK hydrogen economy and support businesses across the value chain.

Opportunities for research

Investigate electrolyser design optimisation for installation at off-shore wind farms. Opportunities include methods to reduce size, weight and maintenance requirements, and further develop direct electrolysis of seawater.

Identify and develop use cases for electrolytically produced hydrogen and oxygen where the business case can withstand the higher cost of decarbonised products. This could enable investment, demonstrate usability and contribute to long-term cost reduction in decarbonised hydrogen production. E.g. using the oxygen stream in oxy-combustion for steel.

Hydrogen adsorption materials, such as metal organic frameworks, for cost-effective long-term hydrogen storage and hydrogen distribution solutions.

Hydrogen detection to identify and locate leaks. Localised detection using low cost sensors embedded into the hydrogen infrastructure and sensing hydrogen by satellite to identify and monitor large scale hydrogen leaks.

[4] https://www.irena.org/Energy-Transition/Technology/Hydrogen
[5] https://www.irena.org/Publications/2022/Mar/World-Energy-Transitions-Outlook-2022

E-Fuels

E-fuels are synthetic fuels, resulting from the combination of hydrogen and CO_2 in the presence of a catalyst. The hydrogen must have been produced by electrolysis of water with renewable electricity and the CO_2 must have been captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuels are also described in the literature as electrofuels, power-to-X (PtX), power-to-liquids (PtL), power-to-gas (PtG) and synthetic fuels.

IRENA scenarios assume e-fuels will contribute to the energy mix by 2050.[6] They are an attractive solution for hard-to-electrify sectors as they promise a (near) drop-in replacement to conventional fuels. Today, the economics of e-fuel production is dominated by the availability of reliable cheap sources of renewable energy.

Highlighted industry challenges

Scale-up capability is a fundamental challenge for this emerging industry. Both the lack of facilities and know-how for scale-up from lab to demonstrator to commercial scale are limiting the impact of academic research into e-fuels, particularly for the UK. Professor David Reiner's research highlights

"the fundamental disagreements amongst experts in predicting technology development timescales and potential cost reductions, showing the challenges faced by early adopters in this sector."

Traceability will be fundamental to provide market confidence in the provenance of e-fuels, which is necessary to take advantage of future carbon credit/taxation incentives and measure the end-to-end carbon impact of e-fuels.

Technologies to improve feedstock stream purity will be important to ensure compatibility with downstream conversion technologies such as electrolysis.

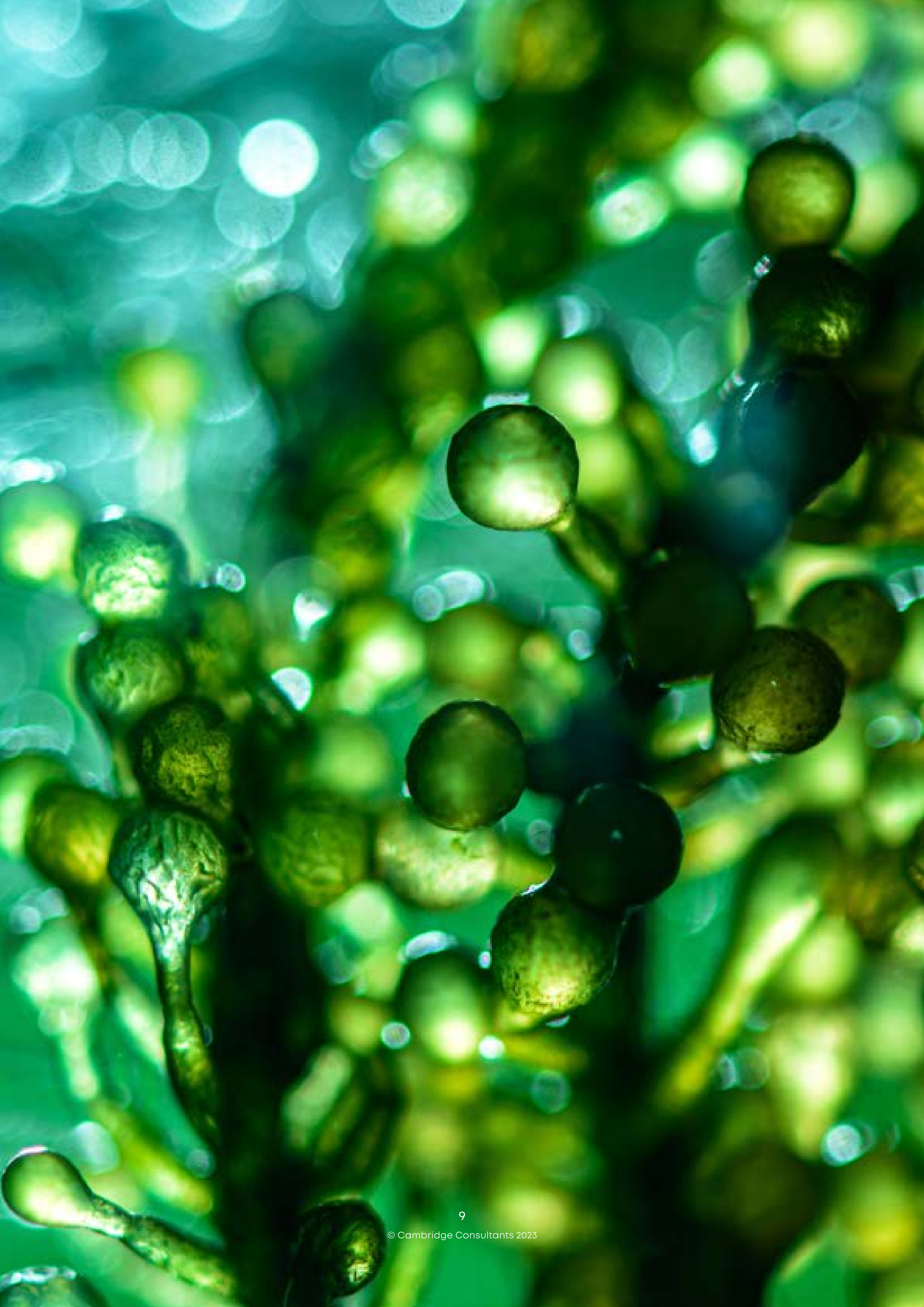
Opportunities for research

AI-directed materials discovery could accelerate the identification of new catalysts that improve the performance of the chemical reaction to make the e-fuel. This could bring down the operational cost, for example by increasing yield, lowering reaction temperature, or lengthening the lifetime of the catalyst.

Development and optimisation of a scaled-down production process to enable widespread deployment of small-scale, distributed production to sites where the feedstock is available in smaller quantities. This could require chemical engineering of new equipment and processes as well as optimisation of reaction conditions, including development of new catalyst materials.

Telescoping processes to reduce the number of process steps. Fewer steps could dramatically reduce sequential yield loses as well as lower operational costs.

[4] https://www.irena.org/Energy-Transition/Technology/Hydrogen



Biofuels

Biofuels are produced from an organic feedstock via a range of different processes, such as transesterification, fermentation, or anaerobic digestion. The feedstock can be almost any organic matter and includes plants, agricultural, domestic or industrial waste. The biofuel product (e.g. bioethanol or biodiesel) depends on the feedstock and production process. The IEA Net Zero Scenario for 2030 requires biofuel production to increase by ~16% every year to reach the 15 EJ target.[6] To assist this growth the use of waste sources as feedstock (also known as secondary and tertiary feedstocks) needs to increase from 8% today to 45% in 2030.[7]

Like e-fuels, biofuels can offer a (near) drop-in replacement to conventional fuels. Biofuels can be blended with traditional fuels for aviation, shipping and road transport, and are already providing a valuable steppingstone for transitioning industries such as the electrification of road freight. In addition,

"the role of biofuels in aviation can be explored using the Aviation Impact Accelerator's REECE tool"

demonstrated by Dr Paul Hodgson, which compares alternative decarbonisation pathways. Some biofuels, such as biomethane, can be used directly in combined heat and power applications, for example in peaking power plants, which are designed to augment renewables at times of low renewable electricity production.

Highlighted industry challenges

Diffuse feedstock could limit deployment of large-scale production sites as collection and transportation of biomass, such as livestock waste from farms, domestic food waste, municipal solid waste or wastewater requires energy and increases operational cost. Biofuel production could follow the trend we have seen in the renewables sector to a more decentralised or regional approach to production and usage.

Scaling up biofuel production processes (such as those for municipal solid waste or lignocellulosic feedstock) is proving difficult. This is due to feedstock variability (see below) but also the speed of micro-organisms, bioreactor size trade-offs (larger bioreactors produce more but increase pressure on micro-organisms at the bottom and are more expensive to manufacture) and high downstream processing costs.

Greater variability in the feedstock creates additional processing challenges relative to conventional fossil fuels, which are usually homogenous and energy dense. Toxic impurities in the feedstock can inhibit production or even kill the microorganisms driving the biological conversion process.

The cost of sustainable aviation fuels from biomass are currently much higher than conventional aviation fuel.

There is a limit to how much biofuel can be blended into a conventional fuel without having to adapt the design of a traditional engine. In order to convert to 100% biofuels existing engines will need to be adapted or exchanged for ones optimised for biofuels.

There is competition for land and water that is used for biofuel feedstock and food production.

Opportunities for research

Future areas of academic research are interdisciplinary and could include simulation of the scale up of bioprocesses, decentralised manufacturing models, and cost reduction innovations such as agricultural innovations or novel separation and purification techniques for downstream processing. Synthetic biology approaches also hold a lot of promise in this area for managing feedstock variability (communities of micro-organisms are adept at converting mixed waste into common metabolic intermediaries), converting feedstocks to biofuels, improving process efficiencies, decreasing carbon emissions and improving economic viability. Biorefineries – which produce multiple bio-based products alongside biofuels, are a further potential area of research for improving the economics of biofuels.

Fermentation and anaerobic digestion make short chain hydrocarbons. Chain elongation techniques will produce higher value long-chain hydrocarbons.

Genetically modified algae are outcompeted in open raceways, as genetic modifications to improve efficiency can worsen robustness. Closed raceways require pumping power.

[6] [7] https://www.iea.org/reports/biofuels

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Please note: only delegates that agreed to be named are shown.

Presenter biographies

Ernie Lamza
North Sea Transition Authority

Ernie Lamza is a Chartered Chemical Engineer with over 30 years' experience in technical and management roles in upstream oil & gas for both operators and supply chain companies in the UK and overseas. He holds a BSc in Chemical Engineering and an MSc in Technology Management. Based in Aberdeen, he is the North Sea Transition Authority's Technology Manager with responsibility for offshore energy technologies aligned with energy security and achievement of net zero.

Dr Ilkka Hannula
International Energy Agency

Dr Hannula is a Senior Energy Analyst at the IEA's Renewable Energy Division where he is leading the Agency's analytical work on renewable energy technologies. An engineer by training, Dr Hannula has 15 years' background in renewable energy research and development. His principal fields of interest include low-emissions fuels, system integration of renewables, electrification of industrial processes and negative emissions technologies.

Professor David Cebon
Department of Engineering
University of Cambridge

David Cebon, FREng, is Professor of Mechanical Engineering in Cambridge and Director of the Centre for Sustainable Road Freight (www.csrf.ac.uk). His research focusses on the safety, performance, productivity and environmental impact of heavy goods vehicles.

Professor Simone Hochgreb
Department of Engineering
University of Cambridge

Professor Simone Hochgreb is a Fellow of the Royal Aeronautical Society and the Combustion Institute. She has received the Wolfson Merit Award and the Society of Automotive Engineers Ralph R. Teetor Award. Her research involves understanding processes in combustion and reacting flows, as relevant to engines, gas turbines, and industrial processes. Her more recent interests are in the application of optical diagnostics to the measurements of temperatures and species in turbulent flames, hydrogen combustion, thermoacoustics, aerosols and flame synthesis.

Professor Laura Torrente Murciano
Department of Chemical Engineering & Biotechnology
University of Cambridge

Leader of the Process Integration and Catalysis Group in the Department of Chemical Engineering & Biotechnology at the University of Cambridge. Her focus areas include new ammonia synthesis processes to cope with the intermittent nature of renewable energy, ammonia cracking and novel optimisation tools based on AI.

Professor David Reiner
Cambridge Judge Business School

David Reiner is Professor of Technology Policy at Judge Business School, University of Cambridge and Assistant Director of the Energy Policy Research Group at Cambridge. His research focuses on the political economy of net zero and carbon dioxide removal, deep decarbonisation and hard-to-abate sectors (e.g., energy-intensive industries, residential heat, aviation, etc) and the challenges of technology deployment.

Dr Paul Hodgson,
Aviation Impact Accelerator, Whittle Lab

Technical Lead Aviation Impact Accelerator, Whittle Lab, University of Cambridge. A chemical engineer with a research background in biofuel manufacture, hydrogen distribution and carbon capture processes. Paul leads the core modelling team.

About the organisers

University of Cambridge Decarbonisation Network

The Decarbonisation Network provides a forum for academics, industry and the public sector to identify accelerated routes to decarbonisation through Special interest Groups (SIGs), and is currently working alongside the School of Technology, Cambridge Zero, the Energy Interdisciplinary Research Centre and the Maxwell Centre.

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