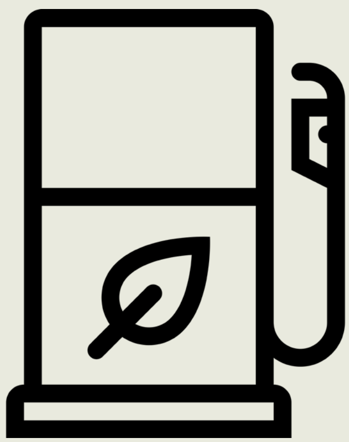
Global Innovation Needs Assessment

Low-carbon fuels

November 1, 2021



Funded by:

climateworks FOUNDATION

Foreign, Commonwealth & Development Office

Analytical support from:

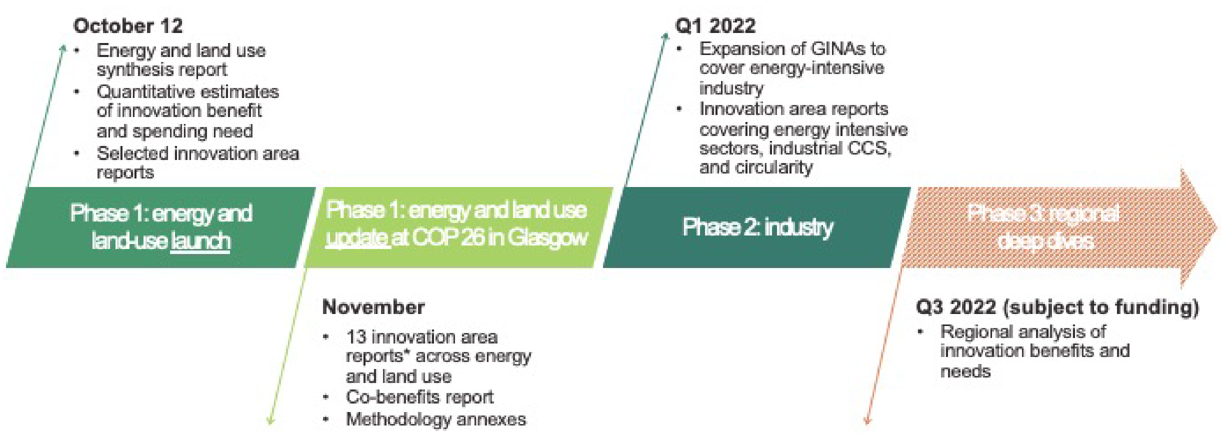
:vivideconomics

The Global Innovation Needs Assessments

The Global Innovation Needs Assessments (GINAs) is a first-of-its-kind platform for assessing the case for low-carbon innovation. The GINAs take a systemwide perspective, explicitly modeling the impact of innovations across the global economy. Uniquely, the analysis quantifies the economic benefits of low-carbon innovation and identifies the levels of public investment—from research and development to commercialization—needed to unlock these benefits. The analysis is divided into three phases: Phase 1, global energy and land use; Phase 2, global industry; and Phase 3, regional deep dives. This report is part of Phase 1's investigation of innovative technologies in the energy and land systems.

The analyses do not assess all relevant technologies, nor do they evaluate all relevant factors for policy judgments. Instead, the work is intended to provide a novel evidence base to better inform policy decisions. The Phase 1 analysis looks across a broad range of climate mitigation technologies in energy and land use, including demand response to protein diversification, to model the economic value of related innovation investment. Later phases expand the research. As with adoption of all technologies, including some controversial ones described in this report, there are risks and potential downsides. Technology investment is ultimately a policy judgment. This analysis provides no policy recommendations for that investment.

Phases of the Global Innovation Needs Assessments



The Global Innovation Needs Assessments project is funded by the ClimateWorks Foundation and the UK Foreign, Commonwealth & Development Office. Analysis was conducted by Vivid Economics. Thank you to the UK Department for Business, Energy and Industrial Strategy (BEIS) and to the Mission Innovation Secretariat, both of which were consulted on aspects of this work, and to BEIS support for the 2017–2019 Energy Innovation Needs Assessments, which developed the methodological approach taken here.

The findings and views expressed here do not reflect the view of ClimateWorks, the Government of the United Kingdom, or Mission Innovation.

Phase 1 GINA outputs

The suite of reports across innovation areas, methodological annexes, and a synthesis report for GINAs are available on the GINA website at https://www.climateworks.org/report/ginas/.

The suite of outputs for Phase 1 of the Global Innovation Needs Assessments

1. **Energy and land use synthesis report: slide-based summary for policymakers and executives**
   Synthesis of the findings across the innovations considered in energy and land use
2. **Innovation reports** – in depth quantitative analysis for industry and policy analysts

Energy

- **Wind power** – Offshore and onshore wind turbines
- **Low carbon hydrogen** – Electrolyzers and gas reforming with CCS
- **Solar power** – Utility-scale and distributed PV
- **Low carbon fuels** – 2nd generation biofuels, synthetic fuels ($H_2 + CO_2$)
- **Nuclear power** – Small modular and large-scale advanced reactors
- **System flexibility** – Battery storage, power-to-X, demand response
- **Buildings** – Heat pumps, building fabric
- **Power CCS** – CCS in power generation (coal, gas and biomass)
- **Zero-carbon road transport** – Battery electric vehicles, fuel cell electric vehicles

Land use & agriculture

- **Protein diversity** – Novel protein-rich food and feed
- **Decarbonizing agrochemical inputs** – Innovative fertilisers and pesticides
- **Yield enhancing technologies** – Digital agriculture and vertical farming
- **Irrigation** – Improved irrigation methods and systems

The selected innovation areas were selected for their potential for further innovation and the potential magnitude of the associated system benefits. Their selection here is because they could play a key role in a net zero pathway but does not imply that an optimal net zero pathway necessarily includes them. Further notes on the rationale behind their selection is provided in the methodology annex on the GINA website

3. **Co-benefits of innovation report** – qualitative analysis of the environmental and other non-economic benefits of net-zero innovation
4. **European case study** – analysis of jobs and growth benefits in Europe specifically
5. **Methodology annex** – description of the modeling approach

Executive Summary

Low-carbon fuels provide a practical low-carbon substitute for fossil fuels where alternatives to conventional engines are costly or imply losses in service quality (e.g., reduced speed and increased travel time). Synthetic fuels (sometimes referred to as synfuels) and advanced liquid biofuels can replace fossil fuels with minimal changes to the engine, transport fleet, and fuel distribution infrastructure, making them a potentially practical low-carbon alternative to fossil fuels in some transportation applications.[1] Alternatives to conventional engines are still expensive in transport modes like aviation and would lead to losses in performance, such as reduced airplane speed. Supported by mandated blending, large supply chains for biofuel already exist in major markets like the European Union, United States, and Brazil. However, advanced biofuels remain immature and represent only 7% of total liquid biofuel production. Similarly, synthetic fuels are not yet produced or used at scale. They are more expensive than advanced biofuels but are not subject to physical constraints in terms of feedstock availability. They will likely be deployed much later than advanced biofuels, when the hydrogen and CO_2 used as feedstocks become available at scale and low costs.

Strong innovation and commercialization could more than halve the costs of conversion plants, for both advanced biofuel and synfuel, reducing overall fuel production costs by up to 20%.[2] High costs represent a substantial barrier to commercialization of advanced fuels; one liter of advanced biofuels and synthetic fuels costs, respectively, two and five times more than one liter of gasoline. Reducing the production costs of hydrogen, carbon dioxide, and bio-based feedstocks will have an important role in ensuring the competitiveness of advanced fuels overall. However, innovations in the synthesizing of feedstocks into liquid fuels will also play a substantial part in reducing costs. Key innovations in this area include new synthesis processes that yield higher conversion efficiencies for synthetic fuels and combined conversion steps that minimize energy losses and improve the efficiency of advanced biofuels.

By the year 2100, innovations could reduce global energy system costs by a cumulative US$2.8 trillion (undiscounted): US$45 billion per year by 2050 and US$100 billion per year by 2090. Discounting at a 5% annual rate, cumulative system benefits could amount to US$220 billion. The supply of cheaper low-carbon fuels at greater quantities would reduce the cost of decarbonization in the transport sector. It would also reduce the need to make costly adjustments to existing infrastructure; advanced fuels can be used with only minor conversions to existing engines and storage facilities. Further, reduced emissions from the transport sector would reduce the need to deploy expensive mitigation solutions, such as carbon-removal technologies, elsewhere. Most of the system benefits would be realized during the second half of the century, when technology reaches maturity and supply chains become well-developed. System benefits could be much larger if feedstock costs are reduced at the same time. Hydrogen production costs are expected to drop by more than 60% by 2030.

---

[1] Advanced biofuels, also defined as second-generation biofuels, are liquid fuels manufactured using non-food and non-feed biomass as feedstock.
[2] This cost halving assumes feedstock costs reductions for hydrogen and carbon dioxide to $1.5 /kgH2 and $0.01 /kgCO2, respectively, by 2050.

To realize the full benefits of low-cost, low-carbon fuels, public spending on research, development, and deployment (RD&D) and commercialization of some US$3.2 billion per year and US$2.8 billion per year, respectively, is required. This spending is equivalent to more than 10 times the current annual investment in advanced fuels from private and public sources combined, but it is less than 15% of the benefits, estimated at US$45 billion, that would be realized in 2050 from increased innovation in advanced fuels. Government support for RD&D and commercialization will need to be accompanied by so-called pull policies that address market barriers and drive deployment. These policies can include carbon pricing as well as other sector-specific policies, such as the use of mandates and updated fuel taxation frameworks.

Innovation in the low-carbon fuels industry could be a valuable business opportunity for suppliers and developers across the value chain, with the market size for conversion plants projected to reach more than US$60 billion by 2050. Innovation could drive the low-carbon fuel market to reach a market size of more than US$600 billion by 2050.[3] Within this market, highly innovative and trade-exposed sectors will include the fuel conversion sector, which could support a direct gross value added (GVA) of US$30 billion and 300,000-plus high-value jobs each year by 2050. However, gains across the economy are likely to be much larger as the upstream and downstream stages of the value chain, such as feedstock production, are included.

Public benefits (i.e., energy system cost savings)	Cumulative for 2021–50, undiscounted: US$0.8 trillion Cumulative for 2051–2100, undiscounted: US$2 trillion Cumulative for 2021–2100, discounted at 5% per year: US$0.2 trillion
Business opportunities	2035: US$20 billion GVA, 260,000 direct jobs 2050: US$30 billion GVA, 300,000 direct jobs
Public spending required	Commercialization, annual average for 2021–2035: US$2.8 billion RD&D, annual average for 2021–2035: US$3.2 billion

[3] The market size of the entire advanced fuel market is indicative.

1. Low-carbon fuels and the energy system

Current role in the energy system

Low-carbon fuels include advanced biofuels and synthetic fuels:

- **Advanced biofuels are liquid fuels manufactured using non-food and non-feed biomass as feedstock.**[4] Advanced biofuels are generally defined as second-generation biofuels, and the feedstocks from which they are derived include forest residues, agricultural residues, and waste. Unlike the feedstocks of first-generation (conventional) biofuels, the feedstocks of advanced biofuels cannot be used for food or feed production. As a result, advanced biofuels have a lower impact on food resources and on direct and indirect land use change, including deforestation and biodiversity loss (Royal Academy of Engineering 2017). For these reasons, this report will focus on second-generation biofuels.

- **Synthetic fuels are fuels manufactured using hydrogen and carbon dioxide, which can be produced in a climate-neutral way.** Hydrogen and carbon dioxide are produced and reacted into a liquid fuel using a synthesizer. For synthetic fuels to be climate-neutral, the carbon dioxide and hydrogen must be derived from sustainable zero-carbon sources.

Supported by pull policies, first-generation biofuels are currently deployed at scale in road transport, but the use of advanced biofuels remains limited. In 2020, liquid biofuels helped meet 4% of global transport demand, entirely from road transport. Biofuels are widespread in some countries, but largely as first-generation biofuels: of the 3.7 exajoules (EJ) of liquid biofuels produced in 2020, 93% was produced from conventional crops such as sugarcane, corn, and soybeans. However, biofuel producers still rely on pull policies such as blending mandates to bring their products to market. Only 7% of liquid biofuels are advanced biofuels produced from feedstocks such as wastes and residues (IEA 2021).

Synthetic fuels are not yet produced at commercial scale, but various pilot projects have recently been rolled out in the transport sector. For example, in January 2021, a major airline operated the first passenger flight using synthetic fuels (Proper 2021). However, high production costs and a lack of regulatory incentives have so far prevented a market ramp-up that would allow significant capacity and economies of scale to be achieved. Furthermore, the feedstocks required for synfuel production, namely carbon dioxide and hydrogen, are still not available at scale.

[4] The focus of this report is on liquid biofuels, hence the use and innovation opportunities of gaseous biofuels are not analyzed in detail. IEA (2021b) expects that most of the production of biogases will be used to decarbonize the gas network by 2050.

Future role and deployment potential

Low-carbon fuels provide a practical low-carbon substitute to fossil fuels where alternatives to conventional engines are costly or imply losses in service quality (e.g., reduced speed and increased travel time). Drop-in compatible synthetic fuels and advanced liquid biofuels can replace fossil fuels with minimal changes to the engine, transport fleet, and fuel distribution infrastructure. For this reason, they are practical solutions to decarbonize transport modes such as shipping, aviation, and heavy-duty transport wherever the infrastructure to support trucks powered by batteries or fuel cells is unavailable. Other transport modes can find more effective decarbonization solutions away from low-carbon fuels. For example, battery electric passenger vehicles are a low-carbon alternative to conventional vehicles with lower costs and higher conversion efficiencies than vehicles running on low-carbon fuels.[5] To decarbonize long-distance transport, alternative solutions to low-carbon fuels are under development, but they are unlikely to be effective across all transport segments and will require expensive changes to the engine, transport fleet, and fuel distribution infrastructure. Battery electric planes could be used for short regional flights, but longer flights would require installation of heavy batteries on the aircraft and a threefold increase in current battery density. Even then, battery electric planes would not meet range requirements for mid-haul and long-haul flights (IEA 2020b).

Most 1.5°C scenarios suggest that biofuel production could increase to 10–25 EJ per year by 2050, but land availability and competition for biomass could limit its growth. In scenarios that imply a global mean temperature rise of 1.5°C, projections of biofuel production vary, depending on feedstock availability and the cost of alternative decarbonization solutions. However, most of the scenarios envision an increase in biofuel use, including in long-distance transport, of up to 25 EJ per year in 2050.[6] The International Energy Agency (IEA) suggests that biofuels could account for about 20% of energy use in shipping and 30% of fuel consumption in aviation by 2050 (IEA 2020b). Most production will focus on advanced second-generation biofuels because the biomass used to produce them guarantees a more efficient use of land compared with that of conventional biofuels. However, sustainable biomass production is limited. Furthermore, different bioenergy uses across the energy system compete for sustainable biomass. Bioenergy with carbon capture is expected to become an important driver of biomass demand, which could limit biomass availability to produce advanced biofuels. Of the global energy demand from the transport sector, estimated at 100–170 EJ in 2050, only about 12% could be covered by advanced biofuels (Lövenich et al. 2018).

Synthetic fuels can complement biofuels to help decarbonize long-distance transport, providing up to 36 EJ per year by 2050, but they will require feedstocks to be available at scale. Synthetic fuels are more expensive than advanced biofuels but are not subject to physical constraints in terms of feedstock availability. Their uptake is still uncertain, but in many scenarios they are projected to complement biofuels in decarbonizing transport in the absence of other low-carbon options and to provide

---

[5] Expert interviews have suggested that low-carbon fuels could also find use cases in passenger vehicles: in the short term, using low-carbon fuels can reduce the carbon footprint of vehicles running on fossil fuels while requiring minimal adjustments to engines and distribution infrastructure. In the long term, using low-carbon fuels in hybrid vehicles could lead to installation of smaller, lighter batteries on vehicles and reliance on fuel for long-distance trips with limited recharging points.

[6] This projection is based on a range of scenarios developed for the Network of Central Banks and Supervisors for a Green Financial System.

5–36 EJ per year by 2050 (IEA 2021b; Ram et al. 2020). However, deployment of synthetic fuels, which rely on currently expensive and relatively scarce feedstocks, will likely occur at a later stage than deployment of advanced biofuels. The IEA suggests that production of commercial-scale synthetic jet kerosene through captured carbon dioxide could start in the 2030s and make up more than 40% of the jet fuel market in aviation by 2070. Combined with biofuels, low-carbon fuels would account for about 75% of demand for jet fuels by 2070 (IEA 2020b). However, the role of synthetic fuels in the energy system will hinge on the availability of low-cost hydrogen, carbon dioxide, and renewable electricity at scale.

Limits of biomass production

Biomass production is constrained by land availability. If all suitable lands (excluding lands currently used in agriculture) were available for biomass plantations, total supply would theoretically be 2,000–2,300 EJ per year (Jans et al. 2018). However, not all biomass is sustainable. To be sustainable, biomass must have low life-cycle emissions and must avoid competing with use of land for food production, triggering land use changes that could release carbon into the atmosphere (e.g., deforestation), and reducing biodiversity. On this basis, sustainable biomass is estimated to be 40–60 EJ per year (Energy Transitions Commission 2021).

2. Innovation opportunities

Costs and deployment barriers

Advanced biofuels and synthetic fuels today are, respectively, two and five times more expensive than fossil fuels—a substantial barrier to their uptake at scale. Production costs of advanced biofuels and synthetic fuels are at about US$1 per liter and US$2.3 per liter, respectively (IRENA 2017). In comparison, the retail price of gasoline in the United States over the past few years has been about US$0.5 per liter. The price gap between low-carbon fuels and fossil fuel alternatives is a substantial barrier to uptake of low-carbon fuels.

The key cost components of advanced biofuels are the feedstock costs and the capital and operating costs of fuel refineries:[7]

- **Feedstock costs** represent some 50% of total production costs. However, these costs can vary, depending on the specific feedstock used. The production of feedstock is an input to the production process of advanced biofuels and, therefore, not considered in detail in this report.
- **Capital costs** of advanced biofuel refineries represent about 25% of total production costs. These costs include the cost of conversion equipment as well as the costs of engineering, procurement, and construction of the plant.
- **Operating costs** of advanced biofuel refineries represent some 25% of total production costs. These costs include the costs of operation and maintenance of advanced biofuel plants throughout their lifetime.

The key cost components of synthetic fuels are the costs of hydrogen and carbon dioxide as well as the capital and operating costs of conversion plants (Concawe 2019)**:**

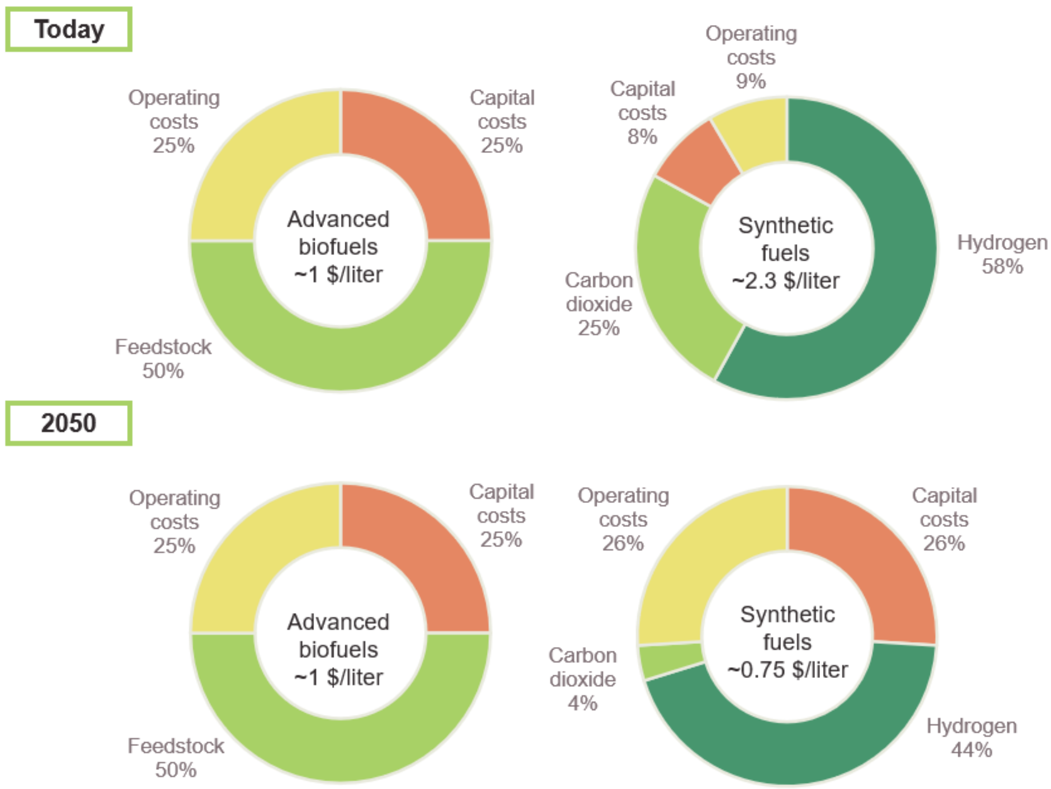
- **Hydrogen production costs** make up roughly 58% of production costs of synthetic fuels at the current hydrogen price of $5/kgH_2$ (Hydrogen Council 2021).[8]
- **Carbon dioxide production costs** are responsible for some 25% of synthetic fuels production costs at a wholesale cost of $0.2/kgCO_2$. This cost assumes that carbon dioxide is produced using direct air capture technologies. However, carbon dioxide can also be captured from power generation and industrial facilities. These methods are cheaper than direct air capture thanks to carbon dioxide's relatively higher density in industrial processes. However, the sequestration of carbon dioxide directly from the air ensures that production of the gas for synthetic fuels is carbon-neutral.

[7] Many types of biofuels and corresponding conversion processes are available. Throughout this report, we consider lignocellulosic ethanol production through hydrolysis and fermentation as a representative process for the cost profile of advanced biofuels. Because ethanol takes some 75% of the liquid biofuel market share, it can be converted into other biofuels such as methanol, and the conversion process of lignocellulosic ethanol is at an advanced stage (TRL 6-8) compared with other conversion processes.
[8] This price assumes that hydrogen is produced using electrolyzers and renewable electricity. The costs of hydrogen production using this production route are explored in more detail in the Low-Carbon Hydrogen report.

- **Capital costs** of synthesis plants represent about 8% of total production costs. These costs include the cost of conversion equipment as well as the costs of plant engineering, procurement, and construction.

- **Operating costs** of synthesis plants represent some 9% of total production costs. These costs include operation and maintenance costs of synthetic fuel plants throughout their lifetime.

Figure 1. Distribution of costs for synthetic fuels and advanced biofuels



Source: Vivid Economics based on Concawe (2019), IRENA (2017), and Hydrogen Council (2021).

As feedstock production becomes cheaper, opportunities for cost reductions will increasingly involve the capital and operating costs of conversion plants. For advanced biofuels, studies suggest that opportunities for innovation in this area are limited, and cost reductions could instead rely on reduced feedstock demand from higher process efficiencies (IEA 2020a). However, reductions in the cost of hydrogen and carbon dioxide could be substantial: estimates indicate that the cost of renewable hydrogen could drop by approximately 75% by 2040, from \$5/kgH_2 today to less than \$2 /kgH_2 (Hydrogen Council 2021). Innovations that could unlock these cost reductions will be treated in detail in the forthcoming GINAs Hydrogen report. Furthermore, the abundance of carbon capture facilities in the future could increase the availability of carbon dioxide, substantially reducing its cost for users, such as synfuel production plants. For these reasons, feedstock costs could drop to less than 50% of synfuel production costs before mid-century, as shown in Figure 1. By then, capital and operating costs of conversion plants would represent about half of the production costs of low-carbon fuels, highlighting the importance of unlocking cost reductions in this area. The remainder of this report focuses on innovations in the conversion processes for low-carbon fuels.

New investment in advanced biofuels and synthetic fuels is held back by significant barriers to commercial deployment:

- **The high production costs** of advanced biofuels and synthetic fuels hinder their competitiveness with conventional fossil fuels. Synthetic fuels are currently more than four times costlier than regular gasoline. In addition, the risk of developing early-stage technologies increases the cost of financing advanced-fuel projects. The combination of high production and financing costs is a barrier for commercial deployment.
- **The lack of supporting infrastructure** poses a technical barrier to deployment. For advanced biofuels, adequate systems of collection, storage, and transport of feedstocks, along with downstream infrastructure such as blending and storage terminals, must be developed (IRENA 2017). These systems have been already rolled out for the production of conventional biofuels but need to be deployed at scale to support growth in biofuel production. For synthetic fuels, hydrogen and carbon dioxide production, transport to the site of fuel synthesis, and storage must be developed and deployed in the next decade.
- **Other policy and regulatory barriers** involve the lack of clear, long-term policy signals.

Key innovations

Innovation in low-carbon fuel production processes could further reduce capital costs of synthetic fuel and advanced biofuel refineries by 40–45%, leading to total cost reductions up to 20%. Table 1 below reports the cost reduction pathways to 2050 for both the high- and low-innovation scenarios, split into capital and fixed operating costs. Cost declines also occur in the low-innovation scenario, largely due to economies of scale, learning-by-doing, and foreseeable near-term technological improvements. However, the high-innovation scenario sees additional cost reductions to 2050. Reductions in feedstock costs, which are important given their contribution to total costs, occur thanks to innovations in other sectors. They are, therefore, not considered in the table below. Cost reductions in synthesis capital and operating costs translate into an overall fuel cost reduction of up to 20%. Larger overall cost reductions are envisaged in advanced biofuels, for which capital and operating costs represent a larger share of total costs.

Table 1. Cost assumptions under high- and low-innovation scenarios

Technology	Cost component	2020	2050 low innovation	2050 high innovation	% further cost reduction under high innovation	% further LCOE reduction under high innovation
Synthetic fuels	Synthesis capex, $m/GW	890	590	340	42%	42%

Technology	Cost component	2020	2050 low innovation	2050 high innovation	% further cost reduction under high innovation	% further LCOE reduction under high innovation
	Synthesis opex, $m/GW/year	35.6	23.7	13.7	42%	
Advanced biofuels	Synthesis capex, $m/GW	2,750	2,250	1,250	44%	32%
	Synthesis opex, $m/GW/year	188	154	85	45%	

Note: Operating costs include operation and maintenance costs related to the conversion plant but do not include variable electricity costs that are generated during the plant's operation.
Source: Vivid Economics based on IRENA, European Commission, IEA, Agora Verkehrswende, Agora Energiewende, and Frontier Economics (Lövenich et al. 2018; IRENA 2017; IEA 2019; European Commission 2017).

Key innovations in the production process of synthetic fuels include improving the efficiency of synthesis processes and building standardized, modular plants at scale:

- **Innovation in the process of fuel synthesis** is required to obtain high-conversion efficiencies and yields while using carbon dioxide as the main carbon source. Processes for fuel synthesis, such as Fischer-Tropsch and methanol synthesis, are already used to synthesize other gases and produce, for example, industrial methanol (The Royal Society 2019).

- **Modularization** can be used to quickly build small synthesis plants, reducing risks and costs during construction. Greater flexibility in the construction process could enable plants to be built close to isolated renewable electricity or carbon sources, providing feedstocks at lowered costs.

- **Developing large-scale, standardized production plants** would help generate economies of scale and produce plant components that are easy to replicate in case of system failure (Lövenich et al. 2018).

- **Production routes alternative to synthesis** are being studied. For example, solar conversion of carbon dioxide directly into fuels such as methanol has led to promising intermediate results, but further research is needed to improve conversion rates and yields (The Royal Society 2019).

Innovations in the production of advanced biofuels are specific to the conversion process adopted. Many production processes are available in the market, but only two are in active technological development (IRENA 2019):

- **Hydrolysis and fermentation**—Improvements and process-step integration, such as combining the hydrolysis and fermentation stages into a single step, could increase process efficiency (IEA 2020a).

Increased enzyme activity and enhanced yield production per ton of feedstock could lower enzyme use. These changes, paired with continued enzyme cost reductions, could lower the operating costs of conversion plants (IRENA 2017).

- **Gasification and pyrolysis**—Energy integration across the plant is considered a key opportunity for efficiency improvements: connecting the thermal demands and losses of different steps can improve the overall energy balance of the plant, improving yields and reducing energy imports (IRENA 2017). Development of fast pyrolysis processes to maximize yields represents another opportunity for cost reductions.

3. Benefits of innovation

Low-cost decarbonized energy

Lower energy costs are unlocked by the system benefits of innovation. System benefits of innovation refer to net reduction in costs across the entire energy system as a result of RD&D *and* commercialization of technologies. In the context of this report, system benefits are calculated as the difference in total system costs of a high-innovation scenario and those of a low-innovation scenario, whereby

- System costs are all capital, operating, and fuel costs within the global energy system[9]
- Low-innovation scenario represents market-driven progress in the absence of government support
- High-innovation scenario represents progress driven in part by government support of RD&D and deployment (i.e., commercialization) that accelerates cost reductions.

This metric provides an aggregate estimate of how innovations in selected technologies can reduce system costs after least-cost optimization of all energy carriers and technologies from both the supply and the demand sides.

Strong innovation in the production of low-carbon fuels can provide US$2.8 trillion (worth $220 billion today) in cumulative (undiscounted) system benefits to the energy system through 2100, with savings realized especially during the second half of the century. In both the low- and high-innovation scenarios, global energy system costs start at US$10 trillion a year in 2021. System costs in the scenarios begin to diverge in the 2030s, and by 2040 the (undiscounted) annual system costs in the high-innovation scenario are US $70 billion lower than in the low-innovation scenario. During these years, production of advanced biofuels attain scale, but synfuels lag behind due to their higher price premium. The gap between system costs in the two scenarios increases significantly over the second half of the century, at which point synthetic fuel production attains scale thanks to cheap production of hydrogen and carbon dioxide. Table 2 reports the system benefits in the high-innovation scenario for low-carbon fuels, measured as the difference between that scenario's cost and the low-innovation scenario's cost.

[9] System benefits may be calculated on an annual basis, or cumulatively between 2020 and 2050 (with or without discounting).

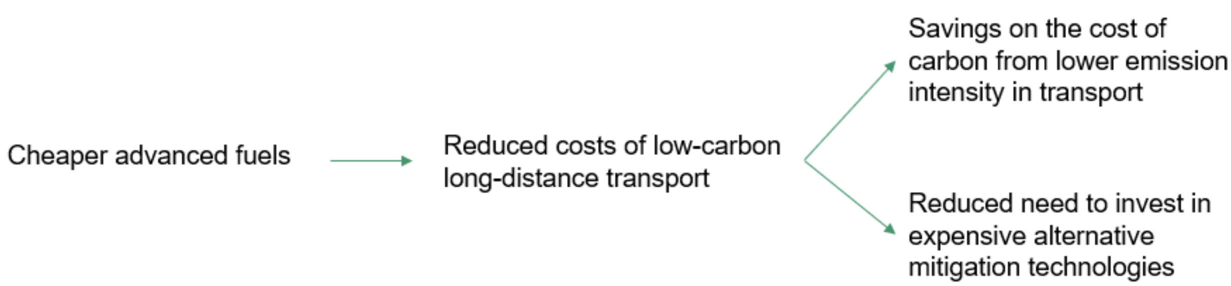
Table 2. Overall system benefits of innovation in low-carbon fuels

System benefits ($b)	2021–2050, cumulative, undiscounted	2051–2100, cumulative, undiscounted	2021–2100, cumulative, discounted 5%
High innovation in low-carbon fuels	US$790 billion	US$2 trillion	US$220 billion

Note: Discounting reduces the present value of future benefits.
Source: Vivid Economics.

Innovation in the production of low-carbon fuels benefits the energy system mainly through reduced cost of low-carbon transport. Cheaper low-carbon fuels help decarbonize long-distance transport by replacing other fuels of fossil origin, such as jet fuels in aviation and conventional heavy fuel oil in commercial vessels. Lowering the cost of low-carbon fuels would reduce the need to rely on other costlier decarbonization solutions, which may require converting existing engine systems and supporting infrastructure. For example, the use of hydrogen in shipping, directly or in the form of ammonia, requires significant modifications to the engine and to transport and storage infrastructure on land and on the vessel. By decarbonizing long-distance transport, savings would accrue directly from the avoided cost of carbon from lower emission intensity in the sector, and indirectly from the reduced need to invest in expensive alternative mitigation technologies, such as negative-emission technologies. Figure 2 presents a schematic of the mechanism under which system benefits would be realized.

Figure 2. Impact of innovation on the energy system.



Note: Illustrative only.
Source: Vivid Economics.

Jobs and Growth

Biofuel project developers have a range of options to set up each stage of the value chain. The value chain of biofuel production starts with feedstocks. These vary and can include wood residues, agriculture residues, and waste. These resources are rarely in the hands of project developers, who need to connect with farmers and forest product industries and their stakeholders to procure them. The conversion technologies that project developers can choose from are many, and the choice depends on the targeted final product. Once produced, advanced biofuels are blended with conventional fuels and sold on the market. However, advanced biofuels will increasingly be used directly (without blending) as fossil fuels are phased out of the market.

The value chain for synthetic fuels relies on the production of hydrogen and carbon dioxide. Developers can partner with companies producing carbon dioxide and hydrogen to ensure a stable supply of feedstocks.[10] Reliance on feedstocks that are currently difficult to transport can condition the project developer's choice of location for the conversion plant. Developers can co-locate production close to partner feedstock-producing companies, for example, near sources of cheap renewable energy or industrial clusters.

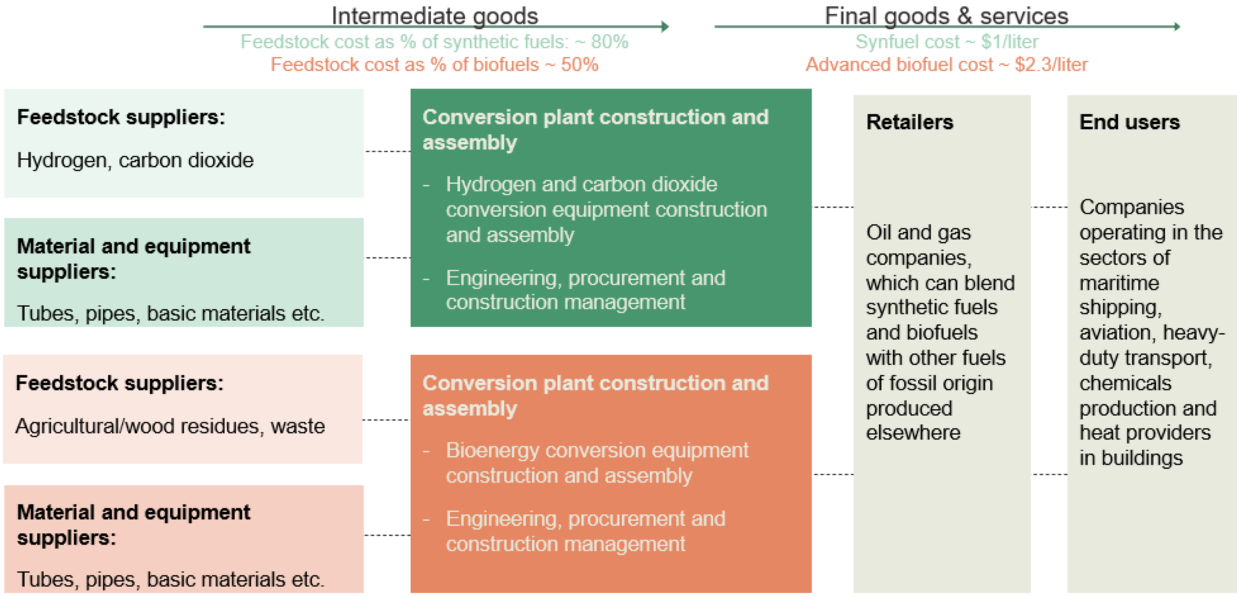
The market for low-carbon fuels could be valued at US$600 billion by 2050, with the stage of the value chain related to conversion plants reaching more than US$60 billion. Today, the market for advanced biofuels is estimated at US$33 billion globally (Precedence Research 2021). But the market for synthetic fuels is still in its infancy, and no industrial-scale plants have yet been built (The Royal Society 2019). By comparison, the market for gasoline today is estimated at US$1,200 billion (IEA 2021). Reduced costs and increased applications of low-carbon fuels through innovation can expand demand for these fuels and can deliver economic benefits across the value chain (Figure 3). These benefits include business opportunities upstream at the feedstock stage, at the conversion stage, and downstream at the distribution stage. Under the high-innovation scenario, the market size of the entire low-carbon fuels value chain could reach US$600 billion by 2050, with approximately 13 EJ of fuel produced in that year.[11] By the same year, the market size specifically related to the conversion stage could reach more than US$60 billion. Other stages of the value chain are important, but opportunities will heavily depend on local characteristics and market concentration and are, therefore, not quantified in detail in this report.

In addition to innovation, adequate policy support is important to expand the market size of low-carbon fuels. The market for low-carbon fuels is driven not only by cost considerations, but also by governments' greenhouse gas (GHG) emission savings targets. Government interventions, such as fuel taxation, blending obligations, and transport sector emission reduction targets, are needed to drive demand for low-carbon fuels and to enlarge markets.

---

[10] For example, in 2020, energy and petrochemical company Repsol announced a plan to build a synthetic fuel production facility in partnership with Petronor, one of Spain's principal industrial centers, and the Energy Agency of the Basque Government (EVE) (*Renewable Energy Magazine* 2020).
[11] Fuel market sizing is indicative.

Figure 3. Simplified value chain for low carbon fuels.



Source: Vivid Economics.

Construction and operation of conversion plants, parts of the supply chain with significant potential for innovation, could generate US$30 billion in direct GVA per year by 2050. In the 2020s and 2030s, as low-carbon fuel refineries are deployed at scale, more than 80% of GVA could derive from the construction and development of conversion equipment. By 2050, more than half of global GVA could derive from the operation and maintenance of refineries built in previous years. This trend is described in detail in Figure 4. Equipment manufacturers and fuel producers have a substantial opportunity to capture part of this market share.

Conversion technologies and plants could support 300,000 jobs, creating opportunities for workers with a wide range of skills. Conversion technologies and plants are trade-exposed and highly innovative. Capturing the market share in these parts of the supply chain could translate to secure industry development and long-term employment opportunities. Highly specialized workers will be required to develop and design new and improved conversion technologies and conversion plants using innovative feedstocks. These workers include microbiologists, biochemists, and agronomists as well as chemical, industrial, and agricultural engineers. Construction and operation of feedstock units and conversion facilities will require construction workers and plant operators. Pipeline operators and truck drivers will be needed to transport the fuels from conversion facilities to retailers. A number of these workers are today employed in the oil and gas industry. Adequate retraining programs will be important to mitigate skills shortages in the low-carbon fuel industry while guaranteeing new employment opportunities for workers in the fossil fuel industry.

Figure 4. GVA and jobs in the low-carbon fuels industry to 2050.

Source: Vivid Economics.

4. The case for supporting innovation

To realize the full benefits of low-cost low carbon fuels, public spending on RD&D and commercialization of US$3.2 billion per year and US$2.8 billion per year, respectively, is required. These sums are equivalent to more than 10 times the current annual investment in low-carbon fuels from private and public sources combined (IRENA 2019). Most of this investment is currently being directed to second-generation biofuels; investment in pilot projects for synfuel refineries has only recently started to ramp up.[12] In the short term, a large share of the RD&D spending could be directed to innovation in synthetic fuels and related value chains, given their limited development to date. But most of the commercialization spending could be directed to deployment at scale of advanced biofuels, which are at a more advanced stage of development and which already have supply chains in place.

Although sizeable, the additional RD&D and commercialization spending is small relative to the benefits. Modeling scenarios suggest that greater innovation in low-carbon fuels, enabled by government RD&D and commercialization support, could bring US$45 billion in system benefits in 2050. The RD&D and commercialization spending by the public sector is, therefore, less than 15% of annual benefits. Furthermore, the estimated spending required is still less than 4% of the annual subsidies directed to oil consumption on average in the last five years (IEA 2019).

Without adequate pull policies, substantial public support is necessary to commercialize low-carbon fuels ahead of their utilization at scale in the 2030s. To support the scale and pace of deployment required, complex supply chains involving multiple feedstock types will need to be set up and managed. With limited carbon prices, uncertainty over future markets, and limited policy support specific to low-carbon fuels, demand for low carbon fuels would be limited, and the deployment of low-carbon fuels projects would remain at the pilot/demonstration stage. These factors limit critical supply chain development and cost reductions, risking unnecessarily high costs when demand rises in the 2030s.

Government support for RD&D and commercialization will need to be accompanied by pull policies that address market barriers and drive deployment. Without pull policies, low-carbon fuels directly compete with their cheaper fossil fuel counterparts solely on a cost basis, potentially reducing demand for these fuels and slowing down their deployment. Carbon pricing covering most sectors would broadly create demand for low-carbon fuels. More sector-specific policies include the use of mandates with clear eligibility criteria, which can be designed with non-compliance penalties and price caps on compliance costs to incentivize compliance while increasing political acceptability. Stable and long-term policy frameworks can provide certainty about future government plans, reducing risk and increasing the bankability of low-carbon fuel projects. Taxation frameworks for transport fuels can be updated to internalize the carbon externality of liquid fuels of fossil origin. Together, a combination of push policies and pull policies can ensure sufficient investments as well as rapid and cost-effective deployment of low-carbon fuel projects at scale.

[12] For example, in January 2021, Germany's largest refinery released plans to add synthetic fuels to its existing mineral oil-based portfolio with an EUR 500 million investment in a pilot project (Amelang 2021).

References

Amelang, S. 2021. "Pilot project in Germany’s largest refinery to produce synthetic fuels." *Clean Energy Wire*, January 21. www.cleanenergywire.org/news/pilot-project-germanys-largest-refinery-produce-synthetic-fuels.*13.*

Concawe. 2019. *Review* 28(1). www.concawe.eu/wp-content/uploads/Concawe-Review-28-1-web-resolution-PDF.pdf.

Energy Transitions Commission. 2021. *Bioresources within a net-zero emissions economy: Making a sustainable approach possible.* www.energy-transitions.org/publications/bioresources-within-a-net-zero-emissions-economy/.

European Commission. 2017. *Building up the future cost of biofuel.* https://op.europa.eu/en/publication-detail/-/publication/13e27082-67a2-11e8-ab9c-01aa75ed71a1 (12)

Hydrogen Council. 2021. *Insights report 2021.* https://hydrogencouncil.com/en/hydrogen-insights-2021/.

IEA (International Energy Agency). 2019. *The future of hydrogen.* www.iea.org/reports/the-future-of-hydrogen.

IEA. 2020a. *Advanced biofuels: Potential for cost reductions.* www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf.

———. 2020b. *Energy technology perspectives: The world's guidebook on clean energy technology.* www.iea.org/topics/energy-technology-perspectives.

———. 2021a. Fossil fuel subsidies database. www.iea.org/data-and-statistics/data-product/fossil-fuel-subsidies-database.

———. 2021b. *Net zero by 2050.* www.iea.org/reports/net-zero-by-2050.

IRENA (International Renewable Energy Agency). 2017. *Innovation outlook: Advanced liquid biofuels.* www.irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels .

———. 2019. *Advanced biofuels: What holds them back?* https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf.

Jans, Y. et al. *2018. "Biomass production in plantations: Land constraints increase dependency on irrigation water." GCB Bioenergy 10(9):628–44.*

Lövenich, A. et al. 2018. *The future cost of electricity-based synthetic fuels.* www.renewableh2.org/wp-content/uploads/2018/11/2018-09-Agora_SynKost_Study_EN_WEB.pdf.

Precedence Research. 2021. *Advanced biofuels market size to surpass US$848 bn by 2030. www.precedenceresearch.com/advanced-biofuels-market.*

Proper, Ellen. 2021. *"KLM makes first regular flight with sustainable synthetic fuel." Bloomberg,* February 8. www.bloomberg.com/news/articles/2021-02-08/klm-makes-first-regular-flight-with-sustainable-synthetic-fuel.

Ram, M., et al. 2020. *Powerfuels in a renewable energy world.* www.powerfuels.org/test/user_upload/Global_Alliance_Powerfuels_Study_Powerfuels_in_a_Renewable_Energy_World_final.pdf.

Renewable *Energy Magazine.* 2020. "Repsol to Develop Two Major Emissions-Reduction Projects in Spain." Renewable Energy Magazine, June 16. www.renewableenergymagazine.com/biogas/repsol-to-develop-two-major-emissionsreduction-projects-20200616.

Research and Markets. 2017. *Global motor gasoline market.* https://www.researchandmarkets.com/reports/4431659/global-motor-gasoline-market-size-market-share.

Royal Academy of Engineering. 2017. *Sustainability of liquid biofuels.* www.raeng.org.uk/publications/reports/biofuels.

The Royal Society. 2019. *Sustainable synthetic carbon-based fuels for transport.* https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/sustainable-synthetic-carbon-based-fuels-for-transport/.