IRENA
International Renewable Energy Agency

INNOVATION OUTLOOK
ADVANCED LIQUID BIOFUELS

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About IRENA

IRENA is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low carbon economic growth and prosperity. ***www.irena.org***

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SUMMARY FOR POLICY MAKERS

The case for advanced biofuels

Biofuels have a vital role to play in the global transition to sustainable, renewable energy. Together with electric vehicles and the increase of renewables in the power mix, they can help us move away from petroleum use in passenger transport. They also provide the only practical alternative to fossil fuel for aeroplanes, ships and heavy freight trucks. Advanced biofuels using lignocellulosic feedstocks, waste and algae could vastly expand the range of resources for fuelling both light and heavy transport.

Advanced liquid biofuels can be refined from a range of sources. These include agricultural residues associated with food crops, as well as forest residues like sawdust from lumber production. Other sources include non-food energy crops, such as rapidly growing grasses like switchgrass and miscanthus, and short rotation tree species like poplar and eucalyptus. Finally, advanced biofuels are produced from solid biogenic waste (including the biogenic fractions of municipal and industrial waste, as well as garden waste) and algae.

These emerging options open up the range of feedstock available to produce biofuels for transport, while mitigating sustainability risks associated with changing land use and competition over food production. Residues do not compete with crop or lumber production but grow alongside it. High-yielding grasses and trees can grow more energy per unit of land area than conventional biofuel crops, potentially mitigating the impact of any land use change.

Innovation Outlook: Advanced Liquid Biofuels provides a global technology outlook for advanced biofuels between 2015 and 2045, specifically for liquid transport fuels for road, shipping and aviation use. It includes details of the technical and non-technical barriers to commercial deployment and the role of innovation in overcoming these barriers. It provides strategies to support advanced biofuels at all stages of the innovation chain. The potential for advanced biofuels is great but so are the challenges. A competitive advanced biofuels industry will depend on innovative technology and supply chains, market development and policy support.

Economic potential of advanced liquid biofuels

Innovation may reduce the cost of advanced biofuels production by up to a third over the next three decades. Yet they may not become consistently competitive without a price on carbon emissions.

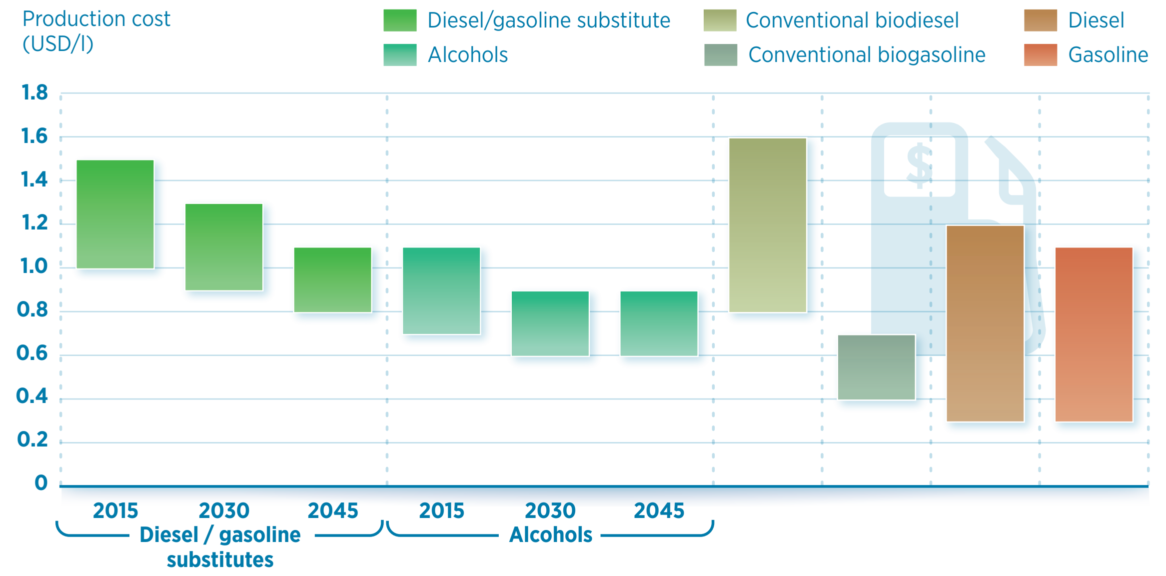
As IRENA's innovation outlook indicates, the production cost of advanced biofuels is likely to amount to USD 0.60-1.10 per litre by 2045. At oil prices below USD 80/bbl, advanced biofuels would have difficulty competing with fossil-based gasoline and diesel. But if oil prices exceed USD 100, most advanced biofuels should be able to compete effectively.

Along with technological innovation, policies and business models are needed to bridge the way, ensuring that plants continue to be built and production costs continue to decline. Different advanced biofuel pathways reduce greenhouse gas (GHG) emissions by 60%-95% compared to the fossil fuel reference value in the European Commission's 2009 Renewable Energy Directive. Carbon pricing in fuel markets, therefore, would promote the emergence of an advanced biofuels industry.

A wide range of feedstocks can be used to produce advanced liquid biofuels. This implies substantial production potential, with different feedstocks presenting different opportunities. In cities, solid municipal waste may be most attractive, since it is cheap and readily available and has few competing non-energy uses. In rural areas, agricultural residues have major potential but also face competing uses such as for animal feed. In countries with substantial wood product industries, forest residues are easy to access and low in cost but also sell into an established and growing market for heat and electricity generation. Dedicated lignocellulosic energy crops have great future potential if more land is made available for a mix of food and fuel. This could be achieved through higher food crop yields and more efficient use of pastureland for livestock, for example.

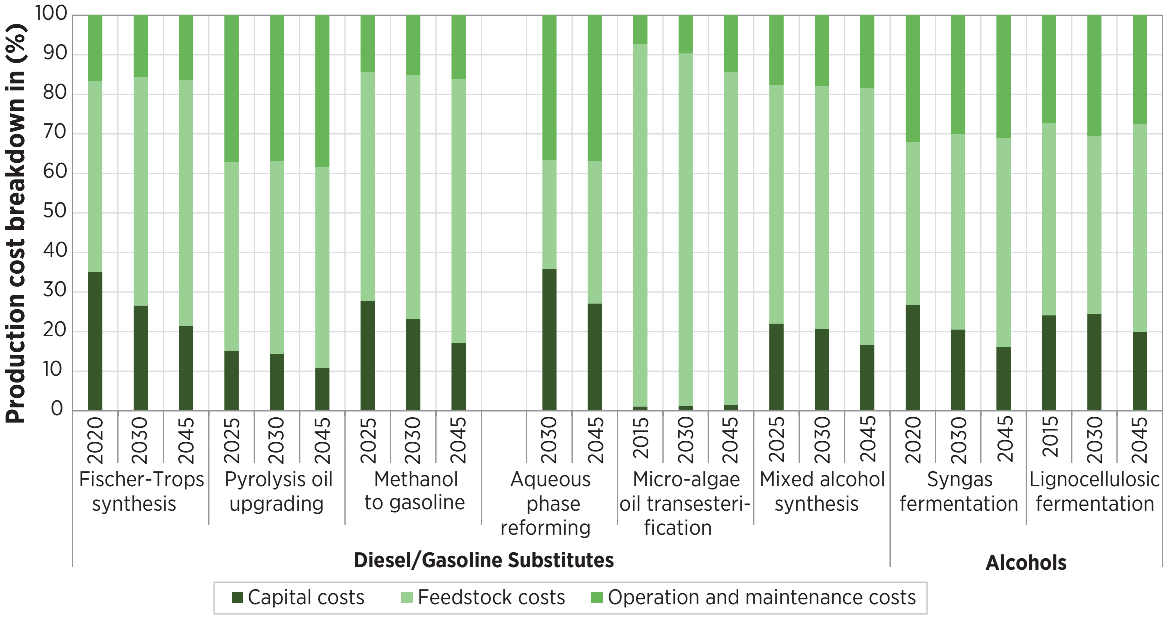
For most advanced biofuels, feedstock costs are the greatest contributor to production costs. Taking into consideration the current costs of wood and agriculture residue, the feedstock cost share is 40%-70% of total production costs. This may grow over time as capital costs decline and technology development makes conversion cheaper and more efficient. Establishing practical, efficient feedstock supply chains at scale, therefore, is crucial for the success of advanced biofuels.

Figure S1: Current and projected fossil-fuel and biofuel production costs



Note: All data have been converted from gigajoules to litres based on lower heating values. Production costs are given in United States dollars (USD) per litre.

Figure S2: Declining capital-cost shares in advanced biofuels production



Note: All data have been converted from gigajoules to litres based on lower heating values. Production costs are given in USD per litre.

Advanced biofuel types and innovation opportunities

Bioethanol (via fermented feedstock) and biomethanol (via gasification) are both ready for commercialisation. Other production pathways are at early stages of development.

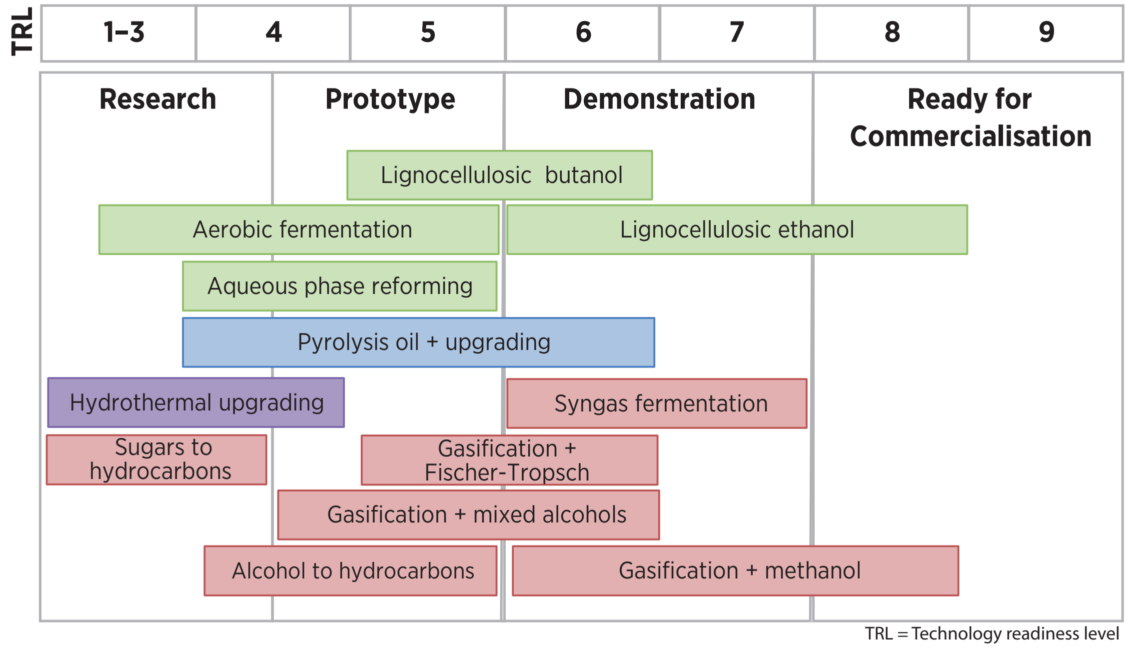
Many technologies can convert lignocellulosic feedstocks into liquid transport fuels:

- **Hydrolysis and fermentation** of lignocellulosic feedstock to produce bioethanol has reached an early commercial phase. In October 2015 DuPont opened the largest such plant in the world with a capacity of 114 million litres per year (DuPont, 2015). Plants using woody biomass are still at an early demonstration stage. Fermentation of ethanol from municipal solid waste is still under development.
- **Gasification** can be applied to a variety of feedstocks to produce a variety of fuels. Many demonstration projects based on gasification with catalytic synthesis have used forestry residues. However, the first commercial plant has been started using municipal solid waste. Enerkem Alberta began producing methanol in 2015 using municipal solid waste from the city of Edmonton, with a capacity of 38 million litres per year (Enerkem, 2015). Gasification followed by syngas fermentation to ethanol is being demonstrated at near-commercial scale using garden waste.
- **Fast pyrolysis and upgrading** can also be applied to a variety of feedstocks to produce a variety of fuels. Agricultural and wood residues and wastes are being used in pilot and demonstration plants. Ensyn has converted its plant in Renfrew, Ontario, to produce around 12 million litres of biofuel per year through fast pyrolysis. It is developing other fast pyrolysis plants in Brazil and Malaysia (Ensyn, 2012).

Advanced biofuels conversion pathways are at different stages of technological maturity. Opportunities for innovation exist across the entire spectrum. Significant improvements to all advanced biofuels pathways will come from process integration.

- **Hydrolysis and fermentation** could be greatly reduced in cost by integrating the two steps to reduce enzyme loading, modifying fermentation organisms and applying membrane separation. In the ButaNexT project, Green Biologics is scaling up its fermentation process and integrating the *in-situ* removal of butanol with a membrane separation process developed by VITO (ButaNexT, 2016).
- **Pyrolysis** is highly efficient and has potentially low processing costs but more effective catalytic upgrading processes are needed. Petrobras and Ensyn have demonstrated co-cracking for pyrolysis oil production in the fluid catalytic cracking process of a conventional refinery.
- **Gasification** needs to prove reliable long-term operation in view of feedstock contaminants. Alter-NRG is working on enhanced pre-treatment and ash removal using plasma gasification or plasma torches. Process optimisation is also needed to achieve target syngas composition.
- **Fischer-Tropsch processes** need to be proved at commercial scale for biomass use. Velocys is one of the companies developing modular units, which may enable reactors to operate at smaller scales to match local feedstock supplies.
- **Alcohol fermentation from syngas** could benefit from modification of fermentation organisms to improve tolerance to contaminants, raise yields and boost selectivity.

Figure S3: Commercialisation status of various advanced biofuels-conversion technologies



Note: Colours represent the principal conversion process, hydrolysis (green), pyrolysis (blue), hydrothermal upgrading (purple) and gasification (red).

Growing needs, slowing deployment

A lack of regulatory clarity and stability, combined with externalities like oil price volatility, hinders investment in advanced biofuel production.

Transport accounts for about a third the world's energy use, half its oil consumption and a fifth of its GHG emissions. There will be around two billion vehicles on the road by 2020. Aviation alone causes nearly 3% of global carbon emissions, a share that is likely to grow. Against this background, further development of sustainable, renewable biofuel options is essential. IRENA's REmap analysis to double the global share of renewable energy by 2030 shows that advanced biofuels production has the potential to grow more than hundredfold over a 15-year period (IRENA, 2016). However, investments have stagnated over the last few years due to lower oil price expectations and a perceived weakening in policy support.

Demonstration and commercial plants at present add 1 billion litres per year of advanced biofuels production capacity, which would meet just 0.04% of the current liquid transport fuel demand. Plants planned or under construction would add another 2 billion litres per year of capacity. These include plants producing ethanol, methanol, mixed alcohols, diesel and jet fuel. Most are in Europe and North America. Clearly, the pace will have to increase exponentially, and projects develop further afield, if advanced liquid biofuels are to fulfil their practical and economic potential for displacing fossil fuels.

Performance prospects over the next three decades

Innovation drives improvements in performance and cuts production costs. This will eliminate the gap in costs between advanced biofuel conversion and today's first-generation biofuels.

Eight advanced biofuels pathways have been compared in terms of potential technical, economic, and environmental performance over the next three decades:

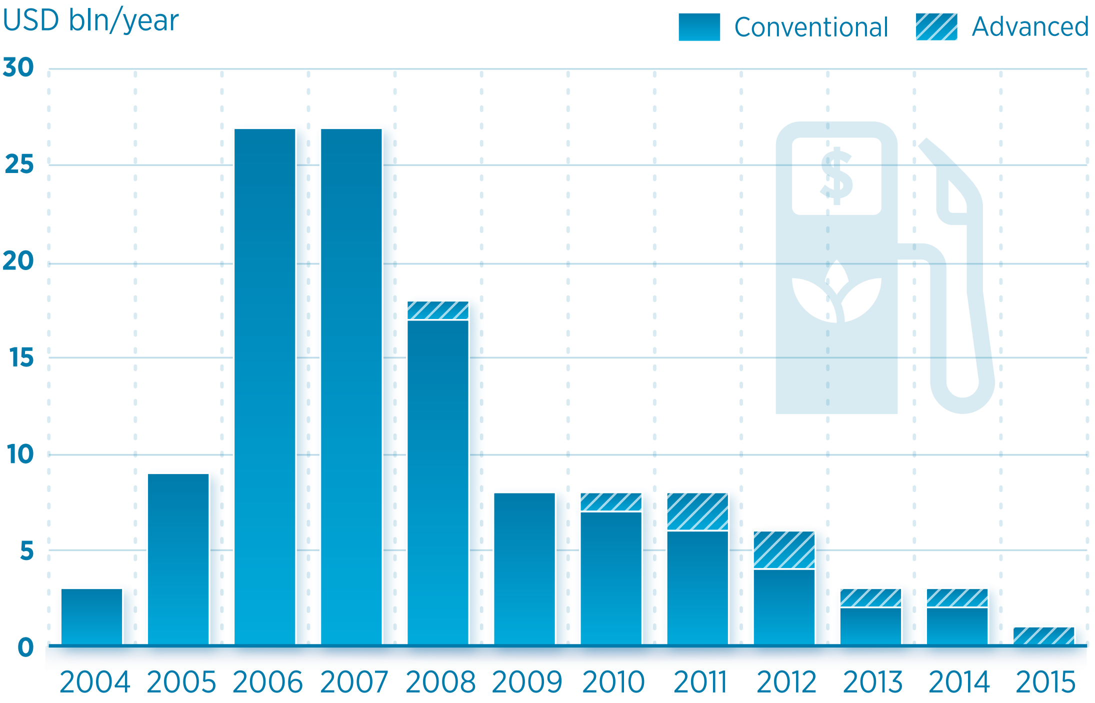
- Forest-residue feedstocks:
  - for gasification and Fischer-Tropsch synthesis to produce diesel and jet fuel
  - in fast pyrolysis and pyrolysis oil upgrading to produce diesel
  - for gasification and methanol synthesis followed by conversion of methanol to gasoline (MTG)
  - in gasification and mixed alcohol synthesis to produce ethanol
  - for gasification and syngas fermentation to produce ethanol
- Agricultural residue conversion to ethanol via hydrolysis and fermentation
- Agricultural residue conversion to diesel via hydrolysis and aqueous phase reforming of sugars
- Micro-algae use for fatty acid methyl ester (FAME) production via oil extraction and transesterification

Processes based on gasification and pyrolysis could produce the highest fuel conversion efficiencies, especially upgraded pyrolysis oil and MTG pathways. Biological conversion processes employed to produce fuel have lower conversion efficiencies, producing lignin as a co-product.

The specific capital investment costs for the first commercial-scale plants up until 2025 are expected to amount to USD 2 000-7 000 per kilowatt $(kW)_{biofuel.}$ Learning rate effects mean all pathways are capable of reducing capital investment costs in the next three decades. Pathways achieving full commercialisation are expected to reduce specific capital investment costs down to USD 700-2000/$kW_{biofuel}$. Between 2035 and 2045 specific capital investment costs for certain advanced biofuels could be similar to the current costs of conventional (corn-based) ethanol. They include lignocellulosic fermentation to ethanol, syngas fermentation, mixed alcohol synthesis, Fischer-Tropsch synthesis, pyrolysis oil upgrading and MTG.

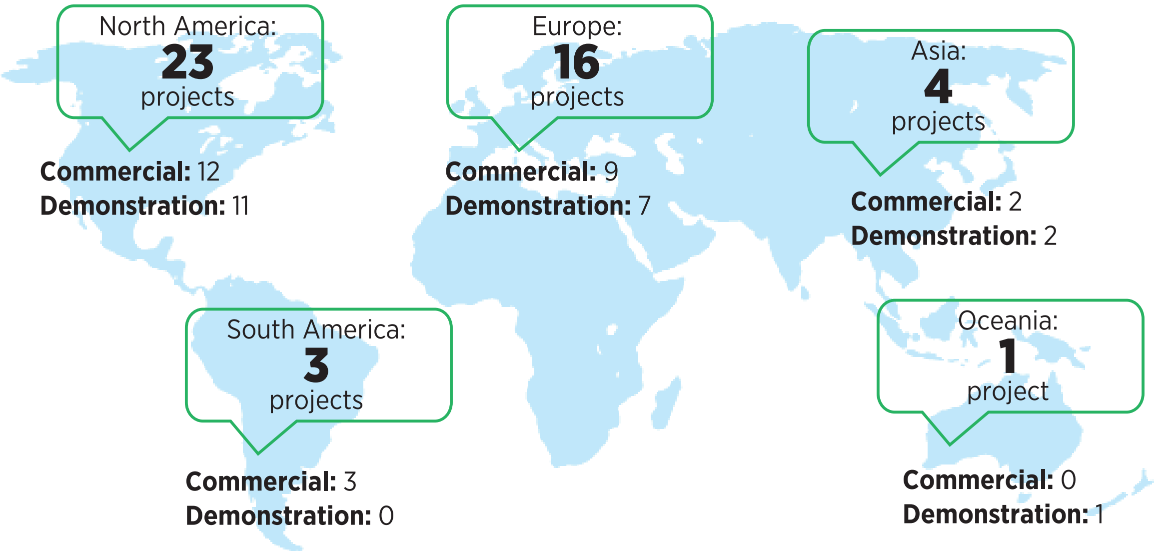
Advanced biofuels pathways produce low GHG, achieving GHG emissions savings of 60%-95% compared to the fossil fuel reference. The exception is micro-algae oil to FAME.

Figure S4: Declining global investment in advanced and conventional biofuels



Note: IRENA analysis based on Bloomberg New Energy Finance (2015), Global Trends in Clean Energy Investment. Investments are given in USD billion per year.

Figure S5: Commercial and demonstration plants for advanced biofuels by region



Supporting advanced liquid biofuels commercialisation

To keep boosting competitiveness, technological development must continue. But other kinds of innovation – related to regulatory frameworks, business models and risk-mitigation instruments – are also vital in order to deploy advanced biofuels at the scale needed.

Speeding up advanced liquid biofuels deployment will require a range of policy support related to energy markets, technology development and enterprise formation.

Technology development: Promising technology pathways need some kind of investment support for early plants to get to the cost-competitive *n*th plant. First-of-a-kind commercial-scale demonstration plants are essential to progress in advanced biofuels technologies because scaling up laboratory conditions creates many problems. These include, for instance, feedstock impurities and logistical requirements and the need for offtake arrangements. But commercial-scale demonstration plants have a high risk profile and will not usually get built if support is not in place. Grants to build prototypes and pilot plants are needed to test and evaluate technical concepts and claims. Loan guarantees and other risk management tools can be an efficient way to stimulate private debt funding for such projects. They allow governments to reduce the credit risk to financial institutions lending to advanced biofuel projects.

Market formation: Policy incentives, targets or mandates are probably needed to overcome barriers such as insufficient operational experience, immature supply chains and uncertain market size. Co-production of fuel additives, chemicals, plastics and cosmetics in biorefineries can compensate biofuel production costs. Internalising carbon costs in the market would encourage lignocellulosic feedstock production and conversion. Niche markets like as shipping and aviation – which attracts strong industry engagement – can nurture technology progress that may enable the future deployment of advanced biofuels in other markets. New applications for ethanol may expand its potential market as octane booster for highly efficient gasoline engine cars, for example.

Enterprise formation: Advanced biofuels projects can be stimulated by facilitating equity investments in start-up companies. Strategic partnerships and joint ventures could allow companies to share expertise and financial risk. Effective business models coupling agricultural and energy sectors can be documented and shared to help expand advanced biofuels markets. The potential for job and income creation can be highlighted to attract local support.

There is clear political commitment to decarbonise the global economy. However, this has yet to be transformed into action to promote clean and competitive energy alternatives for transport. Industry will remain cautious about making the large-scale investments required to scale up the advanced biofuels production until cost-effective technologies are available and an attractive market exists.

GLOSSARY OF TERMS

Acidity	The amount of acid present in a solution, often expressed in terms of pH.
Alcohol to jet	A conversion process in which alcohols undergo dehydration, oligomerisation and hydrogenation in order to produce a replacement paraffinic jet fuel.
Biogas	Gas containing mostly methane and carbon dioxide (CO_2), produced by the bacterial decomposition of organic matter.
Biomass	Material that is biological in origin and derived from living or recently living organisms.
Capital cost	A fixed, one-off expense incurred to acquire, develop or construct a fixed asset (such as a plant). Often referred to as capex.
Consolidated bioprocessing	A single process that combines the hydrolysis and fermentation stages of lignocellulosic biofuel production.
Dehydration	The loss of a water as a result of a chemical reaction. Reverse reaction to hydrolysis.
Distillation	A process used to separate a (pure) component substance from a liquid mixture by selective evaporation and condensation.
Efficiency (conversion)	The ratio between fuel produced (output) and feedstock (input) in energy terms.
Feedstock	Renewable matter of biological origin that may be directly combusted as a fuel or converted to a fuel product.
Fermentation	A metabolic process that converts carbohydrates (starch, sugar) to acid, gas or alcohol using yeasts and/or bacteria.
Flexible-fuel vehicle	A vehicle with an internal combustion engine designed to run on more than one fuel. Also known as flex-fuel vehicle.
Gasification	A thermochemical process that converts materials containing carbon to syngas at high temperature and pressure and with a controlled amount of oxygen and/or steam.
Hydrocracking	A catalytic process used in refineries to convert or upgrade heavy oil to high quality gasoline, diesel and jet fuel, with the addition of hydrogen gas.
Hydro-treating	A process used in refineries to reduce or remove contaminants (such as sulphur, nitrogen and aromatics) to prepare the fuel for further processing or blending.
Hydrolysis	A chemical reaction which breaks the bond in a molecule by adding water to decompose the original molecule into smaller chemical units.
Lignin	A complex organic polymer found in the cells and cell walls of vascular plants. It binds cellulose fibres and contributes to the structure of the plant.
Lignocellulose	A major structural component of woody and non-woody plants, consisting of carbohydrate polymers (cellulose and hemicellulose) and lignin.
Oligomerisation	A chemical process that converts a monomer or monomer mixture to an oligomer through polymerisation.
Operational and maintenance costs	The expenses incurred for any operational or maintenance activity (in a plant). Often referred to as opex.
Osmosis	The movement of water across a semi-permeable membrane to equalise the solute concentrations on both sides.
pH	A measure of the acidity or alkalinity of an aqueous solution.
Polymerisation	An addition reaction in which two or more molecules join together to produce a single product (polymer).
Pyrolysis	The controlled decomposition of organic material at high temperatures in the absence of oxygen to produce oil, syngas and charcoal.
Specific capital investment	The funds paid in return for an asset (fixed or non-fixed), expressed per unit of production capacity (for example per litre).
Syngas	Gas produced from the gasification of biomass, composed mainly of hydrogen and carbon monoxide, along with CO_2 and other impurities.
Transesterification	The process for making biodiesel. Triglycerides and alcohol are reacted to give esters of fatty acids and glycerol.
Viscosity	A fluid property which indicates the degree of resistance to gradual deformation by shear stress or tensile stress (i.e. resistance to flow).
Yield (conversion)	The amount of product produced per amount of feedstock. It is most commonly given as the volume of product specific production per kilogramme (kg) of feedstock supplied to the system.

ABBREVIATIONS

Bbl	Barrel
CO_2	Carbon dioxide
DME	Dimethyl ether
EJ	Exajoule
FAME	Fatty acid methyl ester
G	Gramme
GHG	Greenhouse gases
GJ	Gigajoule
IEA	International Energy Agency
IP	Intellectual property
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
Kg	Kilogramme
kW	Kilowatt
MJ	Megajoule
MTG	Methanol to gasoline
N_2	Nitrogen
NREL	National Renewable Energy Laboratory (US)
TRL	Technology Readiness Level
USDA	US Department of Agriculture
US DOE	US Department of Energy
USD	US Dollar
WEO	World Energy Outlook

INTRODUCTION

The objective of IRENA is to promote the widespread, increased adoption and sustainable use of all forms of renewable energy. One of IRENA's programmes, REmap 2030, provides a global renewable energy roadmap to double the share of renewables in the global energy mix between 2014 and 2030. It was developed in close co-operation with 40 countries that cover 80% of total final global energy demand (IRENA, 2016). REmap 2030 indicates that modern biomass (see glossary of terms) could be the single most important renewable energy resource, accounting for up to 50% of global final renewable energy use. It shows that the use of liquid biofuels could increase substantially between 2010 and 2030, becoming the main alternative renewable energy option for the transport sector. Increasing the use of conventional biofuels from sugar, starch and oil crops has often been problematic due to competition for land with food and feed crops, and land use change. Advanced biofuels (see glossary of terms) produced from high-yielding lignocellulosic feedstocks can considerably widen the range of sustainable options to substitute for fossil fuels. They could represent the bulk of future biofuels growth.

The purpose of the research underlying this report is to provide a global technology outlook for advanced biofuels in 2015-2045 specifically for **liquid transport fuels for road, shipping and aviation use**. This report concentrates on the role of innovation in stimulating **advanced biofuels pathways that have not reached widespread commercialisation**.

The report is aimed at a wide range of stakeholders, including policy makers, investors, and project and technology developers worldwide. It aims to provide insight into potential technology and commercialisation developments and challenges, and the role that different stakeholders and IRENA can play in accelerating advanced biofuels pathway development and deployment. It complements IRENA's Renewable Energy Technology Innovation Process, a guide developed byIRENA to assist countries, upon request, to choose assessment methods, identify key sectors and appropriate strategies, create co-ordinated policy portfolios, and define roles and responsibilities for implementation (IRENA, 2015). This report should also be read in conjunction with IRENA's Renewable Energy Innovation Policy: Success Criteria and Strategies (IRENA, 2013a).

Our review of the prospects for advanced biofuels covers the following areas.

- **Overview of advanced biofuels** including a description of the market for advanced biofuels, a description of conversion pathways and their current status and an assessment of feedstocks.
- **Technical and non-technical barriers** to commercial deployment, including research and innovation needs.
- **Comparative assessment of advanced biofuel pathways** including potential technical, economic and environmental performance of the most important advanced biofuel pathways to 2045.
- **Summary of the prospects** for advanced biofuels production in the next three decades.
- **Strategies to support advanced biofuels** at all stages of the innovation chain.

1 OVERVIEW OF ADVANCED BIOFUELS

1.1 Defining advanced biofuels

Transport biofuels typically refer to liquid and gaseous fuels produced from biomass and are commonly classified as conventional biofuels or advanced biofuels.[1] There are a number of approaches to making this classification. They are based on feedstock, GHG emission savings, technology maturity, and product type and quality:

- Feedstock: biofuels produced from feedstocks that could be used as food or feed are referred to as conventional biofuels. Those produced from agricultural and forestry residues, organic waste and in some cases non-food or feed energy crops are defined as advanced. This definition aims to differentiate between biofuels produced from feedstocks that potentially compete with food or feed production and those that do not.
- GHG emissions savings: biofuels which achieve high GHG emissions savings are defined as advanced in comparison to biofuels which achieve GHG emission savings below a certain threshold.
- Technology maturity: conversion technologies which are widely deployed at a commercial scale are referred to as conventional. Technologies at earlier stages of development (including those in first-of-a-kind commercial plants) defined as advanced.
- Product type and quality: advanced (also referred to as 'drop-in') biofuels are similar to gasoline, diesel, bunker and jet fuels and can be blended in very high proportions in these fuels or used neat while meeting fuel specifications. This distinguishes them from biofuels whose properties restrict them to relatively low blends in conventional (unmodified) engines and which have limited compatibility with current fuel distribution infrastructure.
- There is no standard agreed definition which covers all the above approaches. This leads to differences in advanced biofuels definitions, depending on the reasons for seeking the classification. The majority of biofuel currently produced is classified as conventional. This is because it is derived from crops that could be used to produce food and/or feed using well-established conversion technologies and subject to blending limitations in non-flex-fuel vehicles. The GHG-based definition is dependent on specific supply chain performance.

This report covers advanced liquid biofuels produced from feedstocks not derived from food or feed sources using pre-commercial conversion technologies.

Liquid biofuels may be used in road and rail, substituting gasoline and diesel. In shipping and aviation they replace diesel, bunker and jet fuels. Gaseous biofuels like biomethane are also used in road transport, both in passenger vehicles and heavy goods vehicles, and in maritime transport. Biomethane presents another opportunity to increase the volumes of biofuel used in transport, especially in countries that already have significant vehicle fleets using natural gas and the associated gas refuelling infrastructure. However, the focus of this report is on liquid biofuels and does not discuss gaseous biofuels in transport any further.

Fuels used in all transport sectors are required to meet national or international standards. Advanced biofuels may therefore be blended with conventional fossil fuels according to their properties. Most liquid biofuels are expected to be blended with fossil fuels at different points in the distribution chain depending on the type and supplied to consumers through existing refuelling infrastructure. Table 2: Liquid biofuel product description and applications in transportTable 2 describes different liquid biofuel products.

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[1] Under an alternative classification system, first generation biofuels are derived from sugar, starch or lipids extracted from crops; second generation biofuels are derived from cellulose, hemicellulose or lignin (such as agricultural or forestry residues) and lignocellulosic crops; third generation biofuels are derived from aquatic autotrophic organism (*e.g.* algae) (European Biofuels Technology Platform, 2015).

Table 1: Examples of biofuel classifications based on different definitions, including areas of ambiguity

	Feedstock definition	**Technology definition**	**Product definition[2]**
Conventional biofuels	○ sugar crops ○ starch crops ○ vegetable oils	○ transesterification ○ fermentation ○ hydrogenation ○ (see glossary of terms)	○ FAME ○ ethanol ○ methanol
Area of ambiguity[1]	● energy crops ● used cooking oil ● animal fats ● tall oil		● butanol
Advanced biofuels	○ algae ○ forest residues ○ agricultural residues ○ municipal solid waste	○ cellulose fermentation ○ gasification ○ pyrolysis ○ (see glossary of terms)	○ hydroprocessed esters and fatty acids ○ Fischer-Tropsch diesel and jet fuels

Note: the GHG-based definition is not included within this table because compliance with the definition is based on specific supply chain performance

[1] Some energy crops compete with food and feed crops for land and water or cause indirect land use change. They are thus frequently not considered feedstock for advanced biofuels. Used cooking oil, animal fats and tall oil are converted to biofuel via well-established processes now widely deployed commercially, which means they frequently also do not qualify as feedstock for advanced biofuels.

[2] A description of these products and their applications is provided in Table 2.

Table 2: Liquid biofuel product description and applications in transport

Product	**Description**	**Application and product replacement**	**Blending limits**
Methanol	Single carbon alcohol Energy density approximately 50% lower than gasoline	May be blended with gasoline for use in road transport or converted to methyl tert-butyl ether for blending with gasoline (where vapour pressure limits restrict methanol blending). Use in rail and shipping is limited to dual-fuel converted engines. Methanol may be converted to dimethyl ether (DME) for use as a diesel replacement or to gasoline and diesel range hydrocarbons. Barriers to its use include concerns about human toxicity and corrosive effects on conventional engines.	In the US, regulations allow a 0.3% blend of methanol in gasoline or 2.75% methanol in gasoline with equal volumes of butanol (ASTM D 4814-16b). EU gasoline standards allow up to 3% methanol in gasoline (EN 228). ASTM D5797-16 standards for 70%-85% methanol in gasoline are being updated. In China, a national standard for 85% methanol in gasoline exists (GB/T 23799-200) but standard fuel grades vary across provinces.

Product	Description	Application and product replacement	Blending limits
Ethanol	Two carbon alcohol Energy density approximately 30% lower than gasoline	May be blended with gasoline for use in road transport or converted to ethyl tert-butyl ether for blending with gasoline (where vapour pressure limits restrict ethanol blending). Ethanol may be converted to jet fuel range hydrocarbons via chemical catalysis. Barriers to expanding its use include corrosion in conventional engines at higher blends and incompatibility with existing fossil fuel pipelines.	In Europe and the US, fuel standards allow for up to 10%-15% ethanol in gasoline (EN 228, ASTM D 4814). In Brazil, regulation allows up to 27.5% ethanol in gasoline. Flex-fuel vehicles may use blends of up to 85% ethanol in gasoline or 100% ethanol.
Butanol	Four carbon alcohol Energy density similar to gasoline.	May be blended with gasoline or diesel for use in road transport.	US fuel standard allows up to 16% butanol in gasoline (ASDM D 4814). EU fuel standard allows up to 15% in gasoline (EN 228).
FAME biodiesel	Fatty acid methyl ester (FAME). Energy density similar to diesel	May be blended with diesel for use in road, rail and shipping. Barriers to expanding its use include poorer cold flow properties, which limit use in some areas.	EU fuel standards allow up to 7% in diesel (EN 590). US fuel standards allow up to 5% in diesel (ASTM D 975).
Fischer-Tropsch fuels	Range of paraffinic hydrocarbons Energy density similar to diesel.	Depending on the hydrocarbon chain lengths, Fischer-Tropsch products may be blended with gasoline, diesel or jet fuels for use in road, rail, shipping or aviation.	There are no regulatory limits to blending Fischer-Tropsch diesel. Fischer-Tropsch kerosene is certified for maximum 50% blends with jet fuel (ASTM D7566).
Hydro-treated esters and fatty acids	Range of straight chain paraffinic hydrocarbons. Energy density similar to diesel.	Depending on the hydrocarbon chain lengths, it may be blended with diesel or jet fuels for use in road, rail, shipping or aviation.	There are no regulatory limits to blending hydro-treated esters and fatty acids in diesel. However, it will be blended with conventional diesel fuel to meet fuel specifications. International standard ASTM D 7566 allows up to 50% hydro-treated esters and fatty acids in jet fuel.
Synthetic paraffinic fuel	This category includes straight-chain and branched chain hydrocarbons of various chain lengths (includes Fischer-Tropsch diesel). Energy density similar to diesel or kerosene.	Depending on the hydrocarbon chain lengths, it may be blended with diesel or jet fuels for use in road, rail, shipping or aviation.	Iso-synthetic paraffinic fuels are certified for maximum 10% blends with jet fuel (ASTM D7566).
Synthetic aromatic fuel	Hydrocarbon fuel containing aromatic compounds.	May be blended with jet fuel for use in aviation. Aromatic compounds are an important component of jet fuel and not found in other biofuels. This route may enable fully renewable jet fuels.	ASTM certification currently under way.

1.2 Advanced biofuels drivers

This section provides a description of scenarios of future demand for advanced biofuels and the demand-side factors that will influence their development and deployment over the next three decades.

Applications

Liquid biofuels may be used in road, rail, shipping and aviation. Most biofuel now is used in the road transport sector as the largest user of liquid transport fuels. Small quantities are also used in diesel-powered rail and aviation. Aviation and shipping are important markets because they will continue to rely on liquid fuels. The aviation industry is active in the development and demonstration of biofuels. Commercial sales of aviation biofuels have emerged in the conventional refuelling infrastructure while interest in biofuels for shipping has been increasing.

Liquid biofuels may also be used in heat and power generation as a substitute for diesel. This is currently a minor use for liquid biofuels. It is not expected to act as a major driver for the development of advanced biofuels due to other options for decarbonising heat and power.

Biojet fuel production in Brazil

Brazil has historically been a front-runner in the production of first generation biofuels. Capitalising on its extensive experience and know-how, Brazil is now examining the promising international market for biojet fuel. Through the Air Transport Action Group, the aviation industry has set a target to halve carbon emissions by 2050 compared to 2005. This would mean converting a major share of the 1.5 billion barrels of kerosene consumed by the aviation sector annually from fossil to renewable sources (Air Transport Action Group, n.d.). Carvalho *et al.* (2016) have identified the significant potential for biojet production of the abundant feedstock in the country available at low cost. For example, lignocellulosic feedstock from dedicated eucalyptus plantations appears a feasible option due to the low-cost, highly productive and simplified logistics for conversion routes using the Fischer-Tropsch process. The mature industry for sugar fermentation in Brazil favours conversion routes like fermentation-to-jet. Another option is the use of oleaginous crops cultivated in Brazil but this reduces environmental gains due to dependence on fossil fuel at the agricultural and industrial stages of the supply chain.

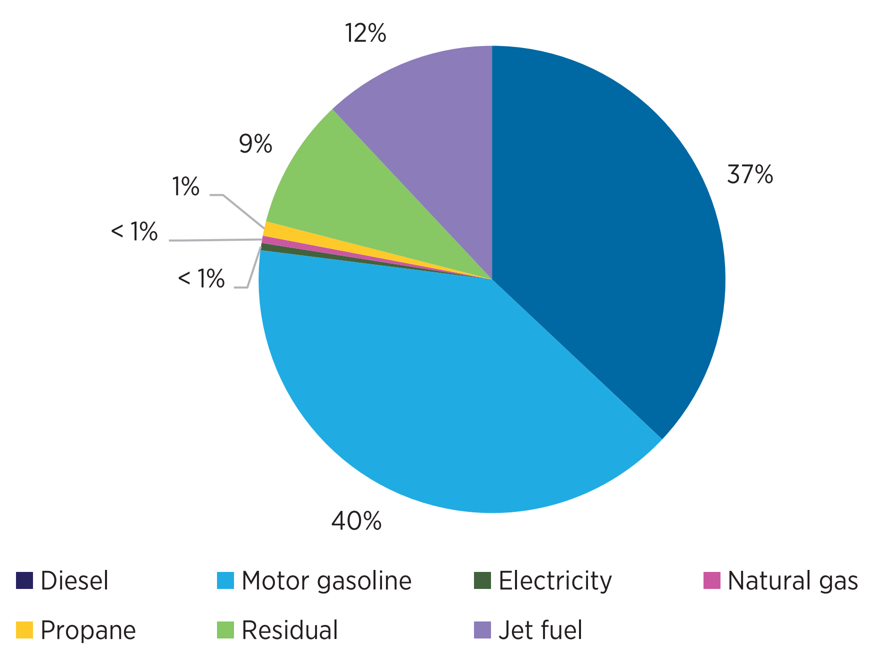
Global drivers for advanced biofuels

Global drivers for the production of biofuels include reducing the GHG emissions associated with transportation. This increases the resource base for fuels, thereby improving security of supply and potentially reducing costs or protecting against oil price increases. This also provokes innovation and local market opportunities, and creates additional revenue streams for the agricultural and forestry sectors. Concerns about the impact of conventional biofuel production on food prices, as well as direct and indirect impacts of increased demand for agricultural land and forest products, also stimulate advanced biofuels production. The mechanisms employed to encourage deployment differ between countries, reflecting the relative importance of these drivers. Given current low oil prices, there is less opportunity for advanced biofuels to reduce fuel costs. For this reason prolonged low oil prices could disincentivise advanced biofuels deployment in some regions. However, advanced biofuels may have a role to play when oil prices recover by providing protection against oil price increases. Opportunities to diversify feedstock sources (including by using local resources), make more efficient use of resources and stimulate technology innovation and economic growth have helped stimulate advanced biofuels. These motivations have also influenced research agendas and funding programmes in many regions. Energy security has created an additional driver for marine and jet fuels. This is particularly evident in the US where the Navy and the Department of Defence have made significant investments supporting biofuel development.

Policy mechanisms

There are currently 64 countries with established or planned biofuel mandates and targets. This includes the 27 member countries of the EU, 13 countries in the Americas and 12 in Asia (Lane, 2016). National biofuel

Figure 1: Global energy consumption in the transport sector by source, 2012 (US Energy Information Administration, 2015)



policies did not differentiate between conventional and advanced biofuels until a few years ago. Since then, some of the leading biofuel user and producer countries have shifted towards advanced biofuels including the US, Europe and China.

The European Commission's 2009 Renewable Energy Directive (Directive 2009/28/EC; EC, 2009) was revised in 2015 following concerns about the impact of indirect land use change on GHG emissions savings. These revisions include a cap on the biofuels contribution from crops for food or feed to national renewable energy targets in 2020, and a voluntary subtarget for advanced biofuels (EU, 2015a). Italy is the first EU member state to mandate an advanced biofuels target which requires all fuel suppliers to include 0.6% advanced biofuel from 2018 rising to 1% by 2022.

In the US, the most important mechanism is the Renewable Fuel Standard, under which refiners, blenders and importers are obliged to blend renewable fuels, including subtargets for cellulosic ethanol. However, the regulating authority for the Renewable Fuel Standard – the Environment Protection Agency – was forced to significantly decrease targets due to a lack of production capacity (Environment Protection Agency, 2015; Lane, 2015b). In addition to the federal Renewable Fuel Standard, California has implemented the California Low Carbon Fuel Standard with separate targets at the state level (California Energy Commission, 2015).

Other policies and programmes in the US include the Biomass Crop Assistance Program, which provides financial assistance to landowners who produce biomass crops for advanced biofuel production facilities (US Department of Agriculture – USDA, 2015b). The US has also implemented a Second Generation Biofuel Producer Tax Credit, which allows producers to claim back USD 0.27 per litre of eligible fuel produced (US DOE, 2015b). In July 2016 the US government released the Federal Alternative Jet Fuel Research and Development Strategy, aiming to address technological and non-technological challenges for the production and deployment of alternative jet fuels.[2]

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[2] *http://www.biofuelsdigest.com/bdigest/2016/07/31/white-house-releases-federal-alternative-jet-fuel-research-and-development-strategy/*

Following domestic grain price increases, China reduced policy support for grain-based ethanol in 2010, and all subsidies have now been removed. Its government has set very ambitious targets for the production of cellulosic and non-grain based ethanol by 2020, and subsidies for cellulosic ethanol have been maintained at approximately USD 0.10 per litre. However, it is very unlikely that the target levels of production can be met (USDA, 2015).

Industrial initiatives to support advanced biofuels deployment

Industry-led initiatives are also playing a role in promoting advanced biofuels deployment. In the aviation sector in particular, there are a large number of strategic partnerships between advanced biofuels producers and airlines or airframe manufacturers aiming to accelerating deployment. Many of the drivers for such initiatives are aligned with policy objectives – to reduce GHG emissions, improve fuel security and potentially guard against fuel price rises. The aviation industry is largely excluded from current biofuel mandates but public-private sector initiatives have been established in many regions to promote the use of advanced biofuels in aviation. For example, the European Commission and industry representatives launched the European Advanced Biofuels Flightpath initiative in 2011. This set a voluntary target of 2.5 billion litres of sustainable biofuels use in aviation in the EU by 2020. In the US, the public-private Commercial Aviation Alternative Fuels Initiative was established to facilitate the exchange of information and co-ordinate stakeholder efforts.

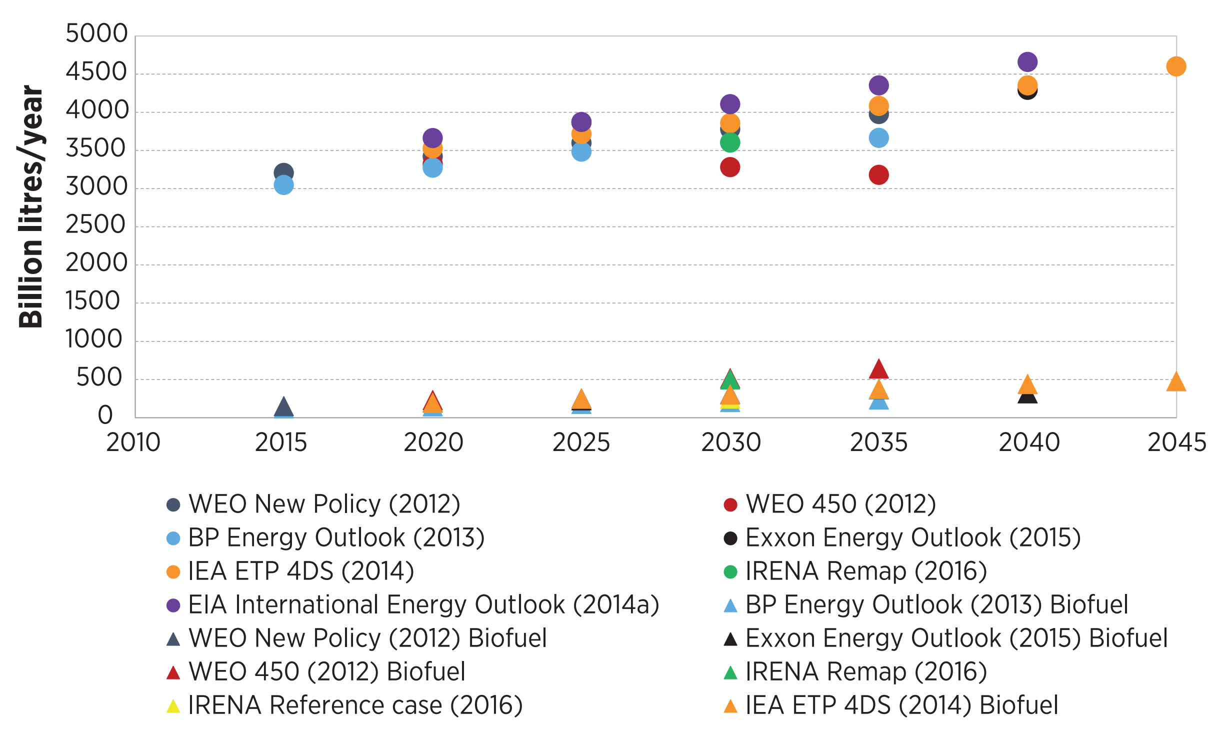
Potential future demand

Liquid fuel demand

Liquid fuel demand is expected to increase globally, with the majority of growth in Asia, especially China and India. Figure 2 presents a number of scenarios for future liquid fuel demand to 2045. These include the Outlook for Energy: A View to 2040 (ExxonMobil, 2015), Energy Technology Perspectives 2014 (IEA, 2014), International Energy Outlook 2014 (Energy Information Administration, 2014a), REmap 2030 (IRENA, 2016), BP Energy Outlook 2030 (BP, 2013) and World Energy Outlook 2012 (WEO) (IEA, 2012).

These scenarios expect total annual liquid fuel demand to range between 3 280 and 4 350 billion litresin 2035.

Figure 2: Scenarios for global liquid fuel demand (circles) and biofuels demand (triangles)



Several key factors influence demand. They include how far energy efficiency gains outweigh vehicle fleet growth, modal shift, overall transport services demand, and liquid fuel substitution by alternative fuel sources, including electricity.

Some scenarios are based on achieving environmental goals. Examples include IRENA REmap and WEO 450, which is based on an ambition to limit global warming to 2°Celsius (°C). As a result, these scenarios estimate lower liquid fuel demand. The IEA Energy Technology Perspectives 4DS scenario is the only one analysed here which provides a forecast beyond 2040 (IEA, 2014). It estimates a total liquid fuel demand of almost 4,600 billion litres per year by 2045.

Biofuel demand

Global biofuel demand is expected to at least increase steadily in 2015-2045 according to most scenarios but these differ very broadly. In 2030, the estimates range from 257 to 500 billion litres per year. For comparison, global production of liquid biofuels was 128 billion litres in 2014 (REN21, 2015). The projected demand depends on assumptions about policies and biofuel availability and cost.

The IRENA REmap and WEO 450 scenarios estimate the highest growth, which again reflects the scenario objectives to meet specific environmental goals. WEO 450 requires a share constituting 15% of total liquid fuel demand in 2035. IRENA REmap requires a share constituting approximately 13% of all liquid fuels in 2030. IRENA REmap's approach differs from the other scenarios in not being based on a 'most-likely' scenario. Instead, it explores the potential technological make-up of a world that doubles its renewable energy capacity, taking into account each technology's costs and technical performance.

None of the referenced scenarios considers the impact of a prolonged low oil price on the demand for biofuels. However, some of the scenarios were published after the steep oil price decline observed since the second half of 2014. The market for biofuels is currently created by numerous policies and mandates but low oil prices increase the cost of these policies. Continued low oil prices may thus discourage governments from pursuing such policies.

Advanced biofuels demand

Only two of the scenarios provide estimates for advanced biofuels demand: WEO New Policy and IRENA REmap. These are ambitious scenarios aiming to increase the market share of renewables and reduce GHG emissions. Both scenarios require additional policies and market mechanisms to those currently in place.

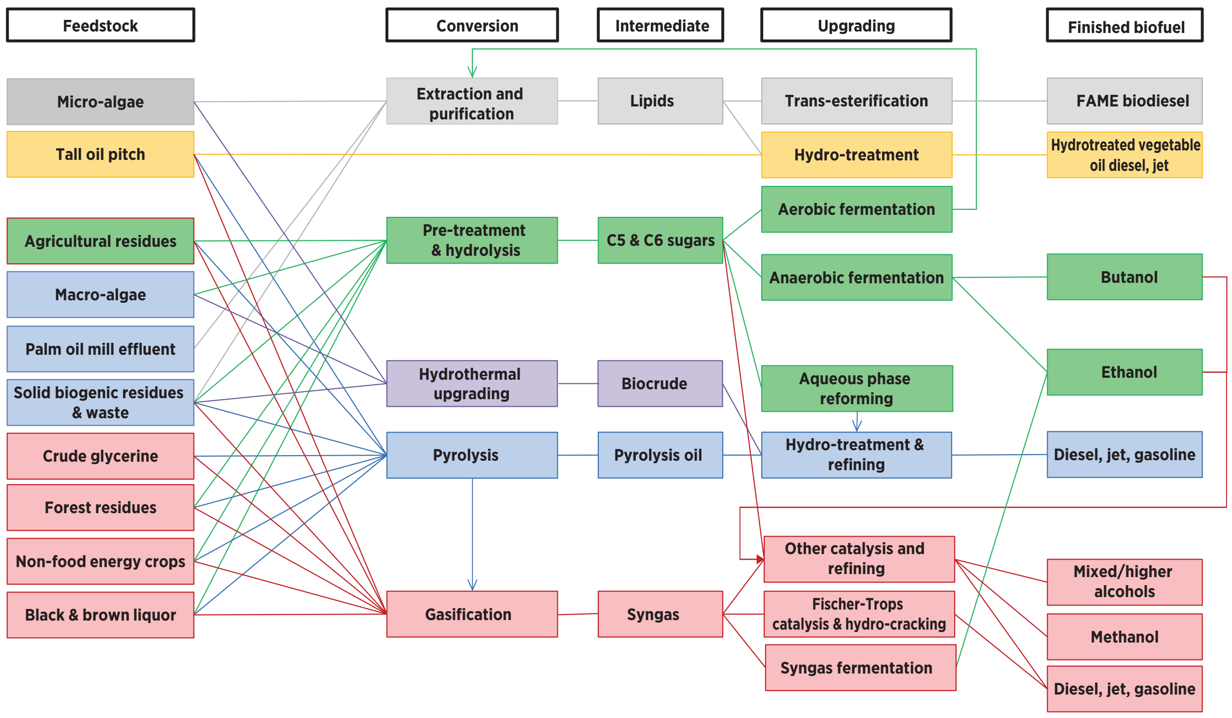
The WEO New Policy scenario estimates that advanced biofuels make up 18% of total biofuel production globally in 2035 (67 billion litres). They are largely deployed in OECD regions where they are expected to account for 27% of all biofuel used. According to WEO analysis, this would require investments of USD 78 billion in production capacity worldwide. In its quest to double the renewable energy contribution in 2030, IRENA REmap estimates that global demand for advanced biofuels could reach 124 billion litres per year by 2030. This equates to about 25% of total biofuels production in energy terms.

1.3 Advanced biofuels technology status

Many conversion technologies are capable of transforming advanced biofuels feedstocks into liquid transport fuels. Most of these have several conversion steps that produce intermediate products. Figure 3 illustrates the pathways to advanced biofuels using either 'advanced' feedstocks or pre-commercial conversion technologies. Some 'advanced' feedstocks such as micro-algae, macro-algae, and tall oil pitch may be converted to advanced biofuels via established processes like transesterification and hydro-treatment. The prospects for these established processes are not the focus of this study, and they are therefore not discussed in further detail.

Table 3 provides a brief description of the main conversion technologies. Further details on each conversion technology, including a description of the process, industry actors and current developments, are available in Annex A.

Figure 3: Advanced biofuels pathways



Note: Colours represent the principal conversion processes.

Table 3: Summary of advanced biofuels conversion and upgrading technologies

Principle process	Technology	Brief description	Products	Technology advantage(s)	Technology drawback(s)
Hydrolysis	**Fermentation to ethanol via hydrolysis of cellulosic biomass**	Biomass is pre-treated and enzymatically hydrolysed to convert the cellulose and hemicellulose fractions to sugars and possibly separate the lignin fraction (see glossary of terms). The soluble C5 and C6 sugar molecules are fermented to ethanol using yeast or bacteria. Ethanol is separated from the fermentation broth using distillation (see glossary of terms) and/or membranes or molecular sieves.	Ethanol	• Fermentation may utilise sugars isolated from a broad range of feedstocks. • Many parts of the process are commercially established, including steam explosion, C6 fermentation and product distillation. It is therefore possible to leverage existing experience. • Potential for co-location with existing sugar or starch-based ethanol plants.	• Pre-treatment and hydrolysis (see glossary of terms) may need to be adapted to specific feedstocks to achieve high efficiency. • The key pre-treatment technologies have high energy demands. • High capital costs compared to sugar or starch-based ethanol plants.

Principle process	Technology	Brief description	Products	Technology advantage(s)	Technology drawback(s)
Hydrolysis	**Fermentation to butanol via hydrolysis of cellulosic biomass**	Biomass is pre-treated and enzymatically hydrolysed to convert the cellulose and hemicellulose fractions to sugars and possibly separate the lignin fraction (see glossary of terms). The soluble C5 and C6 sugar molecules are fermented to butanol using yeast or bacteria. Butanol is separated from the fermentation broth (and possible co-products such as ethanol and acetone) using distillation and/or membranes or molecular sieves.	Butanol	• Fermentation may utilise sugars isolated from a broad range of feedstocks. • Butanol is currently produced using the acetone-butanol-ethanol fermentation process, thus making the most of existing expertise. • Specific interest in the production of iso-butanol, which may be converted to jet fuel.	In addition to the drawbacks outlined for ethanol fermentation: • Butanol is toxic to the fermentation organisms, and therefore the fermentation solution must be very dilute, which makes the product separation step more demanding, or requires more complex *in situ* product removal. • Co-production of acetone and/or ethanol also complicates product separation.
Pyrolysis	**Aqueous phase reforming**	An aqueous solution of sugars is converted through a reforming process with a chemical catalyst and hydrogen. The process takes place in catalytic reactors and involves various reactions including dehydration, oligomerisation, and carbon-carbon bond cleavage (see glossary of terms).	Gasoline, diesel and jet fuel	• Aqueous phase reforming may utilise sugars isolated from a broad range of feedstocks. • No requirement to remove water during the reforming process.	• Current scale-up is directed at hydrogen production, and further processing steps are required to produce gasoline, diesel and jet fuel. • Current scale-up is also directed at the conversion of sugars from sugar and starch crops; the process is likely to need clarified (solid-free) sugars. • High capital costs and probably high operating costs due to hydrogen demand.
	Pyrolysis and upgrading	Pyrolysis is the controlled thermal decomposition of biomass to produce oil, syngas and charcoal (also known as biochar). Fast pyrolysis maximises production of pyrolysis oil. Pyrolysis oil is upgraded by reacting with hydrogen (*e.g.* hydro-cracking or hydro-treating) or through catalytic cracking using zeolite catalysts or fluid catalytic cracking.	Gasoline, diesel and jet fuel	• In principle, the process is suitable for a broad range of feedstocks and may tolerate variations in feedstock composition, potentially taking advantage of lower-cost feedstocks. • Pyrolysis oil is an energy-dense intermediate that may be economically transported. This may provide an opportunity for decentralised process for upgrading. • The upgrading step uses standard refining processes, and it may therefore be possible to co-process pyrolysis oil in existing oil refineries.	• Pyrolysis oil characteristics (high acidity, high viscosity, high water content (see glossary of terms) make it difficult to store and handle; must be stabilised for shipping and storage. • High water and oxygen content of pyrolysis oil can damage catalysts and significantly alter the product range.

Principle process	Technology	Brief description	Products	Technology advantage(s)	Technology drawback(s)
Hydrothermal Upgrading	**Hydrothermal upgrading**	Biomass with a high water content is heated and pressurised to convert it to a more energy dense 'bio-crude' which can be refined in a similar way to conventional crude oil.	Gasoline, diesel and jet fuel	• Allows use of very wet feedstocks such as municipal solid waste or algae without drying. • Bio-crude is an energy-dense intermediate that may be economically transported. This may provide an opportunity for a decentralised upgrading process. • Upgrading uses standard refining processes and it may therefore be possible to co-process bio-crude in existing oil refineries.	• Corrosive conditions and high pressures. • Technology not well developed beyond laboratory-scale. • High water and oxygen content of bio-crude can damage catalysts and significantly alter the product range.
Gasification	**Gasification and Fischer-Tropsch synthesis**	Gasification converts dry biomass to syngas (a mixture of primarily hydrogen and carbon monoxide – see glossary of terms) typically under high temperature and pressure. Syngas is cleaned of contaminants and conditioned via a water-gas shift reaction to meet the catalyst specification. Fischer-Tropsch catalysts convert conditioned syngas to a mixture of hydrocarbons which may be upgraded via standard refinery processes.	Diesel and jet fuel	• In principle, the gasification process could use many low-cost feedstocks and may tolerate heterogeneous feedstock. This is dependent upon specific reactor design. • Each individual process step is well established at commercial scale for fossil feedstocks, thus enabling the maximum use of existing expertise. • The Fischer-Tropsch process produces high-quality fuels for road transport and aviation.	• The Fischer-Tropsch process has strict syngas quality requirements. The crude syngas from the gasifier must undergo a number of intermediate processes to meet these requirements, increasing capital and operational costs (see glossary of terms). • High capital costs compared to conventional biofuels and many advanced biofuels. • Multiple temperature and pressure changes occur throughout the conversion pathway from feedstock to fuel; this can increase energy demand. • Existing Fischer-Tropsch processes operate at very large scale not suitable for biomass.
	Gasification and mixed alcohol synthesis	Gasification converts dry biomass to syngas typically under high temperatures and pressure. Contaminates are removed from the syngas, which is conditioned via a water-gas shift reaction to meet the catalyst specification. Syngas is converted via chemical catalysis typically using a modified methanol catalyst or Fischer-Tropsch catalyst. Catalyst and syngas compositions and reaction conditions determine alcohol product distribution.	Mixture of alcohols including methanol, ethanol, and butanol	• In principle, the process is suitable for a broad range of feedstocks and may tolerate heterogeneous feedstock. This is dependent on specific reactor design. • Mixed alcohol synthesis has higher tolerance to sulphur in the syngas than other chemical syntheses, and a lower water-gas shift requirement.	• Low product yields and poor selectivity to alcohols other than methanol. • Synthesis step typically operates at high pressure compared to other synthesis processes.

Principle process	Technology	Brief description	Products	Technology advantage(s)	Technology drawback(s)
Gasification	**Gasification and methanol synthesis**	Gasification converts dry biomass to syngas typically under high temperatures and pressure. Syngas is cleaned of contaminates and conditioned via a water-gas shift reaction to meet the catalyst specification. Syngas is then reacted with small amount of CO_2 over a catalyst to produce methanol.	Methanol	- In principle, the process is suitable for a broad range of feedstocks and may tolerate heterogeneous feedstock. This is dependent upon specific reactor design. - Technology is well established for fossil feedstocks, thus enabling good use of existing expertise. Catalysts are less expensive than those required for Fischer-Tropsch synthesis.	- Depending on the quality and composition of the syngas, side reactions can result in by-products, reducing conversion efficiency (see glossary of terms) and increasing product separation costs. - Limited market demand for methanol as a fuel due to its relatively low energy density, corrosive nature, high water solubility and toxicity to humans.
	Gasification and syngas fermentation	Gasification converts dry biomass to syngas typically under high temperatures and pressure. Syngas is cleaned and conditioned to meet biological catalyst specifications and then fermented using anaerobic micro-organisms.	Ethanol	- The fermentation step is not sensitive to the syngas ratio and is tolerant to sulphur. The syngas clean-up and conditioning requirements are therefore generally lower (albeit different than for inorganic catalysts). - Syngas fermentation operates at low temperatures and pressure, resulting in potentially lower production costs. - The process may be economically feasible at smaller scale than other processes based on gasification.	- Syngas fermentation processes achieve lower product concentration than traditional fermentation and therefore require more demanding product separation.
	Catalytic conversion of alcohols (including alcohol to jet)	Short chain alcohols, including methanol, ethanol and butanol, may be catalytically converted to paraffinic fuels. Conversion involves a combination of dehydration, oligomerisation, hydrogenation and distillation.	Gasoline, diesel and jet fuel	- Opportunity to produce high-quality fuels using ethanol as a feedstock.	- Conversion yields (see glossary of terms) and selectivity are currently poor and must be improved to reduce production costs. Process complexity and high capital costs.
	Sugars to hydrocarbons via cellulosic sugars	Chemical or biological method for conversion of sugars directly to useful hydrocarbons. The conversion processes generally produce intermediate products that still contain double bonds or oxygen and must be hydro-treated to produce a finished fuel.	Diesel, gasoline, jet fuel	- The processes produce high-quality fuels for road transport and aviation; some processes have been certified for use in aviation.	- Almost all processes only use first generation sugar feedstocks. Process complexity and high capital costs.

1.4 Feedstock potential and cost

The technological maturity of the production pathways depends on the feedstock used in each case. The following categories are frequently defined in advanced biofuels production:

- **Solid biogenic waste:** the definition and classification of biogenic waste is not consistent across the literature. This category usually includes solid industrial biogenic waste, the biogenic fraction of municipal solid waste and garden waste (including collections from households, parks and roadside maintenance).
- **Agricultural residues:** post-harvest residues that need to be collected such as straw and corn stover, and captive processing residues such as bagasse, husks, shells and cobs.
- **Forestry residues:** woody biomass residues from forestry activities including branches and leaves, and residues from wood processing activities such as sawdust and cutter shavings.
- **Non-food energy crops: t**ypically wood and grass crops, including short rotation coppice (*e.g.* poplar and willow) and energy grasses (*e.g.* switchgrass, miscanthus and reed canary grass).
- **Micro-algae:** refers to algae with a high lipid content. Typically grown in dedicated systems like open ponds or photobioreactors.
- **Macro-algae (or seaweed):** plant-like resource that may be harvested from wild stocks or dedicated farms in the sea.

The assessment in this chapter excludes crops for food and feed like sugar, starch and vegetable oil crops because these are established feedstocks with fully commercial biofuels conversion pathways. Very high moisture content wastes such as animal manure and sewage sludge are also excluded because these feedstocks are more suited to anaerobic digestion to produce biogas or biomethane. Macro-algae represents a potential source of carbohydrates but very few references quantify the global sustainable harvestable volumes. It is therefore excluded from this assessment. In addition, macro-algae also have high ash and water content. Current research is thus aimed at anaerobic digestion to produce biogas.

A meta-analysis of the literature has been carried out as part of this study to provide an overview of biomass potential estimates over the next three decades (see Annex C). There are major differences in the studies reviewed. These arise predominantly from the different methodologies applied and the different categories of potentials considered. For example:

- **Theoretical potential:** describes the physical theoretically usable energetic potential of a feedstock within a specific region.
- **Technical potential:** the component of theoretical potential that remains after unavoidable losses due to technical restrictions (such as harvesting and collection efficiency or processing issues) are deducted.
- **Economic potential:** the component of technical potential that is economically viable for cultivation or extraction, taking into account the density of the resource and the costs of cultivation or collection.
- **Sustainable potential:** considers further social and ecological aspects such as food security, cultivation methods, preservation of soil quality, water use or limits to application of synthetic fertilisers or pesticides.

Competing uses are important in determining the amount of resource that could be destined for a certain use. Economic and sustainable potential should take competing uses into consideration to a different extent. Figure 4 illustrates the wide variation in estimates but also provides an indication of the potential significance of the biomass potential. Estimates of potential vary widely, then. However, many studies conclude that the biomass potential is substantial in terms of residues and wastes, and potentially in terms of energy crops once food demands are satisfied.

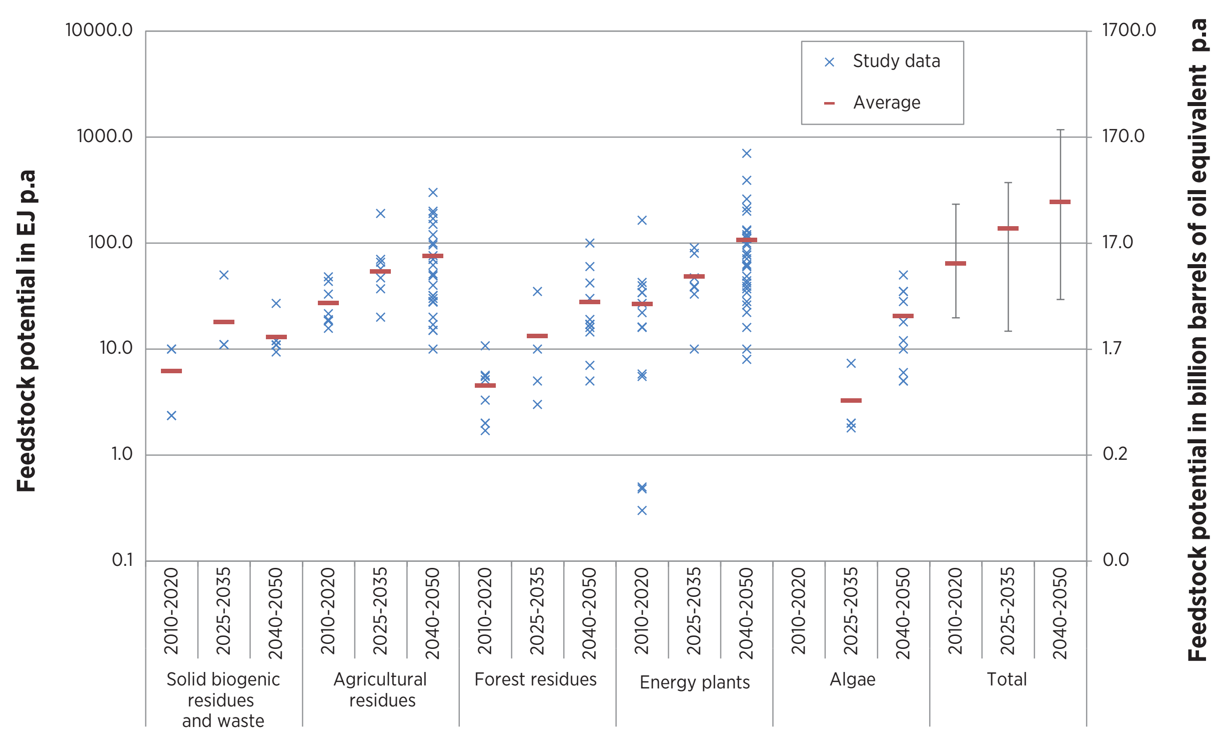
According to the Intergovernmental Panel on Climate Change (IPCC), this potential is likely to be at least 100 exajoules (EJ) in 2050 – or a fifth of current global primary energy demand (Smith *et al.*, 2014). Figure 5 illustrates the costs of feedstocks at farm or field gate. Feedstock costs are at USD 1.6-5.2 per gigajoule (GJ) in 2010-2020, excluding solid biogenic waste, which could incur negative costs, and algae, which have very high production costs. Agricultural and forest residue costs are expected to remain stable or increase slightly in price over the next three decades while costs for non-food-energy crops are projected to decrease during this period. Solid biogenic wastes are generally available at a negative cost, reflecting the cost of alternative disposal routes (*e.g.* landfill). Feedstock costs for algae are primarily determined by the cultivation technology and are very high due to the early stage of the technology. Only at the lowest production cost estimates are algal oils an economically feasible feedstock for advanced biofuel production. Advanced biofuel demand alone will thus not lead to algae commercialisation but there will need to be other value drivers associated with other (co-) products.

- **Solid biogenic waste**: this category has the lowest potential overall but is nonetheless significant and attractive because of its concentration, need for collection and disposal and low competing uses. Its potential is expected to increase in time mainly due to increasing population and the development of waste collection infrastructure. Costs largely depend on the type of waste, alternatives for its disposal and any potential uses. But wastes will generally be available at a negative cost *i.e.* biofuel plants could be paid to receive the waste. Valuable uses of the biogenic fraction of post-consumer waste include the production of heat and/or power. This can occur either directly in an incineration plant, for example, or following pre-treatment to produce a refuse-derived fuel. Fractions such as paper and cardboard can be recycled, and green waste processed and returned to the fields. The use of wastes thus needs to be considered in the context of waste minimisation, reuse and recycling.
- **Agricultural residues**: agricultural residues are a potentially very large feedstock source and may be the biggest biomass resource depending on the potential for energy crops. Costs will generally be low, reflecting costs of collection and transport, though prices may be relatively high where there is local competition and limited supply for other uses (*e.g.* use of straw for animal bedding). One constraint to be considered is the need to leave a fraction of the residues in the field to maintain soil structure and fertility. Heat and power production and landscape mulching are other possible valuable uses of agricultural residues.
- **Forest residues**: the potential of forest residues is lower than that of agricultural residues but also substantial and concentrated in areas with major commercial forestry activities. Current forest residue costs are relatively low but heat and electricity generation is an established and growing market for them. Growth in the resource is linked to increasing demand for forest products but constrained by the economic and sustainable extraction rates. Access to forest residues in managed but non-commercial forests may be constrained by the collection and transportation infrastructure. Other valuable uses of forest residues include animal bedding and board production. One constraint to consider is the need to leave a fraction of the residues in the forest to maintain and improve soil quality.
- **Non-food energy crops**: the widest range of potential is in non-food energy crops due to differences in methodology, particularly in assumptions on land availability and environmental constraints. Examples include the amount of land required for food production (including the intensification of agriculture due to improved agricultural practices), water availability and sustainable soil management. Non-food energy crops have major potential but the uncertainty surrounding this potential is high, and feedstock costs are higher than in all other categories except algae. The development of supply chains for dedicated non-food energy crops is at an early stage. Cost estimates diverge considerably due to wide differences in crop yields between different crops and different regions. Non-food energy crops are used for heat and/or power generation, and smaller quantities are used for animal bedding. Non-food energy crops may compete for land with other crops.
- **Algae**: the estimation of feedstock potentials from algae cultivation is currently very uncertain because cultivation systems are still under development. Global algae cultivation potential is limited by availability of land with sufficient irradiation, access to water and nutrients. Algae appear to be the most expensive feedstock. Their cultivation is currently limited to high value products example for the cosmetics industry, for example.

1.5 Advanced biofuels pathways and deployment status

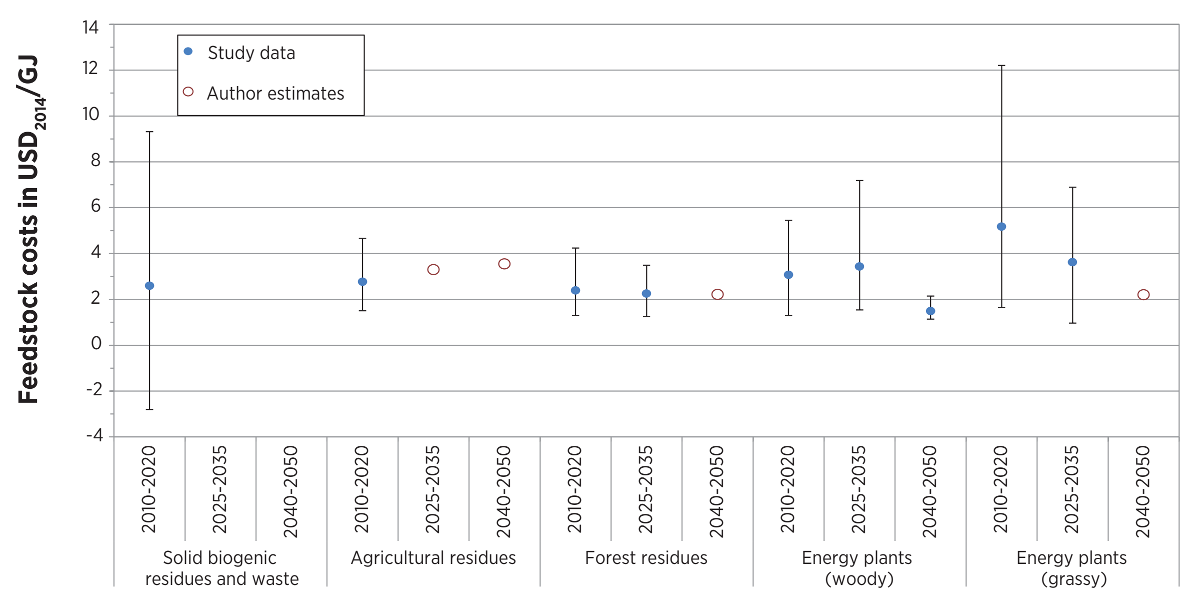
Advanced biofuels pathways are defined as a combination of feedstock, conversion technology and

Figure 4: Summary of estimates of global feedstock potentials for key biomass categories (EJ per year based on lower heating values)



Note: exponential y axes

Figure 5: Summary of global feedstock cost estimates for key biomass categories[3]



Note: the costs of micro-algae are not shown because they are one to two orders of magnitude higher

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[3] 'Study data' refers to the arithmetic average of each category in the cited studies. The ranges represent the minimum and maximum of reported values. 'Author estimates' are based on observable general trends and past developments.

Table 4: Technology Readiness Level scale

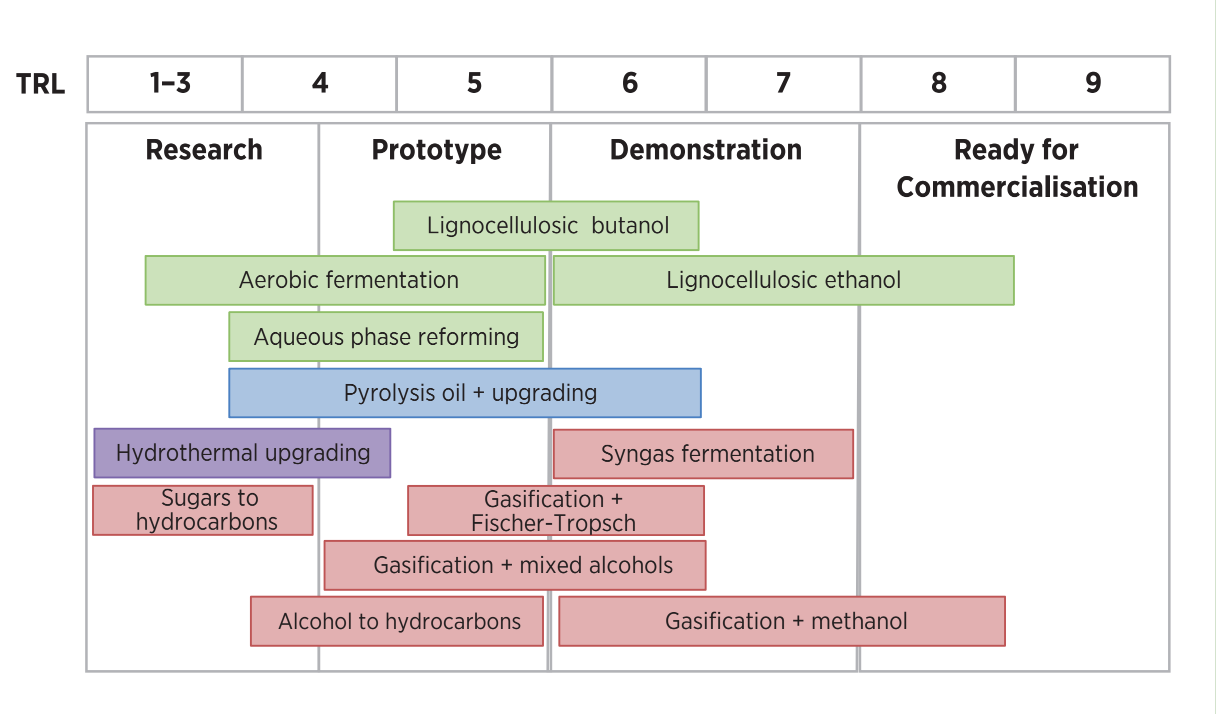
TRL	Definition	Explanation
0	Idea	Unproven concept, no testing has been performed
1	Basic research	Principles postulated and observed but no experimental proof available
2	Technology formulation	Concept and application have been formulated
3	Applied research	First laboratory tests completed; proof of concept
4	Small scale prototype	Built in a laboratory environment
5	Large scale prototype	Tested in intended environment
6	Prototype system	Tested in intended environment close to expected performance
7	Demonstration system	Operating in operational environment at pre-commercial scale
8	First-of-a-kind commercial system	Manufacturing issues solved
9	Ready for commercialisation	Technology available for consumers

product type. Figure 63 illustrates the main advanced biofuel pathways, indicating which conversion technologies are most commonly associated with each feedstock.

The advanced biofuels pathways are at various stages of commercial development, which may be defined by Technology Readiness Level (TRL) descriptors as outlined in Table 4. The TRL for each pathway is summarised in Figure 6 based on an analysis of current industrial activity documented in Annex B.

Lignocellulosic ethanol plants using agricultural residues (corn stover, wheat straw and sugarcane bagasse in particular) and some energy crops (specifically giant cane) have reached early commercial phase (up to

Figure 6: Commercialisation status of various advanced biofuel pathways



Note: Colours represent the principal conversion process, hydrolysis (green), pyrolysis (blue), hydrothermal upgrading (purple) and gasification (red).

TRL 8). The use of woody biomass (forest residues, short rotation forestry and coppice) is at an earlier stage of demonstration (up to TRL 7). Conversion of the biological fraction of municipal solid waste via sugar fermentation to ethanol is at an earlier stage of development (up to TRL 5). This is because processes to isolate a clean source of sugars from municipal solid waste are currently being piloted.

Gasification with catalytic synthesis routes can be used with various feedstocks. The feedstock requirements in terms of ash content, moisture content and size are specific to the type of gasifier. Many demonstration projects to date have used low-ash woody biomass (*e.g.* forestry residues) but Enerkem's first commercial plant is using municipal solid waste. Gasification followed by syngas fermentation to ethanol is currently at TRL 7 in the US, using green waste from gardens.

Fast pyrolysis and upgrading can use mixed and variable feedstock although the composition makes an impact on the yield and pyrolysis oil composition. Agricultural residues, wood residues and wastes are currently being used in pilot and demonstration plants.

Deployment status

In Annex B we provide an inventory of current and planned advanced biofuel projects across the world at end 2015. This includes first-of-a-kind commercial or 'flagship' plants, demonstration plants and key pilot plants where these have not been superceded by demonstration plants. The inventory provides details of 91 plants, including project developer(s), plant location, feedstocks, conversion technology and products, installed capacity, type of plant, and start date.

Current installed production capacity for advanced biofuels (excluding those produced from used cooking oil and animal fats via commercially established processes) is estimated at almost 1 billion litres per year. This excludes plants which have stopped production and equates to 0.04% of liquid transport fuel demand.

BioMCN in the Netherlands accounts for 25% of global installed capacity (250 million litres), producing methanol from crude glycerine and biomethane. The remaining capacity is predominantly lignocellulosic ethanol produced via fermentation. DuPont, Abengoa and Poet-DSM have been operating commercial-scale lignocellulosic ethanol plants in the US. The total installed capacity is 285 million litres with a planned increase to 303 million litres. However, the Abengoa plant has ceased operations as its parent company faces financial difficulties. Similarly, GranBio and Raizen have started production in Brazil (installed capacity 80 million litres and 40 million litres respectively). Shandong Longlife has started production in China (installed capacity 60 million litres) as has Beta Renewables in Italy (installed capacity 50 million litres). In addition, alternative business models may enable plants to operate commercially at much smaller scale. In Finland, St1 produces bioethanol from waste using a number of fermentation plants situated near the sources of waste and carrying out dehydration in a central dehydration plant.

Actual production of advanced biofuels to date is much lower than the installed capacity, in part due to the use of innovative technologies. In the first few years of operation, first-of-a-kind or flagship plants may be expected to ramp up production volumes to perform testing and optimisation activities. However, many of these first-of-a-kind commercial plants are also experiencing technical difficulties. In most cases these are not insurmountable need time to be addressed. They include issues related to feeding, handling and processing large quantities of feedstock. In addition, external factors such as feedstock price, availability and low oil prices have also affected production.

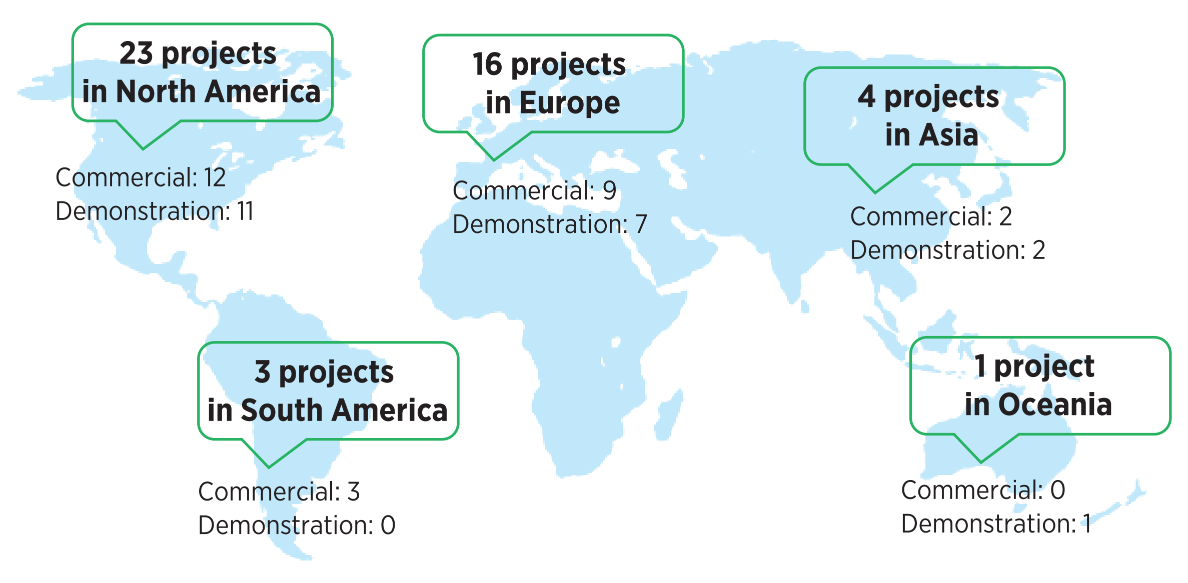
Biomass gasification for liquid fuel production has less operational capacity. Enerkem operates a first-of-a-kind commercial-scale plant with the capacity to produce around 28 million litres per year of methanol from municipal solid waste via gasification. INEOS Bio operates a commercial demonstration plant for lignocellulosic ethanol production via syngas fermentation in the US (installed capacity 30 million litres). CHOREN' s gasification and Fischer-Tropsch synthesis process trial failed after the demonstration plant experienced a series of delays in meeting key performance milestones relating to biomass handling and syngas quality. Several of the technology components were subsequently bought and are under development by other engineering companies. Solena had been planning to develop gasification and Fischer-Tropsch synthesis projects in partnership with British Airways and others. However, the company has recently gone into administration. Other companies, such as Coskata, have shifted their business strategy from biomass feedstocks to natural gas.

An additional 2 billion litres of annual capacity is planned or under construction. This includes more lignocellulosic ethanol plants and many demonstration and first-of-a-kind commercial thermochemical plants. These produce methanol, mixed alcohols and Fischer-Tropsch diesel and/or jet fuels. Figure 7 illustrates the number of advanced biofuels plants planned or in operation in each region. Figure 8 illustrates the total installed capacity of demonstration and commercial plants in each region. The majority of demonstration plants and first-of-a-kind commercial plants are being developed in the US and Europe – regions where most technology development is taking place. Most lignocellulosic ethanol plant development is in the US and Brazil. These countries are attractive because of the availability of agricultural residues and the potential opportunity to either retrofit or expand existing ethanol production facilities to use lignocellulosic feedstocks.

Around 8.2 billion litres of new capacity would have to be installed per year to reach IRENA REmap estimates. These show an advanced biofuels global production potential of 124 billion litres per year by 2030 from the current installed production capacity of around 1 billion litres per year. This means that meeting the global production potential would require the construction of around 205 plants with average annual installed capacity of 40 million litres over the next 15 years. According to IRENA REmap, the total average annual capital investment needed to install the new capacity to fulfil the advanced biofuels production potential worldwide amounts to USD 10 billion in 2014-2030 (IRENA, 2016). This would require a portfolio of stable policies over this timeframe to attract investors and the participation and partnership of the public and private sector, among other urgent measures. Some of these measures and strategies are further discussed in Chapter 5.

Many European projects have been subject to delays as a result of policy uncertainty. There is currently no European framework to support biofuels beyond 2020 although some individual member states have implemented their own targets, in some cases extending beyond 2020. This provides some market certainty to project developers. As a result several projects have been cancelled, including two gasification projects led by industrial partnerships between Ajos and Vapo, and Neste and Stora Enso, New projects struggle to make financial sense while oil prices remain low.

Figure 7: Number of advanced biofuels plants by region (demonstration and commercial plants[4])



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[4] 'Commercial' refers to plants at commercial scale, some of which may still have received financial support

Figure 8: Planned and operational production capacity of advanced biofuels plants by region (demonstration and commercial plants only; data labels show number of plants)

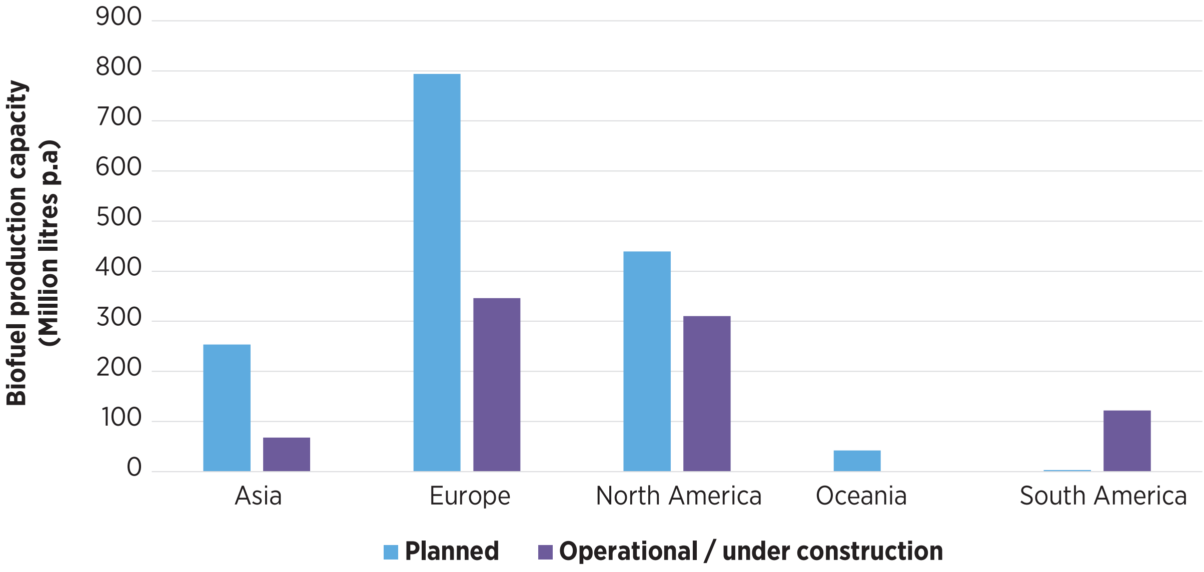
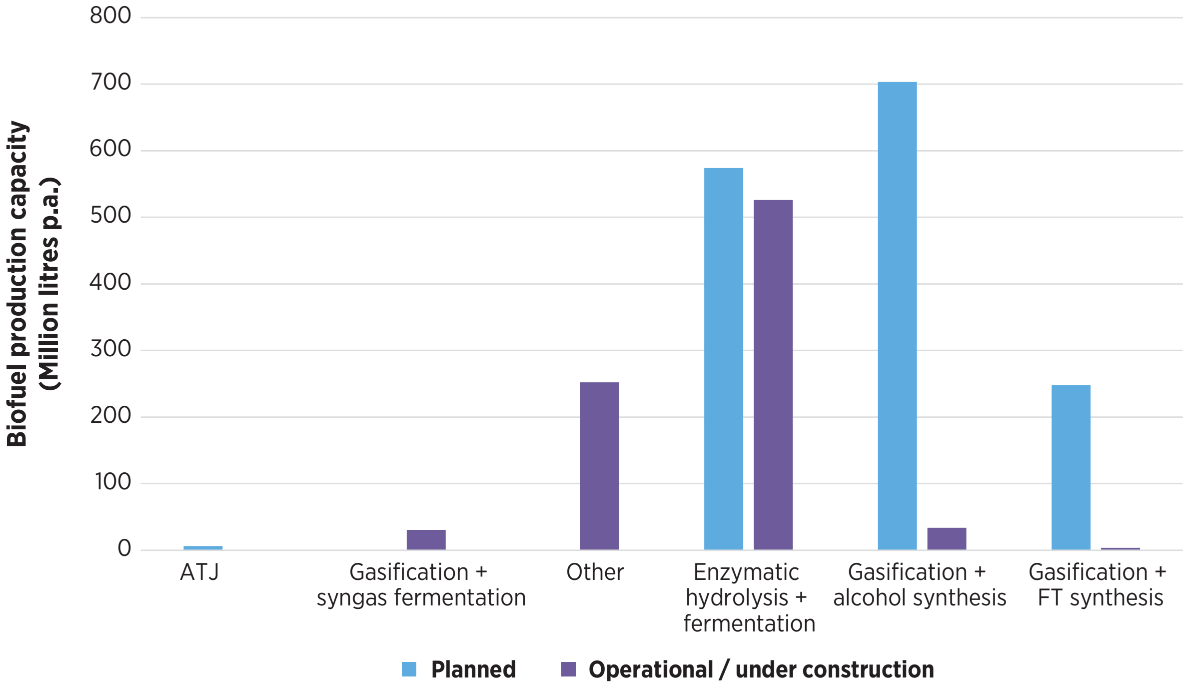


Figure 9 illustrates the current state of development of the main advanced biofuels conversion technologies. In general, the production of alcohols (specifically ethanol and methanol) dominates globally. In Europe, North America and Oceania (Australia), there are also initiatives to introduce hydrocarbon fuel, such as jet, diesel and gasoline via catalytic processes.

Figure 9: Planned and operational production capacity of advanced biofuels plants by technology category (demonstration and commercial plants only; data labels show number of plants)



Feedstock utilisation status

Current advanced biofuels plants utilise a range of feedstocks, including by-products of biodiesel and paper and pulp production, municipal solid waste and agricultural residues, such as corn stover, bagasse and straw. Some starch ethanol plants in the US are also extending their operations to include conversion of the cellulosic portion of the corn kernel, making an incremental additional amount of ethanol. These feedstocks have two advantages. They are already in production (typically as a result of other economic activities) and are available at relatively low cost due to limited local demand. However, the cost of collecting and transporting the feedstock can be significant. Some progress is being made in establishing advanced biofuels feedstock supply chains as part of existing demonstration and early commercial projects. However, significant efforts are still required to improve the efficiency of these chains, establish effective business models and prove their sustainability. This could be achieved by monitoring the impact of extracting residues from the field on crop yields, for instance.

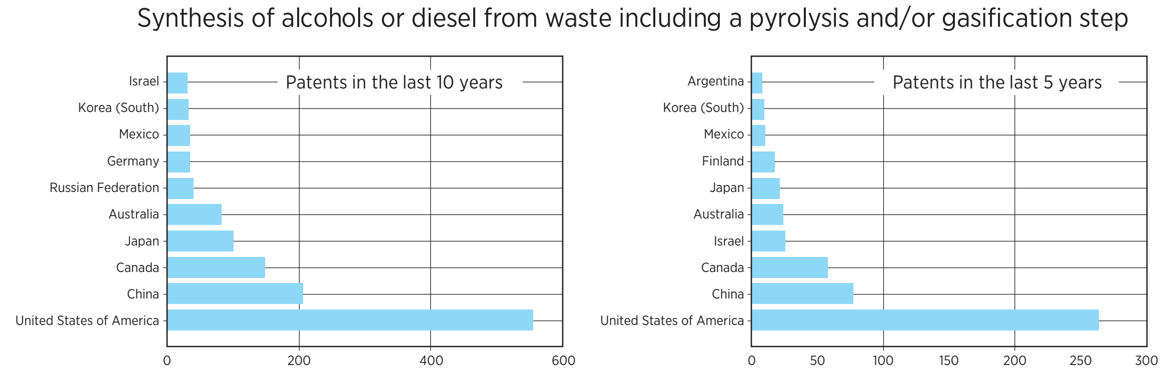
Woody biomass is also being tested as a feedstock in advanced biofuels production facilities. This is mostly waste wood and forest residues, as well as some woody energy crops. However, these tend to be feedstocks experiencing stronger competition for heat and power use. The conversion of micro-algae oils to transport fuels has not been demonstrated at scale, and algal products are currently directed at higher value markets.

Further development of the most attractive biomass supply chains would increase knowledge of their potential as well as their constraints, particularly for energy crops. This could improve future estimates of global and regional bioenergy potential (Slade *et al.*, 2014). Demonstrating viable advanced biofuels feedstock supply chains at scale is critical to the development of the sector, generating learning and replication.

This analysis of patents filed gives an insight into the historical development and geographical distribution of advanced liquid biofuels. The patent analysis uses the IRENA Inspire Tool inspire.irena.org/Pages/patents/techprofiles.aspx).

Cellulosic bioethanol is the advanced liquid biofuel with the highest activity. The US, China and Canada seem to lead patent activity although it has decreased over the last five years in the US and China. Intense patenting activity in cellulosic bioethanol registered by other countries over the last ten years, such as Brazil, has declined. Increasing interest is observed in Australia, Mexico, Israel, France and Colombia.

In the last five years, patent activity in biomass pyrolysis has maintained momentum in China and the US – the two most active countries in this category. Japan and Germany, on the other hand, have registered a less intense activity over this period.



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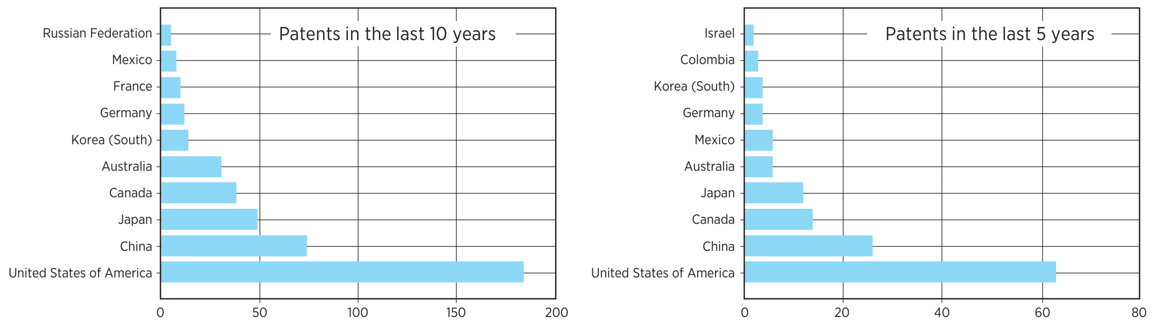
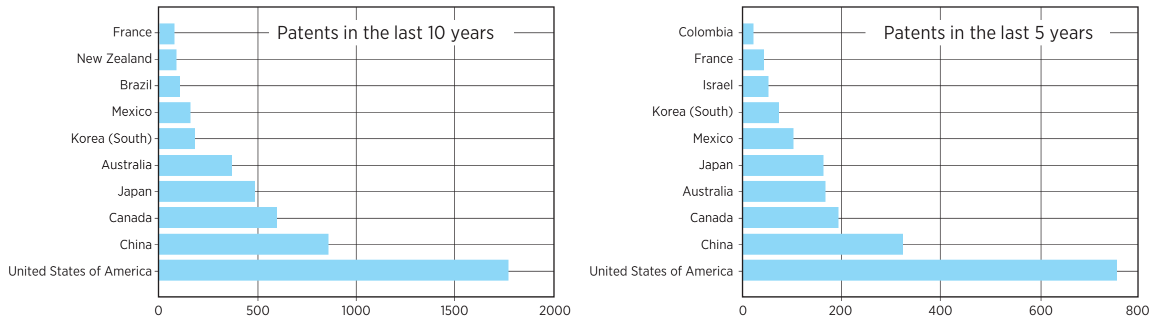
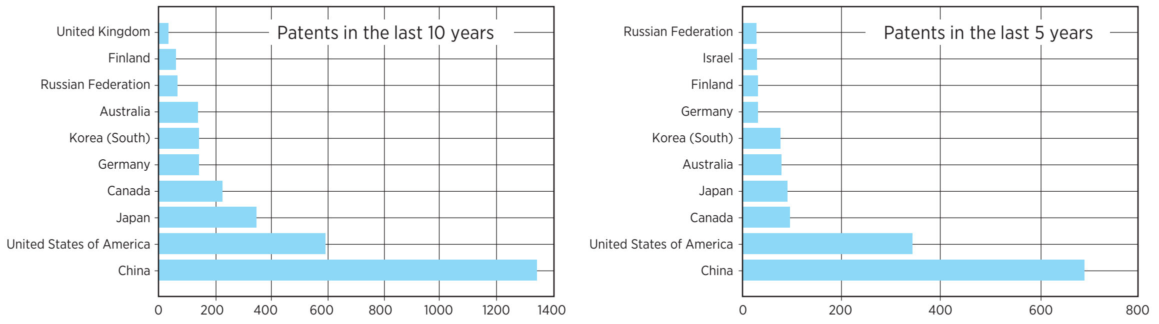

Bio-alcohols produced by other means than fermentation


Cellulosic bio-ethanol


Bio-pyrolysis

General patent numbers in technologies for synthesising fuels from biomass waste, including pyrolysis and/or gasification, has increased slightly in the last five years. Israel and Finland are significantly increasing their activity in this category, which has been predominantly led by US, China and Canada.

Patent activity in technologies producing alcohols by other means than fermentation has slowed down in the last five years in the top countries in this category: the US, China, Canada and Japan. Increased activity can be observed for Mexico, Colombia and Israel.

More detailed information on this patent analysis can be found in Annex E.

Options for policy makers

Advanced biofuels can be defined in different ways. This report focuses on two key elements, innovation and sustainability. It thus concentrates on technologies and pathways as yet uncommercial using lignocellulosic biomass feedstocks.

Energy scenarios indicate that liquid fuel demand is likely to rise or at best be contained at current levels over the next 20 or 30 years. Current scenarios indicate that the **contribution of all biofuels is expected to grow and at least double in the period to 2030** compared to the current level of supply. However, these scenarios do not consider the impact of a prolonged low oil price on biofuel demand.

Private sector activity in advanced biofuels has increased significantly in the last decade. This is testified by the long list of technology developers and their involvement in pilot, demonstration and early commercial activities. This is largely in **response to government mechanisms including financial support for research, development and demonstration activities, and the introduction of advanced biofuel mandates.**

Lignocellulosic ethanol production is being proved at commercial scale using agricultural residues both via hydrolysis and fermentation routes, and syngas fermentation routes. Many other **demonstration plants are aiming to prove the technical viability of producing a range of gasoline, diesel and jet fuel substitutes** from a range of feedstocks.

Installed advanced biofuels production capacity is now approximately 1 billion litres but output from plants is much lower as plants test and optimise operation. Many plants are also experiencing technical difficulties, including issues related to feeding, handling and processing large quantities of feedstock. In addition, external factors such as feedstock price and availability have also affected production.

A wide range of feedstocks could be used to produce advanced biofuels. Municipal solid biomass waste may be most attractive because it is less costly and does not compete with non-energy uses. Agricultural residues have the greatest potential but certain types may attract existing local markets, and this leads to competition for the resource. Dedicated lignocellulosic energy crops are cultivated in small quantities today. They have great but uncertain potential because of competition with crops for food and feed, growth potential on unused lands and relatively high costs. Micro-algae offer the promise of production on non-agricultural land but their potential is significantly constrained by the need for very significant cost reductions.

2 TECHNICAL BARRIERS, NEEDS AND OPPORTUNITIES

Advanced biofuel conversion technologies must overcome technical challenges for widespread commercial deployment. These relate to, *inter alia*, the supply of suitable feedstocks that meets the required specification throughout the year, and conversion technology performance and cost effectiveness.

Many advanced biofuels pathways are affected by the seasonal nature of the production of some biomass feedstocks (especially agricultural residues and energy crops). This can mean supply chains are required to store very large volumes of feedstock – which can add to investment costs and feedstock degradation during storage. This may affect downstream processing and conversion efficiency. Potential technology solutions include biomass pre-treatment to increase its energy density and reduce susceptibility to degradation (via torrefaction or pelleting, for example). Another solution is the adoption of conversion processes able to use (a blend of) different feedstocks throughout the year depending on availability.

Many plant stoppages have occurred due to feedstock blockages in handling systems. This is particularly troublesome for heterogeneous waste feedstocks and when feeding high-pressure equipment downstream. This technical barrier can be resolved through greater biomass testing at scale, more tightly specified feedstocks or the development of intermediate feedstocks like refined biomass.

In the following section, we present the key technical challenges relating to each of the main conversion steps of advanced biofuels pathways. We define what is needed for these advanced biofuel pathways to achieve commercialisation. Where possible, ongoing research is featured to provide an example of the ground-breaking innovations that could potentially unlock advanced biofuels as the energy supply of the future. However, not all research presented in this chapter will result in commercialised products. The endeavours outlined are only a sample of the numerous research and development efforts in progress at different institutions.

2.1 Pre-treatment and hydrolysis

Technical barriers and needs

Pre-treatment and hydrolysis are crucial process steps in fermentation pathways to convert lignocellulosic

Figure 10: Pre-treatment and hydrolysis pathway

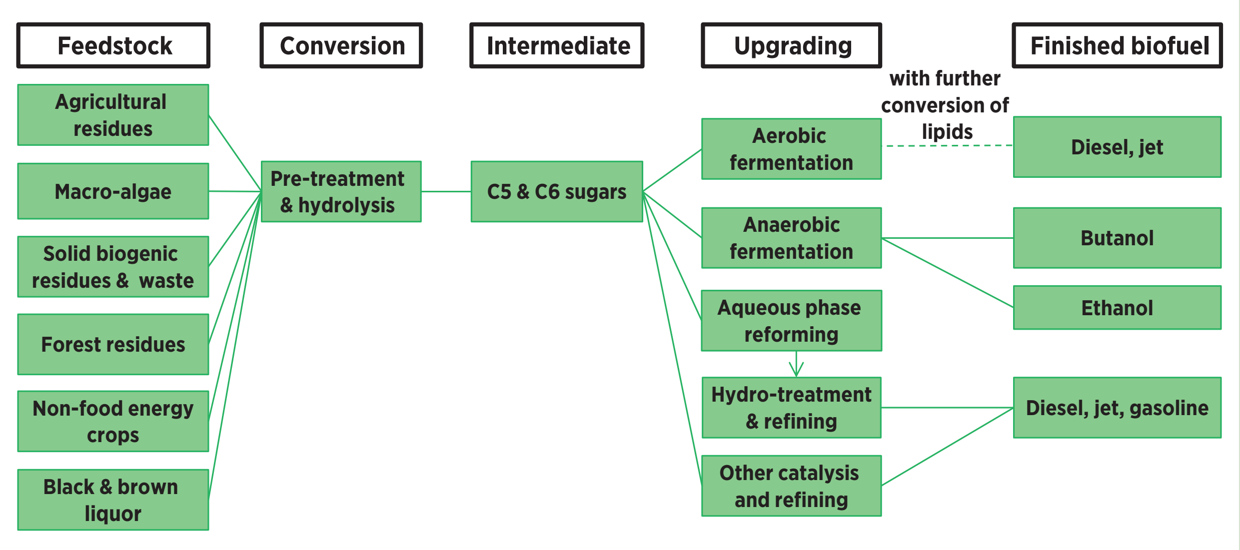


Table 5: Technical barriers and needs relating to the commercialisation of biomass pre-treatment and hydrolysis

Technical barriers	Technical needs
Insufficient separation of cellulose and lignin in the pre-treatment step reduces the effectiveness of the hydrolysis step and therefore overall conversion efficiency.	Effective delignification processes.
Severe pre-treatment conditions cause degradation products which can inhibit downstream fermentation.	Optimisation of pre-treatment conditions and/or development of detoxification methods.
Pre-treatment and hydrolysis steps are energy-intensive and/or use a great deal of chemicals, increasing operational costs and reducing energy efficiency.	Reduce energy and materials demand.
Enzymes used for the hydrolysis process are typically dedicated to the feedstock and not suited to mixed feedstocks, limiting the flexibility of the full process.	More flexible hydrolysis.
Solid loading is often limited, resulting in low product concentrations and large mass flows to be treated downstream.	Optimisation of pre-treatment and hydrolysis to increase solid loading.

References: Chiaramonti et al., 2012; Harmen et al., 2013

biomass. They are recognised as the most expensive process steps and the most technically difficult tasks. A number of technology approaches are in operation and under development. The main technical barriers are outlined in Table 5.

Opportunities for improvement

Hydrolysis enzyme costs will fall and could decline by 90% by 2050.

Table 6 describes the different technical options for pre-treating lignocellulosic biomass and the opportunities identified for improving each of these different processes.

Some pre-treatment technologies are still at the early research and development stage *e.g.* ionic liquids or biological pre-treatment using fungi.

Steam explosion, hydrothermal pre-treatment, concentrated acid hydrolysis and dilute acid pre-treatment are the most mature pre-treatment technologies. There has been some progress in overcoming some of the key concerns:

- In processes using acid or alkali solutions, the use of corrosive chemicals adds to production costs due to the need for expensive corrosion-resistant metals in plant construction. However, processes have been developed requiring no chemical pre-treatment, thereby reducing overall capital costs.
- Inhibitors or compounds with a negative effect on downstream fermentation are produced in the pre-treatment processes. For example, sugars are degraded into furfurals under high temperature and acidic conditions such as steam explosion and acid hydrolysis. The furfurals act as fermentation inhibitors. Under alkaline conditions, the solubilisation of lignin monomers or organic acids also results in inhibitors. In other processes, the presence of acids inhibits the microbial growth needed for the fermentation. Purification processes that remove inhibitors are expensive. Efforts are thus under way to develop **pre-treatment processes which produce fewer inhibitors** and fermentation organisms with **greater tolerance to inhibitors**. The BIOCORE project (Biocore, 2015) has successfully demonstrated improved tolerance to formic acid for the production of chemicals from xylose.

The cost of enzymes used in hydrolysis are one of the major cost components in the production of ethanol from lignocellulosic biomass, estimated at around USD 0.1/litre ethanol. **Enzyme costs** have fallen rapidly in

Table 6: Lignocellulosic biomass pre-treatment technologies

Technology	TRL	Advantages	Disadvantages	Opportunities	Notes
Steam explosion	6-8	Cost-effective High glucose yields Lignin and hemicellulose removal Low environmental impact	Catalyst often needed to optimise pre-treatment Formation of inhibitors and toxic compounds	Development of new catalysts Developing micro-organisms more tolerant to inhibitors	Suitable for variety of herbaceous and woody feedstocks
Dilute acid pre-treatment	5-7	Good removal of hemicellulose	Degradation by-products (salts) and inhibitors Corrosion	Developing micro-organisms more tolerant to inhibitors Reducing intensity of pre-treatment New enzyme developments	Particularly suited to low lignin feedstocks
Concentrated acid hydrolysis	4-5	No enzymes needed Good removal of hemicellulose	High chemical use and capex Corrosion and toxic hazard Degradation by-products (salts) and inhibitors	Recovery and reuse of chemicals Developing new catalysts More tolerant micro-organisms	Suitable for variety of feedstocks including municipal solid waste
Auto-catalysis/ hydrothermal	4-6	No chemical use High glucose yields	Higher operating temperature Inhibitor formation		Suitable only for low % lignin
Organosolv treatment	4-6	Causes lignin and hemicellulose hydrolysis	High capital and operating costs Solvent may inhibit cell growth	Recovery and reuse of chemicals Develop methods to add value to lignin	High quality lignin co-product
Alkaline pre-treatment (*e.g.* dilute ammonia, sodium hydroxide, lime)	5-7	Low capital costs Low inhibitor formation High glucose yields	Residue formation Need to recycle chemicals Enzyme adjustment needed	New enzyme development Recovery and reuse of chemicals	Suitable for smaller-scale plants
Ammonia fibre explosion	3-5	No need for small particles Low inhibitor formation High accessible surface area	High cost due to solvent	Recovery and reuse of chemicals	Suitable for smaller decentralised plants Not effective for high % lignin
Supercritical CO_2 pre-treatment	2-4	Increases accessible surface area Low inhibitors or residues	Does not affect lignin and hemicellulose Very high pressure, high capex	Improve process technology Develop methods to add value to lignin	Continuous technology Suitable for smaller-scale plants
Ionic liquids	2-3	Effective dissolution of all Lignocellulose components (see glossary of terms) Low degradation products	Expensive technology and recovery required	Recovery and reuse of chemicals Develop process technology	
Microbial/fungi	3-4	Low energy requirement No corrosion Suitable for lignin and hemicellulose removal	Time-consuming Some saccharide losses	Development of robust micro-organisms	
Mechanical milling	5-6	Reduces cellulose crystallinity No inhibitors or residues	High energy consumption Poor sugar yields	Process integration, combine with mild chemical treatments	

(taken from E4tech, 2015, with reference to Garcia et al., 2014; Harmsen et al., 2010)

recent years because pre-treatment techniques have been optimised, resulting in lower enzyme use, and enzyme production has increased in scale (Bloomberg New Energy Finance, 2013). Enzyme costs will continue to fall as deployment increases and could cost 90% less by 2050 (Carbon Trust, 2011).

Clariant in Germany has developed the sunliquid® process. The company claims it is commercially among the best in class in lignocellulosic technology providers when it comes to total costs per litre of ethanol. It claims to have achieved four types of cost reductions through the different hydrolysis and fermentation process stages, such as chemical-free feedstock pre-treatment and process-integrated enzyme production avoiding formulation or logistics costs. Similarly, costs are reduced through enzyme adaptation to different feedstock and process conditions, and increased yield from the simultaneous fermentation of C5 and C6 sugars in a one-pot reaction. Its pre-commercial plant in Straubing, Germany, has been operating since 2012, producing nearly 1,000 tonnes of ethanol per year via the sunliquid® process (Clariant, 2016).

The **performance of the enzymes** is also critical to pathway performance. Efforts are under way to improve current enzymatic cocktails, and many more improvements could still be made. Enzyme development from a variety of other micro-organisms is another dynamic research area. Specialist enzyme suppliers like Novozymes compete intensely with companies developing cellulosic ethanol plants, some of whom hold in-house intellectual property (IP). The first commercial plants have taken different approaches. Some produce enzymes on site and others buy them in. Experience over the next five years should provide more evidence of the relative cost and operational benefits of this choice.

2.2 Hydrothermal upgrading

Technical barriers and needs

Hydrothermal upgrading is a process for converting biomass with high water content into a more energy-dense oil known as bio-crude. Biomass feedstock with a very high water content is subject to raised pressures

Figure 11: Hydrothermal upgrading pathway

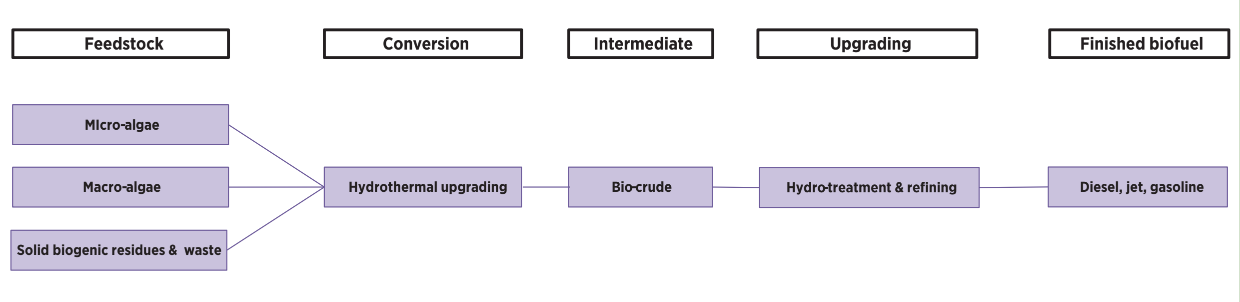


Table 7: Technical barriers and needs relating to the commercialisation of hydrothermal upgrading

Technical barriers	Technical needs
The corrosive nature of the bio-crude intermediate produced by hydrothermal upgrading creates problems in downstream processing.	Demonstration of a consistent and stable intermediate product suitable for downstream processes. Development of downstream processes which can operate with bio-crude.
Handling large quantities of feedstock with high water content at elevated pressures.	Improved feedstock handling technologies (*e.g.* pumping).
High processing or recycling costs for waste water containing significant amounts of organic material.	Minimise loss of organic material to waste water and improve waste-water treatment.

References: Elliot et al. (2015a), VTT (2015) and temperatures to produce a range of products. These include biochar, bio-crude and gaseous products. The bio-crude liquid product may be upgraded to diesel and gasoline fuels via hydro-treatment processes. There is limited activity in hydrothermal upgrading biomass processing worldwide. Changing World Technologies developed a thermal-depolymerisation hydrothermal upgrading process but the status of its plant is currently uncertain. SCF Technologies runs a pilot plant. The most high-profile pilot plant has been developed by Shell in Apeldoorn, Netherlands. However, none of these plants has yet scaled up any further.

Opportunities for improvement

Hydrothermally stable catalysts could improve the yield and quality of the bio-crude produced.

Improvement of **feedstock handling** technologies like pumps and stirrers for feedstock slurries with high water content would improve the reliability of hydrothermal upgrading processes. In particular, a continuous process requires feedstock handling improvements to allow the continuous introduction of biomass slurry into a pressurised reactor vessel (VTT, 2015). The bio-crude chemistry is very specific to the feedstock type. It has thus been suggested that the development of the technology would benefit greatly from testing a wide range of feedstocks and characterising the properties of the resulting bio-crude (Elliot *et al.*, 2015b).

Some researchers are working on hydrothermally stable **catalysts** to improve the yield and quality of the bio-crude produced. Yields could also be improved through better **separation technologies** (Elliot *et al.*, 2015b).

In general, hydrothermal upgrading technology will benefit from efforts to **scale up** the technology, especially for continuous flow processes, which have not been widely operated beyond pilot-scale. This will allow greater understanding of the technologies required to operate the hydrothermal upgrading process at commercial scale, and consequently a greater understanding of the costs of the process.

Further opportunities exist to improve the **upgrading** of bio-crude to a usable fuel oil. This can be achieved through processes such as catalytic hydro-treatment, catalytic hydrothermal gasification or by using bio-crude in an existing oil refinery. This will require a detailed understanding of the chemical composition of the bio-crude, its stability and the consistency in quality and composition achievable through the hydrothermal upgrading process. Improvements in these qualities will help integrate the technology with existing crude oil refineries.

2.3 Fast pyrolysis and upgrading

Technical barriers and needs

Conventional pyrolysis for biochar has a long history whereas fast pyrolysis only emerged in the 1980s. Today, a number of demonstration and early commercial plants are running (*e.g.* Fortum, Ensyn, BTG) producing pyrolysis oil for use in heat and power applications. Much of the focus to date has been on scaling up reactor technologies, improving pyrolysis oil oxidative stability, decreasing solids produced and reducing product moisture content to improve storage and combustion characteristics. Technologies for pyrolysis oil stabilisation are being developed to improve pyrolysis oil quality and the impact on downstream processing. There are several examples, such as the addition of polar solvents and water separation from the liquid phase (Zheng, 2011). Other processes with similar effects include the separation of acetic acid (*e.g.* EMPYRO project) and the removal of unwanted elements by physical separation. This has been developed by Aston University in the UK and NREL.

However, upgrading pyrolysis oil to transport fuels has yet to be demonstrated on a continuous basis, and full integration of fast pyrolysis with upgrading is still required. Many of the upgrading processes are only at the proof of concept stage. The main technical barriers to development of the fast pyrolysis pathway relate to pyrolysis oil production and upgrading as well as their integration. This is shown in Table 8.

Opportunities for improvement

Upgrading innovations could lead to a fuel cost reduction of 10%-30%.

Major opportunities to improve the pyrolysis process relate to the development of fast pyrolysis **processes**

Figure 12: Fast pyrolysis and upgrading pathway

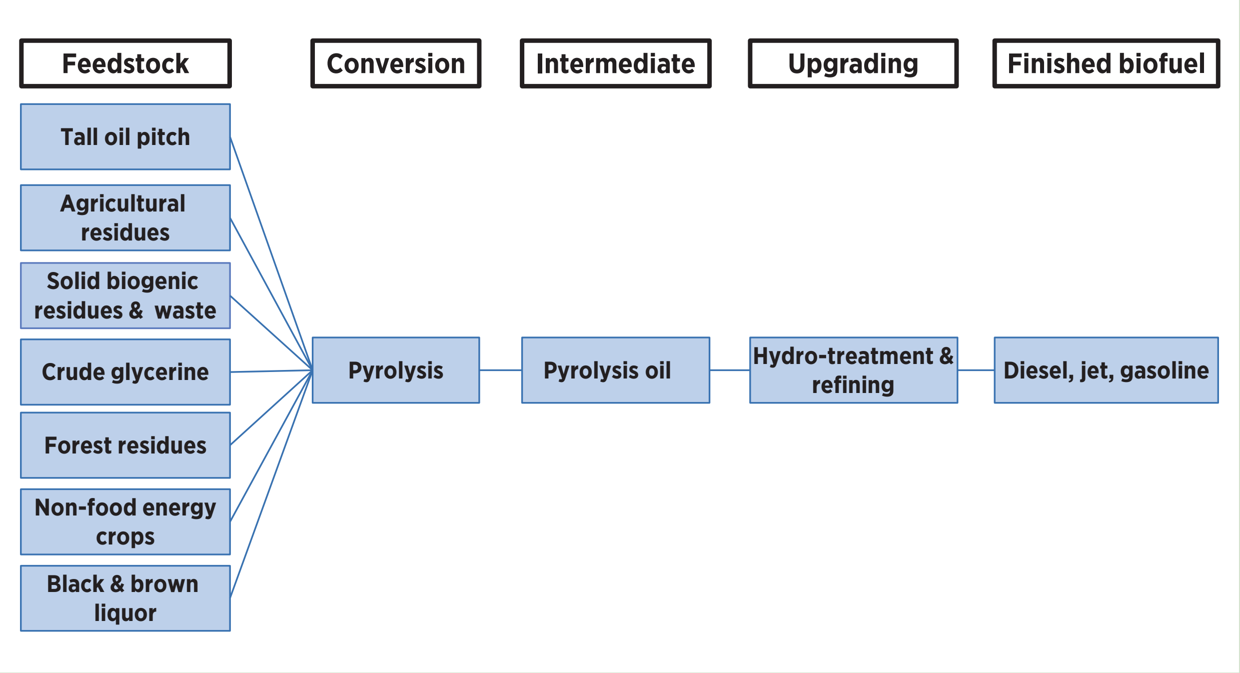


Table 8: Technical barriers and needs relating to the commercialisation of pyrolysis for advanced biofuels

Technical barriers	Technical needs
Pyrolysis produces solid, liquid and gaseous fractions. Only the liquid fraction is converted to liquid transport fuels. Maximising liquid production is therefore necessary to realise the potential yields. The presence of feedstock ash can dramatically lower liquid yields.	Optimised pyrolysis processes with high yields of pyrolysis oils; gas recycling for process energy needs.
The characteristics of pyrolysis oil make storage and downstream processing problematic. Pyrolysis oil is typically unstable and has high acidity, viscosity and water content, and a tendency to polymerise.	Demonstration of a consistent and stable intermediate product suitable for downstream processes.
Catalysts used in the pyrolysis oil upgrade stage are deactivated due to high water and oxygen content of the pyrolysis oil.	Improve the pyrolysis processes to decrease pyrolysis oil water and oxygen content.

References: Biddy, 2013; Karatzos et al., 2014; US DOE, 2015a

to maximise liquid yields, and **catalyst introduction** to promote higher selectivity of desirable alkanes in the bio-oil. VTT Technical Research Centre of Finland, the Pacific Northwest National Laboratory and NREL have all been working on this. There are several areas of catalyst improvements such as deactivation, longer lifetime, better stability and cost. Projects such as the EU CASCATBEL project have already published several technical developments using a cascade of catalytic fast pyrolysis, intermediate deoxygenation and hydro-deoxygenation. However, this needs to be scaled up. Research into catalytic reactor design is also under way.

Catalyst improvements are also a major opportunity in the upgrading step. Hydro-deoxygenation has been shown to be feasible but further development and piloting is required (Prins & Ronsse, 2015). More dedicated research is required to reduce hydrogen consumption during hydro-treatment.

Co-feeding pyrolysis oil in conventional refinery units using existing infrastructure and commercial technologies is another opportunity. This would bring significant cost savings compared to dedicated upgrading units. Pyrolysis oil contains a substantial amount of oxygen, the removal of which is required to reach alkane fuels. In collaboration with Ensyn, Petrobras has demonstrated pyrolysis oil co-cracking (both upgraded and crude) in a fluid catalytic cracking process with promising results (NREL, 2015; Prins & Ronsse, 2015). The Gas Technology Institute is also operating a pilot plant to test a novel catalytic thermochemical process, IH^2. It has licensed the technology to be scaled up by CRI Catalyst Company, owned by Shell (CRI, 2015). US company UOP also has planned pilot upgrading activities.

The majority of **cost reductions** are expected to occur in upgrading, and innovation could ultimately lead to a 10%-30% fuel cost reduction (Low Carbon Innovation Co-ordination Group, 2012).

Autothermal chemical reaction systems

When scaling up fast pyrolysis systems, a key challenge is to efficiently transport thermal energy into the reactor to provide the endothermic enthalpy of pyrolysis. These systems for external heat transfer add substantially to the capital and operating costs of the pyrolysis system. They are also high-maintenance operations prone to erosion and fouling. The concept of autothermal chemical reaction systems is well-known in solid fuel gasification and in steam reforming of gaseous fuels. These reaction systems balance the energy demand of endothermic reactions with energy release from exothermic reactions. However, they strive for chemical equilibrium, ideally yielding carbon monoxide and hydrogen as the final products. Adding oxygen to a pyrolysis reactor would appear counter-productive to the goal of maximising liquid yields. However, research from the Bioeconomy Institute at Iowa State University claimed to have proved that autothermal pyrolysis simplifies and intensifies the pyrolysis process, eliminating heat exchange and ancillary equipment. This would result in a feedstock throughput increase of as much as 500% without degrading product yield or quality.

2.4 Gasification and syngas cleaning

Technical barriers and needs

Gasification is already an established technology for large-scale coal applications in the liquid fuels and power markets. Although a handful of developers already have commercial offerings in the power and heat markets using biomass and wastes (developed since the 1970s), industrial experience with biofuel applications is at a much earlier stage. Very few commercial-scale systems are operational, and the largest of these mainly produce ethanol and methanol using downstream technologies with greater tolerance to contaminants. Alternatively, they use wastes and crude glycerol, low-cost feedstocks which potentially balance high capital and operational costs.

Pressurised production of syngas eliminates the need to compress the syngas before synthesis and reduces downstream equipment size and cost. Several developers now operate at pressure under steam or oxygen, such as Linde, Karlsruhe Institute of Technology, Carbona, EPI/APP, Enerkem, VTT Technical Research Centre of Finland and Uhde. They use plasma gasifiers all typically operating at atmospheric pressure but without air (see Annex A for a detailed description of gasifier designs).

Dual fluidised bed designs began in the early 2000s. Steam replaces air, thereby avoiding syngas nitrogen dilution and increasing hydrogen and methane yields. Liquid biofuel projects have been planned but the gasifier produced by Repotec-CTU, the main developer, has thus far only been used in small power plants and a bio-synthetic natural gas plant in Gothenburg, Sweden. Plasma gasifiers can handle mixed feedstocks, although with high power consumption. Technology developers such as Alter-NRG and Plasco have produced syngas from waste for power generation. Several waste gasifiers are also running in Asia, especially Japan.

Significant progress has been made in dealing with the technical challenge of tars in the syngas, and commercial solutions are now available. Water scrubbing technology is being used at full commercial scale at Enerkem's biofuel plant in Edmonton, Canada. Biodiesel scrubbing is also possible but not practised at commercial scale. However, several other technical challenges still remain, as detailed in Table 9.

Figure 13: Gasification and syngas cleaning pathway

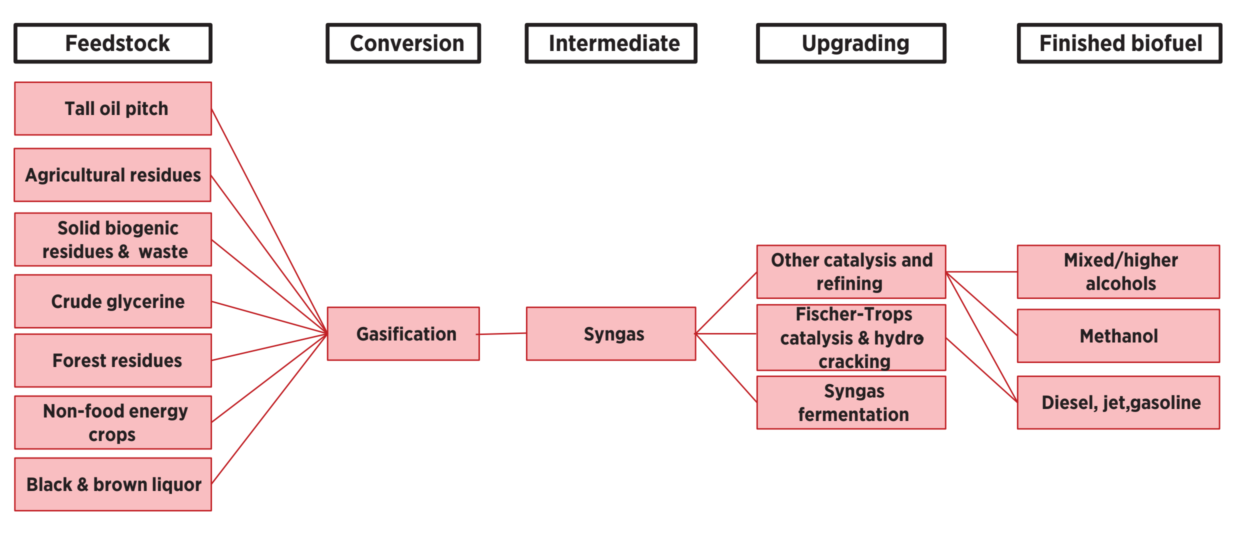


Table 9: Technical barriers and needs relating to the commercialisation of biomass gasification and syngas cleaning

Technical barriers	Technical needs
The more established gasification systems require high quality, homogeneous feedstocks in order to operate reliably and efficiently. Entrained flow gasifiers have strict specifications relating to particle size and moisture. Fluidised bed gasifiers are susceptible to agglomeration of the inert bed material by molten ash (or slagging) which reduces performance and availability.	Robust gasifier performance with industrially relevant biomass feedstocks *i.e.* that meet an achievable specification. Alternatively, use of more flexible gasifier designs able to handle mixed feedstocks, such as plasma gasifiers.
Most downstream processes require a high-quality syngas, and therefore the raw syngas must be cleaned to remove dust, alkali metals, halogens, sulphur, tars and potentially CO_2. This process usually means the crude syngas must be cooled, cleaned in a variety of different steps (such as filtering, reforming, quenching, polishing), and then compressed and heated before final use. These changes in temperature and pressure can impact capital costs and increase energy demand.	Integrated processes optimised for energy efficiency, or the use of syngas clean-up technologies that operate at high temperatures in order to avoid large changes.
Technical challenges facing some systems	**Technical needs**
Some gasifier systems produce high tar levels, which can clog heat transfer equipment and pipes when they condense during cooling processes (fouling). This leads to increased corrosion and erosion, higher maintenance requirements to avoid pipe blockages or reduced performance.	Robust performance of the integrated gasifier and gas cleaning, and correct design to minimise fouling.
Fluidised bed gasifiers produce a relatively high fraction of hydrocarbons (methane, ethylene etc.) This reduces the process conversion yield for some processes and may increase the size of the downstream process units.	Efficient production of high-quality syngas by optimising the gasifier operating conditions.
Some gas cleaning processes (specifically low temperature processes such as water scrubbing) produce significant volumes of contaminated waste water.	Processes optimised to minimise the environmental and economic impacts of effluents, or installation of waste water treatment plants.

References: Atsonios, 2015; Fei Yu, 2012; Griffin, 2012; US DOE, 2012; US DOE, 2015a; van Eijck, 2014; Villanueva, 2011; Wagner, 2013

Opportunities for improvement

Linking energy demands and losses could save up to 15% of current Fischer-Tropsch diesel production costs, mostly in opex savings and higher co-product revenues. High temperature tar cleaning could result in 2%-3% efficiency gains.

Biomass gasification using oxygen and steam oxidants (*i.e.* not using air) started with demonstration activities in the late 1990s. There is thus still work to be done to prove **reliable long-term operation** of the different gasifier types at scale with a variety of feedstocks while meeting the syngas specifications of downstream biofuel applications. Many gasifier developers using pressurised oxygen or steam-blown designs have yet to produce biofuels. The self-modulation work to **optimise gasifier conditions and specific syngas compositions** has thus yet to take place.

The greatest opportunity for efficiency savings comes from **energy integration** within the whole plant. This connects the thermal demands and losses of different steps and generates enough power on site to meet parasitic loads (for compressors, oxygen separation, pumps and fans). Waste heat from syngas cooling and catalysis (*e.g.* Fischer-Tropsch reactors) can be used to raise steam, for onsite electricity generation, drying feedstock or reheating syngas before conversion. This level of process integration produces a very great benefit to the overall energy balance of the plant, improving biomass yields or reducing/removing the need for natural gas or power imports. However, it requires complex control systems for multiple interdependent components (particularly for start-up/shutdown). Given thermal losses, high integration levels typically only make economic sense within large-scale plants; many pilot and demonstration plants have poor levels of thermal integration, concentrating instead on operation and testing. This integration saving is estimated to be worth up to 15% of current production costs for Fischer-Tropsch diesel, mostly in opex savings and higher co-product revenues (Carbon Trust, 2011).

Opportunities for improvement exist in the developing biomass handling systems and gasification systems with **greater feedstock tolerances**. Examples include entrained flow gasifiers with adequate ash removal, and the use of plasma gasification or plasma torches within gasifier systems, as developed by Alter-NRG, for example. In some biomass and waste feedstocks, ash contents can be high, exceeding 10%. This creates downstream fouling and requires enhanced filtering. Above all, it incurs the risk that fluidised beds will cause the bed material to agglomerate, which can reduce efficiency by several percentage points, or even result in plant shutdown for several days. An alternative approach for more difficult feedstocks is to use **pre-treatment technologies** to improve the biomass quality. One example is the integration of fast pyrolysis processes before gasification developed by the Karlsruhe Institute of Technology in the Bioliq project.

Despite previous efforts invested in tar cleaning and success with water scrubbing, tars remain a key problem, and several **higher temperature tar cleaning** options are under development. Small-scale demonstration plants have been set up followed by initiatives to scale them up. Reliable cleaning at high temperatures can avoid thermal energy losses from syngas cooling and reheating. This produces a 2%-3% efficiency gain in the overall chain (Carbon Trust, 2011). Some of the more promising concepts are outlined below:

- **Hot gas clean-up via thermal cracking.** Raw syngas is held above 1200°C-1400°C, breaking aromatics down into smaller syngas molecules without the use of catalysts. CHOREN developed this approach before failing, and Linde took over the IP (Linde Group, 2012).
- **Tar cracking using plasma.** Exposing tars to an electrical arc (and in some cases ultra-violet light) cracks them to syngas, with inorganic fractions in the ashes converted into a vitrified slag. This the approach is followed by APP, Plasco and Europlasma but although the resulting syngas is of high quality, power consumption is significant (Chapman, 2014).
- **Multi-stage oil scrubbing.** Tars are captured by bubbling through oil, which is regenerated using a heat source. The tars are recycled back to the gasifier. This also reduces waste water treatment needs. The Netherlands Energy Research Foundation's OLGA technology using this procedure has already been demonstrated in the power sector.
- **Catalytic tar removal.** Metal-based catalysts or dolomites achieve tar cracking at gasifier temperatures (600°C-800°C), sometimes

requiring part-combustion to drive the reaction. Issues relating to deactivation by sulphur remain. This technology is being tested by Nexterra, Darmstadt Technical University and Lund University (Sundac, 2007).

Similar efficiency savings might be possible from **high temperature sulphur removal** using sorbent-based technologies (*e.g.* National Energy Technology Laboratory, US DOE) or membrane technology (as developed by the Clausthal Institute of Environmental Technology).

2.5 Fermentation to butanol and product upgrading

Technical barriers and needs

Fermentation to butanol is similar to fermentation to ethanol but suffers from additional technical barriers mainly related to product selectivity. Details of the main barriers are in Table 10.

Opportunities for improvement

Innovation in acid recovery of consolidated bioprocessing could result in a 10%-15% yield gain. The costs of enzymes in 2050 could amount to just 10% of the level in 2020.

The pathway for lignocellulosic butanol is similar in many respects to the ethanol method. It will benefit from the development of pre-treatment processes outlined in Table 6 and the reduced cost of enzymatic hydrolysis. In addition, an improved fermentation process is needed **to increase conversion yield and selectivity** for butanol and to **reduce the energy requirement** of the product separation step.

Several innovative approaches are being developed to meet these needs, including the modification of

Figure 14: Fermentation to butanol and product upgrading pathway

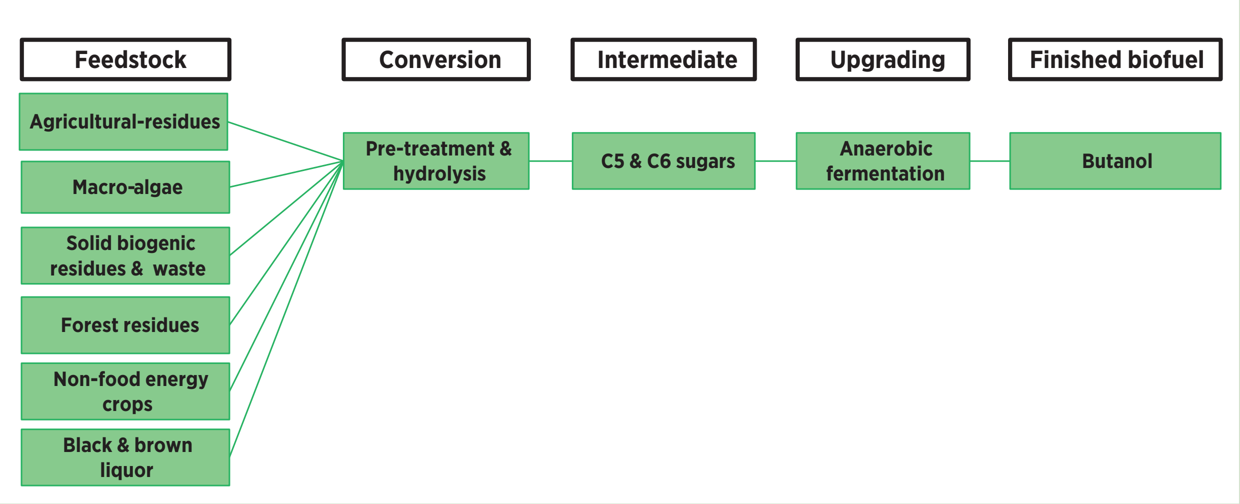


Table 10: Technical barriers and needs relating to the commercialisation of C5 and C6 fermentation to butanol

Technical barriers	Technical needs
The inhibition of fermentation organisms by the fermentation products means the process must take place with high dilution and low product concentration in the fermentation broth. This consumes a large amount of energy in the product separation stage.	Improved fermentation organisms
Acetone and ethanol are produced as co-products limiting the yield of butanol and increasing the complexity of product separation (*e.g.* liquid-liquid extraction), which can be very energy-intensive.	Improved product selectivity and/ or improved separation processes

References: Chen, 2013; Kujawska, 2015; Quereshi, 2013; Raganati, 2012 conventional fermentation organisms to produce butanol as the sole fermentation product. Both yeast and bacteria (specifically *Clostridium*) are being optimised to increase yield and product selectivity.

Butanol fermentation has thus far been optimised for high sugar content feedstocks, which were more expensive as a result. However, some technology developers, such as Celtic Renewables, are also looking at the **conversion of low sugar content substrates** (and therefore lower-cost feedstocks) to butanol.

In addition, much of the recent research has concentrated on the challenges of fermentation to butanol and product purification. This indicates existing challenges and opportunities remain for further research relating to the overall **process integration.** This means combining lignocellulosic feedstock pre-treatment and hydrolysis with the fermentation and purification processes.

Industry is trying to **scale up** the fermentation process with improved bacteria strains and yeast. Green Biologics is testing, validating and optimising its process based on *Clostridium* at pilot scale over the next three years in the ButaNext project. It is also validating and optimising the integration of a method for the *in-situ* removal of butanol and separation using pervaporation (membrane separation) developed by VITO. The **in-situ removal of butanol** aims to improve energy efficiency and reduce product inhibition, resulting in a step change in productivity. Alternative energy efficient thermal separation processes include vapour compression distillation developed by Cobalt Technologies. This fluid separation technology reduces water usage because it may be recycled back into the process.

As for lignocellulosic ethanol, **consolidated bioprocessing** could be the single largest cost saving opportunity for lignocellulosic butanol production. Improvements in acid recovery could have a 10%-15% yield gain with no side products or inhibitors. Enzyme costs in 2050 could be 10% of 2020 enzyme costs. Alternatives to distillation would also make a significant difference to the energy requirements of the process *e.g.* up to 50% compared with vapour compression distillation. Less waste water would also be produced although capex would probably remain similar.

2.6 Fermentation to ethanol and product upgrading

Technical barriers and needs

The fermentation of sugars from agricultural residues for ethanol production has been deployed over the past few years in several early commercial-scale plants. These processes claim to be robust and economically feasible. However, further improvements are likely as they gain operational experience. Technical improvements can be made to improve the economics of the process and the prospects for ethanol production. These are shown in table 11.

Figure 15: Fermentation to ethanol and product upgrading pathway

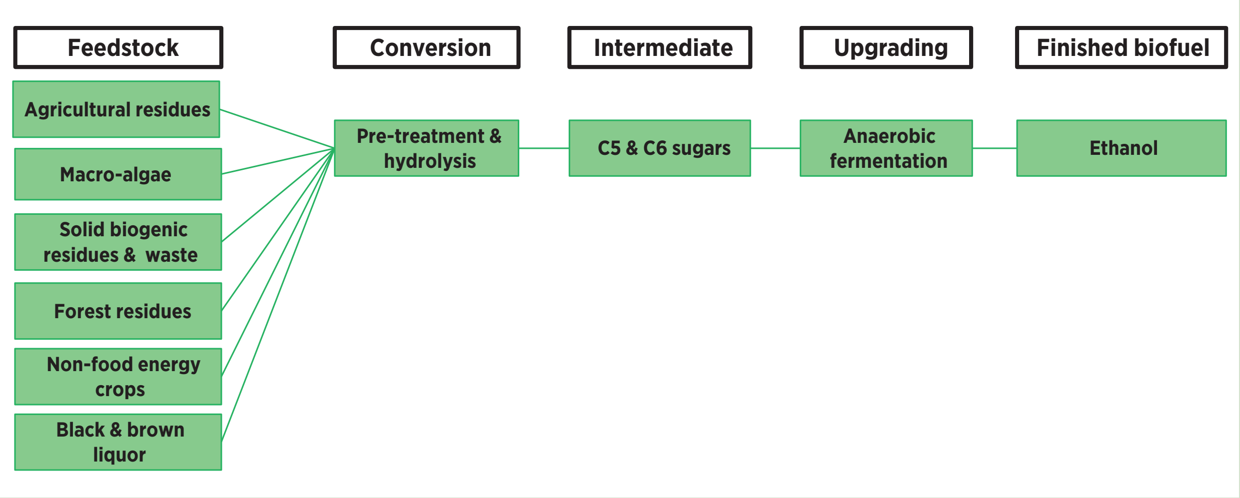


Table 11: Technical barriers and needs relating to the commercialisation of C5 and C6 fermentation to ethanol

Technical challenges	Technical needs
Limited capabilities of C5 and C6 sugar co-fermentation	Fermentation of C5 and C6 sugars for maximum ethanol yields
Energy-intensive ethanol recovery caused by low ethanol concentration	Separation processes which have low energy consumption, or ethanol concentration increase

References: Humbird, 2011; US DOE, 2012; Wagner, 2013

Opportunities for improvement

Advanced separation technologies could save over half the energy used in distillation and produce less waste water. Plant efficiency is expected to increase to 42% by 2030.

As with pre-treatment and hydrolysis, considerable improvements have been achieved in fermentation to ethanol. More are expected over the next few years due to the current first wave of commercial-scale plants. Challenges relating to **operation at scale** will need to be overcome, such as maintaining hygiene within the plant. Companies are taking different approaches to **additional value streams** in the overall process**,** such as biogas and electricity production for export. This may improve plant economics.

Although many biofuel companies claim they have no problem fermenting C5 sugars, the yeast performance affects the yield, rate, capex and cost of ethanol from the process. Continuous development is therefore worthwhile. Work continues on **improving yeasts** by selecting the best host organism, identifying and modifying individual genes to put in the host. There is further potential for improvement by **optimising the yeast and the process conditions** in the plant together.

Opportunities to improve **process integration** between the pre-treatment, enzymatic hydrolysis and fermentation stages include processes where hydrolysis and fermentation occur simultaneously (*e.g.* consolidated bioprocessing). These could reduce costs through lower enzyme use, lower capital costs, reduced processing times and increased conversion efficiency. Consolidated bioprocessing is not yet commercial but an area of ongoing research and development.

There are opportunities to **reduce the energy demand** required for product separation. Distillation is typically used for separating and purifying but is an energy-intensive process. Advanced separation techniques, such as membrane separation/osmosis and induced phase separation (see glossary of terms) are an opportunity to improve the overall fermentation and upgrading process. **Advanced separation technologies** are being developed at laboratory scale and are expected to be more energy efficient and/or selective in the products separated, leading to reduced energy demand and increased process efficiency. However, these techniques still need to be scaled up and demonstrated before they are commercially available solution. These technologies are considered to have the potential to save over half the energy of distillation. They produce less waste water but probably need high capex.

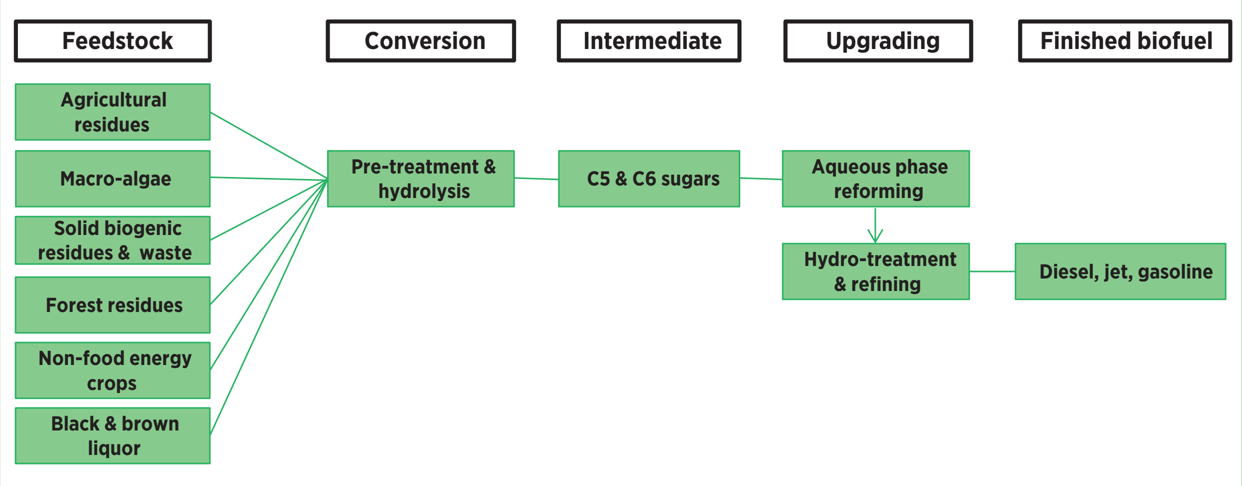
There is still a major opportunity to improve the process integration of the different elements of lignocellulosic ethanol production. Overall plant efficiency is expected to increase from 37% to 42% by 2030 via balance-of-plant optimisation, improved control systems and reduced losses.

2.7 Aqueous phase reforming

Technical barriers and needs

Aqueous phase reforming is a thermochemical catalytic process used to produce alkanes and hydrogen from biomass-derived sugars. It originated at the University of Wisconsin where researchers found a means to react oxygenated compounds and water over catalysts to generate hydrogen (Virent, 2011). Virent has continued to develop this technology, patenting its BioForming™ process – a combination of the original aqueous phase reforming process with traditional upgrading technologies. Much of the development so far has been on corn-based sugars, with limited testing on lignocellulosic feedstocks.

Figure 16: Aqueous phase reforming pathway



The process is currently primarily used for the production of hydrogen, of which light alkanes (primarily methane) are a by-product. However, the reaction conditions, catalyst composition and reactor design may be adjusted to produce higher selectivity of heavier alkanes.

A limited number of organisations are working on the development of aqueous phase reforming. Virent has a pilot plant in Madison, US. Royal Dutch Shell also operates an advanced biofuel pilot plant in Houston, US, to produce drop-in biofuels using licenced Virent technology (Shell, 2012). Other research activities (*e.g.* EU SUSFUELCAT research programme) focus almost exclusively on the production of hydrogen rather than liquid fuels.

Publicly available information on the specific technical barriers to the technology application to liquid transport fuels production from advanced biofuel feedstock is quite limited. The key barriers that have been highlighted at industry conferences are outlined in Table 12.

Opportunities for improvement

Biomass-to-petrol efficiency has the potential to increase to around 55% in future from around 25% now.

The reaction conditions, catalyst composition and reactor design may be adapted to achieve a **higher selectivity** of heavier alkanes. There should be a shift away from microreactors to new reactor designs that can rapidly separate products but can accommodate larger volumes and concentrations of reactants (Chen *et al*., 2015). It may also be possible to **consolidate several of the steps for biomass pre-treatment**, aqueous phase reforming and upgrading into a single process, thereby significantly reducing capital costs.

Table 12: Technical barriers and needs relating to the commercialisation of aqueous phase reforming for advanced biofuels

Technical barriers	Technical needs
Low selectivity to liquid hydrocarbons – current production has large gaseous yields and wide range of aromatics.	Increase selectivity to liquid hydrocarbons
Catalyst lifetime is short due to deactivation and coking.	New or optimised catalysts with longer lifetime at given process conditions
Very limited testing and low yields when using lignocellulosic sugars (C5 sugars) due to less homogeneous feedstock and impurities introduced from the lignocellulosic biomass pre-treatment.	Catalyst adaptation to improve tolerance and conversion of C5 structures

References: Karatzos, 2014; US DOE, 2015a; Virent, 2015

The process has thus far mostly used commercially available catalysts and faces similar catalyst challenges to pyrolysis oil upgrading, including deactivation and coking. Minimal coking through effective **catalyst regeneration** systems is vital to the commercialisation of aqueous phase reforming technology (Karatzos *et al*., 2014). Further areas for novel hydro treating (see glossary of terms) catalyst development or catalyst-based improvements include decreased **deactivation** and therefore increased **lifetime**, better **efficiency** and **stability performance**, and **lower cost**. Virent investor presentations have indicated that efficiencies from sugars to gasoline are 30%-70%. Efficiencies from biomass to gasoline are thus likely to be below 25%, with a potential to increase this to around 55% in the future.

2.8 Mixed alcohol synthesis

Technical barriers and needs

Mixed alcohol synthesis produces a mixture of methanol, ethanol and higher alcohols. Catalyst systems are commercially available, but have not been commercially applied for the conversion of biomass-derived syngas. These catalysts are typically derived from methanol or Fischer-Tropsch catalysts (but with alkali metals added). They thus have very similar syngas requirements, except for the required hydrogen: carbon monoxide ratio of only 1:1.2.

Research activities have predominantly focused on developing catalysts to improve selectivity, although this remains low. NREL and the Pacific Northwest National Laboratory conducted a screening of available and experimental catalysts. Improvements have been made to C_{2+} selectivity but none of the tested catalysts have yet been found to be commercially available. Sulphide catalysts have also been created that actually require some sulphur (50-100 parts per million) in the syngas, rather than needing to be reduced to parts per billion.

Low selectivity and low conversion rates remain the main technical barrier (as shown in Table 13) although most of the technical barriers from Table 13 also apply.

Figure 17: Mixed alcohol synthesis pathway

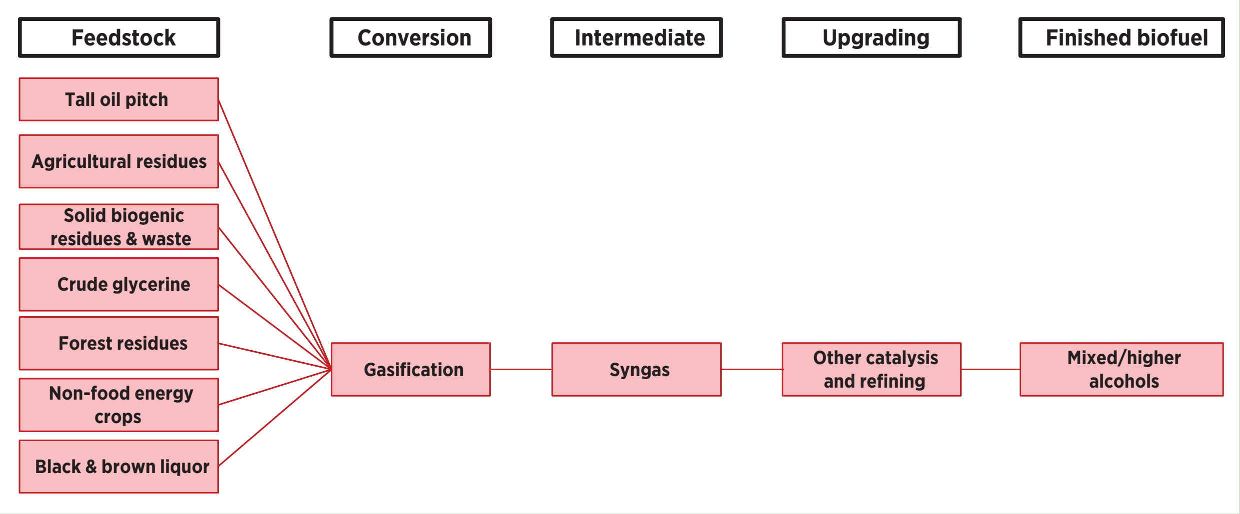
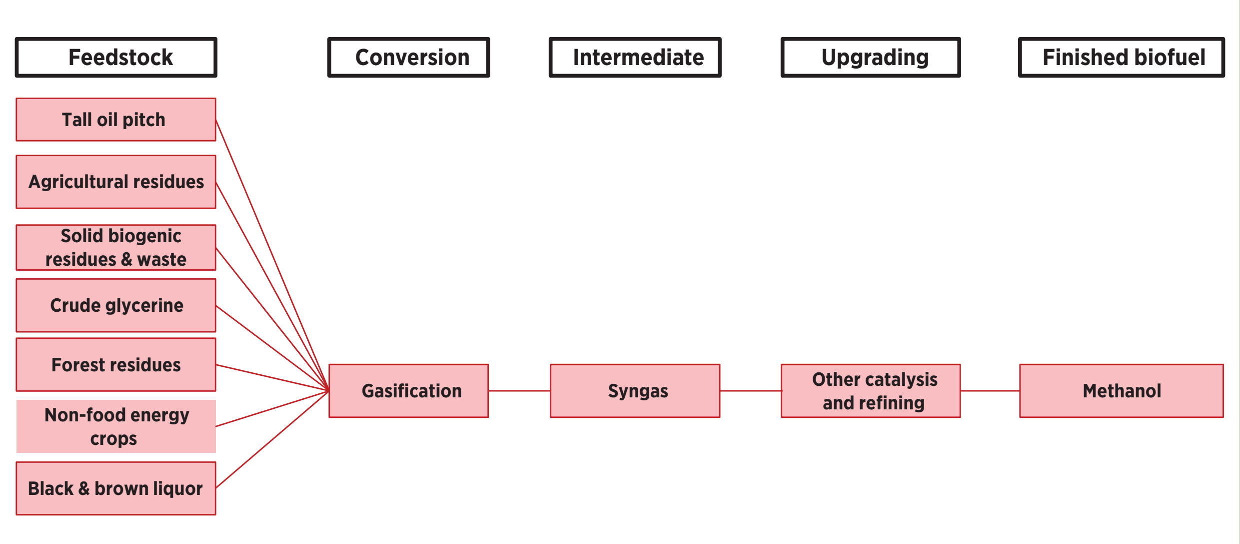


Table 13: Technical barriers and needs relating to the commercialisation of mixed alcohol synthesis for advanced biofuels

Technical barriers	Technical needs
Commercially available catalysts typically achieve low syngas conversion per pass, resulting in the need for recycling and large process systems at greater capital and operational cost. They also have low selectivity towards desired alcohols and operate at high pressure, resulting in a high energy demand.	Improved catalyst performance to increase syngas conversion rates and product selectivity

References: Wagner, 2013; Atsonios, 2013

Figure 18: Methanol synthesis pathway



The main exception is the downstream refining of Fischer-Tropsch waxes, which does not apply here.

Opportunities for improvement

New catalyst materials and structures, as well as upgraded reactor designs, have potential to improve the efficiency and reduce the cost of mixed alcohols synthesis.

The major technical need for the development of the mixed alcohol synthesis pathways is improved catalyst performance. The following approaches are under development to increase syngas conversion rates and product selectivity

- **Use of new materials or combination of materials.** Catalysts such as Alkali/Cu/ZnO(Al_2O_3), Alkali/ZnO/Cr_2O_3, Alkali/CuO/CoO and Alkali/MoS_2[5] have been investigated, and syngas requirements assessed.
- Development of **new catalyst structures and catalyst production methods** focusing on the stability and activity of nano-sized particles. Velocys uses Organic Matric Combustion to produce high metal loadings on terraced surfaces without sacrificing stability or increasing crystal size (Velocys, 2015).
- Development of **new reactor designs** and use of **process intensification**. Micro-channel reactors like those developed by Velocys, for example, could also have a significant role to play in improving the efficiency and cost of mixed alcohols synthesis. However, this has yet to be tested at pilot scale.
- In general, further work is needed to demonstrate the reliable operation of mixed alcohol catalysts and reactor designs with different syngas streams from different biomass and waste feedstocks, particularly at a larger scale. Very little consideration has been given to plant thermal integration to date because no successful demonstration plant has yet been operated.

2.9 Methanol synthesis

Technical barriers and needs

Methanol catalysis has been commercially operated for many decades on natural gas and coal syngas. A few early commercial plants are operating using biomass-derived syngas, such as BioMCN (from glycerine cracking), and Enerkem (from wastes). A number of projects are planned (*e.g.* Woodspirit, Värmlandsmetanol and SunDrop). Current road transport fleets in many regions are limited in their ability to use methanol but it may be catalytically converted to gasoline.

Although the reaction is highly selective, the syngas has to be cleaned of contaminants and condition to meet the

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[5] Details on these catalysts can be found in Annex A.

catalyst specifications. Syngas clean-up requirements are similar to those of Fischer-Tropsch synthesis. For methanol synthesis, 4%-8% CO_2 is typically required to catalyse the reaction. Some of the Fischer-Tropsch barriers from Table 13 relating to sulphur poisoning and catalyst lifetimes also apply, as does the need to avoid alkali metals (to prevent mixed alcohol synthesis).

Opportunities for improvement

Large-scale methanol synthesis performance from new biomass or waste feedstocks could benefit from higher tolerance to contaminants.

Given the selectivity of methanol synthesis, opportunities to improve the process are more limited. Greater **demonstration of contaminant tolerance in large-scale plants** using new biomass or waste feedstocks, for example, will be required to guarantee future performance. **Process intensification** (*e.g* via micro-channel technology) is also possible but has not yet been investigated. However, methanol reactions are already highly exothermic and need careful cooling and thermal integration. The cost savings and efficiency gains it achieves are expected to be significantly lower than for Fischer-Tropsch synthesis. This is because methanol synthesis is around three times cheaper than Fischer-Tropsch + upgrading and more efficient.

2.10 Fischer-Tropsch synthesis

Technical barriers and needs

The process is commercially available for converting natural gas and coal syngas to liquid fuels. Several catalyst companies (*e.g.* Shell, Axens and previously Rentech) and academic research institutions (*e.g.* Newcastle University in the UK, Karlsruhe Institute of Technology in Germany) have worked on developing and optimising on Fischer-Tropsch catalysts. The objective is to deal with biomass-derived syngas compositions and avoid catalyst poisoning, for example. They have developed Fischer-Tropsch catalysts with greater tolerance to sulphur contamination. However, initiatives are also in progress to make the syngas as clean as possible and similar to the syngas produced from coal or natural gas systems to facilitate integration. There are further efforts to realise longer catalyst lifetimes, cheaper catalyst materials and increased yields from specific product ranges.

Demonstration plants have been established to scale down the Fischer-Tropsch process to a size appropriate to a supply chain based on biomass. The micro-channel Fischer-Tropsch developer Velocys has a pilot running on bio-syngas at Güssing and a landfill gas demonstration in Oklahoma City, US.

Figure 19: Fischer-Tropsch synthesis pathway

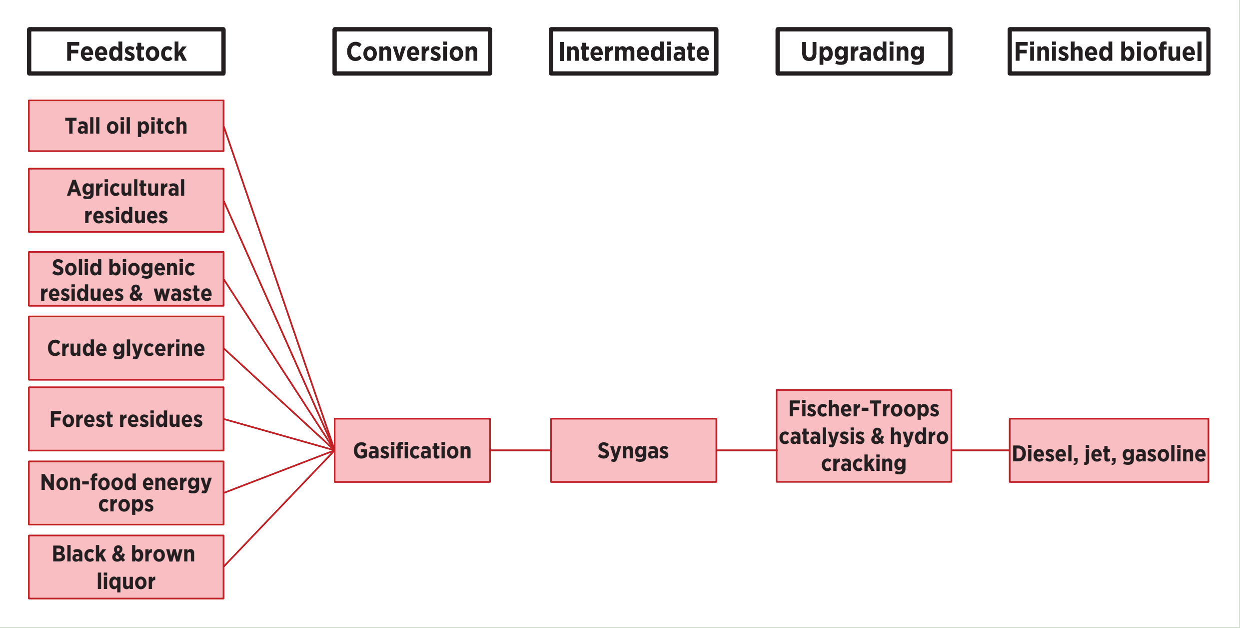

Table 14: Technical barriers and needs relating to the commercialisation of Fischer-Tropsch synthesis for advanced biofuels

Technical barriers	Technical needs
Fischer-Tropsch catalysts are deactivated by sulphur poisoning. Maximum sulphur content (around 10-100 parts per billion) is significantly lower than that typically found in biomass-derived syngas. Technical solutions are available (*e.g.* ZnO guard beds) but there a cost trade-off still exists between high syngas clean-up costs and high catalyst replacement rates.	Robust operation of Fischer-Tropsch catalysts with biomass-derived syngas, minimising the loss of catalyst activity and lifetime through sulphur poisoning; reduction in cost of sulphur removal technology.
Selectivity to required diesel, jet or gasoline fractions are typically limited to less than 40%. Significant amounts of unwanted olefins, alcohols, acids, ketones, water and CO_2 are also produced.	More selective catalysts and more efficient recycling. Alternatively, back-end upgrading steps can be taken to improve selectivity.
Fischer-Tropsch catalysts need a tightly specified carbon monoxide to hydrogen ratio, which can require a water gas reaction after syngas clean-up. This adds to costs and loss of yield because CO_2 is emitted to produce hydrogen.	Optimising gasifier or choice of appropriate oxidant and gasifier reactor type so that the syngas is a closer match to the catalyst demands.
The Fischer-Tropsch reactor design influences the catalyst lifetime and reaction rate. Carbon deposition in fixed bed reactors results in catalyst deactivation. In fluidised bed reactors, catalysts are lost due to entrainment in the gas stream and attrition. The reactor design also affects heat and mass transfer limits.	Improve all Fischer-Tropsch reactor types and develop advanced catalyst and catalyst separation systems.
Fischer-Tropsch catalysts produce a range of hydrocarbon products, including waxes, which must be upgraded and fractionated to end production. This is achieved through hydrogenation, isomerisation, reforming, cracking and distillation. This increases the complexity of the process and therefore capital costs. At the small scale relevant to biomass gasification (compared to fossil), capital costs can be very high.	Fischer-Tropsch synthesis and upgrading processes that are economical at small scale and hence relevant to biomass gasification.

References: Hannula, 2013; Tuna, 2014; US DOE, 2012

The application of this technology for advanced biofuels pathways faces a number of obstacles. This is because the typical scale of operation of biomass gasification is several orders of magnitude less than that of current applications (such as natural gas). At the same time, biomass-derived syngas has a different quality. The main technical barriers are detailed in Table 14.

Opportunities for improvement

In the long term, micro-channel reactors could increase efficiency by 8% and save 10% in capex.

Major barriers affecting Fischer-Tropsch synthesis still remain when using syngas from biomass and wastes. Developers need to demonstrate that their gasification plant can operate reliably with industrially relevant biomass and waste feedstocks. They need to show that it will still always meet the syngas specification of the catalytic process even with variable truckloads of feedstock. Performance guarantees of this type are not yet available.

There is also a need to improve the economics of the Fischer-Tropsch catalyst and upgrading process. **Process intensification** using advanced reactor designs and customised catalysts is a major opportunity in this area. **Modular micro-channel reactors** are the main solution being pursued to achieve very high heat transfer rates and improved reaction times. Smaller units also reduce capex, plant footprint and utility usage. This could enable Fischer-Tropsch reactors to be viable at a scale where cheap biomass feedstock can be found locally. Larger plants based on biomass typically have to pay more for their feedstock due to increased transport distances. The leading proponent of small-scale Fischer-Tropsch is Velocys. However, other fossil fuel Fischer-Tropsch developers are also developing solutions at an earlier stage, such as CompactGTL. These novel approaches may also be employed to target a certain product range or develop catalyst systems that achieve synthesis and cracking in one reactor vessel. This avoids long chain hydrocarbon (wax) formation and the need for another reactor vessel. The micro-channel reactor approach could improve efficiency by 8% over the long-term, and provide an additional 10% savings in plant capex from smaller equipment (Carbon Trust, 2011).

Co-processing Fischer-Tropsch waxes at existing crude oil refineries (*e.g.* as developed at the company OMV) is another potential innovation opportunity. This achieves greater economies of scale and efficiencies than can be found at small-scale facilities. However, extremely limited volumes of Fischer-Tropsch waxes from biomass are available so the extent of tests conducted so far is unclear. This opportunity also depends on logistics, locations and the availability and willingness of existing refineries to co-process. Plant capex savings could amount to 15% but use of third-party equipment would probably come with additional costs.

2.11 Syngas fermentation

Technical barriers and needs

Micro-organisms can ferment syngas to produce ethanol, butanol and a range of chemical products. Ethanol is the subject of the current demonstration projects. This is a relatively new technology developed by a limited number of developers – each from different backgrounds. Much of the work so far has concentrated on setting up the new reactor technologies, maintaining stable microbial populations and selecting desirable traits/blocking out particular metabolic pathways to improve ethanol selectivity.

Thus far, Lanzatech has been working on steel mill waste gas conversion, with demonstration activities in China. Ineos Bio has constructed its first commercial plant in Florida gasifying palm fronds and municipal solid waste. Inhibition of the fermentation organisms by hydrogen cyanide is one the technical challenges it has encountered. This has been dealt with by installing syngas scrubbing technology.

Tars or hydrocarbons inhibit fermentation and adversely affect cell growth so there is a need to clean to Fischer-Tropsch catalyst levels. However, many other syngas requirements are not as strict, and wet gas scrubbing is not required. Details of the technical barriers are displayed in Table 15.

Opportunities for improvement

Modifying fermentation bacteria to increase their tolerance to operating conditions could improve yields and reduce product inhibition.

The literature indicates that the major route to better pathway performance is by modifying (through

Figure 20: Syngas fermentation pathway

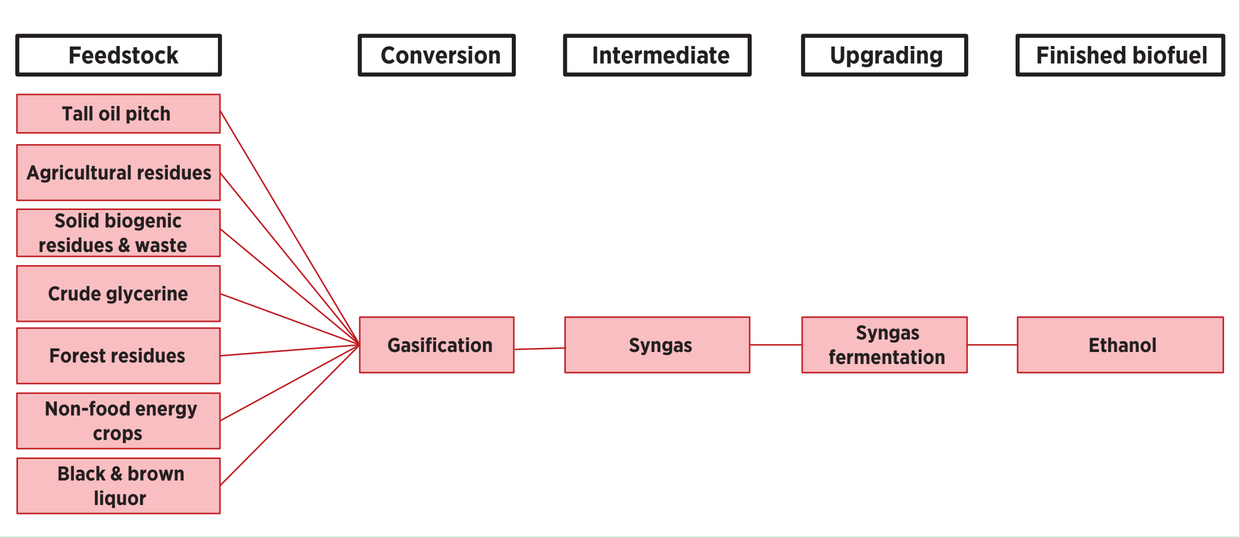

Table 15: Technical barriers and needs relating to the commercialisation of syngas fermentation for advanced biofuels

Technical barriers	Technical needs
To inhibit fermentation organisms through fermentation products, the process must take place at a high dilution, and the concentration of product in the fermentation broth has to be low. This consumes a great deal of energy at the product separation stage (typically distillation).	Reduce the energy demand and thus cost associated with product separation or alternatively genetically engineer or breed more tolerant strains.
Current technology has low gas to liquid mass transfer resulting in low volume specific conversion. This creates a need for large system components (*e.g.* reactor vessels), which raises capital and operational costs in pumping liquids and bubbling gases.	Improved reactors of smaller volumes, improved gas-microbe contact and higher conversion rates.
Syngas fermentation can be disrupted by system contamination from other bacteria, affecting yields and product selectivity. Trace species in the syngas can also cause population loss.	Resilient bacterial strains and reactor systems with reduced susceptibility to contamination; improve removal of particular trace species.
Acetic acid is produced as a by-product, reducing ethanol yields.	Genetically engineer or breed more selective bacteria strains.
High consumption of water, phosphates and nitrates.	Resource recycling via the development of closed water and nutrient cycles.

References: Daniell, 2012; Griffin, 2012; Wagner, 2013

genetic modification or other means) the **fermentation bacteria.** The aim is to improve yields, reduce product inhibition and make them more tolerant to operating conditions uninhabitable to other bacteria strains. This improves operational reliability. Future performance guarantees will require more demonstrations of contaminant tolerance at scale by using new biomass or waste feedstocks, for instance.

Reactor design still needs to be optimised to improve pass-through rates and downsize equipment, as well as integrate energy from using unreacted off-gases when producing heat and power for the plant. As with lignocellulosic ethanol fermentation, new ethanol separation technologies (such as membranes) will also reduce the capital costs.

2.12 Methanol to gasoline conversion

Technical barriers and needs

The methanol to gasoline process was developed by Mobil in the 1970s using DME with high selectivity to gasoline fractions. There have been a handful of pilots and one large fossil commercial plant, and new interest has emerged from the coal methanol sector (Haldor Topsøe's TIGAS design). Sundrop Fuels has piloted methanol to gasoline since 2009 and runs a process demonstration facility at North Dakota's Energy and Environmental Research Centre. It has plans to start up a commercial-scale plant in 2020. The main technical barriers related to the final steps are detailed in Table 16.

Figure 21: MTG conversion pathway

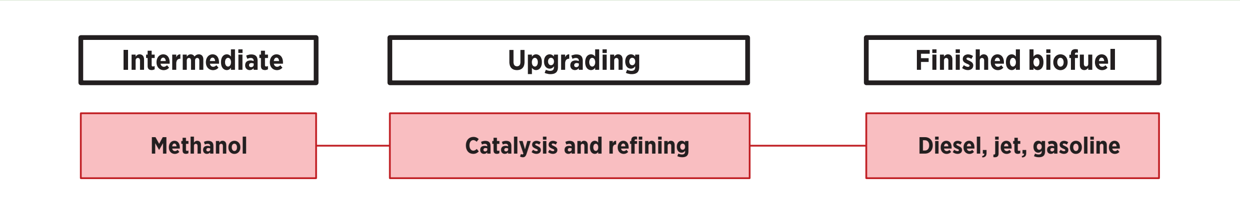

Table 16: Technical barriers and needs relating to the commercialisation of MTG processes for advanced biofuels

Technical barriers	Technical needs
Zeolite catalyst deactivation for converting DME to gasoline by carbon deposition in fixed bed applications. This results in the need for batchwise catalyst regeneration using oxygen and a high number of maintenance intervals.	Resilient catalyst systems.
MTG is conventionally a complex, and sometimescostly, four-step process.	The effective integration of the four conversion processes must be demonstrated together to reduce process costs.

References: Hannula, 2013; Philips, 2011

Opportunities for improvement

MTG conversion will benefit from a more integrated process with less intermediate storage and heat exchanges, and fewer steps involved.

The major technical opportunities for developing the MTG pathway are the creation of robust, easily available **DME to gasoline catalysts**, **process integration** and a **reduction in the number of steps** involved. Current research includes:

- New fluidised bed reactor concepts with integrated catalyst regeneration (University of Akron, US);
- Combining the methanol and DME process steps in one reactor (*e.g.* Chemrec previously piloted Haldor Topsøe catalysts for directly producing bioDME);
- Methanol, DME and gasoline step integration into a single-loop process. This would improve yields and reduce intermediate storage, heat exchanger and compression equipment (*e.g.* Primus Green Energy).

2.13 Micro-algae cultivation, harvesting and oil extraction

Technical barriers and needs

To produce advanced biofuels from micro-algae, the main technical barrier is the economic production of suitable algae oils. This includes micro-algae cultivation and oil harvesting and extraction. Following this extraction, established conversion technologies (such as transesterification and hydro-treatment) may be used to produce biofuels for transport. Table 17 thus details the main technical barriers associated with micro-algae production.

Figure 22: Micro-algae cultivation, harvesting and oil extraction pathway

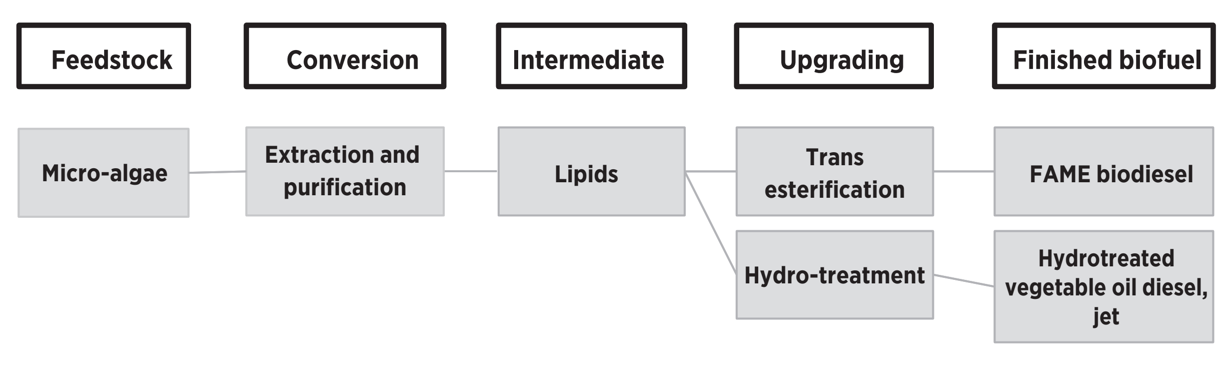

Table 17: Technical barriers and needs relating to the production of algae oil for advanced biofuels production

Technical barriers	Technical needs
Capital intensity of production is high. It is essential to reduce the capital cost of a few main components such as pond liners, paddle wheels, photobioreactors, recovery and extraction technology.	Identify and scale up demonstration projects showing the most cost-effective and efficient micro-algae production systems capable of producing algal oils at competitive feedstock prices.
Open cultivation systems for micro-algae production are susceptible to contamination from external sources and to the presence of grazers, which damages productivity.	Improve resilience of strains. Understand the conditions under which grazers do not reproduce (*e.g.* particular temperature ranges) and locate the facility accordingly.
High lipid productivity at a commercial scale is difficult.	Scale up the cultivation of micro-algae species with high lipid content.
Harvesting, concentrating and dewatering algae incurs high energy costs (and associated GHG impacts).	Develop fractionation or alternative technology to separate lipids, carbohydrates and proteins efficiently and to produce value-adding co-products with minimal energy requirements.

References: Lee, 2014; Pienkos, 2009; Scott, 2010; US DOE, 2015a; US DOE, 2012

Opportunities for improvement

Biofuel production from micro-algae is a vast research field. It provides plenty of opportunities to increase the efficiency of solar energy conversion into organic energy and reduce the production cost.

Key opportunities to meet these needs include:

Further **algae species screening** and modification (genetic and otherwise) of known algae species to achieve the characteristics desired.

- Minimising the need for expensive photobioreactors by developing algal strains that do not need to be kept inside the photobioreactors for a great length of time.
- The development of **cheap and effective pond liners** to cover open ponds. This could be achieved, for example, by researching low-cost but durable materials that withstand the conditions of the open ponds for long periods of time (*i.e.* ideally the lifetime of the plant).
- **Optimisation of paddle wheel designs** (*e.g.* number, size, position) or low-cost alternative mixing techniques to ensure minimum cost for desired functionality.
- Further **research on the metabolic pathways** linking nitrogen deficiency, fertiliser input, lipid content and productivity, and manipulating them to optimise lipid content and productivity.
- Advanced **energy efficient separation technology** as an alternative to centrifuges which can be expensive. Alternatives include using an electromagnetic field (OriginOil's approach) or extracting solvents.

Very little progress has been made in the last ten years in commercialising biofuels based on algal oil despite the proliferation of algae companies that have taken this on. The efficiency of converting solar energy into organic energy remains low regardless of concerted efforts by academics and companies. Cost of production remains significantly higher than that of other advanced biofuels discussed in this report.

Some progress has been made in hydrothermal liquefaction routes, which to some extent overcomes oil extraction problems since the entire biomass is processed and there is no need to dewater. However, this is not a mature technology, and catalyst performance and efficiency needs to improve. Other considerations include the quality of the product and disposal of the waste water stream. This option too still requires significant investigation.

Options for policy-makers

Enormous progress has been made in the production of ethanol from lignocellulosic biomass hydrolysis and fermentation in the last decade. **Continued innovation in the pre-treatment and hydrolysis steps is required to reduce production costs.** This includes integrating both steps to reduce enzyme loading, for example. Continued improvements in the pre-treatment and hydrolysis processes are the key that will unlock low-cost cellulosic sugars. Several biofuel pathways will benefit from this.

Butanol can be produced from cellulosic sugars and will benefit from advances in biomass pre-treatment and hydrolysis processes. In addition, improvements in the selectivity of the butanol fermentation and/or product separation process are required. This may be achieved by modifying the fermentation organisms and/or by using membrane separation technology, especially through *in-situ* product separation.

Cellulosic sugars can also be converted to longer hydrocarbon chain fuels via aqueous phase reforming. This process will again benefit from advances in biomass pre-treatment and hydrolysis but there is very limited experience in converting cellulosic sugars to hydrocarbons. The specific research needs are therefore not well documented.

Fuels from biomass pyrolysis are in principle attractive. This is due to the potentially achievable relatively high efficiency and low processing costs, and the possibility of decentralising production of pyrolysis oil that could be upgraded at bigger sites or conventional refineries. Scientists need to improve the resilience of pyrolysis oil production of sufficient quality for downstream catalysts, and produce reliable and effective catalytic upgrading processes.

Biomass gasification still needs to prove that plants can operate reliably for a long time by tolerating feedstock contaminants, for example. Process optimisation is needed to achieve target syngas compositions.

It needs to be proved that Fischer-Tropsch processes can operate at an appropriate scale. There is a great deal of interest in innovative technologies such as micro-channels to achieve this goal. The potential for upgrading Fischer-Tropsch waxes in conventional refineries has received less attention but merits further consideration.

Significant advances have been made towards demonstrating the production of alcohols from syngas (methanol and ethanol). Additional process improvements may be realised through improved tolerance to contaminants present in syngas.

Syngas fermentation is available today at demonstration scale. The main opportunities for process improvements are in modifying fermentation organisms to improve contaminant tolerance and selectivity, and increase yields.

Significant improvements in all advanced biofuel pathways will arise from process integration. For pathways based on gasification and pyrolysis, this will include energy integration. For processes based on fermentation, this may take many forms. Consolidated bioprocessing is one example.

3 NON-TECHNICAL BARRIERS, NEEDS AND OPPORTUNITIES

The advanced biofuels pathways discussed in previous chapters are also face significant non-technical barriers to commercial deployment. They incur high costs because they are at an early stage of development and deployment. There are barriers to market access for certain advanced biofuel products and requirements on environmental and social impacts and policy support are uncertain.

3.1 High production costs compared to fossil fuels and conventional biofuels

Advanced biofuels production tends to be more costly than fossil fuels and conventional biofuels. The market for advanced biofuels is therefore based on policy mechanisms such as mandates.

The price differential between advanced biofuels and fossil fuels is higher now that oil prices are low. This is exacerbated by fossil fuel energy subsidies in many countries amounting to around 6.5% of global gross domestic product (International Monetary Fund, 2015), which creates additional price disparity. Stable, long-term policies are needed in the face of these insecurities to provide certainty over advanced biofuels demand and product value. If oil prices stay low for a long time, the market for advanced biofuels will remain dependent on policy frameworks and mandates. However, the cost of meeting advanced biofuel mandates could increase and the appetite of governments around the world to continue to support advanced biofuels may decline. This depends on the other options available to meet their decarbonisation targets, and the relative cost of these options. No policy exists in the EU to incentivise the use of biofuels after 2020. It is unclear whether one will be introduced. Furthermore, mechanisms up until 2020 to incentivise the use of advanced biofuels (such as allowing them to count multiple times toward national targets) have not been effective in generating investment. This is due to uncertainty in the economic value. Policy uncertainty has also affected the US. Its Environmental Protection Agency announced a three-year biofuel volume target (part of the Renewable Fuel Standard) pegged to the 2016 target and only slightly exceeding current production levels. Clear, consistent and stable policy frameworks are needed resulting in bankable incentives leading to sufficient financial reward with reasonable certainty. This to stimulate demand for advanced biofuels and provide investors with the confidence needed to support technology development and deployment. Policies need to avoid excessive costs to consumers or certain industry players.

Supply chain development is not only about supporting the end-products or their conversion technologies. It is also about supporting the range of activities along the value chain. Policy should thus consider how it incentivises and mitigates the risks of players along the entire value chain. Beside fuel production, this includes biomass production in agriculture and forestry, fuel distribution and vehicle end-use. Feedstock accessibility and costs can make a major contribution to overall advanced biofuels costs, especially where dedicated energy crops or algae are used as feedstocks.

3.2 Finance availability and supply chain risk

There are considerable financial barriers to advanced biofuels development and deployment. Access to project finance is perhaps the most significant of these. In general, capital has become more scarce, and project finance and early stage capital providers have become more risk-averse since the 2008-2009 financial crisis. This particularly affects high capital projects. High capital investment requirements combined with risks experienced during the emergence of advanced biofuels restrict access to project finance. This makes a particular impact on high capital pathways such as systems based on gasification. Furthermore, financial barriers are exacerbated by the higher cost of capital and country risk factors in some developing economies.

The availability of funding, including from the public sector, is critical to providing an acceptable balance of risk. Major public support programmes exist for advanced biofuels such as the US DOE's Biomass Program, the EU 7th Framework Programme, NER 300 and Horizon 2020. However, public support mechanisms must extend across the development spectrum – from research and development funding to support for scale-up through to early commercial facilities. They also need to be available to start-ups and SMEs.

Supply chain risk mainly associated with feedstock security and price can be a major obstacle affecting finance availability. Robust feedstock supply business models and partnerships can help address or mitigate such risk.

3.3 Development of bio-based chemicals and biorefineries

The chemicals industry is not subject to mandates for the use of renewable or bio-based feedstocks, and there are few market-based policy mechanisms around the world to accelerate demand for bio-based chemical and material products. However, production capacity is growing and significant investment is being made in research, development and demonstration of new products and processes. This is under way, for example, within the US Biorefinery Assistance Program and Horizon 2020 in Europe.

This results in an additional demand for feedstock in the advanced biofuels industry, which could compete locally. However, it also represents an opportunity for biofuel producers to diversify product ranges and end markets. Biorefineries, which integrate materials, chemicals, fuels and energy production from biomass, present an opportunity to maximise the value derived from biomass resources. It could reduce market-based risks by supplying into more than one market. One of the potential benefits of integrating the production of biofuels and higher-value materials or chemicals is the opportunity to improve process economics. This is because fuel production can achieve greater economies of scale than speciality chemicals while low volume, high value co-products increase revenues. However, non-fuel applications can offer a higher value market for the products made by developers of new technologies, especially when the novel or improved properties of new products can be monetised. Several technology companies have decided to direct their efforts at supplying high-value (non-fuel) markets because the financial returns are more attractive. The resulting technology development could in the long term also benefit the supply of advanced biofuels provided the right market conditions are in place.

3.4 Uncertainty about environmental performance requirements

Advanced biofuels feedstocks are generally perceived as less risky than conventional feedstocks in terms of environmental and social impacts. This especially true for waste and residues but advanced feedstocks may result in a number of environmental impacts outlined below.

- Land use change: dedicated energy crops or tree plantations could be established on valuable land used for agriculture or conservation. Displacement of other land use can also create indirect land use change
- Biodiversity/ecosystem services: unsustainably managed tree plantations may lead to a decrease in biodiversity and ecosystem services. Several energy crops also have invasive traits, which could represent a threat for local species and ecosystems.
- Water/soil: the removal of agricultural and forestry residues from the soil can make a negative impact on soli carbon and structure. Understanding local soil conditions and sustainable removal rates is therefore essential. Certain tree species used for short rotation forestry/coppices are known to consume large amounts of water, which would not be appropriate in regions where water is scarce.
- GHG savings: climate change benefits arising from advanced biofuels could be offset by poor management practices (*e.g.* forest harvesting) or energy-intensive transformation processes. However, estimates generally predict that advanced biofuels will create high GHG savings, as illustrated in Chapter 4.

Most of the above environmental impacts could be resolved by individual companies on a project basis.

Sustainability criteria are developed by voluntary initiatives such as the Roundtable on Sustainable Biomaterials, International Sustainability and Carbon Certification System, Global Bioenergy Partnership and International Organisation for Standardisation. However, compliance with such criteria usually immediately increases operational costs. These additional operational costs are expected to be offset by a number of economic benefits. These include additional market share, improved management techniques leading to better productivity and yields, and a decrease in legal expenses due to environmental penalties or social unrest.

Under Europe's Renewable Energy Directive, biofuels must demonstrate compliance with environmental sustainability criteria. Advanced biofuels are defined as those produced from feedstocks in the Annex IX of the Renewable Energy Directive and must also comply with the sustainability criteria. However, this is somewhat simplified for wastes and residues other than agricultural, fisheries and forestry residues. Compliance with the EU sustainability criteria may be demonstrated through third-party certification by voluntary schemes. These include the Roundtable on Sustainable Biomaterials, International Sustainability and Carbon Certification System and several others.[6] Certification is usually a significant undertaking requiring detailed data and evidence throughout the supply chain.

The importance of compliance with sustainability criteria and standards is indisputable. However, these requirements include the need for supporting evidence, audits and verification. This could represent a market entry barrier along with the associated costs.

The different approaches to sustainability taken by governments globally and the development of differing sustainability criteria by voluntary schemes (Worldwide Fund for Nature, 2013; International Union for Conservation of Nature 2013; Natural Resources Defense Council, 2014) may lead to inconsistent results in addressing environmental and social impacts, reduced trust from the public, and ultimately market fragmentation. The burden associated with sustainability certification may also penalise smaller market players, especially those from developing regions. However, certain voluntary schemes have developed specific certification protocols for smallholders (*e.g.* Round Table for Sustainable Palm Oil, Roundtable on Sustainable Biomaterials).

Sustainability criteria have emerged to address a broad range of environmental concerns. However, discussions are still in progress on how to address 'indirect land use change,' the 'carbon debt' that may result from forest biomass use and how these can be included in policy. The lack of robust methodologies to assess these impacts, and uncertainty on the appropriate policy and sustainability standards, may affect the prospects of some feedstocks, especially energy crops and forest biomass. These questions create a barrier to market access, testing the willingness of project developers and investors to consider such feedstocks.

3.5 Perceptions and uncertainty about social impacts

As with environmental impacts, social concerns about advanced biofuels may mirror those relating to conventional biofuels. Examples include human rights concerns (such as land grabbing, involuntary resettlement and reduced access to resources) and food insecurity. This is especially true in developing countries.

However, social impacts are not currently included in EU sustainability requirements, unlike certain environmental aspects. This has prompted criticism about the origin of certain feedstocks. Voluntary standards such as the Round Table for Sustainable Palm Oil, Roundtable on Sustainable Biomaterials and Bonsucro include social criteria as part of the compulsory compliance process for certification.

Significant feedstock potential exists for sustainable advanced biofuels deployment in developing countries. However, many operators lack access to the same levels of funding, knowledge and research, facilities and skills as more developed countries, and this is a key social barrier. It leaves them unable to productively participate in the value chain. International collaboration and knowledge transfer are therefore important, and best practice should be shared. Supportive regulatory and policy frameworks in developing countries also supports capacity building.

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[6] A full list of voluntary schemes recognised by the EU is available at *http://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/voluntary-schemes*

Biofuel development has been the target of considerable negative attention throughout the media and in public debates on food security, land use change, cost to the consumer etc. The debate is often very emotive and subject to a complex and still developing evidence base. In some cases advanced biofuels are not distinguished from conventional biofuels, and this may damage perceptions of advanced biofuels.

Policy has an important role to play in providing a framework with guarantees on the environmental and social sustainability of biofuels. The basis for this is the potential risk they may bring with them but the onus is on industry to demonstrate its sustainability.

3.6 Development of infrastructure and logistics

The infrastructure barriers to advanced biofuels deployment vary according to the particular pathway and differ by region. In general, advanced biofuels commercial production requires reliable access to suitable feedstocks. For some feedstocks this requires the development of new and possibly complex collection, storage and transport systems and may include new or specialised equipment.

Access to specialised equipment and the skills required for operation and maintenance may create a significant barrier to entry, especially in developing countries. Further logistical barriers may be raised by the absence of public infrastructure, such as suitable roads and ports where required. Large companies often have access to capital and resources for the creation and maintenance of transport routes. By contrast, smallholders have to rely on already existing infrastructure for the movement of their products (UN Food and Agricultural Organisation, 2015).

For some advanced biofuels, downstream infrastructure such as blending and storage terminals, dedicated distribution pipelines, fuel stations and vehicles raises a critical barrier against the deployment of advanced biofuels. Besides stimulating demand and mitigating financial risks, policy could resolve other barriers to market access. For example, it could inform consumers and support the development of required fuel standards and infrastructure needed to distribute and use fuels.

Options for policy makers

The pre-commercial nature of all advanced biofuels means **stable and long-term policy frameworks are needed** to stimulate demand and make projects bankable. Current policy frameworks in all leading markets have been criticised for failing to provide certainty about market size through reduced targets. For example, in the EU, Italy is the first member state to introduce a mandated advanced biofuels target for 2022. However, it is not yet possible to see the impact on production capacity.

Long-term policy frameworks can also facilitate the development of the required infrastructure and rollout of additional regulation where necessary to ensure that advanced biofuels can gain **market access.** This may benefit a range of fuels, including ethanol and methanol, the uptake of which is restricted by fuel blending limits in some markets. Aviation biofuels may also benefit. In some markets, their distribution within the existing pipeline infrastructure is limited.

Policy frameworks should consider the long-term energy needs. Current advanced biofuels policy is directed at road transport and has been successful in supporting the production of alcohols such as ethanol and methanol. However, the production of diesel and jet fuels is not progressing at the same rate.

Advanced biofuels do not come without environmental and social risks. **Understanding and mitigating these risks is critical to the long-term prospects of the industry,** particularly the use of energy crops and forestry residues. Robust sustainability standards and certification systems are required, as is clear and transparent communication of advanced biofuels sustainability.

(continued on next page)

Public sector finance is needed across all technology innovation stages and all advanced biofuels pathways to complement private sector investment. Support across the whole innovation spectrum is needed to take technologies to market and provide technology developers and investors with a route to commercialisation. The US has a strong history of supporting advanced biofuels development. This includes the USDA 9003 Biorefinery Assistance Program and the Biorefinery, Renewable Chemical and Biobased Product Manufacture Assistance Program. This provided loan guarantees for commercial-scale biorefinery construction, development and retrofit. Programmes for earlier innovation stages (pilot and demonstration) have also targeted specific fuels and feedstocks. Examples include the Innovative Pilot and Demonstration Scale Production of Advanced Biofuels (DE-FOA-0000739), which targeted fuels for aviation, and the Advancements in Sustainable Algal Production Funding Opportunity (DE-FOA-0000615).

Public-private partnerships and international co-operation could help distribute risks and benefits. Funding must be based on a robust private and public sector business case and on business models that create opportunities and mitigate risks across the pathway from feedstock production to fuel use.

Technology developers also have a role to play in overcoming the non-technical barriers to development. They **need innovative business models that reduce the risk** and/or provide early revenue streams to support technology and market development. There are some examples, such as companies that have targeted high value and low volume markets as the first application. Another example is the development of processes to use waste feedstocks, which provide an additional and often significant revenue stream. A third example is targets for existing biofuel producers with technology options specifically aimed at retrofit or co-location with existing production plants.

4 POTENTIAL EVOLUTION OF ADVANCED BIOFUELS PATHWAYS OVER THE NEXT THREE DECADES

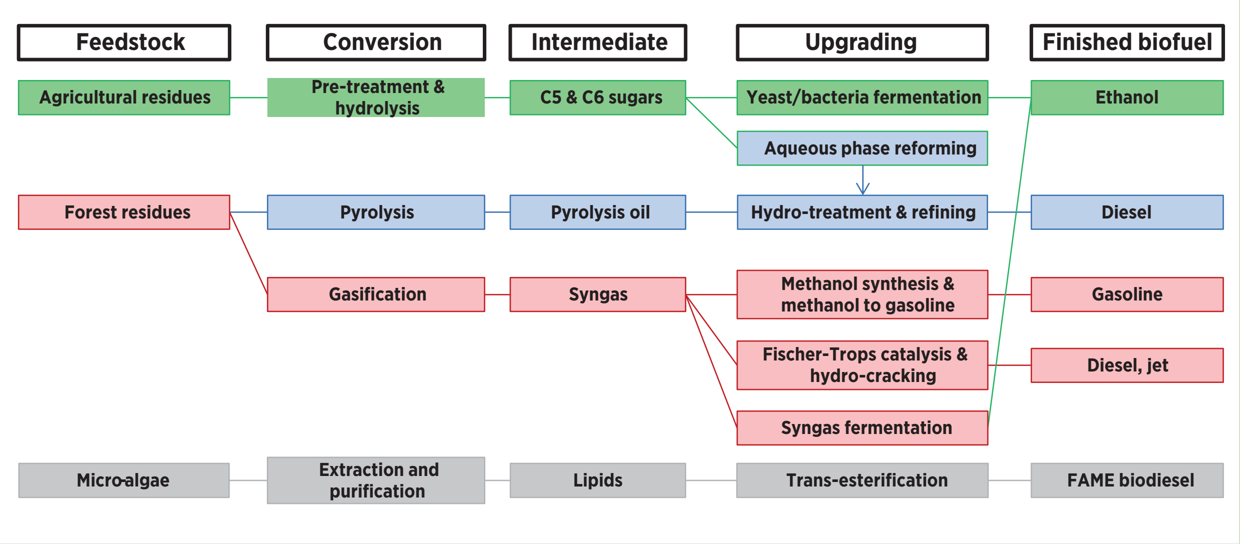
This chapter presents a comparative assessment of different advanced biofuels pathways including technical, economic, and environmental performance indicators in the next three decades. The comparative assessment includes all conversion technologies at demonstration stage and some earlier stage technologies. The comparative analysis relies on published literature on performance from either peer-reviewed scientific publications or independent techno-economic assessments. The definition of the pathways, especially the combination of feedstock and conversion technology, is based on that most commonly described in the literature and evidence in the project inventory (Annex B).

The following eight pathways are included in the comparative assessments, which covers 21 of the 50 early commercial and demonstration plants included in the project inventory. These pathways are considered relevant to provide a global innovation outlook (Figure 23).

i. Forest residues – gasification and Fischer-Tropsch synthesis to produce diesel and jet fuel.
ii. Forest residues – fast pyrolysis and pyrolysis oil upgrading to produce diesel.
iii. Forest residues – gasification and methanol synthesis followed by MTG.
iv. Agricultural residues – hydrolysis and aqueous phase reforming of sugars followed by upgrading to diesel.
v. Micro-algae – oil extraction and transesterification to produce FAME.[7]
vi. Forest residues – gasification and mixed alcohol synthesis to produce ethanol.
vii. Forest residues – gasification and syngas fermentation to produce ethanol.
viii. Agricultural residues – hydrolysis and fermentation to produce ethanol.

Many of the early commercial and demonstration plants included in the project inventory use or plan to use solid biogenic wastes, including the biogenic fraction of

Figure 23: Advanced biofuels pathways included in the comparative assessment



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[7] In this pathway, innovation in micro-algae production and in micro-algae oil extraction and purification is required. It is assumed that micro-algae oil will be upgraded to biofuel product via transesterification – a commercially mature process.

municipal solid waste, and garden waste. Wastes can be a very attractive feedstock because biofuel plants could be paid to receive the waste. However, the cost or value of waste depends on local factors such as alternatives for its disposal. Very little information is available on global pricing. Advanced biofuels using solid biogenic waste are therefore not included in the comparative assessment.

The future innovation potential of the conversion technologies selected is assessed by quantifying the following indicators:

- conversion efficiency
- capital and operational costs, and production cost range
- direct life cycle GHG emissions and emission savings, excluding land use change impacts

The performance indicators presented represent the expected performance at commercial scale. The first point reflects a feasible operational start date for the first commercial-scale plant. Details of the methodology, assumptions and references used to determine each pathway's technical and economic performance is provided in Annex D.

The evidence base for some advanced biofuels pathway assessments is very limited, especially fast pyrolysis, pyrolysis oil upgrading to produce diesel, and aqueous phase reforming with upgrading to diesel.

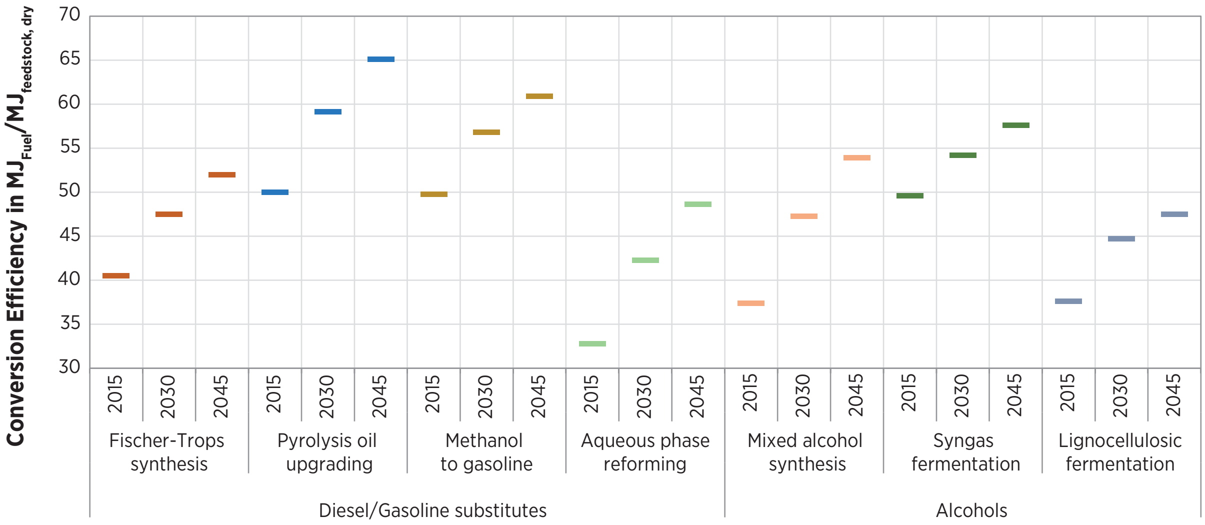
4.1 Technical performance of pathways over the next three decades

Figure 24 presents the expected conversion efficiency expressed in megajoule (MJ) $_{\text{fuel}}$ per MJ$_{\text{feedstock}}$ and potential improvements over the next three decades.

This illustrates that transesterification demonstrates the highest efficiency at around 92% mainly because the algal oil is a high quality feedstock. The lowest potential for improvement is the transesterification process. An established technology, it is close to the technical optimum. Gasification and pyrolysis pathways show higher maximum theoretical conversion efficiencies compared to hydrolysis pathways. The majority of these pathways may still achieve significant improvements in overall conversion efficiency, with the exception of syngas fermentation. The maximum conversion yield for hydrolysis pathways is limited because they use only the cellulosic and hemicellulosic fractions of the biomass input. However, more destructive processes like gasification and pyrolysis do not have this constraint. Hydrolysis pathways also produce lignin as a co-product which could find other energy uses besides providing the plant with process energy.

Lignocellulosic fermentation and syngas fermentation pathways to ethanol are currently operating closer to their maximum theoretical yields. There is thus less scope

Figure 24: Comparison of process efficiencies



to increase yields. It is not appropriate to compare the conversion efficiencies of advanced biofuels pathways to those of conventional biodiesel and bioethanol or fossil fuels. This is because the input starting materials are very different in terms of their chemical and physical properties and the ease with which they are processed.

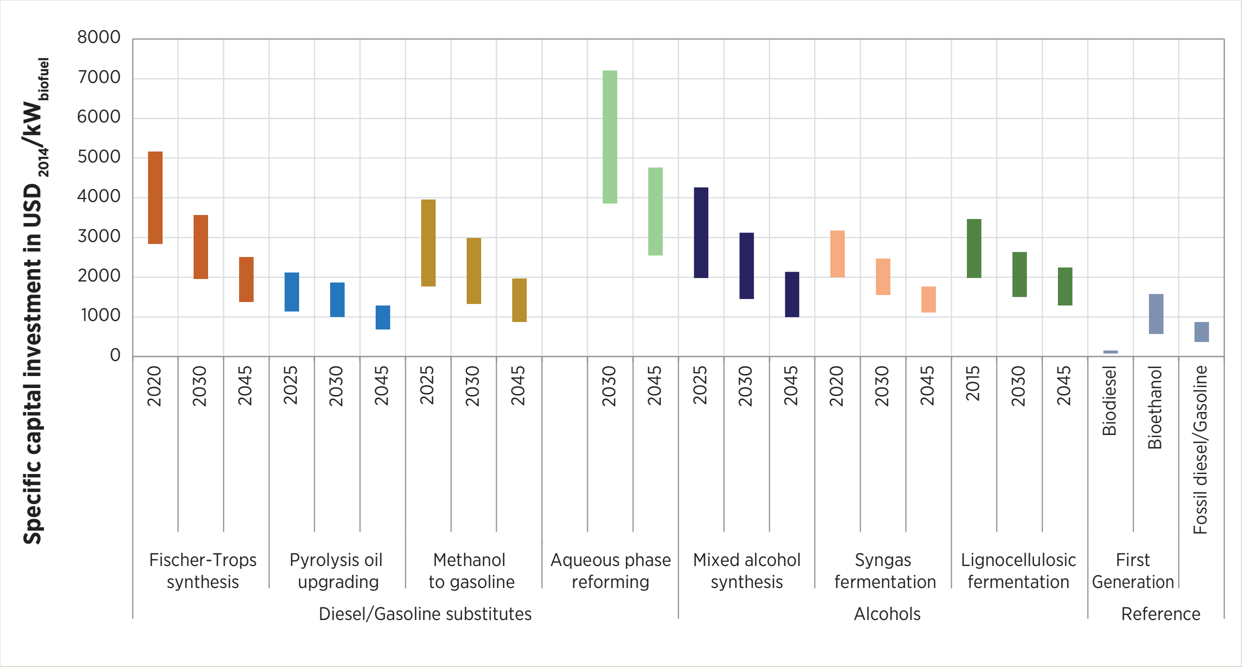
4.2 Economic performance of pathways over the next three decades

The reported commercial-scale operation ranges do not differ much between advanced biofuels pathways, especially given the potential for future downscaling and cost reductions in certain technology components. Most biofuel pathways potentially operate at 75-750 MW feedstock input, equivalent to 120,000 and 1.2 million dry tonnes of biomass per year.[8] Fast pyrolysis and aqueous phase reforming operate at smaller plant scales (minimum 50 MW feedstock input). Current capacities for conventional bioethanol plants are similar ranging at 50-110 MW in feedstock input. Significantly higher plant scales are expected for transesterification processes because the high energy density feedstock can be transported more cost effectively. This is in line with conventional biodiesel plants operating at a much broader range of capacities, 15-1,200 MW feedstock input. Fossil oil refineries are typically built at about one to two orders of magnitude greater than conventional or advanced biofuels plants.

Estimated total capital costs ranges are presented in Figure 25 in USD$_{2014}$/kW$_{biofuel}$. Capital investment in current lignocellulosic fermentation plants is around USD 2,000-3,500/kW biofuel. It is estimated that future learning will reduce this by around 35%. Commercial-scale syngas fermentation and Fischer-Tropsch synthesis processes may emerge from 2020. Their capital investment will range at USD 2,000-3,000/kW biofuel and USD 3,000-5,000/kW biofuels respectively. Once at commercial scale, syngas fermentation processes are expected to have similar specific capital investment costs to lignocellulosic fermentation processes.

Other gasification conversion processes (with different downstream catalysts) are expected to have slightly lower specific capital costs than is the case for Fischer-Tropsch synthesis. The gasification and catalysis processes will initially have greater specific

Figure 25: Specific capital investment



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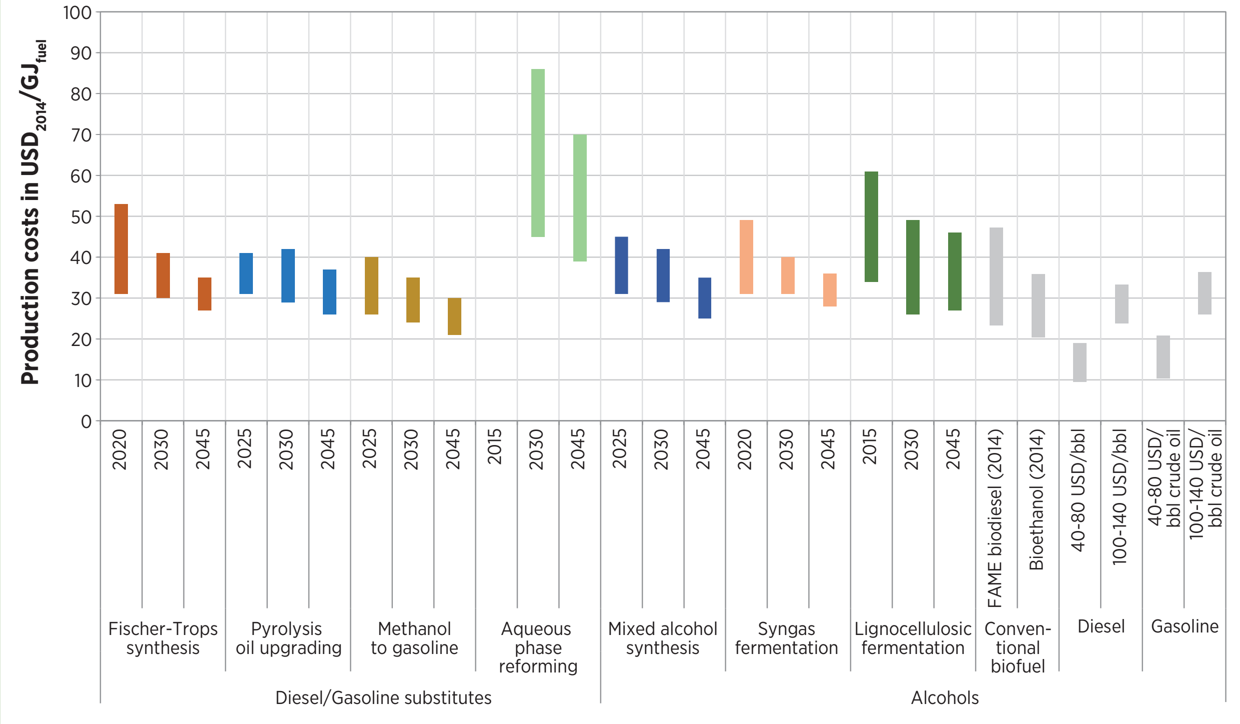
[8] The corresponding biofuel production capacity will vary depending on the conversion efficiency.

Figure 26: Fuel production cost comparison[9]



capital investment costs. However, the opportunity for cost reductions with increased installed capacity and learning is expected to be greater than for lignocellulosic fermentation. With future learning, the gasification pathways may become competitive with lignocellulosic fermentation.

Specific capital investment costs for pyrolysis processes are expected to be very competitive. At commercial scale, these are expected to be USD 1,000-2,000/$kW_{biofuel}$. Aqueous phase reforming incurs the greatest reported capital investment costs although this is from a very limited evidence base. Transesterification technology has low specific capital costs because the capital investment for micro-algae cultivation is included in the feedstock cost.

Improvements through learning and scaling up the commercial rollout of advanced biofuel pathways may make their specific capital investment close to or comparable to that of conventional (corn-based) bioethanol in 2035-2045. However, the specific capital investment for FAME biodiesel is very low at USD 83-156/$kW_{biofuel}$. Due to economies of scale, capital investment in conventional oil refineries is USD 380-870/kW_{fuel}.

Estimated production cost ranges are presented in Figure 26 in USD_{2014}/GJ_{fuel} and amount to USD 20-60/GJ. The exceptions are algal oil transesterification and aqueous phase reforming. These would need to achieve production costs at the lowest end of the calculated range in order to compete with other advanced biofuels pathways. The low end of these production cost ranges is comparable to current conventional FAME biodiesel and (corn) bioethanol prices. Due to very high feedstock costs, the estimated cost of biodiesel from the transesterification of micro-algae oil ranges at USD 30-430/GJ. This wide range is explained by different assumptions in the production, harvesting and extraction processes related to algal oil production.

For all pathways except aqueous phase reforming, feedstock costs account for 40%-70% of production costs and represent the greatest single contribution to costs. The percentage contribution increases over time as learning rates and improved conversion efficiencies reduce the specific capital costs (Figure 27). This shows how efforts to reduce production costs should include

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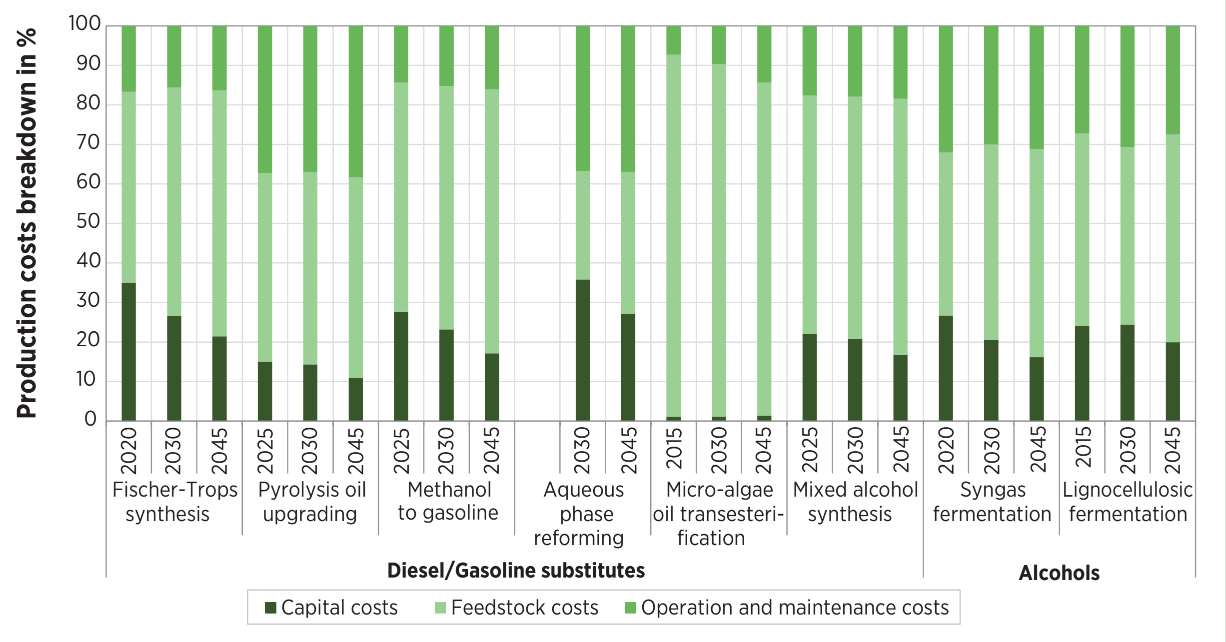
[9] Excludes micro-algae oil transesterification

Figure 27: Production cost breakdown



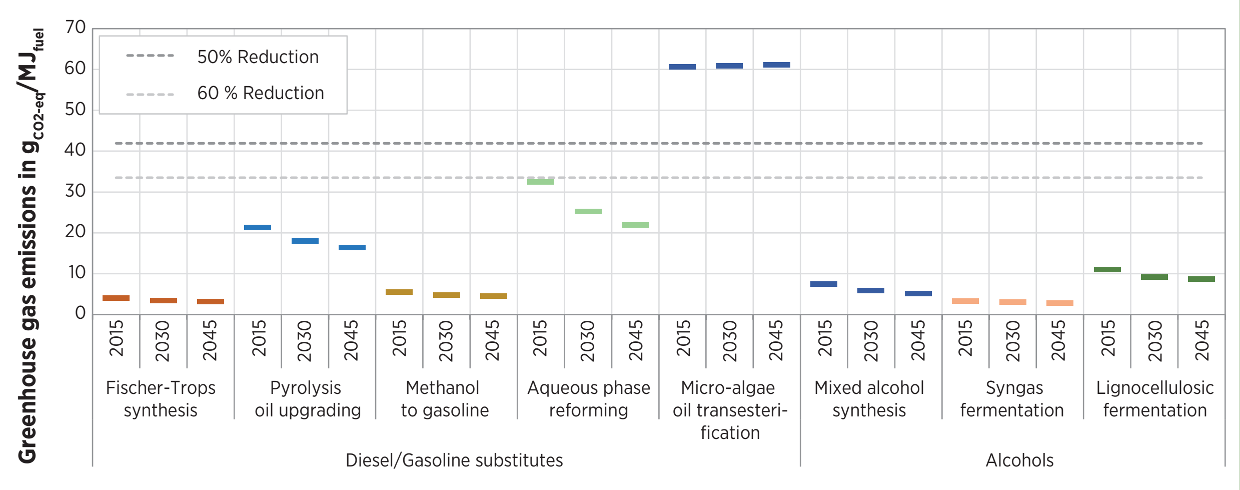
opportunities to reduce the cost of feedstock supply. The production costs of aqueous phase reforming are at USD 39-86/GJ due mainly to the combination of low conversion efficiency with high capital and operating and maintenance costs.

Based on potential improvements in conversion efficiency and capital cost reduction, the advanced biofuels production costs could become competitive with fossil fuel at above USD 100/bbl. At below USD 80/bbl, advanced biofuels pathways are very unlikely to be able to compete directly with gasoline and diesel over the next three decades unless very low or negative cost feedstocks are available.

4.3 Environmental performance of pathways over the next three decades

Expressed as GHG in units of grammes-CO_2 equivalent per MJ biofuel, the environmental performance is presented in Figure 28. The dashed lines show a GHG emissions reduction of 50% and 60% compared to

Figure 28: GHG emissions of advanced biofuel pathways and their emissions reduction compared to fossil fuel



a fossil fuel reference value of 83.8 $g_{CO2\text{-}eq}/MJ_{fuel}$. The improvements in GHG emissions are due to better conversion efficiencies.

GHG emissions associated with advanced biofuels pathways are 3-33 $g_{CO2\text{-}eq}/MJ_{fuel}$. These pathways achieve at least a 60% reduction compared to the fossil reference. Gasification pathways using forest residues as feedstock produce the lowest emissions at 3-7 $g_{CO2\text{-}eq}/MJ_{fuel.}$ This is because emissions associated with the feedstock are very low, and the conversion plants are assumed to be self-sufficient in energy. Hydrolysis, fermentation and fast pyrolysis pathways also produce very low emissions at 11-21 $g_{CO2\text{-}eq}/MJ_{fuel.}$ Some additional emissions result from enzyme, chemicals and external energy inputs. The transesterification of micro-algae oil and aqueous phase reforming currently produces the highest emissions at about 33 $g_{CO2\text{-}eq}/MJ_{fuel.}$ However, these could decrease to 22 $g_{CO2\text{-}eq}/MJ_{fuel}$ in the long term. The transesterification of oil from micro-algae also produces emissions of around 33 $g_{CO2\text{-}eq}/MJ_{fuel}$.

Options for policy makers

The following can be summarised on the basis of the presented analysis of the technical, economic and environmental performance of the pathways selected:

- **Gasification and pyrolysis processes achieve the highest** conversion efficiencies, especially upgraded pyrolysis oil and MTG.
- The expected commercial plant scale for advanced biofuels production is similar to that of conventional biofuels production. However, the plant scale of conventional refineries processing crude oil is up to two orders of magnitude greater.
- Advanced biofuels plants need significantly higher specific capital investment than conventional biofuels. The specific capital investment costs for the first commercial-scale plants are expected to amount to USD 2,000-7,000/$kW_{biofuel}$. As a result of learning rate effects, all pathways are capable of reducing capital investment costs over the next three decades. **Pathways achieving full commercialisation are expected to reduce specific capital investment costs to USD 700-2,000/$kW_{biofuel}$.**
- Feedstock in most pathways accounts for 40%-70 % of production costs, using typical wood or agricultural residue cost assumptions. As learning rates increase and efficiencies improve, the contribution of feedstock cost to the overall costs may increase over time. **Reducing the feedstock supply cost is key to reducing production costs.** This justifies efforts dedicated to achieving this aim.
- **At an oil price of less than USD 80/bbl, advanced biofuels are very unlikely to compete directly with gasoline and diesel.** However, at oil prices above USD 100/bbl, most advanced biofuels pathways may be able to compete directly with gasoline and diesel by 2030 or 2045.
- **All advanced biofuels pathways produce low GHG, achieving 60%-95% in GHG emissions savings** compared to the fossil fuel reference. Gasification pathways using forest residues are expected to achieve GHG emissions savings of more than 90%.

5 STRATEGIES TO SUPPORT ADVANCED BIOFUELS COMMERCIALISATION

Advanced biofuels pathways face technical and non-technical barriers to widespread commercial deployment. These include the need to demonstrate efficient and reliable performance, high production costs, market access, availability of finance and uncertainty about requirements on environmental and social impacts. The sector therefore requires a range of interventions to support development. Interventions need to address four key areas: technology development, company development, market formation and policy development. These different types of interventions will form an overall strategy to support advanced biofuels innovation.

5.1 TRL 8 and 9: market formation and policy development

The common barriers facing technologies ready for commercialisation include lack of sufficient operational experience, immature supply chains, higher production costs than conventional biofuels and fossil fuels, and uncertainty around the size of the market. This can be addressed by the introduction of mandates or incentives by national governments. Governments can mitigate the additional costs of advanced biofuels production via direct financial incentives like price premiums, tax exemptions and other means, and indirectly by mandates providing a price response. Mandates have successfully created a market for road transport biofuels in many countries, most notably in the US and many EU member states. Depending on the national government's priorities, support can be linked to GHG emissions savings or renewable energy delivered.

Opportunities to support the development of a market for aviation biofuels are more limited due to the cross-boundary nature of the industry and international agreements exempting aviation fuel from national taxes. **Public procurement initiatives** can stimulate demand for advanced biofuels products. For instance, the US Navy and Department of Defence have supported the production of biofuels at scale for marine and aviation applications.

Access to project finance for first-of-a-kind commercial or flagship plants can be very limited because they have a high risk profile, especially plants requiring high capital costs or immature supply chains. An efficient way through which governments can stimulate private debt funding is to back risk management tools sharing the credit risk of commercial loans between the government and the financial institution. **Loan guarantees** are developed by national governments in partnership with commercial financial institutions and development banks.

Governments or development banks provide grants to help financial institutions provide loans to eligible companies through loan softening programmes. These programmes could initiate loans by financial institutions for new products or technologies.

5.2 TRL 6 and 7: technology and company development

Proving the technology is a key barrier to achieving key performance parameters that will enable the process to be competitive at commercial scale. This affects organisations demonstrating viable routes to market for new products and processes. The specific nature of the technical challenge is project-specific. However, these activities can be supported through public sector funds *e.g.* grants to build demonstration projects for research and evaluation of the technology. Governments and supranational organisations like the European Commission can provide funding through their research and innovation agencies or other departments (*e.g.* the UK Department for Transport Advanced Biofuels Demonstration Competition). There are many examples of government grants supporting advanced biofuels demonstration projects through a wide range of initiatives backing innovation in low carbon technologies, in the agricultural sector, and in general technology.

Additional barriers relate to the enterprise's commercial expansion, especially if it is a small company. They also relate to market access, including access to necessary infrastructure and the need to meet fuel standards. These barriers may be addressed by strategic partnerships and joint ventures. **Strategic partnerships** can allow several companies across the supply chain to share expertise and financial risk. Sector networks especially aimed at early stage companies have a key role to play in facilitating the development of industrial partnerships. Examples within the lignocellulosic ethanol industry include the partnership between biorefining company POET and Royal DSM which led to Project Liberty, and Beta Renewables. This is a joint venture between Biochemtex, Texas Pacific Group, and Novozymes operating the Crescentino plant in Italy.

The lack of debt or equity investment in unproven technologies can lead to financing gaps in technology development, in particular for small companies. This may be supported through **public sector programmes to derisk investment** such as project investment insurance or by soft loan programmes from governments or innovation agencies. **Public and private sector partnerships** are also an important mechanism for funding technology development and demonstration, and sharing risk. One example is the Bio-based Industries Joint Undertaking, a EUR 3.7 billion partnership between the EU and the Bio-based Industries Consortium. Such partnerships can also effectively identify research and innovation priorities.

5.3 TRL 4 and 5: technology development and early stage company development

The most important barriers for technologies progressing from applied research to demonstration are generally technical in nature. They include the need to test and evaluate technical concepts and claims, which usually requires pilot facilities or prototype construction. These activities may be supported by grants to build pilot facilities for technology research and evaluation. In Europe, a network of open access pilot facilities emerged to facilitate this process, offering equipment, skills and expertise. Voucher schemes are in place to help small companies access this type of support.

The risk of investing in early stage organisations and start-ups can constrain technology development activities. There is a need for various forms of equity investment at this stage, and potentially a role for governments to **facilitate investment in early stage companies.** Investment tax incentives are one way to do this – favourable tax terms for investors in pre-commercialised technology.

Other barriers to development relate to IP exploitation, including IP protection and enforcing IP ownership. These processes can be expensive and time-consuming for small companies in particular. Governments and innovation agencies have a role in **providing support structures to assist early stage company formation.** For instance they can provide expertise (and possibly financial assistance) to ensure that small companies are able to protect and exploit their IP.

A dialogue is needed between researchers and industrial actors at TRL 1-3 to ensure the potential for relevant research applications is understood, and that basic and applied research capabilities are known to industry actors. This is also important to define targeted early stage research to meet the innovation needs identified by industry actors. Research and industry networks enable this dialogue, which may be facilitated by governments and research and innovation agencies.

5.4 Summary of barriers and action

Table 18 outlines interventions that may reduce key barriers influencing all or many of the advanced biofuels pathways. They indicate which specific stakeholders may be involved.

Table 18: Interventions against barriers affecting advanced biofuels pathways

Barriers and risks			Opportunities and action	Key actors[1, 2]			
				Gov/ IO	RI	Cor	NGO
Technical and economic	1	Technology readiness	Business case for investment in technology; capacity assessment for technology development; investment in research, development and demonstration; international cooperation.	✓	✓	✓	
	2	High costs	Policies to ensure a level playing field between new and established fuels, and to encourage more desirable products or behaviour *e.g.* pricing based on environmental performance, such as carbon price.	✓	(✓)	(✓)	
			Financial support for research, development, demonstration and early deployment activities which lead to reduced biomass supply and fuel production costs.	✓	(✓)	(✓)	
			Financial support to develop feedstock supply chains.	✓		✓	
			Policies that consider synergies with the production of non-fuel products *i.e.* food, feed, heat, electricity, chemicals and other materials.	✓		(✓)	
			International co-operation efforts.	✓	✓	✓	
Investment	3	Lack of demand	Long-term policies creating (stable) market demand for biofuels and advanced biofuels in particular *e.g.* specific advanced biofuels mandates.	✓		(✓)	
			International co-operation on mandates or alternative mechanisms in the aviation sector which do not penalise market players on the basis of location.	✓		✓	
	4	Technical risk	Financial support for research, development, demonstration and early deployment activities.	✓	(✓)	✓	
			Financial mechanisms that facilitate private funding *e.g.* grants, loan guarantees and tax credits.	✓		(✓)	
	5	Feedstock risk	Studies of regional feedstock potential.	✓	✓	✓	
			Robust replicable business models and partnerships for feedstock supply.			✓	
			Policies supporting the development of feedstock supply chains *e.g.* infrastructure development grants.	✓			

Barriers and risks			**Opportunities and action**	**Key actors[1, 2]**			
				Gov/ IO	**RI**	**Cor**	**NGO**
Environmental	6	Market fragmentation as a result of differing national requirements and schemes	Global harmonisation of environmental and social criteria for certification systems, avoiding uncertainty for producers and consumers and thwarting trade barriers.	✓			
			Internationally agreed life cycle analysis approach.	(✓)	✓	✓	✓
	7	Resources and costs associated with sustainability certification	Standards that provide sufficient environmental guarantees while being cost-effective.	(✓)	✓	✓	(✓)
			Incentives for market uptake of certified feedstocks and fuels *e.g.* mandates and tax benefits for certified fuels.	✓			
	8	Uncertainty on potentially more stringent sustainability criteria	Industry and government engagement with NGOs and research institutions to research impacts and develop resilient approaches to environmental concerns, such as indirect land use change and carbon debt.	✓	✓	✓	✓
Social	9	Lack of assurance on socially responsible practices in advanced biofuels supply chains	Promote use of social standards; make legal compliance with social criteria compulsory.	(✓)	✓	✓	✓
	10	Lack of capacity in certain countries	Encourage international collaboration and knowledge transfer; develop skills and expertise in all regions.	✓	✓	✓	✓
			Capacity building in developing countries, including through supportive regulatory and policy frameworks.	✓			
	11	Negative public perception	Create a more nuanced and constructive debate on sustainable biofuels by engaging NGOs as representatives of civil society.			✓	✓
Infrastructure	12	Lack of infrastructure for feedstock supply and traceability	Involve actors along the whole value chain to develop necessary logistics systems; potential mechanisms include financial incentives and public private partnerships.	✓		✓	
	13	Lack of downstream infrastructure and market access	Support for the development of fuel standards and infrastructure needed to distribute and use fuels; information to consumers.	✓		✓	(✓)
			Develop verifiable chain-of-custody systems as part of standards and sustainability certification schemes to improve traceability.	✓		✓	✓

[1] *✓ Primary actor; (✓) Secondary actor*

[2] *Gov/IO = government/international organisation; Cor = corporate/industry; RI= research institutions; NGO = non-governmental organisation*

6 PROSPECTS FOR ADVANCED BIOFUELS

This report shows there are plenty of feedstock, technology and fuel options, and that innovation has led to significant progress in developing some advanced biofuels pathways. It also shows that innovation can contribute further to the development of a range of pathways. But the success of advanced biofuels pathways depends not just on the ability of the technology to perform reliably and at acceptable costs. It depends equally on which biomass feedstocks will be more readily available and the demand for different fuels or constraints on their use. Hence there is need for innovation in feedstock supply in addition to innovation in conversion technologies. Examples include appropriate equipment, pre-treatment, logistics and business models. There is also a need for innovation and action to overcome barriers to the end-use of advanced biofuels *e.g.* blend limitsin the case of advanced ethanol and fuel standards.

This analysis indicates that at a continued low oil price of below USD 80/bbl, very few advanced biofuels pathways could compete directly with gasoline and diesel over the next three decades. The market for advanced biofuels would remain dependent on policy frameworks and mandates. However, at higher oil prices above USD 100/bbl, more pathways could compete directly with gasoline and diesel. This depends on the specific technical needs being met so that the processes reach commercial scale in the next five, 10 or 15 years and benefit from learning from rollouts thereafter.

6.1 Ethanol and other alcohols

Pathways to ethanol and methanol are the areas with the greatest progress, especially in extracting sugars from lignocellulosic biomass and converting to ethanol.

Ethanol via hydrolysis and fermentation has shown the greatest progress with the deployment of early commercial plants. It is currently the cheapest and most developed advanced biofuels route, and several proprietary technologies are available. The highest priority is for continued market development and support, including the continuation of mandates and/or incentives to support the market while production capacity increases. Current demonstration and early commercial projects should lead to technology performance guarantees that will allow investment in commercial plants. Feedstock costs are and will continue to be a significant contributor to production costs, so their competitiveness will depend on access to low cost feedstocks. There is thus a need to demonstrate viable low-cost feedstock supply chains and to innovate in technology (*e.g.* for residue collection), supply chain logistics (*e.g.* for relatively low density residues) and business models (*e.g.* for supply arrangements between biofuel producers and multiple farm owners). Continued improvements in pre-treatment technology and in hydrolysis and fermentation organisms will further reduce capital and operating costs. It will also improve the performance and cost of butanol production. Consolidated bioprocessing, allowing hydrolysis and fermentation to occur simultaneously, could also significantly contribute to cost reductions.

Ethanol from syngas fermentation is also emerging as an attractive option, and ethanol production from biomass-derived syngas is under demonstration at present. This may provide a route competitive with lignocellulosic ethanol via hydrolysis and fermentation since its potential conversion efficiencies are reported to be higher. In addition, production costs could attain similar levels over the next three decades. Continued technology development is required to fulfil this potential. This covers fermentation organism improvement to increase yields, reduce product inhibition and increase tolerance to contaminants, and improvement in reactor pass-through rates and design.

Gasification platforms to produce methanol and ethanol via catalytic routes have also made significant progress on the back of gasification deployment in the power sector (including waste to energy). First-of-a-kind commercial-scale plants are in operation for the production of **methanol from syngas**. These simpler, more selective and scalable catalytic processes may prove more viable than Fischer-Tropsch synthesis as long as demand for these products is attractive.

For biomass **gasification-based pathways,** whole plant energy integration is a high priority to reduce production costs but this can only be addressed in large-scale demonstrations. Syngas cleaning remains an important area of development, specifically high temperature processes for the removal of tar. Several approaches have been proved at pilot or small demonstration scale.

Overall, technologies for producing alcohols like ethanol and methanol could be poised for rapid growth. They could displace a significant share of gasoline but their uptake may be constrained by blending limits within current fuel standards. Alcohols could be used in diesel engines through appropriate fuel additives, blends and engine modifications. Alcohols could also be used as intermediates in the production of synthetic **gasoline and jet fuels,** which would expand the accessible market. Catalytic processes for converting alcohols to synthetic gasoline and jet fuels have not yet been integrated with advanced biofuel pathways. The prospects for these routes will depend on the value attached to the derived fuel in relation to the alcohol.

6.2 Diesel and jet fuel substitutes

The search for diesel and jet fuel substitutes continues with continued efforts to commercialise known processes such as Fischer-Tropsch or to develop biological routes to hydrocarbons. However, these technologies lag behind the ethanol and methanol production technologies.

Limited attempts to demonstrate the production of **hydrocarbon biofuels via Fischer-Tropsch synthesis** have been successful but efforts persist due to interest in diesel and jet substitute production. The potential to achieve commercial viability at a scale suitable for biomass remains in question. Significant advances have been made in the development of modular micro-channel **Fischer-Tropsch** reactors. However, the integration of this technology with biomass gasification at industrial scale is still required. Producing unrefined products like Fischer-Tropsch waxes and refining these at petrochemical refineries is under consideration to reduce the cost at biomass scale.

The production of **hydrocarbon fuels by upgrading pyrolysis oil** is proved only at pilot or small-scale demonstration, and some of the upgrading processes are still at proof-of-concept stage. Commercialisation will require further technical innovation in fast pyrolysis and upgrading processes. However, the majority of cost reductions are expected to occur at the upgrading step, through either improved catalytic processes or by using existing oil refinery infrastructure.

Technology development in these thermochemical routes is under way, and support for demonstration projects will be vital in the short term. Strategic partnerships could provide a route to achieving reduced capital investment and production costs, especially via the use of existing refinery assets and by co-processing biofuel intermediates with fossil fuels. Processes with high capital costs, such as gasification and Fischer-Tropsch synthesis, will require mechanisms to leverage private sector project finance between 2020 and 2030.

Other conversion routes are under development for the production of hydrocarbon fuels from biomass. These include, for instance, **aqueous phase reforming** and **direct sugar to hydrocarbon routes**. These pathways will benefit from efforts to improve lignocellulosic biomass pre-treatment and hydrolysis since generally they aim to demonstrate the processes on sugar and starch crops. The production of **hydrocarbon fuels from micro-algae** is at the research and development and pilot stage. It requires much further development prior to commercialisation. Efforts in recent years have not yielded the improvements that had been hoped for. Costs remain high, and productivity low.

In conclusion, the opportunities and potential for advanced biofuels are great and varied. Nevertheless, establishing a competitive advanced biofuels industry remains a significant challenge. It will rely on further innovation in technology and biomass supply chains, continued policy support and market development. This will require co-ordinated action from many players including the research community, industry and governments, to continue building momentum in the sector and improving its prospects for widespread commercialisation.

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ANNEX A

TECHNOLOGY STATUS ASSESSMENT

Fermentation (including pre-treatment and hydrolysis)

Brief description

Lignocellulosic biomass may be converted via hydrolysis and fermentation to ethanol and butanol. The chemical structure of lignocellulose means that feedstocks must be pre-treated and then hydrolysed prior to fermentation to break down the feedstock into simple sugars. Pre-treatment separates the cellulose, hemicellulose and lignin fractions, and hydrolysis converts cellulose to simple sugars suitable for fermentation. Efficient hydrolysis relies on the breakdown of hemicellulose and lignin. Hydrolysis may be initiated by chemical treatment, typically dilute acid, or by enzymes. The sugars are then fermented by yeast or bacteria to produce ethanol and butanol. Fermentation products are separated from the fermentation broth.

The pathway may use any lignocellulosic biomass feedstock. However, all feedstocks have a different composition of lignin, cellulose and hemicellulose which impacts the efficiency of the pre-treatment and hydrolysis steps. Straw and grassy feedstocks have a lower lignin content, which facilitates the pre-treatments steps. Ethanol is the most commercially advanced product, and butanol is also in development.

Technology parameters, advantages and drawbacks

Pre-treatment options include physical, chemical, biological processes and combinations of these. Steam explosion is the most widely used pre-treatment technology by industrial companies. It reduces the size of the biomass and begins the breakdown of hemicellulose and lignin. However, the process demands a great deal of energy and leads to the creation of by-products that inhibit downstream fermentation. Adding sulphur dioxide to the steam explosion leads to better recovery of cellulose and hemicellulose (Chiaramonti *et al.*, 2012). Other pre-treatment options are CO_2 explosion, which is still restricted by higher costs, and ammonia fibre explosion.

Following pre-treatment, cellulose and hemicellulose may be hydrolysed to simple sugars using dilute acid or enzymes. Enzymatic hydrolysis is the most common route, although the cost of enzymes is currently high and a major contribution to current production costs. The cost of enzymes is expected to decline as enzyme loading is reduced, and enzyme prices decrease due to larger-scale production (Bloomberg New Energy Finance, 2013). Treatment with dilute acid hydrolysis at high temperatures is another widely used process to create simple sugars. However, acid hydrolysis leads to the creation of inhibitors that have a negative impact on the fermentation process (Chiaramonti *et al.*, 2012).

The fermentation process can be initiated by either yeast or bacteria; the former is used in most commercial and demonstration ethanol facilities at the moment. Greater engineering of micro-organisms to improve their selectivity, tolerance to inhibitors and yield are future areas of innovation.

Fermentation is an advanced biofuel route available at scale for the production of ethanol. It is an efficient use of sugars. Butanol is currently produced using the Acetone-Butanol-Ethanol fermentation process. Research using fermentation bacteria in ongoing, especially bacteria that are tolerant to inhibitors produced during the pre-treatment step (Ezeji *et al.*, 2014). Ethanol and butanol are separated by commercially available techniques but the yields still have considerable potential for improvement, particularly for butanol.

Technology status and industrial activities

Globally, there are several first-of-a-kind commercial-scale lignocellulosic ethanol plants, most of which are in the process of commissioning or ramping up to full scale operation. They include Beta Renewables in Italy, Raizen and GranBio in Brazil, Shangdong Longlive in China and Poet-DSM in the US. Several others are nearing the

Abengoa

Abengoa began producing ethanol at a commercial-scale demonstration facility in Kansas, US, in 2014 with installed capacity of 95 million litres per year. However, the plant has ceased operation and has an uncertain future as its parent company is facing bankruptcy. The plant and lignocellulosic ethanol technology may be sold (as part of Abengoa Bioenergy) within a restructuring plan and may thus start up in the future.

end of construction, including Dupont. There are many processes for converting biomass to ethanol at TRL 8.

Butanol is produced commercially using the ABE fermentation process (mostly in China) to supply the chemical industry. This is an established and robust process but process yields and production costs are not competitive for fuel production, and research is ongoing to engineer fermentation yeasts and bacteria to increase butanol yields.

The optimisation of fermentation yeasts and identification of bacteria that maximise butanol production was demonstrated in 2012 at 3.2 million litre fermentation scale by Green Biologics in China (TRL 6) (Green Biologics, 2013). Fewer industrial actors are optimising lignocellulosic production processes for butanol than for ethanol. Cobalt Biofuels have reported pilot activities (De Guzman, 2013). Other companies are focussed on the production of isobutanol from sugar and starch feedstocks (Butamax and Gevo).

Technology challenges

The main challenges experienced in improving the economic viability of lignocellulosic ethanol and butanol production lie in the pre-treatment, and in the case of the ABE process, alcohol separation phase. High enzyme costs in the hydrolysis step are already falling rapidly. The technical challenges of pre-treatment arise because the separation of cellulose and lignin is not complete. In addition, by-products form during the hydrolysis step which act as inhibitor in the fermentation step. Finally, the process creates a high demand for energy and/or chemicals (Chiaramonti *et al.*, 2012). The delignification of raw material is the rate-limiting step in the sequence and the most technically difficult task. Important technology challenges need to be overcome in the separation of ethanol and butanol and in relation to micro-organism toxicity effects. These need to increase the yields of end-products from the fermentation broth. Creating an integrated process of fermentation and downstream separation could represent a way to increase yields, and some groups are examining consolidated bioprocessing options to reduce capital costs.

The additional problems specifically related to butanol are concerned with the creation of robust and selective micro-organisms. These need to be more tolerant to other products in the fermentation broth and produce higher yields of butanol compared to ethanol and acetone. Reducing the toxicity of butanol to fermentation micro-organisms will be crucial as this currently limits the sugar loading and increases the water usage and separation energy.

Aqueous phase reforming

Brief description

Aqueous phase reforming is a thermochemical catalytic process to produce alkanes and hydrogen from biomass-derived sugar and sugar alcohols. This includes complex sugars and mixed sugar streams not suitable for fermentation processes.

The process takes place in catalytic reactors and involves various reactions including dehydration, oligomerisation, and carbon-carbon bond cleavage (Crabtree, 2014). The process is currently primarily used for the production of hydrogen, of which light alkanes (primarily methane) are a by-product. Whatever the reaction conditions, catalyst composition and reactor design may be adjusted to produce heavier alkanes.

Technical parameters, advantages and disadvantages

The process takes place at a relatively low temperature (typically around 230° C) (Aiouache, 2013), and the reforming takes place in the liquid phase – a characteristic unique to this process (Biorefine, n.d). This reduces the cost by negating the need to remove water from the feedstock. By reacting at low temperatures, the process substantially reduces the energy requirement of production and unwanted side reactions which occur when carbohydrates are heated (Wei, 2014; Biorefine, n.d).

Technology status and industrial activity

Virent has a 38 000 million litres per year pilot plant in Madison, US. This was built in collaboration with funding partners Shell, Cargill and Honda (Virent, 2015a). Further government funding was provided by the US DOE, USDA, US Department of Commerce and Federal Aviation Administration (Virent, 2015b). After showing promising commercialisation potential, Virent was selected by the US DOE National Advanced Biofuels Consortium programme to lead the Catalysis of Lignocellulosic Sugars pathway development, working with NREL (NABC, 2011).

In 2012 Royal Dutch Shell opened a pilot plant in Houston, US to produce drop-in biofuels. The technology used in this plant is licensed from Virent, and feedstocks being tested include sugars and non-food cellulosic alternatives (Shell, 2012).

Pyrolysis

Brief description

Pyrolysis is the controlled thermal decomposition of biomass to produce oil, syngas and charcoal (also known as biochar). Fast pyrolysis maximises the production of pyrolysis oil, which can be upgraded to transport fuels. In principle, any dry biomass feedstock can be used as an input. However, the composition of the feedstock will affect the yield and composition of the pyrolysis oil. Pyrolysis oil can be used for heat and power generation or alternatively upgraded for use as transport fuel.

Technology parameters, advantages and drawbacks

The key parameters affecting the yield and quality of the pyrolysis oil are biomass quality, combustion temperature, residence time and type of reactor. Rapid heating and cooling is crucial to maximise oil yields as high heat transfer rates guarantee maximum vaporisation. This is achieved by drying and grounding biomass and in optimised reactor designs (Bridgewater, 2012; Karatzos *et al.*, 2014). Bubbling fluidised bed, circulating fluidised bed, rotating cone reactors and ablative pyrolysis reactors all achieve high heat transfer rates. Circulating fluidised bed reactors are more expensive than bubbling fluidised bed but achieve a higher throughput. Pyrolysis oil is highly acidic, has high viscosity and high water content. These characteristics prove difficult for storage, transportation and downstream processing, and the quality of pyrolysis oil can deteriorate over time depending on storage conditions (Karatzos *et al.*, 2014).

Technology status and industrial activities

Despite widespread research and commercial activities on pyrolysis over the last decade, current production capacity is very limited (IEA, 2014). Currently only three companies are operating a fast pyrolysis plant at the demonstration to early commercial stage (TRL 7-8): Fortum in Finland, Ensyn in Canada and BTG in Malaysia (Karatzos *et al.*, 2014; Lehto *et al.*, 2014). Ensyn is developing further plants in Brazil, Canada and the US (Graham, 2015). Fortum and Ensyn are using a circulating fluidised bed design, while the BTG technology is based on a rotating cone reactor. BTG is currently constructing a second plant in the Netherlands, and Green Fuel Nordic Oy is in the permitting phase for a plant in Finland (BTG-BTL, 2015; Green Fuel Nordic Oy, 2013).

Other companies such as Pyrogrot in Sweden, KiOR in the US and Dynamotive in Canada have ceased operating over the last few years due to limited uptake markets, economic and technical difficulties (NER300, 2014; Mufson 2014).

Technology challenges

Further scale-up is required to achieve more economic and widespread use of fast pyrolysis. In addition, reactor designs with improved heat transfer and reaction rates are needed, alongside designs that facilitate the removal of impurities (Bridgewater, 2012). Pre-treatment processes need to be demonstrated that decrease the ash content of biomass feedstocks to produce better quality pyrolysis oil (Butler *et al.*, 2011). Improvements in oil quality include reducing chars, alkali metals and water content, and reducing the viscosity and acidity of the oil. There is also a need to improve the yield of pyrolysis oil, diminishing production of gas and char. These improvements may be achieved with new pyrolysis processes such as microwave pyrolysis, and/or by optimising the process for the specific feedstock (Karatzos *et al.*, 2014; Lehto *et al.*, 2014). Zeolite catalysts may also be used in the pyrolysis reaction to improve oil quality.

Pyrolysis oil upgrades

Brief description

Pyrolysis oil needs to be upgraded before it can be used as fuel in existing engines. Upgrading pyrolysis oil means treating it with hydrogen (*e.g.* by hydrocracking or Hydro-treating) or through catalytic processes (*e.g.* zeolite cracking or fluid catalytic cracking) (Holmgren, 2007; Karatzos, 2014).

The oil may be upgraded in a standalone plant or co-processed in existing crude oil refineries. Upgrading processes are very similar in both cases. Standalone processes can be optimised for the characteristics of the specific pyrolysis oil. Crude oil refineries operate at large capacities (with the benefit of economics of scale), and the use of existing processing capacity can lower investment costs. Figure 29 shows possible entry points for pyrolysis and other bio-oils within a conventional refinery process.

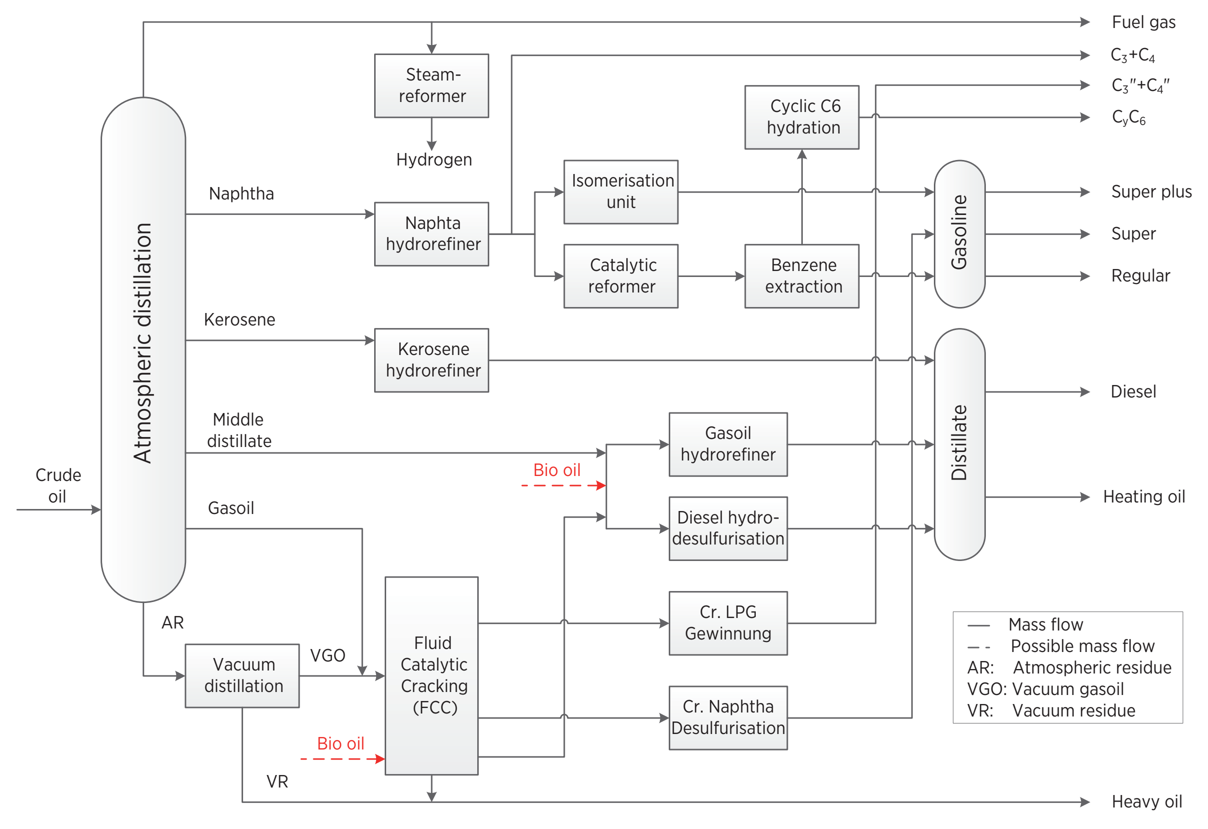
KiOR

KiOR built its first commercial plant with an annual capacity of 49 million litres before encountering significant technical problems and filing for bankruptcy in 2014.

Technology status and industrial activities

Several companies and scientific facilities are considering this process. Honeywell's UOP is investigating pyrolysis oil upgrading and has formed a joint venture with Ensyn, under the name Envergent, to further pursue pyrolysis technology (Holmgren, 2007). Envergent has been awarded USD 25 million by the US DOE to build a demonstration plant in Hawaii (Envergent, 2012; Lane, 2012). However, the status of this project is uncertain at present.

Figure 29: Diagram of a conventional refinery with possible bio-oil entry points



Research carried out on biomass pyrolysis at Fraunhofer UMSICHT, a German industrial research organisation, has resulted in the development of the Thermo-Catalytic Reforming (TCR®) technology. This converts solid biomass into biogas, bio-oil or biochar, allowing the deployment of the technology for different application markets. Advantages associated with this technology are the use of biomass with a moisture content of up to 30%. It produces no dust or tar and is a modular technology that can be delivered in a container. It produces significant savings because up to 75% of the chemical energy of the feedstock is transferred to the final products (Fraunhofer UMSICHT, n.d).

Technology challenges

Pyrolysis oil upgrading means dealing with the major concern of water (15%-30% of weight) and oxygen content (40%-50% of weight) (Karatzos *et al.*, 2014), both of which are higher than crude oil. For co-refining processes, this will damage the catalysts and significantly alter the product range, reducing the yield of desired products. Oxygen content can be reduced with hydrodeoxygenation, which requires a hydrogen source. Significant research on catalysts and reactors is still needed (Choudhary, 2011).

Hydrothermal upgrades

Brief description

Hydrothermal upgrading (also known as hydrothermal liquefaction) is a process for converting biomass with high water content. Biomass is heated and pressurised to convert it to a more energy-dense oil known as bio-crude. This liquid intermediate has more energy density than the original biomass, is thus easier to transport and can be refined in a similar manner to conventional crude oil.

Technical parameters, advantages and disadvantages

Hydrothermal upgrading works with a wide variety of feedstocks. It is particularly beneficial with feedstocks with high water content such as municipal solid waste because the biomass can be used directly in the hydrothermal upgrading process without expensive drying beforehand. For feedstocks like algae with very high water content, some water must be removed before it can be used in hydrothermal upgrading.

Biomass feedstock containing typically 5%-35% dry solids is subjected to raised pressures (10-25 MPa) and temperatures (280°C-370°C) for 5-20 minutes (Biomass Energy Centre; Toor *et al.*, 2011). The main products from this process are bio-crude, char, an aqueous steam containing water-soluble substances, and gas (predominantly CO_2 and carbon monoxide). The reaction conditions can affect the mixture of products. At temperatures below 250°C the main product is biochar while gasification reactions become dominant at temperatures and pressures above 375°C (Elliott *et al.*, 2015a). Conditions are usually selected to optimise the production of the liquid bio-crude fraction and are heavily dependent on feedstock characteristics.

Hydrothermal upgrading does not necessarily need a catalyst but some catalysts have been investigated to improve the efficiency of the process and suppress the formation of undesirable by-products. Aqueous alkali salts are the most commonly used catalysts, although heterogeneous catalysts containing nickel have also been reported.

Bio-crude is a viscous liquid with a lower heating value of around 30-35 MJ/kg. It is a dense organic liquid immiscible with water but the exact chemical composition is highly dependent on the biomass feedstock. Bio-crude can be used as a direct replacement for heavy fuel oil. Upgrading to more useful hydrocarbon fuels (such as gasoline and diesel) can be achieved by hydro-treating, a process similar to that used in conventional oil refineries. This has been demonstrated only at a very small scale.

Technology status and industrial activity

Hydrothermal upgrading has been investigated over several decades, mostly at the laboratory scale. There are very few pilot projects and no commercial facilities.

Pilot activities include the hydrothermal liquefaction of wood in the US from 1975 to 1981 (Bouvier *et al.*, 1988) and the CatLiq® process developed by the Danish company SCF Technologies A/S (Toor, 2010). Changing World Technologies of Carthage, Missouri, US, developed a thermal-depolymerisation process using turkey offal as feedstock, but production was irregular. Since being acquired by Ridgeline Energy Services (which subsequently changed its name to RDX Technologies Corporation) it is uncertain whether the plant is still operating as a hydrothermal upgrading facility. The most high-profile pilot plant was developed by Shell in Apeldoorn in the Netherlands. That production facility, with a capacity of around 100 kg per hour (Wim *et al.*, 2015), was successfully built and tested but has not yet been scaled up.

Technology challenges

Due to the severe process conditions, hydrothermal upgrading industrial applications are afflicted by various difficulties. It is often necessary to use expensive alloy materials for the process equipment to avoid corrosion, and the high pressures can damage system components. In addition, moving and stirring large volume of biomass slurry creates technical problems.

Moreover, hydrothermal upgrading needs a significant amount of water. Obtaining the water is usually not a problem because the majority of it is in slurry with the biomass feedstock. However, large volumes of waste water, often containing a significant amount of organic material, can lead to high processing or recycling costs. Researchers have tried treating the aqueous by-product through anaerobic digestion, catalytic hydrothermal gasification or as nutrients for algae cultivation but have not yet discovered an optimum solution.

Gasification and syngas cleaning

Brief description

Gasification is a thermochemical process in which biomass is converted into synthesis gas – commonly known as syngas – a mixture of hydrogen, carbon monoxide and other contaminants. The process typically takes place under high pressure and temperatures, and the composition of the syngas varies according to both feedstock and process conditions.

Gasification typically utilises solid or low moisture feedstocks. Industrial activity has specifically concentrated on waste feedstock (including municipal solid waste) and forest residues. Syngas may be used for heat and/or power generation or converted to liquid or gaseous transport fuel via Fischer-Tropsch catalysis, methanol synthesis, mixed alcohol synthesis or syngas fermentation.

Technical parameters, advantages and disadvantages

Several gasification processes have been developed for the conversion of biomass feedstocks. Processes differ in the way biomass is fed into and around the gasifier, the source of oxygen, operating temperature and pressure, and heat source. The main types of gasifiers under development for the production of liquid biofuels are listed in Table 19. Gasification may use a very broad range of feedstock including low cost wastes. With a highly efficient process for the conversion of syngas, gasification pathways may be cost-competitive and produce fuels with very low GHG. Gasifiers could accept feedstocks of variable composition, and this flexibility may be an advantage in terms of accessing the lowest-cost feedstocks.

Downstream processes for converting syngas to liquid fuels often rely on difficult requirements. These concern the composition of the syngas, including the specific hydrogen to carbon monoxide ratio, and the removal of contaminants. The moisture content of feedstocks and the operating conditions influence the proportion of hydrogen, carbon monoxide and CO_2 in the syngas (Karatzos *et al.*, 2014; Bain, 2011). As a waste treatment process, gasification systems incur higher capital and operating costs than straightforward combustion systems, and this presents a barrier to uptake.

Technology status and industrial activity

Several commercial-scale biomass gasification facilities are running or under construction. The majority of these have been built for heat and power generation. Commercial or almost commercial-scale plants are in operation for producing methanol and ethanol. One demonstration plant is producing Fischer-Tropsch liquids.

Technology challenges

A number of key technical parameters in gasification require developing and optimising in order to adequately feed downstream upgrading processes. Reliable methods need to be found for handling and feeding biomass into the gasifier. Improvements are also needed to the feed speed, gasification temperature effects and impact of gasifying agents on product properties. The effects of biomass ash on gasifier performance need to be reduced (Fei Yu, 2012). It should be possible to overcome these technological challenges but they need to be resolved to construct plants that can accept significant fractions of biomass. This will improve the readiness of the technology for commercial application (Hileman *et al*., 2009).

Table 19: Gasifier technology types for liquid biofuel production

Gasifier type	Description	Advantages	Disadvantages	Developers
Entrained flow	Biomass is fed in powered form with pressurised oxygen and/or steam. Some of the biomass is burnt in a flame to provide the required heat. The gasifier is operated at high temperature (1200°C-1500°C) to produce very high quality syngas. Ash from the biomass is discharged as molten slag.	Syngas very low in tar and CO_2. High exit gas temperature.	Extreme feedstock size reduction required Complex operational control Carbon loss with ash Ash slagging	ThyssenKrupp Uhde Karlsruhe Institute of Technology Linde (previously CHOREN) Mitsubishi Heavy Industries
Bubbling fluidised bed	Air, oxygen or steam enters the gasifier through a bed of fine inert material, and biomass enters via another inlet. Some of the biomass is combusted to provide the required heat. The gasifier operates at temperatures of up to 900°C and may operate at elevated pressure. The lower temperature prevents ash from melting.	Relatively low operating temperature	Molten ash can cause agglomeration	Carbona (part of UPM) Foster Wheeler Energy Products of Idaho/Advanced Plasma Power Enerkem ThermoChem Recovery International (TRI)
Circulating fluidised bed	Air, oxygen or steam enters the gasifier through a bed of fine inert material, fast enough to suspend the inert material throughout the gasifier. Biomass is fed through another inlet and suspended. Some of the biomass is combusted to provide the required heat. Syngas is separated from the suspended particles by a cyclone. The gasifier operates at temperatures up to 900°C and may operate at elevated pressure. The lower operating temperature prevents ash melting.	Flexible process Relatively low operating temperature	Corrosion and attrition problems Poor operational control using biomass	Foster Wheeler ThyssenKrupp Uhde VTT Technical Research Centre of Finland Ltd Clausthal Institute of Environmental Technology (Cutec Institute, Germany) Fraunhofer

Gasifier type	Description	Advantages	Disadvantages	Developers
Dual fluidised bed	This system has one gasification chamber and one combustion chamber, with biomass and steam entering the gasification chamber. The biomass is converted to nitrogen-free syngas in the presence of steam. Char enters the combustion chamber, where it is burnt in the presence of air, heating the suspended fine inert material. The inert material circulates the two chambers, providing heat. The gasifier operates at temperatures up to 900°C, and can operate at elevated pressure. The lower operating temperature prevents ash from melting.	Relatively low operating temperature		Vienna University of Technology Güssing Renewable Energy Netherlands Energy Research Foundation
Plasma	Untreated biomass enters the gasifier where it comes into contact with electrically generated plasma. The gasifier operates at very high temperatures of 1,500°C-5,000°C and can operate at atmospheric pressure. The process produces a very high quality syngas and an inert slag from the ash. Note that plasma gasification uses plasma torches. It is also possible to use plasma arcs after gasification as a syngas cleaning process.	Suitable with modular systems High quality syngas Tolerant of heterogeneous feedstocks (such as mixed waste)	High energy demand	Alter-NRG (Westinghouse) Plasco InEnTech / Fulcrum BioEnergy

(Updated from E4tech, 2009)

Methanol synthesis

Brief description

Syngas maybe reacted with a small amount of CO_2 over a catalyst to produce methanol.

Technical parameters, advantages and disadvantages

Methanol synthesis typically takes place at low pressures of 5-10 MPa and within a temperature range of 220˚C-300˚C (E4tech, 2009). It commonly uses a relatively inexpensive copper-zinc oxide (Cu/ZnO) or copper-zinc oxide-alumina ($Cu/ZnO/Al_2O_3$) catalyst. However, by-products can arise from side reactions due to CO_2-carbon monoxide ratios, gas purity and catalyst age. These side reactions lead to the formation of dimethyl ether, methyl formate, ethanol, isobutanol and other by-products.

Technology status and industrial activity

Methanol synthesis technology is well established, and commercial-scale plants are already in operation (TRL 8). Companies such as Haldor Topsøe, Lurgi, Davy Process Technology (owned by Johnson Matthey) and Mitsubishi Gas Chemicals lead in this area.

Two commercial projects currently use bio-based feedstocks. BioMCN has production capacity to convert crude glycerine to 250 million litres per year of methanol in the Netherlands (by cracking instead of gasification). Enerkem has been operating a demonstration plant with annual production capacity of five million litres in

VärmlandsMetanol

The VärmlandsMetanol project in Sweden was due to start production of methanol from forest residues in 2013 but has not yet found all the funding it needs. The start-up date is therefore unknown.

Range Fuels

Range Fuels ceased operating in 2010, and the site designated to demonstrate the gasification and methanol synthesis process in Georgia, US, was subsequently sold. Despite significant public sector funding, the demonstration plant did not achieve full-scale operation due to technical challenges.

Westbury, Canada since 2009. Its first commercial-scale plant, with a capacity of 38 million litres, is in Edmonton and started up in 2015. Further projects are under development in Canada and Europe (Lane, 2015a).

BioMCN is researching the potential to use waste wood feedstocks. It was awarded funding from the European Commission to support the development of a plant with annual production of 500 million litres in the *Woodspirit* project.

Technology challenges

Syngas derived from natural gas and coal has been converted to methanol for some time and is fundamentally suited to biomass feedstocks. The economic feasibility of biomass gasification at high pressure and raw synthesis gas conditioning are the main challenges (EBTP, 2015a). A good deal of research is in progress on reaction conditions and catalysis use in methanol synthesis.

Despite its low cost, high octane number and low well-to-wheel GHG emissions, there are questions concerning the compatibility of methanol with vehicle applications. Some people have thus rejected methanol as a transport fuel in favour of more suitable alternatives (Stark, 2010). Low energy density and poor cold-start properties (avoided by blending with fossil fuels) are two concerns. Methanol is corrosive, and this affects pipeline transport and storage. It is highly soluble in water, which raises contamination concerns similar to ethanol. Both are blended at terminals before being distributed to forecourts to avoid pipeline problems. Nevertheless, particular standards allow and govern methanol blending in Europe, the US and China.

Mixed alcohol synthesis

Brief description

The key product of this catalytic process is a mixture of alcohols, including methanol, ethanol, propanol and butanol (E4tech, 2009). Some developers produce a mix of alcohols for blending whereas others focus exclusively on optimising for ethanol production, selling co-produced alcohols and excess power (E4tech *et al.*, 2011).

Technical parameters, advantages and disadvantages

The process itself is similar to both Fischer-Tropsch and methanol synthesis and often uses catalysts modified from these processes. However, a unique feature of these catalysts is the addition of alkali metals to promote the reaction (E4tech, 2009). One group of catalysts consists of modified high pressure methanol catalysts (alkali-doped ZnO/Cr_2O_3 operating at 12-25 MPa) or low pressure (alkali-doped Cu/ZnO or $Cu/ZnO/Al_2O_3$ operating at 5-10 MPa), operating at temperatures of 250°C-425°C. The second group is based on modified Fischer-Tropsch catalysts (alkali-doped $CuO/CoO/Al_2O_3$) operating at 5-10 MPa and 260°C-320°C. Further catalysis based on ZrO_2 and molybdenum has been investigated, as well as alkali-doped sulphide catalysis. The catalyst composition and reaction conditions determine the alcohol product distribution (Andersson, 2015). A number of by-products may arise in side reactions, including methane, short paraffins and olefins. Oxygenated by-products such as aldehydes, esters and ethers may also be formed depending on the catalyst and operation conditions (Andersson, 2015).

Mixed alcohols have lower vapour pressure and better solubility than methanol when blended with petrol, as well as a greater energy density. These are the key drivers for developing mixed alcohol synthesis. The environmental impact of oxygenates in gasoline increased interest in mixed alcohols in the 1990s.

Technology status and industrial activity

Mixed alcohol synthesis has only been developed and tested at pilot scale (TRL 5 to 6). Dow, Lurgi, IFP and Snamprogetti/Haldor Topsøe, have in the past been the main players in mixed alcohols synthesis. However, most only demonstrated their technologies at pilot scale (including using natural gas or coal) and few are still working in this area. There are currently no known developers working on mixed alcohols liquids routes; they have either failed or shifted their focus to other synthesis options. Fulcrum Bioenergy, for example, is now concentrating on Fischer-Tropsch synthesis.

Technology challenges

Despite the attractiveness of mixed alcohols as a blending stock and their desirable physical properties, no commercial plants are in operation. The route suffers from low yields and poor selectivity. Single-pass yields amount to around 39% for carbon monoxide conversion to alcohols, and methanol is usually the dominant product (Phillips *et al.*, 2007). Research needs to increase the single-pass carbon monoxide conversion and the selectivity to alcohols. It also needs to reduce the operating pressure to significantly lower production costs, and reactor designs need to improve for more precise temperature controls (E4tech *et al.,* 2011).

Fischer-Tropsch synthesis

Brief description

Fischer-Tropsch synthesis is a catalytic process which converts syngas to range of hydrocarbons (including methanol and liquid alkanes) for subsequent upgrading to diesel, naphtha and jet fuel. These are used as fuels in road transport, shipping and aviation.

Technical parameters, advantages and disadvantages

Fischer-Tropsch synthesis typically takes place at pressures of 1-4 MPa and within a temperature range of 200˚C-250˚C or 300˚C-350˚C (E4tech, 2009). It uses specialised catalysts – most commonly cobalt and iron. Together with the temperature, these influence the hydrocarbon produced. Iron catalysts and higher temperatures produce a lighter gasoline product while cobalt catalysts and lower temperatures produce waxy, long-chained products that can be cracked to diesel.

Solena Fuels

Solena Fuels was planning to develop several Fischer-Tropsch plants around the world to produce aviation fuels from waste. It produced co-operation agreements with airlines SAS in Sweden, Alitalia in Italy, Quantas in Australia, and a partnership with British Airways to develop the first plant in London (GreenSky).

However, the company recently filed for bankruptcy in the US, citing failing oil prices as a contributing factor. In the UK, British Airways also indicated that the GreenSky project may have failed due to lack of government support for aviation biofuels.

Fischer-Tropsch processes have tight specifications for syngas composition. These include a specific ratio between hydrogen and carbon monoxide, very low limits to sulphur content and limits to tar content. Minimising the content of non-reactive gases like nitrogen and methane is also an advantage because these increase equipment size and cost (E4tech, 2009). Fischer-Tropsch synthesis produces a high quality, low-sulphur fuel.

Technology status and industrial activity

The Fischer-Tropsch process is well established and has been operating commercially for decades. However, the use of biomass as a feedstock is fairly new and a limited number of plants are operating. These are the pilot and demonstration plants at TRL 5-6.

Fulcrum BioEnergy is focusing on the production of jet fuel and diesel using municipal solid waste feedstocks. In 2013 Fulcrum successfully tested its process at pilot scale (Fulcrum BioEnergy, 2013). They are yet to start constructing a commercial-scale plant – the Sierra BioFuels Plant, which was due to start up in 2017. This plant is expected to process around 82,000 tonnes per annum of prepared municipal solid waste feedstock into more than 40 million litres jet fuel or diesel (Fulcrum BioEnergy, 2015).

The BioTfueL project will see the construction of two gasification demonstration plants in Europe to produce renewable diesel and jet fuels. Project partners include ThyssenKrupp Uhde, who will supply their PRENFLOTM™ gasification platform, and the Axens Fischer-Tropsch synthesis process (Peckham, 2014).

Velocys has developed small-scale microchannel Fischer-Tropsch reactors using super-active cobalt catalysts (Velocys 2015a, 2015b). In 2010 this technology was successfully demonstrated in Güssing, Austria (Velocys, 2015a). Red Rock Biofuels plan to use Velocys technology in Oregon, US, to convert forestry waste to 45 million litres of diesel, naphtha and jet fuel (Culverwell, 2015). There are other prominent Fischer-Tropsch technology providers, such as Shell and Sasol. However, they are prioritising fossil feedstocks and currently have no operations or projects focusing on biomass.

Technology challenges

Fischer-Tropsch synthesis processes are well established for converting fossil fuels but applying the technology to syngas derived from biomass remains technically challenging. One key problem is how to process a more heterogeneous biomass feedstock, which currently results in lower quality syngas. Another is the smaller-scale operation associated with biomass (compared to fossil fuel), which is being addressed by technologies such as Velocys micro-channel (Karatzos *et al.*, 2014). The next step towards commercialisation is the reliable operation of integrated demonstration plants.

Catalyst design improvements are also required to optimise product selectivity and increase catalyst lifetimes with less catalyst decay. Other technical challenges include increasing carbon utilisation in the syngas conversion, promoting the overall rate of conversion to liquid fuels (Fei Yu, 2012). Catalyst and syngas clean-up improvements will deliver more reliable processes and should reduce production costs, improving the economics of small-scale plants (Arup *et al.*, 2014). Research is under way to minimise the cost associated with the temperature and pressure changes that take place during each step of the process. These shifts between high and low temperature and/or pressure increase capital costs because additional equipment such as gas compressors is required. The fluctuations increase energy losses.

Syngas fermentation

Brief description

Syngas may be fermented to ethanol and other biofuels or intermediates (including butanol, acetic acid, and 2,3 butanediol) using micro-organisms which act as biocatalysts. Potential micro-organisms include both aerobic and anaerobic species (such as the species *Clostridia*) (Daniell *et al.*, 2012; Karatzos *et al.*, 2014). Several companies are developing proprietary fermentation organisms and combinations of trace minerals, metals and vitamins which serve to direct and optimise energy flows within the pathway, maximising product production (Advanced Biofuels USA, 2011).

Technical parameters, advantages and disadvantages

Syngas fermentation typically takes place at very low temperatures of 20 °C-40 °C and pressure of 0.1-0.2 MPa, resulting in potentially low production costs (E4tech, 2009). A further advantage of the process is the higher tolerance of fermentation organisms to the syngas ratio and contaminants (compared to catalysts). However recent experience at the Ineos Bio plant highlighted problems with high levels of hydrogen cyanide in the syngas, which affected the syngas fermentation (Lane, 2014b).

Technology status and industrial activity

A handful of companies are working to commercialise different technology platforms and microbial strains for the syngas fermentation process. INEOS Bio's technology platform uses anaerobic bacteria to produce ethanol (Chetna, 2014; IneosBio, 2015). In 2013 INEOS Bio opened a commercial demonstration facility in Florida with annual production of 30 million litres. However, commissioning has taken two years due to syngas purity concerns. The plant also exports 6 MW of

Coskata

Coskata operated a demonstration facility in Pennsylvania, US, using wood and municipal solid waste. However, it has abandoned plans to scale up the biomass process, concentrating instead on natural gas opportunities.

renewable electricity. LanzaTech has developed a gas fermentation process to produce ethanol (and other platform chemicals) from industrial waste gases using proprietary microbes (including *C. autoethanogenum*). The platform is able to utilise gases containing hydrogen and carbon monoxide and possibly smaller amounts of CO_2 (LanzaTech, 2014). The first target market for LanzaTech is non bio-based fuels (*e.g.* waste gases from coal-based steel mills) but the technology may be combined with biomass gasification in the future.

Technology challenges

Processes that operate within a continuous closed loop, enabling water and nutrient recycling, could improve efficiency and reduce production costs (Daniell *et al.*, 2012). Syngas fermentation involves a gas to liquid mass transfer so bioreactor designs aim mainly to improve the gas to liquid contact surface area to improve mass transfer. Syngas fermentation processes report lower product concentration than traditional fermentation. This means energy demand in the separation phase may be higher. Improved titres and/or novel low energy separation processes may improve process performance and production costs. Current primary research includes microbial strain development especially aimed at the *Clostridia* species (Yanwen, 2013), fermentation parameters (temperature, pH etc.), and bioreactor design and configuration (for efficient mass transfer and high cell density).

Sugars to hydrocarbons

Brief description

The term ‘sugars to hydrocarbons’ encompasses a range of conversion technologies aiming to convert the sugars naturally found in biomass directly to useful hydrocarbon fuels such as kerosene and diesel. There are two broad conversion routes – biological and chemical – both of which will be discussed in this section.

Technical parameters, advantages and disadvantages

Biological sugar-to-hydrocarbon pathways use micro-organisms, which can be genetically engineered, in order to produce alternative hydrocarbons from sugars. Chemical routes usually involve catalysts and elevated temperatures (MIT Technology Review, 2008). The conversion processes generally produce intermediate products that still contain double bonds or oxygen and must be hydro-treated to produce a finished fuel.

The finished fuels are more easily integrated than alcohols into current refuelling infrastructures and can potentially produce jet fuels. However, technology development is targeted at conventional sugar feedstocks rather than biomass feedstocks. Significant development will be required for sugars to hydrocarbons technology to be compatible with lignocellulosic feedstocks.

Technology status and industrial activity

Amyris and Total appear to have the most advanced commercialisation of a sugars to hydrocarbons technology. They use genetically modified yeast strains to produce farnesene, which is then upgraded to jet fuel through hydroprocessing (International Civil Aaviation Organisation, 2014). Amyris has a production plant in Brazil called Brotas which can produce 40,000 tonnes per year of farnesene. The company currently sells renewable diesel in Brazil and renewable jet fuel to airlines throughout the world. DSM and BP were also in a partnership to develop biodiesel using micro-organisms but the joint venture was discontinued in 2014 (Lane, 2014a).

Technology challenges

In biological conversion routes, the micro-organisms require oxygen to respire aerobically. However oxygen is only sparingly soluble in aqueous solutions, and keeping the reaction mixture sufficiently aerated is a significant problem that may limit the size of the reaction vessels (NREL, 2013).This problem could be overcome by developing anaerobic bacteria that can transform the sugars into hydrocarbons but this work is at a very early stage.

LS9

LS9 developed a biological conversion route from sugars to diesel that was recently sold to Renewable Energy Group. The new owners of the technology have chosen to focus on the production of higher-value speciality chemicals (MIT Technology Review, 2014).

In addition, using genetically modified bacteria in biological conversion routes could limit the sale of by-products. Industrial development has struggled to improve sugar to oil mass yields much above 20%. As with all biological processes, the micro-organisms are very sensitive to reaction conditions. Genetically engineering them can have unpredictable effects on their industrial resilience.

Catalytic conversion of alcohols (including alcohols-to-jet)

Brief description

Short chain alcohols, including methanol, ethanol and butanol, may be catalytically converted to gasoline, diesel and jet fuel. The conversion involves combining several known processes: dehydration, oligomerisation, hydrogenation and distillation.

Technology parameters, advantages and disadvantages

In the dehydration step, one- to four-carbon alcohols react in the presence of a catalyst (*e.g.* zeolite or metal oxide) to produce one- to four-carbon alkenes and water. Depending on the alcohols used, process temperatures range between 170°C-200°C (Wollrab, 2009). The next step is oligomerisation, which converts short carbon chains into longer carbon chains. The reaction is catalysed, and process conditions depend both on the catalyst and alcohol(s). Typical conditions are 80°C-200°C and 7-25 MPa (Klemps, 2009; Martens, 2000).

The aim of the hydrogenation step is to create alkanes from the mixture of hydrocarbons obtained from oligomerisation through the addition of hydrogen. Catalysts for the reaction include nickel, platinum or palladium (Wollrab, 2009). The reaction can operate at ambient temperature and pressure or at elevated pressures and temperatures (20-35 MPa and 150°C-200°C) (Wollrab, 2013), depending on the catalyst.

Technology status and industrial activities

Gevo, Cobalt Technologies and NAVAIR are working on butanol-based processes for the production of longer-chain hydrocarbon fuels. Gevo is working on the conversion of isobutanol to synthetic paraffinic kerosene for aviation, demonstrated at around 360 000 litres per year (Balzer, 2014).

Byogy Renewables is working on an ethanol-based pilot process (Lane, 2014c). Swedish Biofuels is also running a pilot plant at the Stockholm Royal Institute of Technology. The plant has an annual capacity of 12 500 litres, and it has been awarded EU funding to support the construction of a demonstration plant with an annual capacity of six million litres (Swedish Biofuels, 2012).

Technical challenges

The catalysts for each stage: dehydration, oligomerisation and hydrogenation, are commercially available and applied in the chemical industry (in styrol and olefin production, for example) (Baerns, 2013; Steinborn, 2007). For this specific application, the technical challenges are to improve conversion yields and selectivity towards the desired product to reduce production costs.

Algae production, extraction and conversion

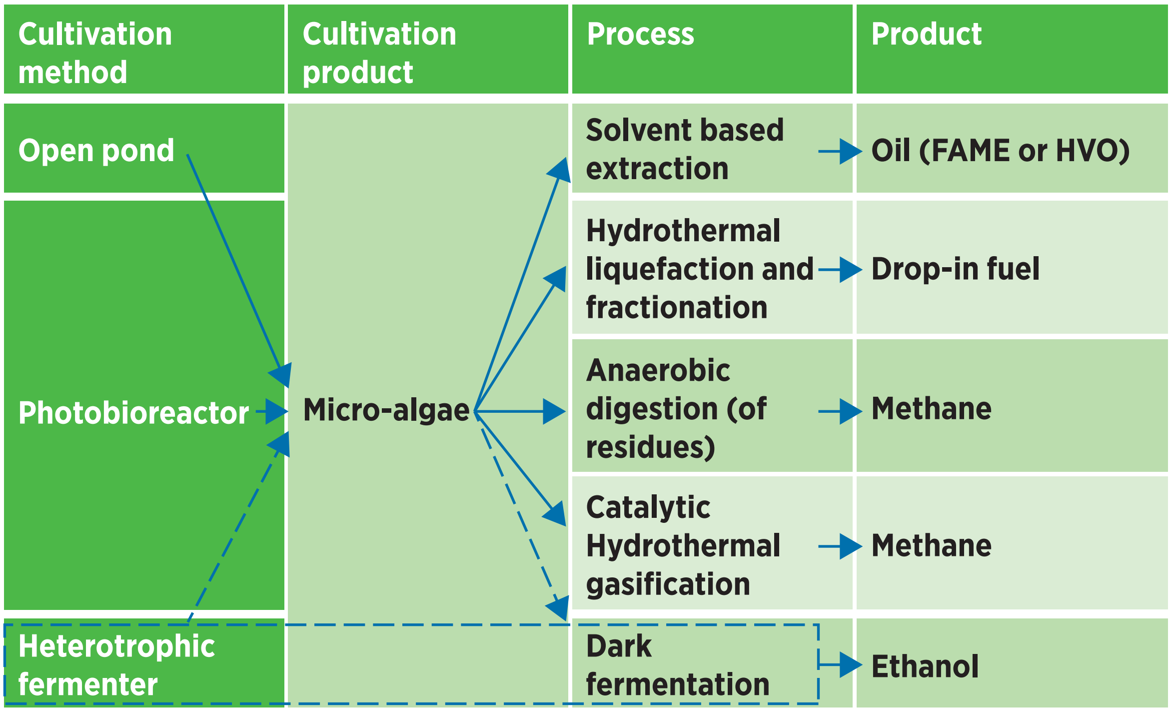
Brief description

Micro-algae are single- or multi-cellular organisms and are able to capture CO_2 directly from the atmosphere and convert it to ethanol and/or lipids, which are then used to produce fuel.

There are multiple steps in algal feedstock processing. The section below briefly covers production (cultivation and harvesting), extraction and conversion. It does not cover downstream processing, as most of the technologies used are well established (transesterification and hydroprocessing) or covered elsewhere in the technology assessment (gasification and pyrolysis).

As shown in Figure 30, a cultivation environment is selected once the algal strain has been chosen. For Micro-algae this is either an open (*e.g.* raceway pond) or closed environment (*e.g.* photobioreactor).

Figure 30: Selected algae cultivation and conversion technologies



(Source: E4tech, 2014)

Open ponds

In this method, micro-algae are cultivated in large open ponds, in which water and CO_2 are circulated to encourage growth. Harvesting occurs through continuous settling followed by gravity thickening.

The advantage of this cultivation method is the relatively low cost. Nevertheless, the system design needs to be improved and the cost of major system components reduced in order to scale the process up. Energy costs from harvesting, concentrating and dewatering algae need to be lowered, and grazer losses caused by the open environment reduced (E4tech, 2014). There are also geographic location constraints.

Photobioreactors

Micro-algae can also be cultivated in a closed environment like a photobioreactor. Typically this is a tubular design supplied with water, CO_2, light and nutrients, in which the algae grow. This closed environment protects the algae from pests and grazers.

Advantages include a high yield per area and no water evaporation. There is also wider geographic suitability than that provided by open ponds. Challenges include high capital costs, energy consumption and mechanisms to keep the inner wall of the photobioreactors clean for effective light penetration. Most algae produce protein for their cell wall membrane, which sticks to the inside of the photobioreactor, blocking the incoming light. Algae grown in some commercial photobioreactors in Israel lack this type of membrane and so do not produce these proteins. However, these algae are not suitable for biofuel production. Disposable bags are one solution in use and under further investigation (E4tech, 2014).

Heterotrophic bioreactors

In contrast to autotrophic algae, heterotrophic algae use sugar as a source of carbon and require no light. These sugars are metabolised by the algae into triglycerides of similar composition to vegetable oils, which can then be converted to biofuels via established processes. However, only a few known micro-algae species adapt to heterotrophic cultivation, and most of them belong to the genus *Chlorella* (Rem, 2013). Early commercial dark fermentation processes use sugar cane as a feedstock but organic wastes are also theoretically possible (E4tech, 2014).

Unlike other methods, there are no geographical limitations to this process because it has no light or temperature requirements. The space required for this technology is also lower than the space necessary for open ponds. However, challenges include technology cost reductions relative to other routes to ethanol production, and developing the technology to use waste sugars rather than conventional sugar sources (E4tech, 2014). Research is also under way to identify and develop new algal strains with high lipid content and suitable carbon sources to maximise cellular composition (IEA, 2011).

Following cultivation, algae is harvested and concentrated. A number of harvesting techniques are used which could be appropriate to particular species or more widely applicable. Harvesting methods include sedimentation or flocculation, centrifugal de-watering, membrane filtration and screening. Harvesting techniques currently in use include (IEA, 2011):

- Filtration using screens with openings >25 microns used for filamentous algae *e.g.* spirulina;
- Simple sedimentation used for *H. pluvialis* after it reaches the red cyst stage;
- Absorption on a hydrophobic material (polystyrene) attached to an iron filament, which is then captured on a high-gradient magnet. Used for harvesting *Dunaliella* in Australia.

Oil extraction, which separates various components of the algal cell, may occur through various physical, chemical and enzymatic mechanisms. Finally, the oil is processed in order to produce a variety of transport fuels, including FAME biodiesel, renewable gasoline, diesel and jet fuel.

Technical parameters, advantages and disadvantages

Algal feedstocks offer the potential for higher environmental performance than land-grown biomass. They show high biomass productivity per hectare and are suitable for cultivation in salt, brackish and fresh water and on non-arable land. Micro-algae production costs are very high, with cultivation currently limited to high value products such as cosmetics.

Technology status and industrial activity

Algal fuel development is largely at demonstration stage, and only one technology developer has reached commercial scale. Solazyme pioneered the heterotrophic algae process and is the largest global producer of algal oil (Solazyme, 2015b). The company has three production facilities, the first of which (Peoria) was developed to demonstrate biofuels production, with installed capacity of over 2 million litres per year. Its joint venture, Solazymes Bunge Produtos Renováveis, operates a commercial-scale plant in Brazil for producing algae oils for higher value markets (not biofuels). Its annual installed capacity is 100 million litres. Another oil-producing plant, based in Clinton, US, has an annual capacity of 20 million litres with 100 million litre expansion potential (Solazyme, 2015c).

Technology challenges

Algae present a technically feasible means for biofuel production, and numerous pilot projects are in progress. However, significant innovation is required to improve production reliability and reduce production costs to competitive levels. Research needs to identify production chains with net energy output, high production rates and oil yields. This may be achieved by optimising strains through breeding or genetic modification. For the photosynthetic routes, the challenge remains to increase the photo efficiency of algae under real-life conditions (E4tech, 2014; IEA, 2011).

ANNEX B

PROJECT INVENTORY

The project inventory is available at:

http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=2741

ANNEX C

FEEDSTOCK ASSESSMENT

Feedstock meta-analysis

The following categories are frequently defined in advanced biofuels production and used within this study:

- **Solid biogenic waste:** the definition and classification of biogenic wastes is not consistent across the literature. Typically this category includes solid industrial biogenic waste, the biogenic fraction of municipal solid waste and garden waste (including household, park and roadside maintenance collection).
- **Agricultural residues:** post-harvest residues like straw and corn stover, and processing residues such as bagasse, husks, shells and cobs.
- **Forestry residues:** woody biomass residues from forestry activities including branches and leaves, and residues from wood processing such as sawdust and cutter shavings.
- **Non-food energy crops:** typically wood and grass crops, including short rotation coppice (*e.g.* poplar and willow) and energy grasses (*e.g.* switchgrass, miscanthus and reed canary grass).
- **Algae:** this category refers to algae with a high lipid content. These are primarily micro-algae grown in dedicated systems like open ponds or photobioreactors.

The references used for the feedstock analysis are summarised in Table 20. Differences in the methodologies applied and categories of potential considered have a significant impact on the final potentials. Most of the studies assessed present technical potentials.

Table 20: Feedstock assessment reference details and type of potential

Source	Geographical scope	Timeframe	Type of potential					Feedstocks covered				
			Theoretical	Technical	Economic	Sustainable	Other	Solid biogenic residues/ wastes	Agricultural residues	Forest residues	Non-food energy crops	Algae
Berien Elbersen 2012	EU 27	2020, 2030				X		X	X	X	X	
Bentsen 2014	Global	2006-2008	X						X			
Beringer 2011	Global	2004, 2025, 2050					X				X	
German Federal Ministry of Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung) 2010	Global (134 countries)	2015, 2020, 2050				X	X					
de Wit 2010	EU 27 + Ukraine	2010, 2020, 2030				X			X	X	X	
E4tech 2014	EU, global	2013, 2020					X	X	X	X	X	
Petersen/European Environment Agency	EU	2006, 2013, 2020		X		X	X	X		X	X	
Erb 2012	Global	2050		X	X	X	X				X	
Esteban 2011	EU (11 countries)	1996-2007		X			X		X	X		
Gallagher 2003	US	n.a					X		X			
Gallagher 2012	US	n.a					X		X			
Gregg 2010	Global	2005		X					X	X		
Haberl 2011	Global	2050		X		X		X	X	X	X	
Haberl 2011a	Global	2050				X					X	
He 2014	US	2015, 2020, 2025, 2030					X			X		
Hoogwijk 2009	Global	2000-2050				X					X	

Source	Geographical scope	Timeframe	Type of potential					Feedstocks covered				
			Theoretical	Technical	Economic	Sustainable	Other	Solid biogenic residues/ wastes	Agricultural residues	Forest residues	Non-food energy crops	Algae
Pat Howes 2011	UK, global	2010, 2015, 2020, 2025, 2030		X				X	X	X	X	
Searle, S. and Malins C. (2013)	EU	2011, 2020, 2030		X				X	X	X		
Institute for Energy and Environment Research (Institut für Energie- und Umweltforschung) 2008	EU, global	2000-2040		X		X	X	X	X	X	X	
International Institute for Sustainability Analysis and Strategy 2014	EU	2010, 2020, 2030	X	X		X				X		
Chum 2011	Global	2050		X				X	X	X	X	
IRENA 2014	Global	2030					X	X	X	X	X	
IRENA_2013b	Africa	2013, 2015, 2020, 2050, 2100		X	X		X	X		X	X	
Panoutsou 2009	EU 27	2000, 2010, 2020		X				X	X	X	X	
Panoutsou 2011	EU 27	various		X					X	X	X	
Ladanai, S. and Vinterbäck, J. (2009)	Global	2050	X						X	X	X	
Smeets 2007	Global	2050					X			X		
Smeets *et al.* 2007	Global	2050	X	X	X	X		X	X	X	X	
Takeshita 2011	Global	2050					X					X
Zeddies, J. (2012)”	Global, EU	various		X	X	X		X	X	X	X	
Slade, R. (2011)	Global	2050	X	X	X		X	X	X	X	X	
Van Harmelen 2014	Global	2020					X					X

Note: brackets indicate the source is a review of previous literature

Feedstock potentials

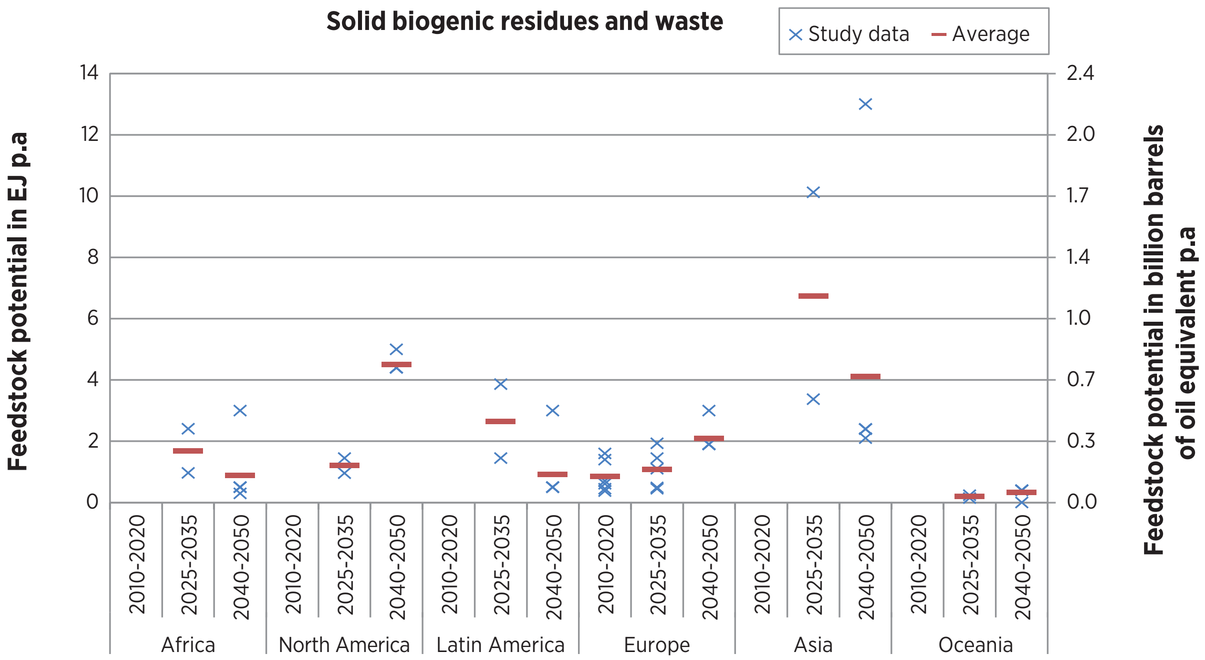
The potential availability of advanced biofuel feedstocks in different regions of the world is shown in Figure 31 to Figure 35. A global summary is presented in Figure 36. This data is estimated on the basis of a meta-analysis of existing studies as well as interviews with experts in the field.

Estimates of the global potential for all feedstocks considered range between 3.4 and 40 billion barrels of oil per year (equivalent to 20-233 EJ), and between 4.3 and 200 billion barrels of oil per year in 2050 (equivalent to 25-1,180).

Solid biogenic waste: current technical biomass potential is estimated at 2-10 EJ per year on a global scale with a potential to increase to 9-27 EJ per year in the next three decades (Figure 31). This is the category with the lowest potential overall. Nonetheless, it is significant and attractive because of its concentration, collection and disposal, and low competing uses. The projected increase in time is mainly due to the increasing population and expanding waste collection infrastructure. Nevertheless, the use of wastes needs to be considered in the context of a waste minimisation, reuse and recycling strategy.

Forest residues: at present global annual forest residue potential is estimated at 2-11 EJ with significant increases forecast in some references over the next three decades to 5-100 EJ per year (Figure 32). The potential for forest residues is lower than for agricultural residues but is also substantial and concentrated in areas with large commercial forestry activities. Growth in the resource is linked to growing demand for forest products but constrained by the economic and sustainable extraction rates. In the case of managed but non-commercial forests, access to forest residues may be restricted by the collection and transportation infrastructure.

Figure 31: Global estimates of solid biogenic residue and waste feedstock potential, 2010-2050 [10] *(EJ per year, based on lower heating values)*



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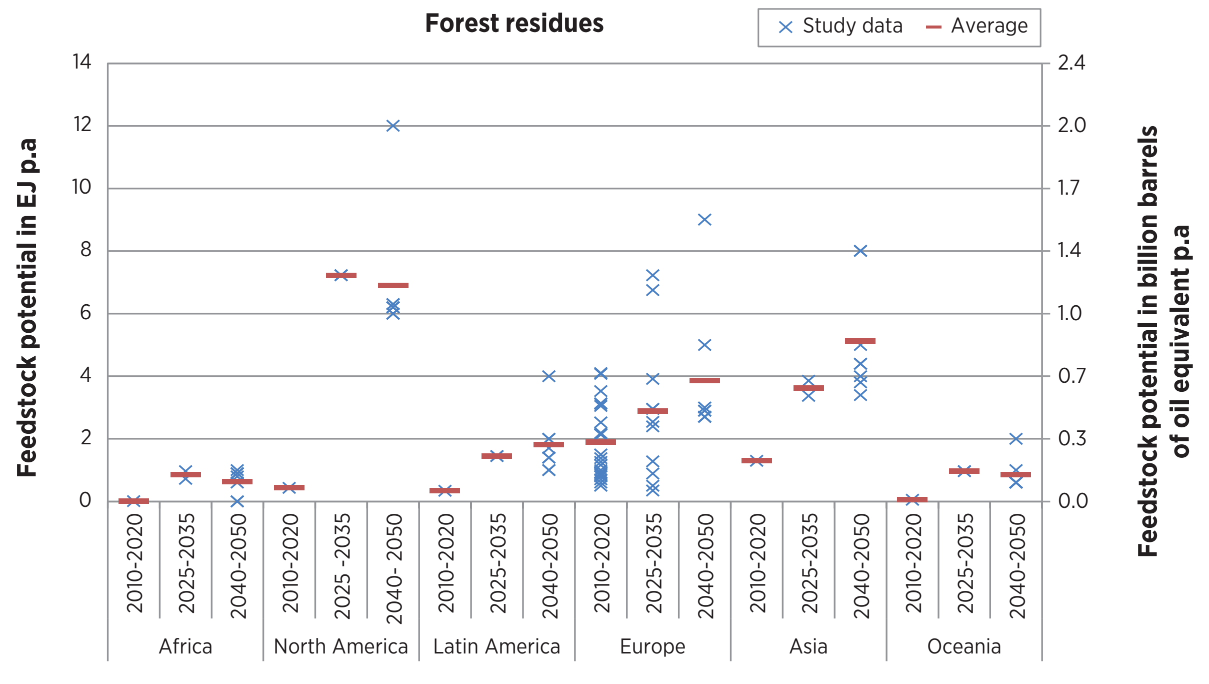
[10] For the graphs in this section, 'average' refers to the arithmetic average as per the studies cited.

Figure 32: Global estimates of forest residue feedstock potential, 2010-2050 (EJ per year, based on lower heating values)



Agricultural residues: the current potential from agricultural residues is estimated at 16-48 EJ per year on a global scale with the potential to increase to 10-300 EJ per year over the next three decades. This is linked to the increased demand for food and feed (Figure 33). Agricultural residues are a potentially

Figure 33: Global estimates of agricultural residue feedstock potential, 2010-2050 (EJ per year, based on lower heating values)

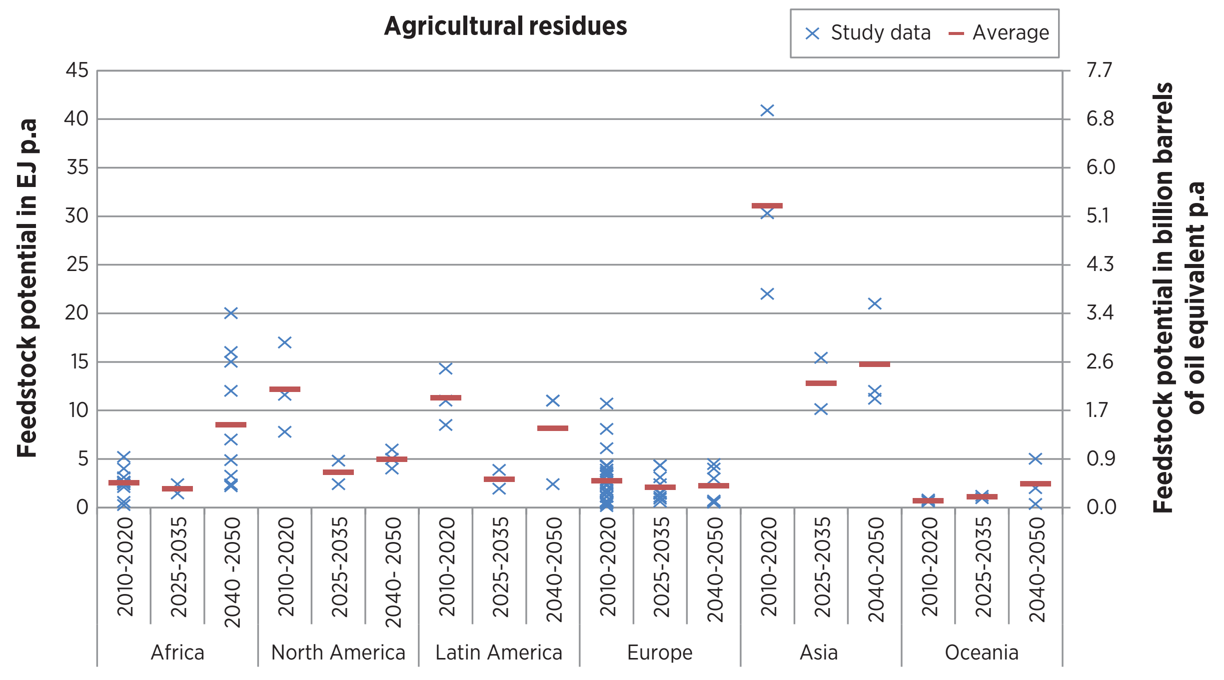
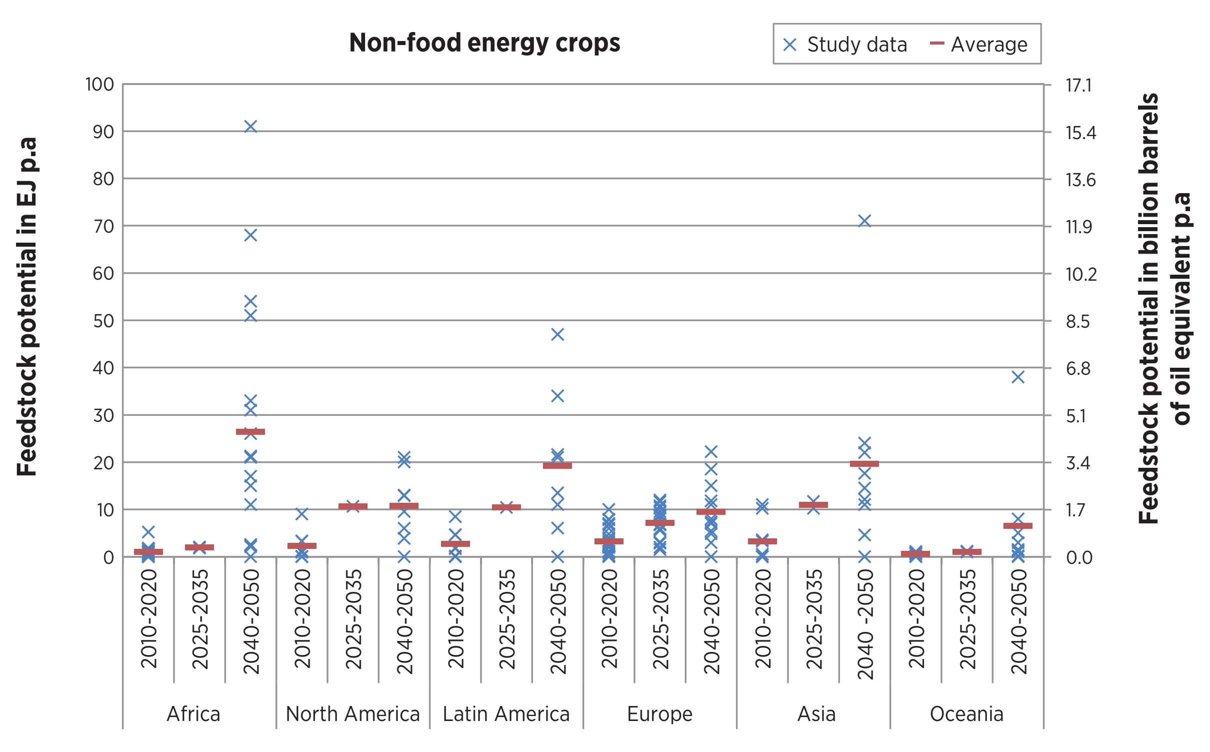


Figure 34: Global estimates of energy crop feedstock potential, 2010-2050 (EJ per year, based on lower heating values)



very large source of feedstock and may be the largest biomass resource depending on the potential for energy crops. However, a fraction of the residues needs to be left in the field to maintain soil structure and fertility – a constraint that needs to be considered. At present, Asia, Latin and North America provide significant potential. In future, potential in Africa may grow significantly.

Non-food energy crops: non-food energy crop potentials show the widest range due to differences in methodology, especially in assumptions on land availability and environmental constraints. This includes, for instance, the amount of land required for food production, water availability and sustainable soil management. The current global potential of energy crops is estimated at 0-164 EJ per year (**Fehler! Verweisquelle konnte nicht gefunden werden.**) demonstrating their major potential but also the considerable uncertainty surrounding these estimates. The potential is forecast to increase to 0-700 EJ per year over the next three decades, with the greatest future potential in Africa and Latin America.

Algae: the estimation of feedstock potentials from algae cultivation is very uncertain because the cultivation systems are still under development. Nevertheless, future potential from these sources is estimated at 0-50 EJ per year in the next three decades (Figure 35). The global algae cultivation potential is limited by the availability of land with sufficient irradiation and by access to water and nutrients.

The regional feedstock potentials in Figure 31-Figure 35 are summarised in Figure 36 at the global scale. Despite the wide variation between these estimates, many studies agree that substantial volumes of biomass will be available in the longer term without compromising food demands. The IPCC reports that this potential will amount to at least 100 EJ of energy in 2050 – or a fifth of current global primary energy demand (Smith *et al.*, 2014). With performance monitoring, further development of the most attractive biomass supply chains will lead to increasing knowledge of their potential, particularly in the case of energy crops. This could improve future estimates of global and regional bioenergy potential (Slade *et al.*, 2014).

Figure 35: Global estimates of algae feedstock potential, 2010-2050 (EJ per year, based on lower heating values)

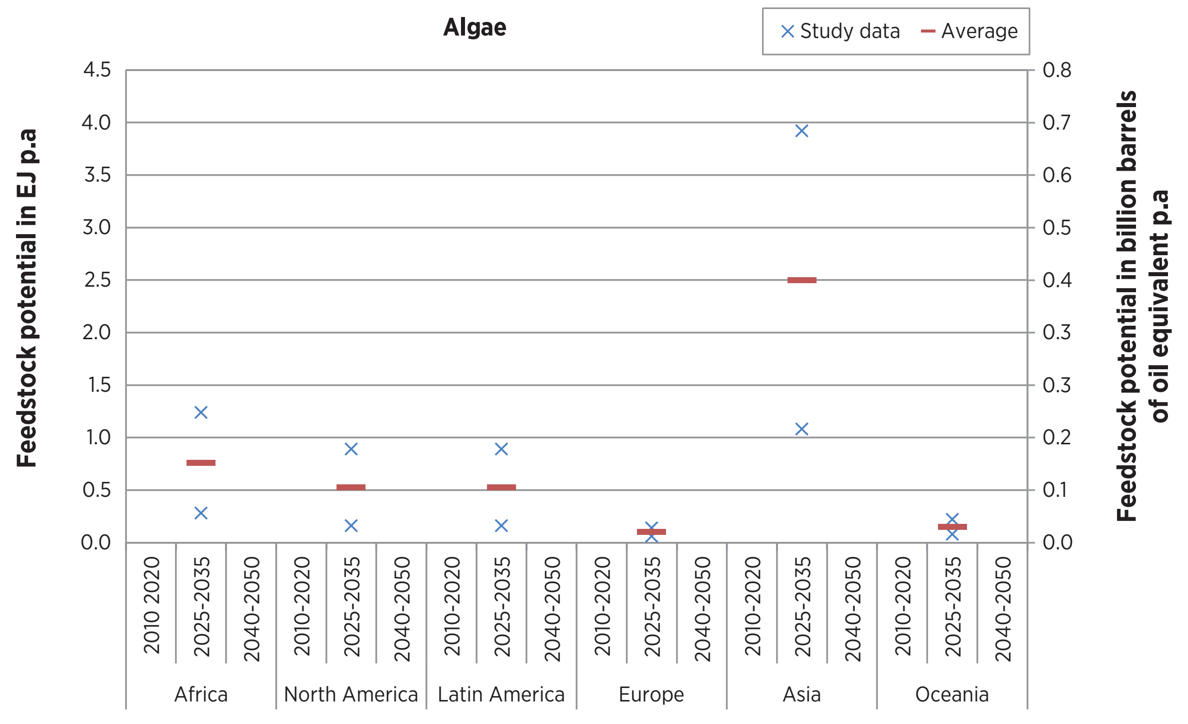
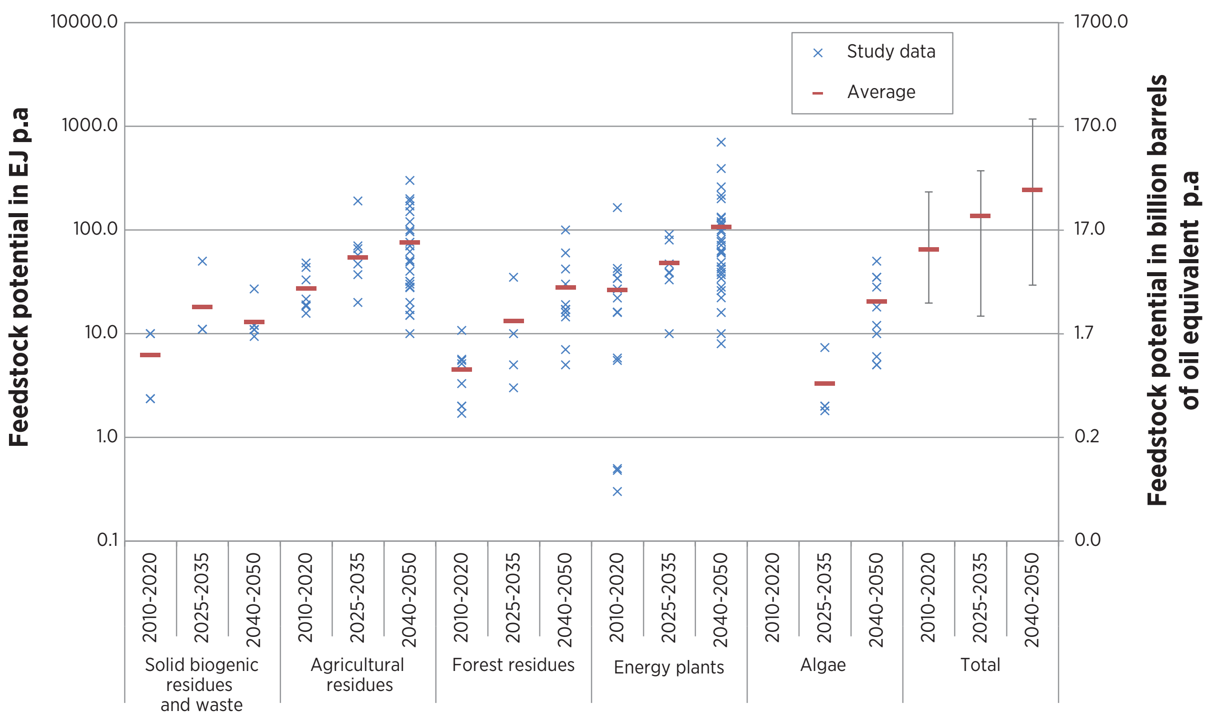


Figure 36: Summary of global estimates of key biomass feedstock potentials (EJ per year, based on lower heating values)



Competing uses

Competing uses are important in determining the amount of resource that could be destined for a certain use. The economic and sustainability potential should take competing uses into consideration to different degrees. The descriptions below provide an illustration of the main competing uses for the different feedstock categories.

- **Solid organic residues and waste:** valuable uses of the biogenic fraction of post-consumer waste include the production of heat and/or power. This occurs either directly in an incineration plant, for example, or following pre-treatment to produce a refuse-derived fuel. Fractions such as paper and cardboard can be recycled, and green waste processed and returned to fields.
- **Agricultural residues:** valuable uses of agricultural residues include heat and power production and use as animal feed and bedding. It is necessary to include a proportion of agricultural residues in the soil to maintain its structure and nutrient content. The precise amount of residues required to maintain soil quality varies according to specific location.
- **Forest residues:** valuable uses of forest residues include heat and power production. This applies particularly to residues like sawdust for pellet production, animal bedding, and the paper and board industry. Forest residues are also left in the forest to maintain and improve soil quality.
- **Non-food energy crops:** non-food energy crops are used for heat and/or power generation, and smaller quantities are used for animal bedding. Non-food energy crops may compete for land with other crops.
- **Algae:** alternative uses of algae are currently limited to high value products such as feedstocks for the cosmetics industry.

Feedstock costs

The production or collection costs of various sustainable feedstocks in regions around the world are summarised in Figure 37. These data are estimated on the basis of a meta-analysis of existing studies as well as interviews with experts in the field.

For **solid biogenic waste,** costs largely depend on the type of waste, alternatives for its disposal and any potential uses. However, wastes will generally be available at a negative cost *i.e.* biofuel plants could be paid to receive the waste. Concrete cost information for solid biogenic waste is very scarce: at present, European data ranges widely at USD-2.8-9.3 per gigajoule (GJ), largely depending on the type of waste (Brinsmead, 2014; Panoutsou, 2009).

Similarly, the cost of **agricultural residues** will generally be low, reflecting collection and transport costs. However, there may be cases where prices are relatively high due to local competition and limited supply for other uses (*e.g.* use of straw for animal bedding). At present, the agricultural residue cost range is USD 1.8-3.7/GJ (Bain, 2007; de Wit, 2010; Gerssen-Gondelach, 2014; IRENA 2014; Panoutsou, 2009).

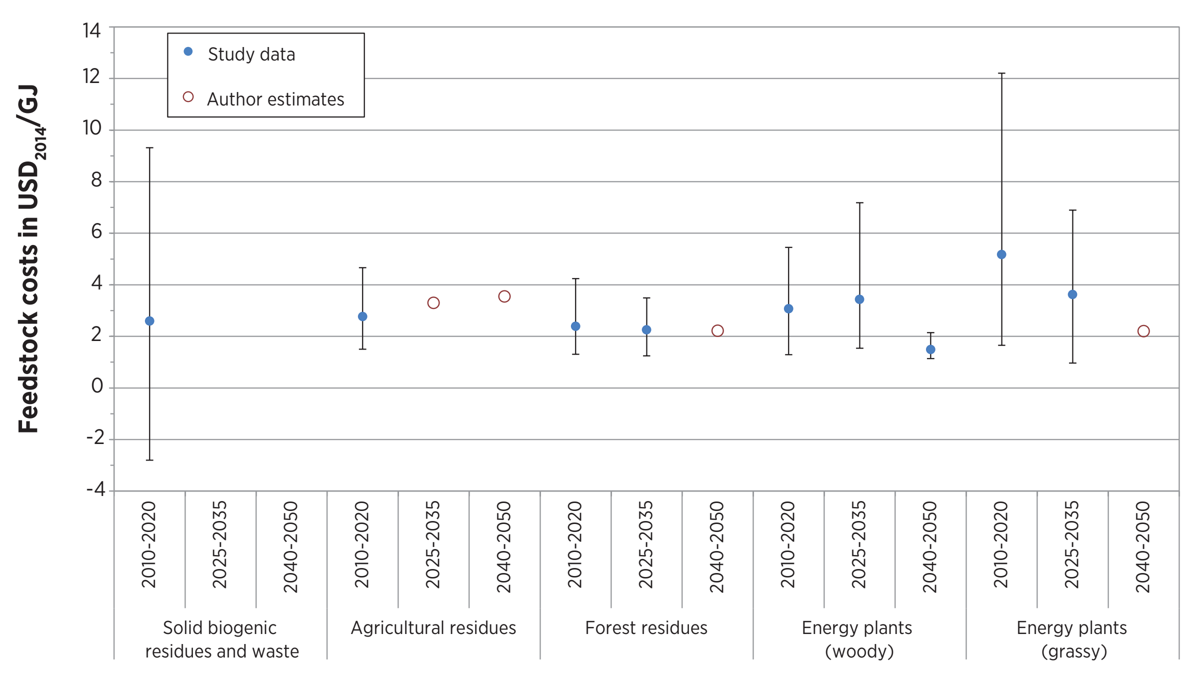
Current **forest residue costs** are relatively low but they benefit from an established and growing market in heat and electricity generation. The cost range is USD 2.3-2.9/GJ (Gerssen-Gondelach, 2014; Panoutsou, 2009; Brinsmead, 2014).

Supply chains for dedicated non-food **energy crops** are at an early stage of development so there are major deviations in cost estimates due to differences in yields between crops and regions. Significant data are available for woody energy plants like short rotation coppice poplar and willow, which have a cost range of USD 2.4-4.3/GJ (Brinsmead, 2014; de Wit, 2014; Gerssen-Gondelach, 2014). Forecasts of energy crops show costs decreasing in all regions down to USD 1-1.6/GJ in the next three decades. Costs are estimated to fall to around USD 3/GJ in the next three decades.

Algae appear to be the most expensive feedstock, with cultivation currently limited to high value products for the cosmetics industry, for example. Only limited cost data are available for algae cultivation on a regional basis. It is assumed that costs realised by optimised reactor systems and harvesting methods will be reached by 2040-2050. Cost projections based on optimised cultivation systems are USD 31-166/GJ.

Figure 37 illustrates the global costs of feedstocks at farm or field gate, allowing comparison of costs across different feedstocks. The feedstock cost range is USD 1.6-5.2/GJ in 2010-2020. This excludes solid biogenic

Figure 37: Summary of global feedstock cost estimates for key biomass categories



(Note: costs of micro-algae are not shown as they are one to two orders of magnitude higher)

waste, which could command negative costs, and algae, which have very high production costs. Agricultural and forest residue costs are expected to remain stable or experience a slight price increase over the next three decades while costs for non-food-energy crops are projected to decrease during this period. Solid biogenic waste is generally available at a negative cost, reflecting the cost of alternative disposal routes (*e.g.* landfill).

Feedstock costs for algae are primarily determined by the cultivation technology and are very high due to the early stage of the technology. Only at the lowest production cost estimates are algal oils an economically feasible feedstock for advanced biofuel production. Advanced biofuel demand alone will not lead to the commercialisation of algae but there other value drivers need to be associated with other (co)products.

ANNEX D

COMPARATIVE PATHWAY ASSESSMENT

The following parameters for each pathway are based on literature and publicly available data. The references for each parameter are cited in Table 222-29. Assumptions and estimations are explained as follows:

- Based on the current status of technology development or industry plans, we have estimated a start date for first-of-a-kind commercial-scale plants and assumed a tenfold increase in installed capacity every 15 years from this point.
- The medium-term performance is indicative of 2030, and the long-term performance is indicative of 2045.
- Conversion efficiency – a ratio calculated using theoretical efficiency limits. This parameter illustrates the efficiency of converting biomass to different fuels, expressed in $MJ_{fuel}/MJ_{feedstock, dry}$ on a lower heating value basis. The conversion efficiency is based on actual or modelled commercial-scale plants (2010-2015 average). Future improvements are based on a saturation curve model approaching technical limits defined for each specific pathway. The model is fitted to historical data and/or projections from other studies depending on data availability.

  $$\mathbf{E(t) = L - (L - E_0)\, e^{-k \cdot t}} \qquad (1)$$

  E(t): efficiency
  t: time (15 years for the medium-term assessment and 30 years for the long-term assessment)
  L: technical conversion efficiency limit or theoretical limit (cited in Table 21)
  E_0: current efficiency (conversion efficiency of the first commercial plant as cited in Tables 22-29)
  k: constant (regressed based on available references, as cited in Tables 22-29)
- **Conversion yields** – calculated using the conversion efficiency and lower heating value.
- **Life cycle GHG emissions** – references typical values of the Renewable Energy Directive. Future improvements correlate to conversion efficiency improvements.
- **GHG emissions savings** – calculated on the basis of the difference between life cycle GHG emissions and the fossil fuel reference value: 83.8 kg CO_2e/GJ.
- **Scale of operation** – the expected range of commercial-scale plants as reported in the existing published literature and evidence base.
- **Specific capital investment** (reported in 2014 USD) – calculated from the capital investment by dividing by the plant capacity. Reported values are mean values based on normalised capital investment for large and small-scale capacities. The specific capital investment is also expressed in $USD/kW_{fuel\ output}$ based on the conversion efficiency.

  $$\mathbf{i_0 = \frac{I_0}{c}} \qquad (2)$$

  i_0: current specific capital investment
  c: plant capacity
  I_0: current capital investment
  The capital investment (in 2014 USD) – capital investment of the first commercial plants is based on existing published literature and evidence. Original data are normalised to small and large-scale capacities applying economies of scale (Equation 2), and the mean value is calculated. Technology-specific scale exponents are used (Table 21).

  $$\mathbf{I_{B,0} = I_{A,0} \left(\frac{c_B}{c_A}\right)^{d}} \qquad (3)$$

  $I_{A,0}$, $I_{B,0}$: current capital investment referring to capacity A and B
  c_A, c_B: plant capacity A and B
  d: scale exponent

Future specific capital investment is projected on the basis of a learning rate model, with average learning rates from literature specific to each pathway. The learning rate represents the cost reduction while doubling installed capacity (*e.g.* a learning rate of 0.9 is equivalent to 10 % cost reduction when installed capacity is doubled) (Table 21). The equation used is shown below.

$$\mathbf{i_n} = \mathbf{i_0} \left(\frac{C_n}{C_0}\right)^{\frac{\log(LR)}{\log(2)}} \qquad (4)$$

i_n: specific capital investment for nth plant capacity
i_0: current specific capital investment
C_n: installed capacity for nth plants (cumulative, cited in Tables 22-29)
C_0: current installed capacity (cumulative, taken from the project inventory and cited in Tables 22-29)

- LR: learning rate (cited in Table 21)
- Operational and maintenance costs – typically calculated as a percentage of capital costs.
- Feedstock costs – based on the global averages presented in Annex C and detailed in Tables 22-29.
- **Production costs** – a sum of the feedstock costs, specific capital cost, and operational and maintenance costs. A range of production costs is provided, reflecting variations in plant size and feedstock costs and assuming a plant lifetime of 20 years, plant availability of 90% and interest rate of 10%.
- **Energy demand** – all calculations assume that plants are self-sufficient in terms of heat and power, and that biomass required to provide these utilities is included in the feedstock consumption.

The performance indicators represent the expected performance of a first commercial plant. This is based on recently published literature with data points adjusted to 2015 values where necessary. The indicators presented do not represent realised conversion yields, efficiency, production costs, and life cycle GHG emissions but expected performance at commercial scale.

The pathway assessment is based on the following general assumptions, which are typical of techno-economic analysis available in the literature:

- plant is self-sufficient in energy (feedstock is the only major energy input)
- fuel calculations (feedstock, biofuel) energy are based on lower heating value

Table 21: Technical parameters[11]

	Fischer-Tropsch synthesis	Pyrolysis oil upgrading	MTG	Mixed alcohol synthesis	Ligno-cellulosic fermentation	Syngas fermentation	Aqueous phase reforming	Micro-algae FAME
Technical conversion efficiency limit [MJ fuel/MJ biomass]	0.61	0.77	0.66	0.66	0.49	0.66	0.61	0.96
Scale exponent (d)	0.74	0.70	0.65	0.67	0.75	0.70	0.70	0.70
Learning rate (LR)	0.92	0.92	0.90	0.93	0.97	0.92	0.92	0.94

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[11] Average values for scale exponents and learning rates for a specific technology are taken from literature. Where no appropriate values are available, exponents and rates from similar technologies with the same TRL are used.

Advanced biofuel pathway performance

Agricultural residues – hydrolysis and fermentation to produce ethanol

Table 22: Assessment of the conversion of agricultural residues to ethanol via hydrolysis and fermentation

Pathway process description: enzymatic hydrolysis – fermentation – distillation of ethanol								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	$MJ_{fuel}/MJ_{feedstock, dry}$	0.38		0.45		0.48		Based on a theoretical limit of 49% assuming 100% conversion of C5 and C6 sugars. (Chen 2012; Gnansounou 2010; van Eijck 2014; de Wit 2010; NREL 2002; US DOE 2010; NREL 2008; Kazi 2010; NREL 2011; Petersen 2015; Hamelink 2004; Sassner 2008; Wertz 2013).
Conversion yields	$t_{fuel}/t_{feedstock, dry}$	0.24		0.29		0.30		Based on conversion efficiency calculated with lower heating value straw 17 MJ/kg and ethanol 26.8 MJ/kg.
Life cycle GHG emissions	kg_{CO2eq}/GJ_{fuel}	11.0		9.2		8.7		Renewable Energy Directive typical value for wheat straw ethanol; projection based on conversion efficiency.
GHG emissions savings	%	86.9		89.0		89.6		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive).
Assumed installed capacity	Million litres/ year	538		5 380		53 800		
Scale of operation	**$MW_{th,input}$**	**Small scale 75**	**Large scale 690**	**Small scale 75**	**Large scale 690**	**Small scale 75**	**Large scale 690**	**(Müller-Langer, 2015)**
Specific capital investment	USD/ $kW_{th,input}$	1,303	748	1,178	676	1,065	611	Cost data adjusted with Chemical Engineering Plant Cost Index (CEPCI); learning rate 0.97 Economy of scale exponent 0.75 (de Wit 2010; van Ejik 2014; Chen 2012; Gnansounou 2010; Hamelink 2004; Kazi 2010; Müller-Langer 2015; NREL 2008; US DOE 2010).
	USD/ $kW_{th,output}$	3,468	1,991	2,634	1,512	2,239	1,286	
O&M costs	USD/ GJ_{fuel}	16	9	14	8	13	7	Assumed 13% of total capital investment per year (de Wit, 2010; NREL, 2010).
Feedstock costs	USD/ GJ_{fuel}	17-30		12-24		14-24		(Panoutsou 2011; Kühner 2013; Gallagher 2003; Bang 2013; van Eijck 2014; Sukumaran 2010 Khanna2011; Gerssen-Gondelach 2014; Fan 2013).
Production costs	USD/ GJ_{fuel}	34-61		26-49		27-46		
	USD/litre	0.73-1.28		0.54-1.03		0.57-0.97		
Regional activity & opportunities	Commercialisation activities in Europe, North and South America, and Asia. Potential synergies with the existing first generation ethanol industry may further promote this pathway in North and South America, and Asia.							

Forest residues – gasification and syngas fermentation to produce ethanol

Table 23: Assessment of the conversion of forest residues to ethanol via gasification and syngas fermentation

Pathway process description: gasification – syngas conditioning – syngas fermentation – distillation of ethanol

Parameter	Unit	First commercial plant		Medium term		Long term		Assumptions and sensitivities
Conversion efficiency	MJ_{fuel}/ $MJ_{feedstock, dry}$	0.51		0.54		0.58		Based on the following theoretical limits: 85% gasification, 98% syngas conditioning, 80% syngas fermentation. (Own calculations and expert interviews; Wagner 2013; Griffin 2012; Piccolo 2009; Wie 2009; Tue 2005; Martin 2011; Spath 2003).
Conversion yields	t_{fuel}/ $t_{feedstock, dry}$	0.34		0.36		0.39		
Life cycle GHG emissions	kg_{CO2eq}/ GJ_{fuel}	3.3		3.1		2.9		Adjusted from the RED typical value for Fischer-Tropsch diesel from wood.
GHG emissions savings	%	96.1		96.3		96.5		Compared to 83.8 $kgCO_2eq$/GJ (Renwable Energy Directive).
Assumed installed capacity	Million litres/ year	499		2 495		24 950		Assumes the first commercial plant is operational in 2020.
Scale of operation	**$MW_{th,input}$**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**(Müller-Langer, 2015)**
Specific capital investment	USD/ $kW_{th,input}$	1,624	1,023	1,338	843	1,015	639	Cost data adjusted with CEPCI; assumed learning rate 0.92 and economy of scale exponent 0.7.
	USD/ $kW_{th,output}$	3,166	1,994	2,468	1,555	1,762	1,110	
O&M costs	USD/ GJ_{fuel}	16	10	15	9	14	9	Assumed 10% of total capital investment per year.
Feedstock costs	USD/ GJ_{fuel}	13-20		15		15		(Panoutsou 2011; Kühner 2013; Gerssen-Gondelach 2014; E4tech 2014; IPCC 2012; Lamers 2013; Brinsmead 2014; de Wit 2010; Panoutsou 2009).
Production costs	USD/ GJ_{fuel}	31-49		31-40		28-36		
	USD/litre	0.65-1.03		0.66-0.85		0.60-0.76		
Regional activity & opportunities	A limited number of organisations are deploying the technology platform. Current activities are focused on North America and China.							

Forest residues – gasification and mixed alcohol synthesis to produce ethanol

Table 24: Assessment of the conversion of forest residues to ethanol via gasification and mixed alcohol synthesis

Pathway process description: Gasification – syngas conditioning – catalytic conversion – distillation of ethanol								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	MJ_{fuel}/ $MJ_{feedstock, dry}$	0.44		0.47		0.54		Based on the following theoretical limits: 85% gasification, 98% syngas conditioning, 80% mixed alcohol synthesis. (Own calculations and expert interviews; Atsonios 2013; He 2011; Phillips 2007; Valle 2013; Jones 2009; NREL 2009; Villanueva 2011; NREL 2011; US DOE 2010).
Conversion yields	t_{fuel}/ $t_{feedstock, dry}$	0.30		0.32		0.36		Based on conversion efficiency calculated with lower heating value forest residues 18 MJ/kg and ethanol 26.8 MJ/kg.
Life cycle GHG emissions	kg_{CO2eq}/ GJ_{fuel}	7.4		6.9		6.1		Adjusted from the Renewable Energy Directive typical value for methanol from wood.
GHG emissions savings	%	91.2		91.8		92.8		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive).
Assumed installed capacity	Million litres/ year	448		895		8 955		Assumes the first commercial plant is operational in 2025.
Scale of operation	$MW_{th,input}$	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**(Müller-Langer, 2015)**
Specific capital investment	USD/ $kW_{th,input}$	1,594	740	1,478	686	1,151	534	Cost data adjusted with CEPCI; learning rate 0.93; economy of scale exponent 0.67 (de Wit 2010; Chen 2012; He 2010, Valle 2013; Villanueva 2011; Daugaard 2015; Atsonios 2015; Dutta 2012; He 2011; NREL 2007; NREL 2009; NREL 2011; US DOE 2010; Valle 2013).
	USD/ $kW_{th,output}$	4,264	1,979	3,122	1,449	2,137	992	
O&M costs	USD/ GJ_{fuel}	12	5	11	5	10	5	Assumes 9% of total capital investment per year (Atsonios 2015; He 2011; Villanueva 2011; Valle 2013).
Feedstock costs	USD/ GJ_{fuel}	19		18		16		(Panoutsou 2011; Kühner 2013; Gerssen-Gondelach 2014; E4tech 2014; IPCC 2012; Lamers 2013; Brinsmead 2014; de Wit 2010; Panoutsou 2009).
Production costs	USD/ GJ_{fuel}	31-45		29-42		25-35		
	USD/litre	0.66-0.96		0.61-0.88		0.52-0.73		
Regional activity & opportunities	A limited number of organisations are deploying the technology platform. Current activities are focused on North America.							

Forest residues – gasification and methanol synthesis followed by MTG

Table 25: Assessment of the conversion of forest residues to gasoline via gasification and methanol synthesis followed by catalytic conversion

Pathway process description: gasification – syngas conditioning – catalytic conversion to methanol – distillation of methanol – catalytic conversion to gasoline – product separation								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	$\mathrm{MJ_{fuel}}$/ $\mathrm{MJ_{feedstock,\ dry}}$	0.55		0.57		0.61		Based on the following theoretical limits: 85% gasification, 98% syngas conditioning, 80% methanol synthesis and MTG conversion (own calculations and expert interviews; Zhu 2011; Hannula 2013; Tuna 2014).
Conversion yields	$\mathrm{t_{fuel}}$/ $\mathrm{t_{feedstock,\ dry}}$	0.24		0.25		0.27		Based on conversion efficiency calculated with lower heating value forest residues 18 MJ/kg and MTG fuel 41 MJ/kg.
Life cycle GHG emissions	$\mathrm{kg_{CO2eq}}$/ $\mathrm{GJ_{fuel}}$	5.5		5.3		5.0		Adjusted from the Renewable Energy Directive typical value for methanol from wood
GHG emissions savings	%	93.4		93.6		94.1		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive).
Assumed installed capacity	Million litres/ year	356		1 782		17 821		Assumes the first commercial plant is operational in 2025.
Scale of operation	$\mathbf{MW_{th,input}}$	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**(Müller-Langer, 2015)**
Specific capital investment	USD/ $\mathrm{kW_{th,input}}$	2,173	970	1,701	760	1,199	535	Cost data adjusted with CEPCI; learning rate 0.9 (assumed)
	USD/ $\mathrm{kW_{th,output}}$	3,956	1,767	2,992	1,337	1,969	879	economy of scale exponent 0.65 (Hannula, 2013; Philips, 2011; Zhu, 2011; Tuna 2014).
O&M costs	USD/ $\mathrm{GJ_{fuel}}$	8	4	8	4	8	3	Assumes 9% of total capital investment per year (Hannula 2013; Philips 2011).
Feedstock costs	USD/ $\mathrm{GJ_{fuel}}$	15		15		14		(Panoutsou 2011; Kühner 2013; Gerssen-Gondelach 2014; E4tech 2014; IPCC 2012; Lamers 2013; Brinsmead 2014; de Wit 2010; Panoutsou 2009).
Production costs	USD/ $\mathrm{GJ_{fuel}}$	26-40		24-35		21-30		
	USD/litre	0.86-1.31		0.78-1.15		0.69-0.98		
Regional activity & opportunities	A limited number of organisations are deploying the technology platform. Current activities are focused on North America.							

Forest residues – gasification and Fischer-Tropsch synthesis to produce diesel

Table 26: Assessment of the conversion of forest residues to diesel via gasification and Fischer-Tropsch synthesis

Pathway process description: gasification – syngas conditioning – Fischer-Tropsch catalysis – product upgrading

Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	$MJ_{fuel}/MJ_{feedstock, dry}$	0.43		0.47		0.52		Based on the following theoretical limits: 85% gasification, 98% syngas conditioning, 75 % Fischer-Tropsch synthesis, 98 % Fischer-Tropsch product upgrading (own calculations and expert interviews).
Conversion yields	$t_{fuel}/t_{feedstock, dry}$	0.18		0.19		0.21		Based on conversion efficiency calculated with lower heating value forest residues 18 MJ/kg and Fischer-Tropsch fuel 44 MJ/kg.
Life cycle GHG emissions	kg_{CO2eq}/GJ_{fuel}	4.0		3.6		3.2		Renewable Energy Directive typical value for Fischer-Tropsch diesel from wood.
GHG emissions savings	%	95.2		95.7		96.0		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive).
Assumed installed capacity	Million litres/ year	206		1 305		13 045		Assumes the first commercial plant is operational in 2020.
Scale of operation	**$MW_{th,input}$**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**Small scale 75**	**Large scale 750**	**(Müller-Langer, 2015)**
Specific capital investment	$USD/kW_{th,input}$	2,089	1,148	1,694	931	1,304	717	Cost data adjusted with CEPCI; learning rate 0.92 economy of scale exponent 0.74 (de Wit, 2010; van Ejik, 2014; Chen, 2012; Knoope, 2013; Chen, 2012; Müller Langer 2015; Müller Langer 2012).
	$USD/kW_{th,output}$	5,161	2,836	3,569	1,962	2,507	1,378	
O&M costs	USD/GJ_{fuel}	9	5	9	5	8	4	Assumes 6% of capital investment per year (de Wit 2010; Knoope 2013; Müller-Langer 2012; van Eijck 2014).
Feedstock costs	USD/GJ_{fuel}	15-24		18		17		(Panoutsou 2011; Kühner 2013; Gerssen-Gondelach 2014; E4tech 2014; IPCC 2012; Lamers 2013; Brinsmead 2014; de Wit 2010; Panoutsou 2009).
Production costs	USD/GJ_{fuel}	31-53		30-41		27-35		
	USD/litre	1.11-1.87		1.07-1.44		0.93-1.22		
Regional activity & opportunities	Current commercialisation activities in Europe, North America and China. Interest in the opportunity to produce aviation fuels in all regions.							

Forest residues – fast pyrolysis and pyrolysis oil upgrade to produce diesel

Table 27: Assessment of the conversion of forest residues to diesel via fast pyrolysis and pyrolysis oil upgrade

Pathway process description: fast pyrolysis – pyrolysis oil upgrade								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	MJ_{fuel}/ $MJ_{feedstock, dry}$	0.57		0.59		0.65		Based on the following theoretical limits: 85% pyrolysis, 90% oil upgrading.
Conversion yields	t_{fuel}/ $t_{feedstock, dry}$	0.24		0.25		0.28		Based on conversion efficiency calculated with lower heating value corn stover 17.5 MJ/kg and upgraded fuel 41 MJ/kg.
Life cycle GHG emissions	kg_{CO2eq}/ GJ_{fuel}	21.3		20.4		18.5		Average value from literature; projection based on conversion efficiency (Jones 2012; Han 2013; Dang 2014).
GHG emissions savings	%	74.6		75.7		77.9		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive).
Assumed installed capacity	Million litres/ year	196		391		3 912		Assumes the first commercial plant is operational in 2025.
Scale of operation	**$MW_{th,input}$**	**Small scale 50**	**Large scale 400**	**Small scale 50**	**Large scale 400**	**Small scale 50**	**Large scale 400**	**(Müller-Langer, 2015; Brown, 2010)**
Specific capital investment	USD/ $kW_{th,input}$	1,195	640	1,099	589	833	447	Cost data adjusted with CEPCI; learning rate 0.92 (assumed); economy of scale exponent 0.7 (Brown 2010).
	USD/ $kW_{th,output}$	2,114	1,133	1,859	996	1,280	686	
O&M costs	USD/ GJ_{fuel}	22	12	21	11	19	10	Assumes 29% of total capital investment per year including import of hydrogen (Brown 2010).
Feedstock costs	USD/ GJ_{fuel}	15		14		13		(Panoutsou 2011; Kühner 2013; Gerssen-Gondelach 2014; E4tech 2014; IPCC 2012; Lamers 2013; Brinsmead 2014; de Wit 2010; Panoutsou 2009).
Production costs	USD/ GJ_{fuel}	31-45		29-42		26-37		
	USD/litre	1.02-1.48		0.96-1.39		0.86-1.22		
Regional activity & opportunities	Ongoing commercialisation activities in Europe, Asia and North America.							

Agricultural residues – hydrolysis and aqueous phase reforming of sugars followed by upgrade to diesel

Table 28: Assessment of the conversion of agricultural residue to diesel via hydrolysis and aqueous phase reforming of sugars

Pathway process description: hydrolysis – aqueous phase reforming – upgrade to diesel								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	MJ_{fuel}/ $MJ_{feedstock, dry}$			0.42		0.49		Based on a theoretical limit of 61 % (own calculations; Karatzos 2014; Virent; Davis 2015).
Conversion yields	t_{fuel}/ $t_{feedstock, dry}$			0.18		0.21		
Life cycle GHG emissions	kg_{CO2eq}/ GJ_{fuel}			25.2		21.9		Average value from literature; projection based on conversion efficiency (Zhu, 2011; Han 2013; Dang 2014).
GHG emissions savings	%			70.0		73.8		Compared to 83.8 kg CO_2e/GJ (Renewable Energy Directive)
Assumed installed capacity	Million litres/ year			114		1 136		Assumes first commercial plant operational in 2030.
Scale of operation	**$MW_{th,input}$**	**Small scale 50**	**Large scale 400**	**Small scale 50**	**Large scale 400**	**Small scale 50**	**Large scale 400**	**(Müller-Langer, 2015; Brown, 2010)**
Specific capital investment	USD/ $kW_{th,input}$			3,050	1,634	2,312	1,239	Cost data adjusted with CEPCI; assumes learning rate 0.92 and economy of scale exponent 0.7 (Davis 2015).
	USD/ $kW_{th,output}$			7,208	3,863	4,761	2,551	
O&M costs	USD/ GJ_{fuel}			31	17	27	14	Assumes 12% of total capital investment per year (Davis 2015).
Feedstock costs	USD/ GJ_{fuel}			12-26		14-23		(NREL 2007; E4tech 2014; IPCC 2012; Lamers 2013; Panoutsou 2009; Gallagher 2003; IRENA 2014; Sukumaran 2010 Khanna 2011; Gerssen-Gondelach 2014; U.S. Department of Energy 2012; Brinsmead 2014; de Wit 2010).
Production costs	USD/ GJ_{fuel}			45-86		39-70		
	USD/litre			1.47-2.83		1.27-2.28		
Regional activity & opportunities	Only one technology provider is commercialising this technology, with commercialisation activities focused on North America. Potential synergies with chemical industry may further promote this pathway.							

Micro-algae – oil extraction and transesterification to produce FAME biodiesel

Table 29: Assessment of the conversion of algal oil to FAME biodiesel via transesterification

Pathway process description: Micro-algae cultivation – oil extraction – transesterification of the algal oil								
Parameter	**Unit**	**First commercial plant**		**Medium term**		**Long term**		**Assumptions and sensitivities**
Conversion efficiency	$MJ_{fuel}/MJ_{feedstock, dry}$	0.92		0.92		0.93		Based on a theoretical limit of 96 %; transesterification of triolein as most common model component (E4tech 2014; Rincon 2014; Silva 2012).
Conversion yields	$t_{fuel}/t_{feedstock, dry}$	0.96		0.97		0.97		For the transesterification process.
Life cycle GHG emissions	kg_{CO2eq}/GJ_{fuel}	33.0		32.8		32.6		(E4tech, 2014)
GHG emissions savings	%	60.6		60.9		61.1		Compared to 83.8 $kgCO_2eq/GJ$ (RED).
Assumed installed capacity	Million litres/ year	988		1 976		19 760		Assumes the first commercial plant is operational in 2025.
Scale of operation	**$MW_{th,input}$**	**Small scale 150**	**Large scale 1,220**	**Small scale 150**	**Large scale 1,220**	**Small scale 150**	**Large scale 1,220**	**(Müller-Langer, 2015; Brown, 2010)**
Specific capital investment	USD/ $kW_{th,input}$	143	76	134	72	109	58	Cost data adjusted with CEPCI; learning rate 0.94
	USD/ $kW_{th,output}$	156	83	146	78	118	63	economy of scale exponent 0.7 (Chen 2012; de Wit 2010; Davis 2012; Abubakar 2015; Lee 2011; Yusuf 2013).
O&M costs	USD/ GJ_{fuel}	4	2	4	2	4	2	(Davis 2012; de Wit 2010; Lee 2011).
Feedstock costs	USD/ GJ_{fuel}	30-427		22-313		14-201		(Van Harmelen 2014; Dahiya 2015; Jonker 2013; Darzins 2010; Slade 2013; Kovacevis 2010).
Production costs	USD/ GJ_{fuel}	32-432		24-318		16-206		
	USD/litre	1.04-13.87		0.78-10.21		0.52-6.61		
Energy demand	Assumes the plants are self-sufficient in terms of heat and power, and the biomass required to provide these utilities is included in the feedstock consumption.							
Feedstock availability	Chapter 1 indicates that the global algae potential can increase to 12.8 EJ per year, equivalent to over 380 million litres (based on the theoretical conversion limit of 96%).							
Regional activity & opportunities	The commercial cultivation of algae is highly dependent on CO_2 sources, the availability of cheap nutrients and solar radiation.							

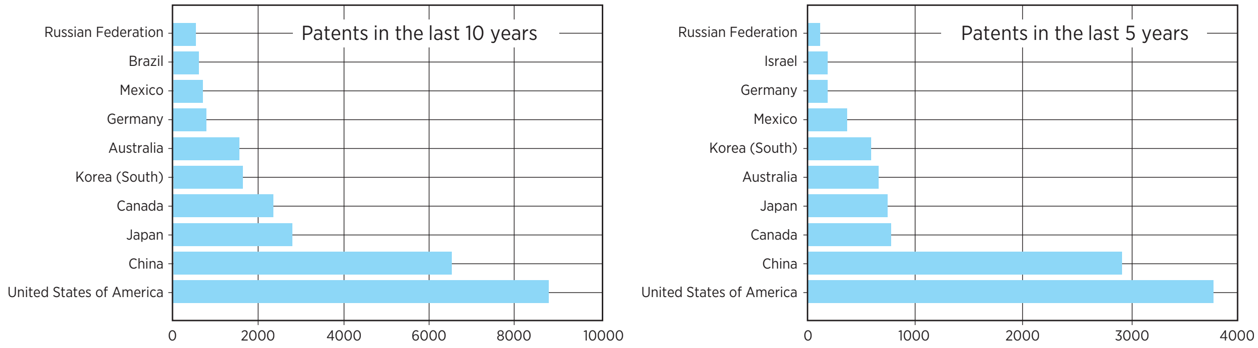
ANNEX E

PATENT ANALYSIS

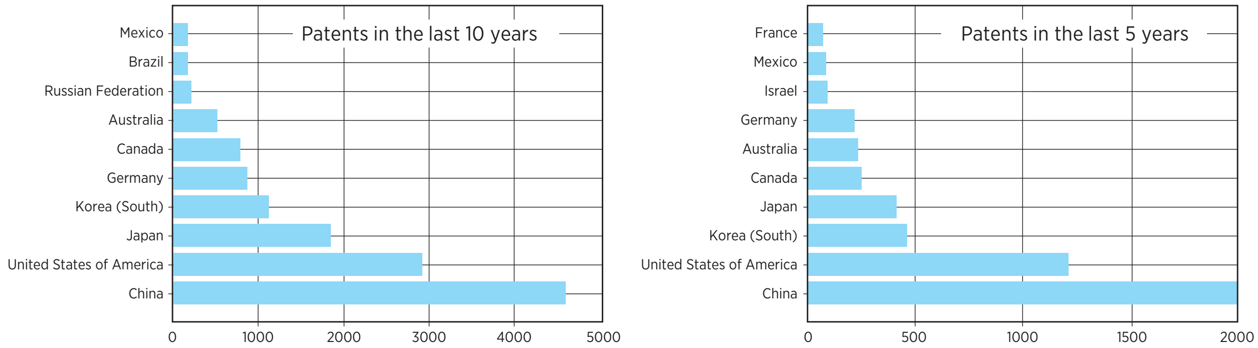
An analysis of the patents filed in this area is presented to provide an insight into the historical development and geographical distribution of activities in the development of advanced biofuels. The patent analysis is based on the IRENA Inspire tool (inspire.irena.org/Pages/patents/techprofiles.aspx).

Using the more generic terms ‘Biofuels’ and ‘Fuel from Waste,’ the general picture of geographical distribution is very stable. The US and China lead, with a stronger focus on all biofuels in the US, and on fuels from waste in China. Other active countries are Canada, Japan, Republic of Korea, Australia, Germany, Mexico, Russian Federation, Israel, Brazil and France. Over the last five years, patent activity has decreased in the US, China, Japan, Canada and Brazil. Increasing interest can be observed in Mexico and Israel.

Biofuels

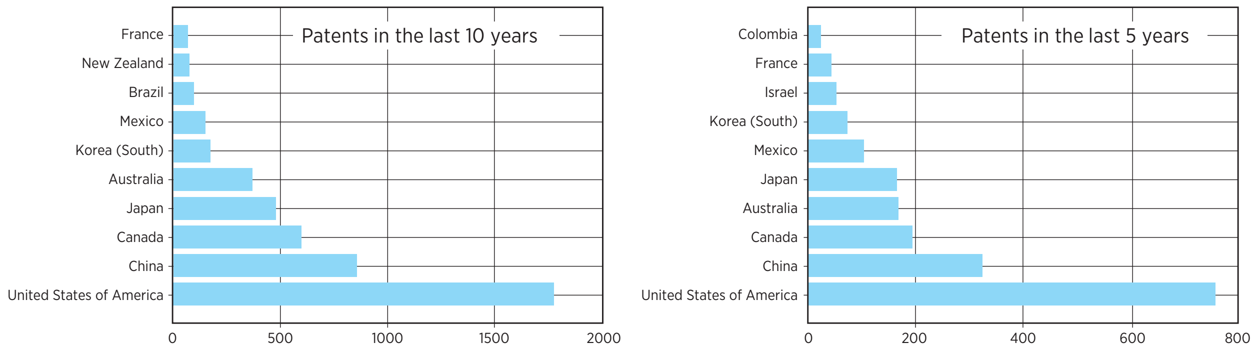


Fuel from waste



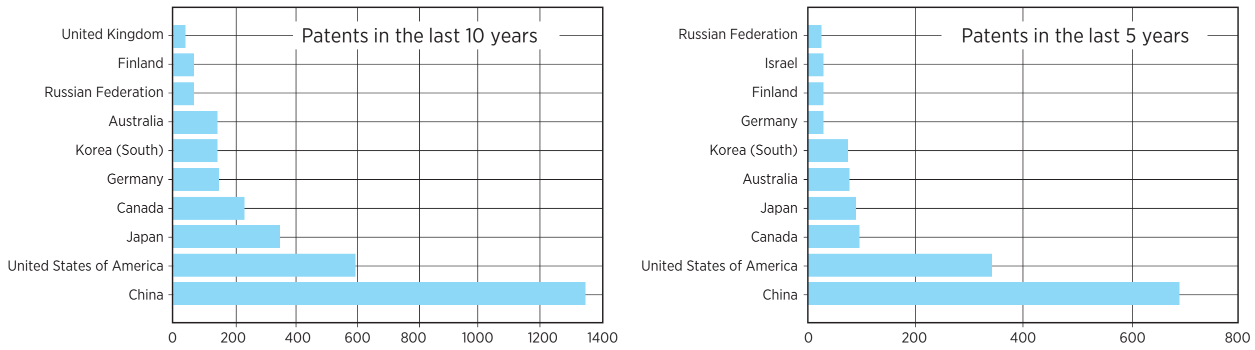
The US and China again lead in all categories which represent advanced biofuels. Other active countries also reflect the results for all biofuels.

Cellulosic bioethanol has the highest activity across all categories, led by the US, China and Canada. Patent activity decreased in the US, China and Brazil in the last five years compared to the previous five years. Increasing interest can be observed in Australia, Mexico, Israel, France and Colombia.



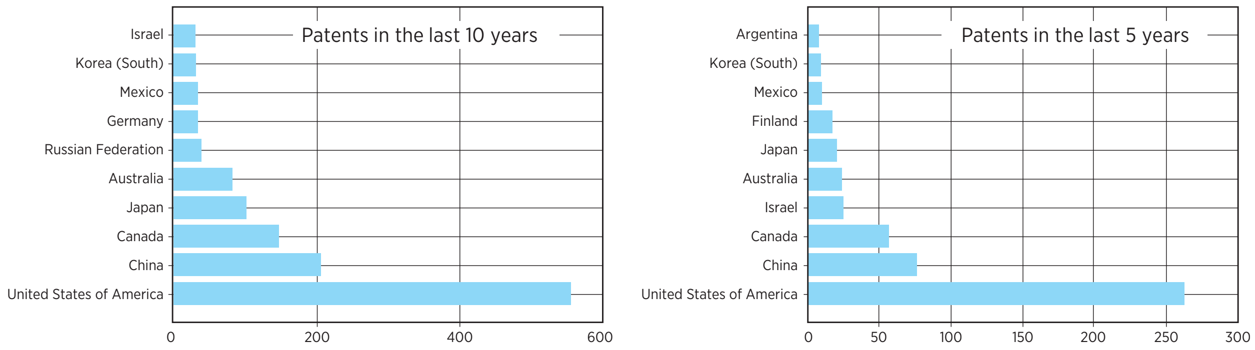
Cellulosic bio-ethanol

China is most active in the pyrolysis of biomass for fuel production, ahead of the US. In the last five years China and the US have maintained momentum but Japan and Germany have reduced their activity.



Bio-pyrolysis

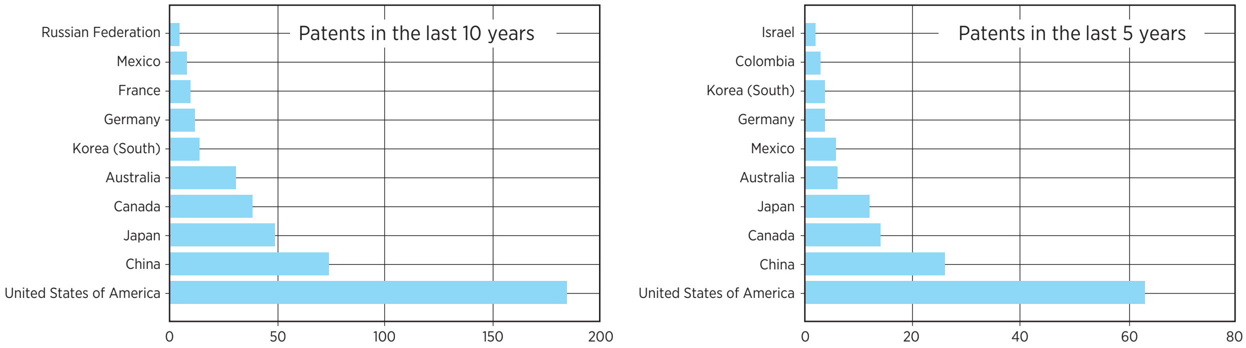
Patent activity in technologies for the synthesis of fuels from biomass waste including pyrolysis and/or gasification is especially high in the US, followed by China and Canada. In general, patent numbers have increased slightly in the last five years. Israel and Finland are coming up as new players with a significant increase in patent activity in this category.



Synthesis of alcohols or diesel from waste including a pyrolysis and/or gasification step

For technologies producing alcohols by other means than fermentation, the top ten players are mainly the same, with the US leading before China, Japan and Canada. In general, patent activity seems to have slowed down in the last five years. Increasing activity can be observed for Mexico. Colombia and Israel are new players in the top ten.

Bio-alcohols produced by other means than fermentation



The potential for advanced biofuels is great, but so are the challenges. A competitive industry will depend on innovative technology and supply chains, market development and policy support.

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