‘EU Biomass Use in a Net-Zero Economy – A course correction for EU biomass’ and ‘Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible’

Assumptions and methodology underlying the sectoral analysis

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Technical Annex

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Methodology and objectives: a framework for prioritising biomass use in the low-carbon transition

This technical annex is provided as a supplement to the reports 'EU Biomass Use in a Net-Zero Economy – A course correction for EU biomass' and 'Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible'.[1] The annex presenting the underlying methodology and assumptions behind these reports.

Biomass, like other resources, will see major shift in use patterns as the economy shifts to net-zero emissions of greenhouse gases

The transition to a net-zero economy will involve substantial changes to how resources are used to produce materials and energy. For example, whereas the largest use of hydrogen today is in the refining of oil and other fossil feedstock to transportation fuels, most net-zero scenarios foresee drastically different uses in the future, not least with hydrogen as a feedstock in industrial processes where it does not feature at all today. Similarly, such scenarios foresee a very different pattern of use for electricity, with much greater rates of electrification, and entirely new conversion processes from electric energy to useful services, such as via new battery electric drivetrains in transportation, or via heat pumps for heat production.

Biomass use, too, will need to change in the transition to net-zero emissions. As discussed in detail in the main reports to which this is an annex, bioenergy already makes a major contribution to EU and world energy systems, while biomaterials (wood products, pulp, paper, fibre, and more) are a key part of materials use in several value chains of the economy. Much like with hydrogen or electricity, we should expect these use patterns to shift as the overall economy shifts production to modes that are compatible with net-zero emissions.

The core question of this study has been to characterise what this reconfiguration could look like: what biomass use should we expect and work towards in a 2050 net-zero economy? As resources are limited, they must be prioritised, and a set of principles and mechanisms are needed for this.

A framework for the value of biomass in a net-zero economy

The approach taken in this study to exploring priorities for biomass use is to consider where it has the most *value*, in a scenario where all sectors of the economy reduce greenhouse gas emissions to net-zero emissions by 2050. To give as full an answer as possible, we integrate an analysis of all major proposed uses for biomass in current applications as well as proposed future scenarios. This includes fibre production, chemicals production, passenger and freight road transport, aviation, shipping, industrial heating, building heating, power, and carbon dioxide removal (CDR, or 'negative emissions'). A key aim is to jointly analyse materials and energy uses of biomass.

Crucially, the analysis is focussed on biomass use in a net-zero economy. It thus does not compare biomass options to fossil fuel-based options, to estimate abatement costs or other relative performance. Instead, the starting point for the analysis is opportunity cost, given the constraint of net-zero CO_2 emissions: 'If not using biomass, what alternative net-zero solution must be used?'.

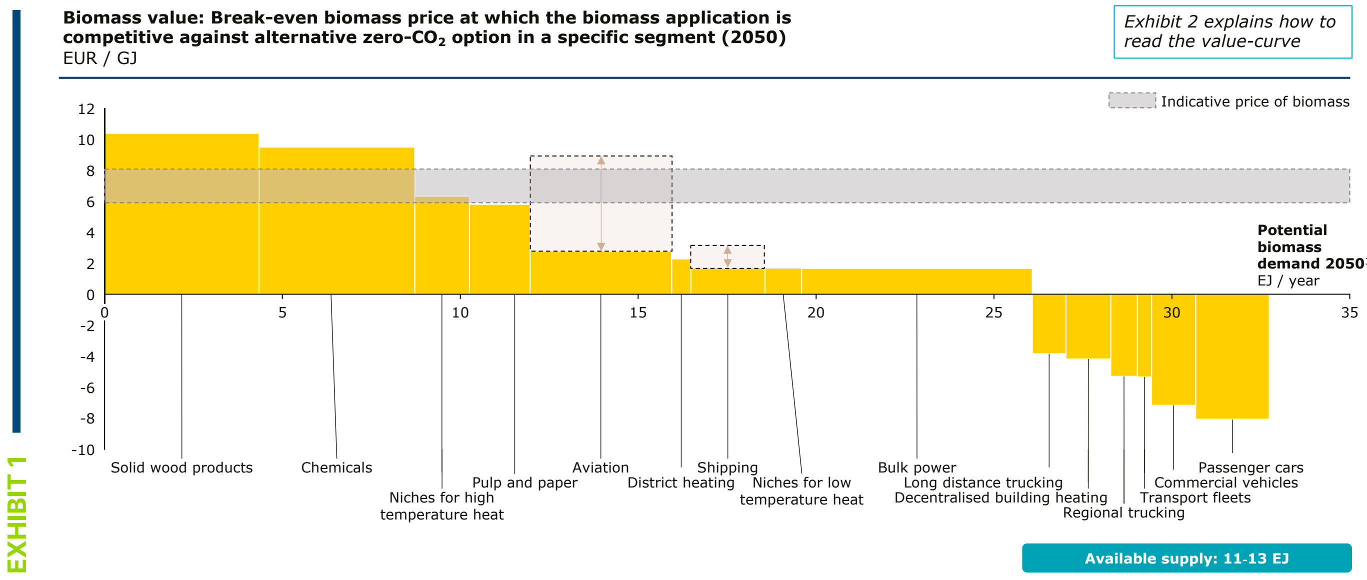
Specifically, biomass and non-biomass net-zero CO_2 options are compared by modelling the cost to provide a specific energy service, material or product: for example, heavy-duty goods transport at a range of 500 km, a specific grade of industrial heat, or one tonne of plastics production. The analysis spans more than 50 different use-cases of biomass and alternative energy and materials solutions. In each case, the analysis identifies the cost of biomass input at which a biomass-based option and its alternative provide the same service or product at the same cost – i.e., the break-even biomass input cost.

This break-even biomass cost then creates a summary metric that allows for comparison across a wide range of use-cases, and a highly intuitive and robust definition of value. If biomass feedstock is only available at higher cost than the break-even level, then an alternative solution provides higher value; conversely, if biomass feedstock is available at a lower cost, using biomass for that application provides higher value. An advantage of this definition of value is that it is closely linked to the willingness to pay for biomass feedstock in the market; if markets work well, value, as conceived here, and (long-run) prices will closely track one another, subject to available supply. Another is that it makes possible a unified analysis of biomass across the many different types of feedstock and end-use applications. For example, there is no single biomass price, but enormous variation depending on quality, location, transportation cost, moisture content, and many other parameters; however, the value curve can provide guidance for a specific case, which then can be set against estimates of the future cost of supply of the feedstock required for that particular end-use application.

The biomass value curve as a summary representation

The results are presented in aggregated form through a 'value curve' for biomass across the different use cases. Along with the break-even level for a representative application, the curve shows the estimated size of different proposed uses of biomass across the economy. Exhibit 1 provides an example for Europe and in the year 2050, while Exhibit 2, provides another a more in-depth guide to how to read the value curve.

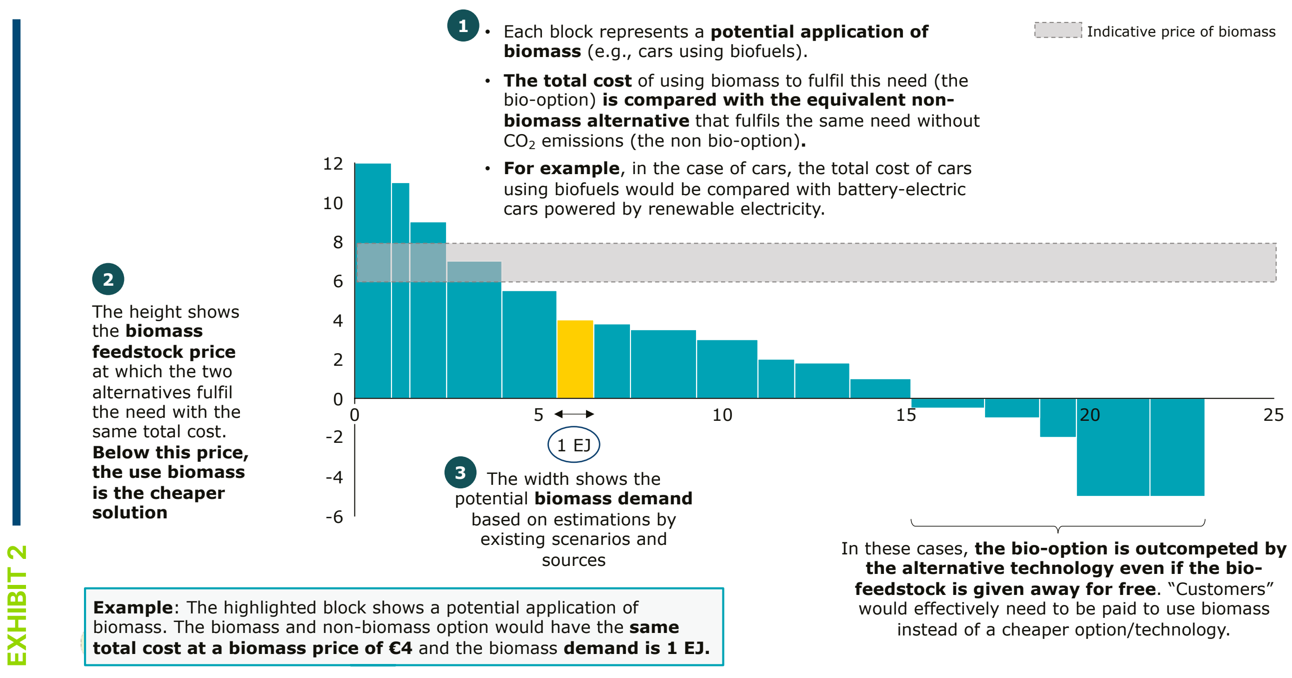
EXHIBIT 1: A VALUE CURVE FOR EU BIOMASS USE IN 2050



Notes: Value shown for wood products and fibre is product price expressed in energy-equivalent terms; for other segments the value shown is the breakeven price against another zero-CO_2 option. The value is calculated without carbon capture and storage (see discussion later in this chapter). 1Based on estimations by existing scenarios and sources. Primary energy equivalents have been used as the measure for both materials and energy in this study to make values comparable. Materials have been converted from mass (kg) or volume (m³) to energy by the specific energy density of the material. The energy is also measured in primary rather than final energy form, to account for conversion losses in the production of biofuels. The values shown are for EU27 + UK.

Sources: Material Economics and ETC analysis.

EXHIBIT 2: HOW TO READ THE VALUE CURVE



The summary value curve shows large variation in the value of the use-cases. The break-even levels at which biomass is cost-competitive with alternative options range from 10–12 EUR/GJ – far higher than the typical cost of most biomass feedstock today – to negative prices, meaning that biomass-based solutions would be economically viable only if feedstock can be obtained at zero cost, or via a gate fee.[2] Importantly, for the large majority of uses, biomass would only be competitive if it were available at significantly lower prices than the 6–8 EUR/GJ cost of producing and processing energy crops at scale.[3]

Limitations and additional analysis required for strategy and policy insight

While the value curve provides a powerful summary metric, it also should be interpreted within a wider set of considerations:

Private vs. social cost. First, the true social cost of both biomass and non-biomass options can vary substantially from market price. For biomass, biodiversity impacts, air pollution from combustion, or additional release of CO_2 from vegetation and soils are examples of such effects. For non-biomass options, similar effects can result from resource depletion, local pollution in the mining of minerals or metals, etc. The study has not estimated the non-market costs in monetary terms. However, it does complement the cost and value estimates with other relevant metrics that can serve as a guide to decision-making. The first is resource efficiency, often expressed in the total energy inputs required for different options. For example, we present a metric of 'electricity equivalents' – i.e., the number of megawatt-hours of electricity required to substitute for one megawatt-hour of biomass. Another is the land requirements for different options, expressed in hectares per functional unit for each use-case.

Aggregate vs. granular assessment. Second, the cost curve shows a representative and aggregate assessment, but the underlying analysis also revealed a lot of nuance and complex cases. At a more granular level, the use of biomass can be more or less advantageous, depending on multiple factors that can make a use-case more economically viable than the averages presented in the value curve. These include access to very cheap local feedstock, the ability to provide additional valuable services or co-benefits (such as waste management or carbon storage), and local conditions that make alternatives costlier or less viable (such as variations in electricity or infrastructure availability). The conclusions in the main reports were informed by detailed sensitivity analysis of these topics, beyond the high-level summary represented by the value curve.

2050 and net-zero value vs. current value and pathways. Third, a reminder that the biomass value framework shows value in a 2050 and net-zero context. It offers guidance to the patterns of future biomass use that businesses and policymakers should aim for. However, it must be complemented with additional analyses to conclude on the best pathways to get there – not least, what the transition path from current to future use patterns might look like.

Details of the biomass value curve methodology for the value curve

To construct the integrated assessment, several additional analytic pieces have been required. The subsequent chapters of this report lays out the key assumptions and methodological choices for each major end-use category. In summary, the key considerations include:

- **Scope and future demand for biomass.** The analysis covers the use of biomass for materials and energy production. The potential future uses of biomass were derived from a literature review. The sources were chosen for their prominence in public debate about the future use of biomass, including scenarios from the European Commission, EU Member States, international agencies, industry associations, and academic research. Each segment in the value curve shows the extent of demand proposed in recent published assessments. (Not documented here; see main report for details of the sources.)

- **Primary energy denomination.** The different uses were put on a comparable volume basis by expressing them in energy terms. The energy amounts shown are the primary energy of the biomass feedstock, before biomass is converted to fuels for end-use. For materials, this required converting tonnage or volume measurements to their energy content, using standard conversion factors for energy density for the relevant feedstock. For energy uses, this required assessing the efficiency of conversion factor of each use-case from primary resource to finished fuel product, including the co-products where available.

- **End-use segmentation.** The modelling next defined the different service or utility that must be met within each sector. In each sector, several different end-use segments were defined. For example, transport applications (road, air, and sea) were divided by passenger and freight applications, by distance travelled, and by weight of vehicle. Similarly, chemicals were analysed at the level of basic chemicals production; power production by bulk generation and by the provision of flexibility resources; heat by the grade of heat and pattern of load; and industrial processes for their specific requirements.

- **Biomass and alternative applications.** For each end-use, a range of different applications was defined, drawing on a wide range of literature. Only applications that eliminate fossil CO_2 emissions were included, consistent with the focus on how biomass should be used in an economy with net-zero emissions in 2050. For biomass options, the conversion pathways were matched to the likely future sources of biomass identified (wood industry by-products, waste, and residues, or perennial grasses or short-term rotation coppice). In most cases, this requires 'second-generation' conversion pathways from woody biomass to final fuels. For alternatives to biomass, a first screening of options was first done, and the application identified that would be most likely to be considered an alternative at the margin. For example, in chemicals, a whole portfolio of options (demand reduction, substitution, mechanical recycling, chemical recycling, electrification, CCS) were considered, and biomass options compared against other options (notably the use of CO_2 as feedstock) for residual emissions reductions once the potential for these options had been exhausted. Likewise, in the segment 'long-distance heavy road transport', lignocellulosic biodiesel from Fisher-Tropsch synthesis was compared against other major contenders (modal shifts, optimisation of logistics, battery electric vehicles, hydrogen fuel cell electric vehicles, or synthetic fuels in diesel engines), but the hydrogen fuel cell option was selected as the most likely marginal comparison.

- **Technology assessment and evolution.** For both the bio and non-bio-options, the focus is on the technologies that are likely to be available in 2050. The technological maturity of different options included in the assessment differs: from fully commercialised technologies (e.g., heat pumps for space heating) to ones that have yet to be used at a commercial scale (e.g., synthetic fuels in aviation or ammonia as fuel in shipping). The assessment therefore included a view on each option's Technology Readiness Level (TRL), which evaluates each option on a scale from 'basic principles are defined' (TRL 1) to 'commercially operation in relevant environment' (TRL 9).[4] With a few notable exceptions noted in the respective chapters, the analysis has been constraints to non-bio-options that require no major breakthroughs. However, it does rely extensively on assumptions about the evolution of platform technologies (especially, renewable power production, hydrogen, and batteries) that are widely used in future energy scenarios. The assumptions about these are presented in Chapter 10.

- **Global cost assessment.** For each of the potential uses of bioenergy, the associated value curve expresses the cost of alternative solutions as a break-even price for primary bioenergy at which the biomass option has the same cost as the alternative, non-biomass option. This requires that all the cost-components of each option are modelled, including capital expenditures, feedstock and energy conversion efficiency, equipment lifetime, cost of capital, and various other operating expenditure. Each non-bio economic assessment is first made in its natural form (e.g., EUR per tonne-km) before being converted into cost per unit of bioenergy required (EUR per GJ) via a calculation of the biomass feedstock required to meet each unit of demand (e.g., GJ biomass per km). For biomaterials, the calculation was simpler, directly assessing the cost of biomass materials required for each segment, expressed in terms of EUR/GJ for comparison to the energy sectors.

The following chapters present a more detailed look at the individual assumptions and calculations behind each sectoral analysis. Each chapter begins with a description of the end-use segments within each sector as well as each segments' use-case requirements. The analysis then continues with a description of the available technologies for decarbonizing each sector in 2050 (including both biomass and non-biomass-based alternatives), and a comparison of these technologies in terms of resource efficiency and cost. The chapter concludes with a description of how the figures presented on the value curve (total potential biomass demand per end-use and break-even price for primary bioenergy) are calculated.

An additional chapter describes the methodology for calculating the land use and greenhouse gas efficiency comparisons between bio and non-bio-options for each sector.[5]

1. Road transport

End-segments and use-case requirements

The modelling of road transport starts from a characterisation of demand for road transport in 2050. Total demand is based on 2050 projections for passenger and freight transport taken from the EU and IEA.[6] The analysis allows for different degrees of modal shifts and operations efficiency.

The modelling of cost is based on a total cost of ownership model for different sub-segments: private passenger transport, large commercial vehicles, fleets, regional heavy-duty trucking, and long-distance heavy-duty trucking. These segments are generally defined by vehicle type as well as usage patterns, range, uptime, and load hauling capacity requirements. In somewhat more detail:

- Passenger transport and large commercial vehicles (LCV) have similar use cases characterized by range requirements of 200 – 500km (or less) with significant periods of downtime, and no binding hauling constraints. The disperse nature of trips taken requires a widely available infrastructure for refuelling, similar to petrol stations today.

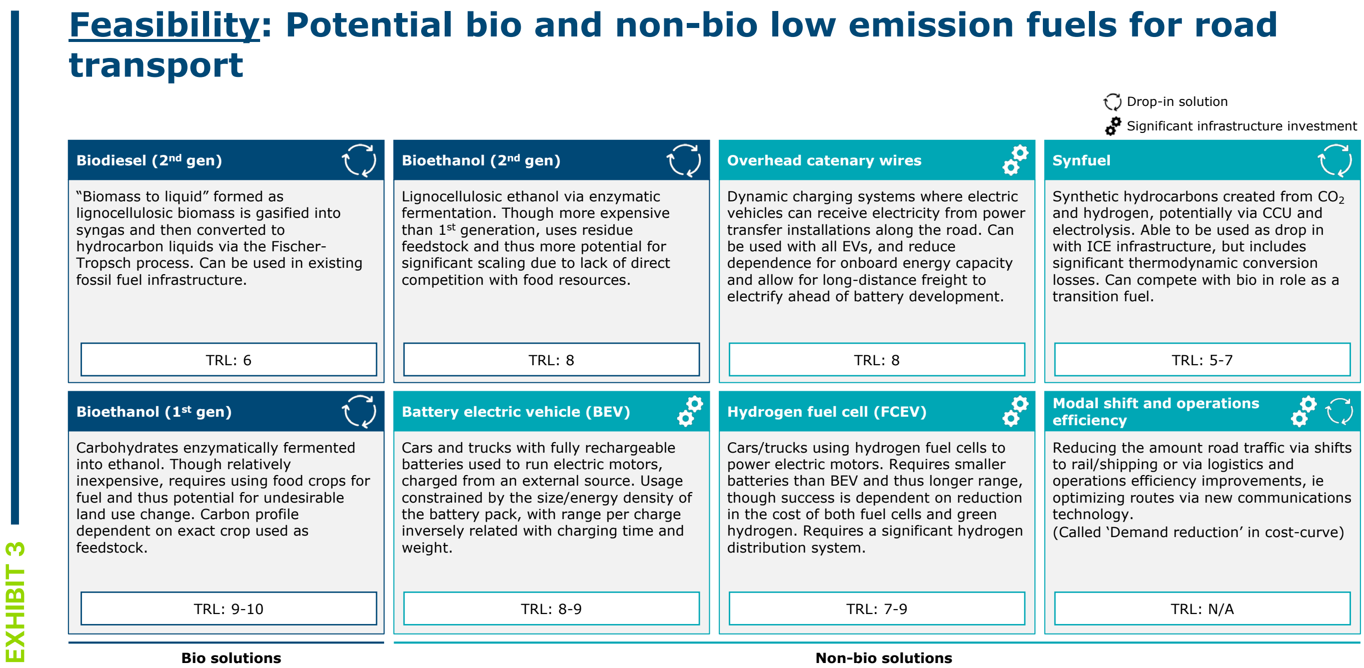
- Fleets consist of buses, emergency vehicles, or similar which are characterized by centralized usage around dedicated infrastructure, with high utilization rates leading to high uptime requirements.

- Trucking consists of several sub-segments, generally defined by distance travelled and weight of freight hauled. Use cases generally become more difficult to meet as distance travelled and payload increase, with long distance heavy-duty trucking requiring significant uptime, range, and payload capacity as well as the ability to operate in adverse conditions.

Net-zero compatible mitigation options

The analysis considered eight main technologies to serve the various road transport segments (Exhibit 3).

EXHIBIT 3: POTENTIAL TECHNOLOGIES FOR DECARBONIZING ROAD TRANSPORT



Sources: International Energy Agency, 'Clean Energy Guide'.

BIOFUELS

All biomass-based mitigation options involve producing fuels for use in internal combustion and diesel engines, the current dominant drivetrain in all road transport subsegments. The exact fuel depends on the biomass feedstock, the pathway for production, and the final fuel produced. A conclusion from the analysis is that currently dominant biofuels for road transport (HVO, corn/sugar-based ethanol) have limited potential in the longer term due to limited feedstock. While they may feature in the overall mix of liquid biofuels, any large-scale use of biofuels in road transport therefore would have to rely on conversion routes starting from woody (lignocellulosic) biomass: Two main two biomass-based fuels were considered.

- Lignocellulosic ethanol from enzymatic fermentation is the biofuel comparison for light transport. This fuel can serve as a "drop-in" replacement fuel for vehicles currently using petrol, and is advantaged over e.g., corn-based ethanol in that it can be created with direct competition with food resources.

- Lignocellulosic biodiesel via Fischer-Tropsch is the biofuel comparison for heavy transport. Lignocellulosic biomass is first gasified into syngas and then converted to hydrocarbon liquids via the Fischer-Tropsch process. This fuel can be used as a drop-in replacement for vehicles currently using diesel, such as busses and heavy-duty trucks.

Interviews with industry actors showed that a third route also is being explored for near-term conversion of lignocellulosic biomass, using pyrolysis to produce bio-oil for further upgrading via refining. The main impetus appears to be the compatibility of this route with the much larger volumes of HVO used as diesel replacement.

BATTERY ELECTRIC VEHICLES (BEV)

BEVs are cars and trucks with fully rechargeable batteries used to run electric motors, charged from an external source. For this analysis, we compare against a use-case with fully zero-CO_2 electricity. The applicability of BEV to the various subsegments depends heavily on the development of battery technology, particularly energy density and charging time.

BEV are currently able to meet all use case requirements of light passenger transport and large commercial vehicles and are thus used as the comparison point for the value curve calculations for these subsegment. The use-cases modelled depends on the widespread availability of megawatt charging, allowing rapid recharging for multiple vehicles simultaneously and thus the ability to meet the use case requirements of fleets. The cost of this charging infrastructure is included in the total cost of ownership analysis to make a like-for-like comparison.

The ability of BEV to meet heavy duty trucking use-cases pivots on two main factors. First, the future energy density of batteries conditions the share of payload dedicated to battery and drivetrain, and the resulting trade-off between range and payload. Second, battery charging times affect the feasibility of use-cases, as well as the cost (time costs as well as infrastructure costs to enable different use-cases). The analysis surveys the literature on potential future developments and follows the standard in all recent assessments of improved battery density and charging times. As a result, BEV technology is fully applicable to the regional trucking segment (range 300 – 500km). The applicability to long-distance, heavy-duty trucking is less clear-cut, though the most optimistic projections for battery density consider this to be a possibility.[7] In this analysis, however, we use a fuel-cell technology option as comparison for this segment instead, while noting that there is a strong possibility

Road transport energy demand could also be met with **overhead catenary wires** in conjunction with FCEV or BEV.

FUEL CELL ELECTRIC VEHICLES (FCEV)

FCEV vehicles use hydrogen fuel cells to power electric motors. The analysis uses a 'green' hydrogen production system based on water electrolysis and powered by renewable energy. FCEV require a significant refuelling infrastructure to be competitive for light transport, similar to the availability of petrol stations today.

FCEVs are used as the main comparison point to biofuels for the long-haul heavy-duty trucking subsegment, given its ability to handle large payloads with quick refuelling times. Additionally, long-haul heavy-duty trucking generally runs along major transport route, lowing the bar for new infrastructure investment. The analysis also suggests FCEVs as a contender for the fleet option, given the reliance on centralized infrastructure that otherwise can be a hurdle for FCEV refuelling, although the analysis did not conclude on the use of BEVs or FCEVs for this segment.

SYNFUELS

Synfuels are liquid hydrocarbons created via carbon capture and use (CCU) from captured CO_2 and green hydrogen that can be used as drop-in replacement in internal combustion or diesel engines. Production costs are driven to a very high degree by the cost of CO_2 and of green hydrogen. Strikingly, the analysis finds that, for low-cost CO_2, many production systems for green hydrogen could produce synfuels at cost parity with a standard diesel powertrain, and thus at lower cost than biofuels. However, costs vary significantly for different world regions, and depending on the capital cost at which electrolysers are available for hydrogen production. In most cases, the analysis finds that synfuels are more expensive than BEV and FCEV. However, some analysts expect that synfuels can be used in the most demanding use cases for heavy duty trucking, over long distances and out of reach of hydrogen infrastructure.[8] One route for this could be that synfuel production for sustainable aviation fuels results in co-products, roughly 20% of which could be suitable for road transport.[9]

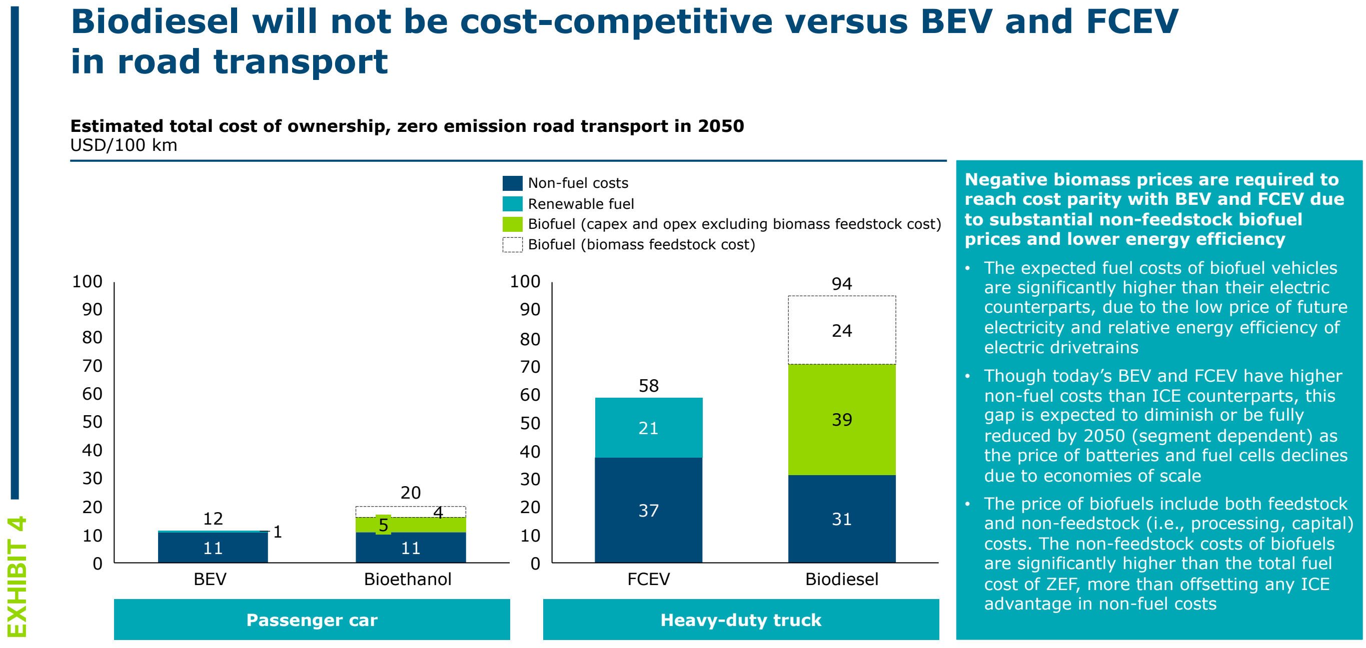
Cost assessment of mitigation options

The economics of each decarbonisation option were assessed on a total cost of ownership (TCO) basis, calculating the cost per km for the bio and non-bio-option for each subsegment. The TCO was built around the initial purchase price of the vehicle, its lifetime, non-fuel OPEX costs (including maintenance, repairs, and taxes), and fuel costs built on the energy demand of each vehicle time and use case. Estimates for the relevant parameters for BEV and FCEV were cross-checked against a range of recent published sources.[10]

Break-even prices were calculated based on comparisons between the TCO of the bio and non-bio alternative for each subsegment. First, the per-km TCO for the non-bio-option is calculated. Next, the per-km TCO for the bio-option excluding feedstock costs is calculated. The difference from these values is taken and converted to cost per GJ engine output. This value is then multiplied by well-to-wheel efficiency to calculate the relevant price of biomass which allows for TCO cost parity between the bio and non-bio-options.

The results replicate the findings from several other recent studies. In brief, most assessments see a cross-over point of around 2030 where total cost of ownership is lower for the relevant BEV and FCEV applications relative to incumbent fossil fuel solutions, in most part of the world. By 2050, a significant cost advantage has is then in place. Given the higher cost of biofuels, the picture is still more pronounced in a comparison of BEV and FCEV use-cases to their biofuel equivalents.

EXHIBIT 4: RELATIVE COSTS OF ROAD TRANSPORT TECHNOLOGIES



Notes: BEV: battery electric vehicle; FCEV: fuel-cell electric vehicle. Assumes a 2050 global levelized cost of electricity of $20/MWh and hydrogen at $1.4/kg. Biofuel assumes a cost reduction by 2050 of 28% on non-feedstock OPEX/CAPEX costs from current figures (-15% 2020 to 2035, -15% 2035 to 2050).

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[11]

For most road transport applications, the cost delta is so large that there is a 'negative value' of biomass, meaning that biofuels-based options have a higher TCO than their BEV or FCEV alternatives even if biomass feedstock is provided for free. In other words, the high capital expenditure associated with biofuels production infrastructure means that the TCO is higher for biofuels transportation even with free feedstock.

As this report attempts to provide a scenario for vehicle costs 30 years in the future it necessarily depends strong on assumptions for the evolution of future cost and performance. Key factors that strongly influence the assessment include:

- The availability of zero carbon electricity. The relative advantages of FCEV and BEV are due to the combination of significant efficiency advantages and cheap fuel. If electricity is not available, or is significantly more expensive, this advantage is reduced.

- The continued decline in costs for batteries, fuel cells, and electrolysers. Compared to several other assessments, this report attempts to take a conservative view of the relative CAPEX requirement of BEV/FCEV vehicles versus ICE equivalents. All segments (except for passenger vehicles) are still at a cost disadvantage in 2050 in pure capex terms. If, as some have projected, the costs of batteries and fuel cells continue to decline rapidly, the relative advantage of these technologies may be even bigger than presented here. In contrast, a slower than projected decline in these costs leads to biofuels being more cost competitive in 2050.

- The availability of ZEV infrastructure for refuelling. Infrastructure costs here are inferred via the prices used for fuel. If infrastructure is not available, or were more expensive, biofuels may remain cost competitive.

Two sensitivity analyses were run as part of this study, analysing whether BEV and FCEV would maintain their cost advantage over biofuels if either 1) biofuels were much cheaper to produce than in the baseline model[12] or 2) renewable energy was much more expensive than in the baseline model. While the advantage of BEV over biofuels in light transport was robust to these sensitivity checks, the advantage of FCEV in heavy duty trucking is dependent on the availability of cheap hydrogen.

Resource Efficiency

The resource efficiency of the mitigation options depends on two factors: the amount of energy required to go from primary resource to fuel tank, and the efficiency of the drive train in taking energy in the tank and transferring it to forward motion of the vehicle. These concepts are defined as “well-to-tank” and “tank-to-wheel” efficiencies, with total efficiency defined as “well-to-wheel”.

BEV are by far the most efficient in both measures, as the initial energy (electricity) is the same as what is required by the drivetrain, meaning there are relatively few points for energy to be lost. Of course, this measure only refers to the energy use, which has to be set against the use of other resources in the overall battery system, such as metals use. FCEV are less efficient in energy terms, as renewable energy in the form of electricity must first be transformed to hydrogen via electrolysis, involving around 25% losses, and then transformed back in electricity within the fuel cell. Biofuels are similarly inefficient, due to the low relative efficiency of internal combustion and diesel engines in transforming fuel chemical energy to kinetic energy of the vehicle. A significant amount of energy is lost to heat, with total well-to-wheel efficiencies of under 20%.

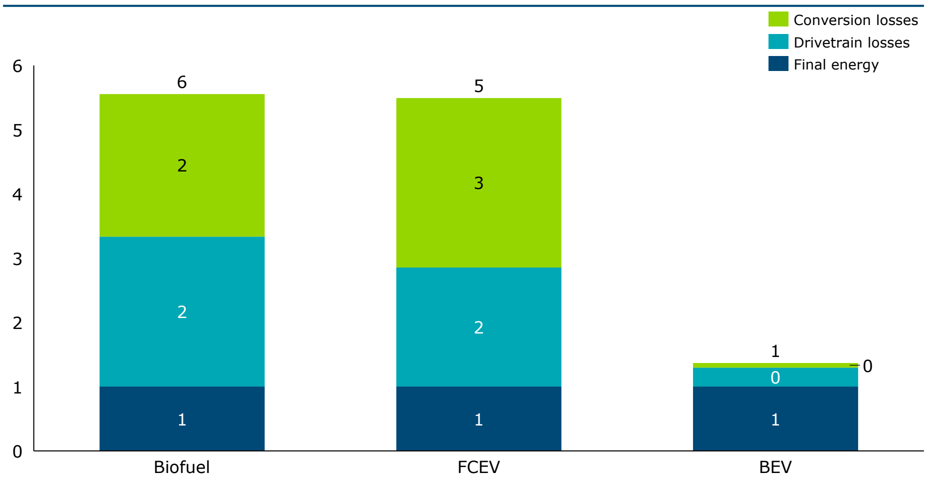
These values of energy efficiency were used to calculate total potential biomass demand. This was calculated by first calculating the final energy demand of each subsegment, derived from expected demand (in passenger km and tonne-km) and per km estimates for energy demand at wheel for each vehicle type. These values were then adjusted for the relevant biomass technology’s well-to-wheel efficiency to calculate the total potential biomass demand by subsegment.[13]

EXHIBIT 5: ENERGY EFFICIENCY OF ROAD TRANSPORT MITIGATION OPTIONS

EXHIBIT 5

Resource efficiency: Biofuel driven ICE are significantly less energy efficient than electric vehicles

Energy input required to reach 1 GJ engine output, by propulsion technology
GJ, 2050 values



- Biofuel ICE are significantly disadvantaged due to the low efficiency of internal combustion engines, with > 50% of the energy in the fuel being lost
- FCEV are likewise significantly disadvantaged to BEV. This stems from the energy required to convert electricity to hydrogen in hydrolysis and the additional losses of turning hydrogen back to electricity in a fuel cell
- Both BEV and FCEV have further upside potential to become more efficient by 2050. BEV could reach well-to-wheel efficiency of 86% (from 73%) and FCEV could increase to 31% (from 18%), which would lead to further cost advantages vs. bio.

Notes: BEV are taken to have conversion efficiencies of 95% well-to-tank and 77% tank-to-wheel, with an upside case increasing to 90% TTW. FCEV are taken to have 52% well-to-tank and 35% tank-to-wheel, with an upside of 60% TTW. Biofuel ICE are taken to be 60% well-to-biofuel and 30% biofuel-to-wheel. WTT BEV losses from transport of electricity, FCEV from electrolysis and transport, bio from the creation of fuels. TWW BEV losses from inversion of electricity, and charge efficiency, FCEV from H2 to electricity conversion, all technology has losses in engine efficiency.

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[14]

2. Shipping

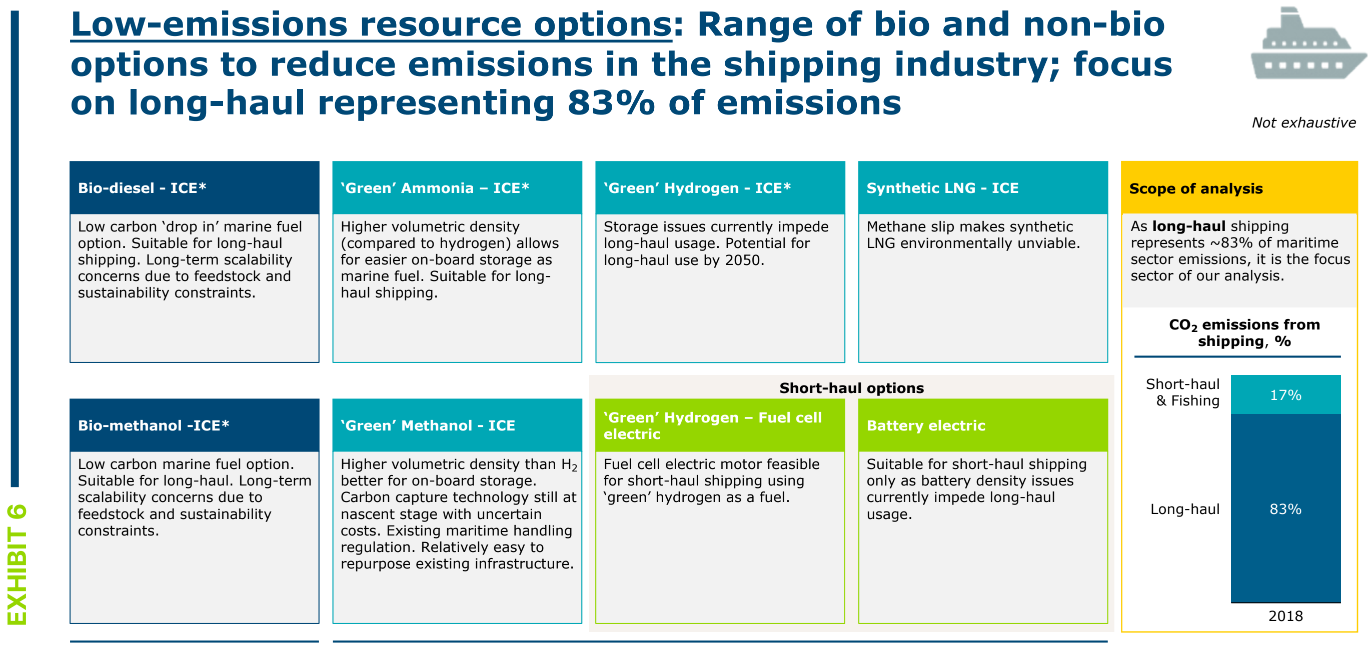
End-segments and use case requirements

For the purpose of this analysis, shipping energy demand is categorized as either long-haul or short-haul and fishing. This analysis focuses on fuels than be used in long-haul shipping, as this accounts for around 70% of maritime sector fuel use and therefore emissions. The focus on long-haul leads to significant weight and volume use-case requirements, as the fuel must have the gravimetric and volumetric energy density to power a ship on a long-distance voyage (electric and hydrogen ships are considered an option for decarbonizing short-haul shipping).[15] As an additional consideration, the shipping industry has very long asset replacement cycles (between 20 and 30 years), giving fuels that utilize existing engines a major advantage (i.e., fuels that can be used in an internal combustion engine).[16]

The energy demand for shipping presented on the value curve is based on 2050 projections for long-haul shipping demand taken from IEA's 2020 Energy Technology Perspectives Sustainable Development Scenario.[17]

Net-zero compatible mitigation options

EXHIBIT 6: SUMMARY OF POTENTIAL TECHNOLOGIES FOR DECARBONIZING SHIPPING



Notes: * Focus of deep dive following; ICE: Internal Combustion Engine

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[18]

BIOBASED MITIGATION OPTIONS:

Two main biofuel options were included in the analysis

- **Biodiesel** created using lignocellulosic biomass through gasification and catalytic synthesis, which can be used as a drop-in fuel in existing engines.

- **Biomethanol** created using lignocellulosic biomass through gasification, fermentation, and catalytic synthesis, requiring engine modifications.

NON-BIOBASED MITIGATION OPTIONS:

Two non-biofuel options for long-haul shipping were used as comparison points for the purposes for evaluating the value of using biofuels:

- 'Green' hydrogen from electrolysis, burnt in existing (modified) engines. Though green hydrogen is technologically feasible today, it is not yet used in shipping due to high cost and complications in storage. Toxicity levels and a lack of existing maritime handling and safety regulations pose potential barriers to adoption.[19]

- 'Green' ammonia produced from green hydrogen. Ammonia has higher volumetric density than hydrogen, is safer to store onboard as marine fuel, and logistics for long-distance transportation and distribution already exist – albeit at smaller scale than required for use as a major shipping fuel. As with hydrogen, ammonia requires engine modifications and the development of new safety and handling regulations. This analysis assumes these regulations will be in place by 2050 and uses green ammonia as the comparison point for calculating the value curve for long haul shipping.'

The analysis also considered other contenders for shipping fuels. Methanol is already considered for near-term pilots in new 'dual fuel' ships. In particular, 'green' methanol produced from captured CO_2 and green hydrogen is proven in technology terms, but not at scale due to high current cost. An analysis of future costs suggests that methanol using 'fossil' CO_2 could be cost-competitive with ammonia for some time periods and locations, but that the use of biogenic CO_2 or CO_2 capture directly from air are much more restricted both in volume and economic terms than green ammonia. While future shipping will likely use a range of solutions, for the purposes of evaluating the value of using biofuels for shipping, ammonia was therefore considered a more useful reference point, and chosen for this analysis. Likewise, synthetic LNG was similarly considered by both less economic and at higher risk of poor GHG performance, due to risks of leakage of methane, a powerful greenhouse gas.

For short-haul shipping, additional solutions are available. Vessels using green hydrogen fuel cells with an electric engine are one option, with the main challenge the cost-intensive storage options of hydrogen. Battery electric options also can be suitable for some short-haul shipping routes, not for long-haul – even with very aggressive improvements in battery technologies.

Cost assessment of mitigation options

The costs for green ammonia are calculated from a bottom-up production model, with input prices of electricity and green hydrogen the key input factors. For 2050, the cost of green hydrogen is calculated under a 2050 assumption for H_2 CAPEX of 200 USD/kW. The analyses consider a number of different use-cases, including generation mixes for the supply of electricity in different world regions. For example, the 2050 levelized cost of electricity is 20 USD/MWh in a representative global analysis, and 25 USD/MWh in the European analysis. Utilisation of the electrolyser follows the underlying mix of solar and wind power, often with a low overall utilisation motivated by the low capex costs.

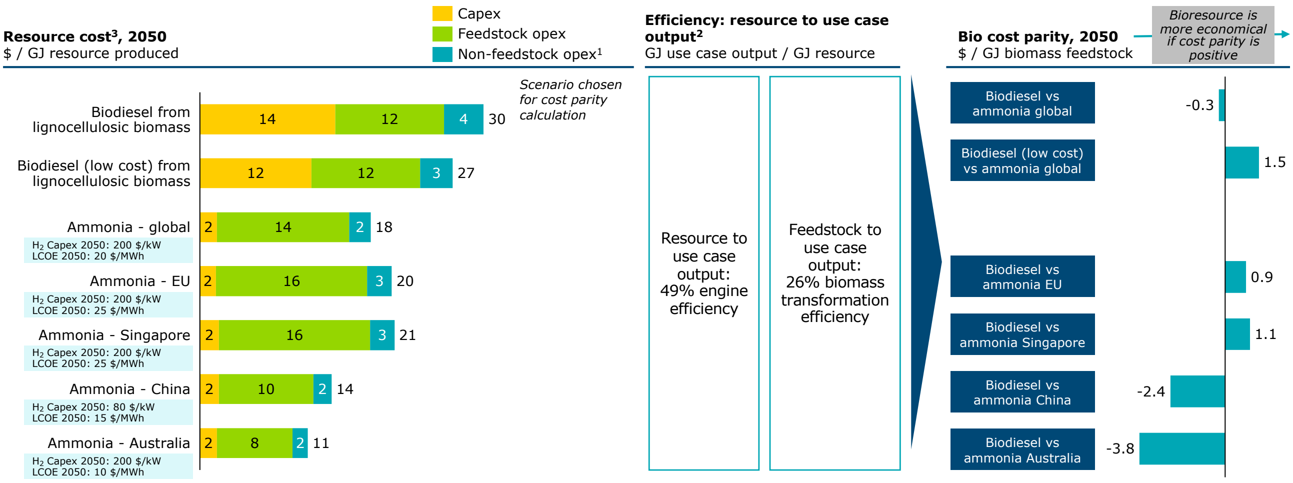
Costs for biofuels production use a production cost model building on those in recent IEA assessments.[20] They include a cost reduction of 28% from current non-feedstock OPEX/CAPEX costs, assuming a 15% reduction from 2020 to 2035 and an additional compound 15% reduction from 2035 to 2050.

A sample of the detailed assumptions and resulting cost estimates for a base case is shown in Exhibit 7. On a pure energy basis (USD per GJ resource produced), the cost of ammonia is significantly lower than biofuel costs for all world regions. The cost parity varies, but biofuels can achieve the same cost only at very low feedstock prices of less than 1.5 USD per GJ or feedstock.

EXHIBIT 7: PROJECTED COSTS FOR DECARBONIZING SHIPPING AND WORKED EXAMPLE OF COST PARITY

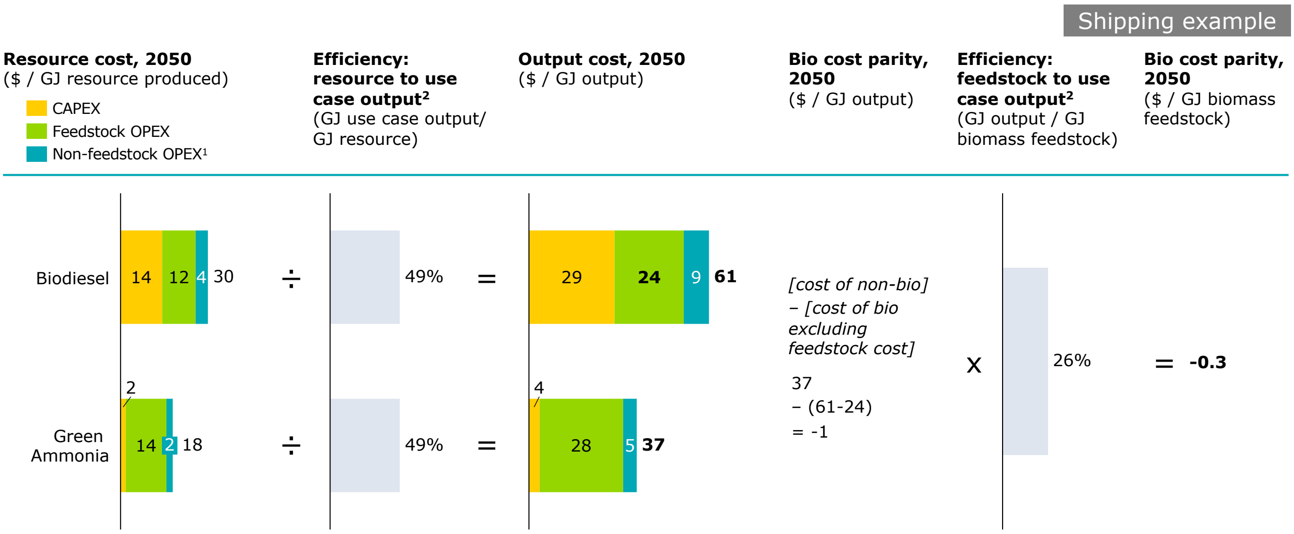
EXHIBIT 7

Economics: By 2050, 'green' ammonia may reach cost parity with bio-diesel from lignocellulosic biomass due to declining costs of hydrogen production from renewable electricity



Economics: *Worked example of cost parity*

Global



Notes: (1) Includes cost of electricity for 'green' ammonia production. (2) Diesel engine efficiencies. Efficiency of conversion from bio feedstock to bioresource (26%) is based on assumed 49% GJ engine output / GJ biofuel and 53% GJ biofuel / GJ lignocellulosic biomass. The latter assumes conversion efficiency of 20% t biofuel / t biomass, 14.2 GJ/t biomass, and 38 MJ/kg biodiesel. (3) Biofuel assumes a cost reduction of 27.8% on non-feedstock opex/capex costs from current figures (15% reduction 2020 to 2035, 15% reduction 2035 to 2050) or a 40.5% reduction (-15% from 2020 to 2035, -30% from 2035 to 2050) in the low cost case. Global green ammonia costs based on a 2050 'green' hydrogen price of ~$1.4/kg.

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[21]

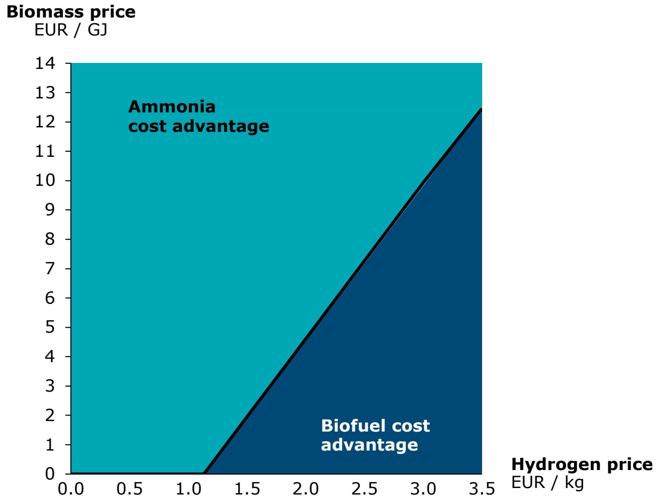
These cost estimates are heavily influenced by the low cost of hydrogen production, at 1.4 USD / kg in 2050 in the base case. This is similar to several other recent assessments, but nonetheless of course uncertain. Exhibit 8 shows how the biomass break-even price varies with the cost of hydrogen production. For example, if hydrogen is available only at a higher cost of 2 USD / kg, the break-even biomass feedstock price is between 4-5 USD / GJ, within the range of various biomass production systems (but lower, for example, than the estimated cost of energy crops in a European context).

EXHIBIT 8: THE COMPETITIVENESS OF BIOENERGY FOR SHIPPING DEPENDS STRONGLY ON HYDROGEN COSTS

EXHIBIT 8

THE COMPETITIVENESS OF BIOENERGY DEPENDS ON HYDROGEN AND CARBON CAPTURE COSTS

Shipping



Notes: The production cost of biofuels for both aviation and shipping are directly dependent on the feedstock price of biomass (the y-axis). For shipping, the production cost of the non-biomass alternative (ammonia) depends on the hydrogen price (the x-axis). For aviation, the production cost of the non-biomass alternative (synthetic aviation fuels) is dependent on both the hydrogen price (the x-axis) and the cost of carbon (the diagonal lines).

Resource Efficiency

Bio and non-bio shipping fuel options present similar energy efficiencies from feedstock to final output, with the former have a 26% efficiency from feedstock to output and the latter 27%. Biofuels and non-biofuels are assumed to use equally efficient internal diesel engines (49%). The upstream efficiencies of converting feedstock to engine fuel also are in a similar range (53% and 55%).[22]

3. Aviation

End-segments and use case requirements

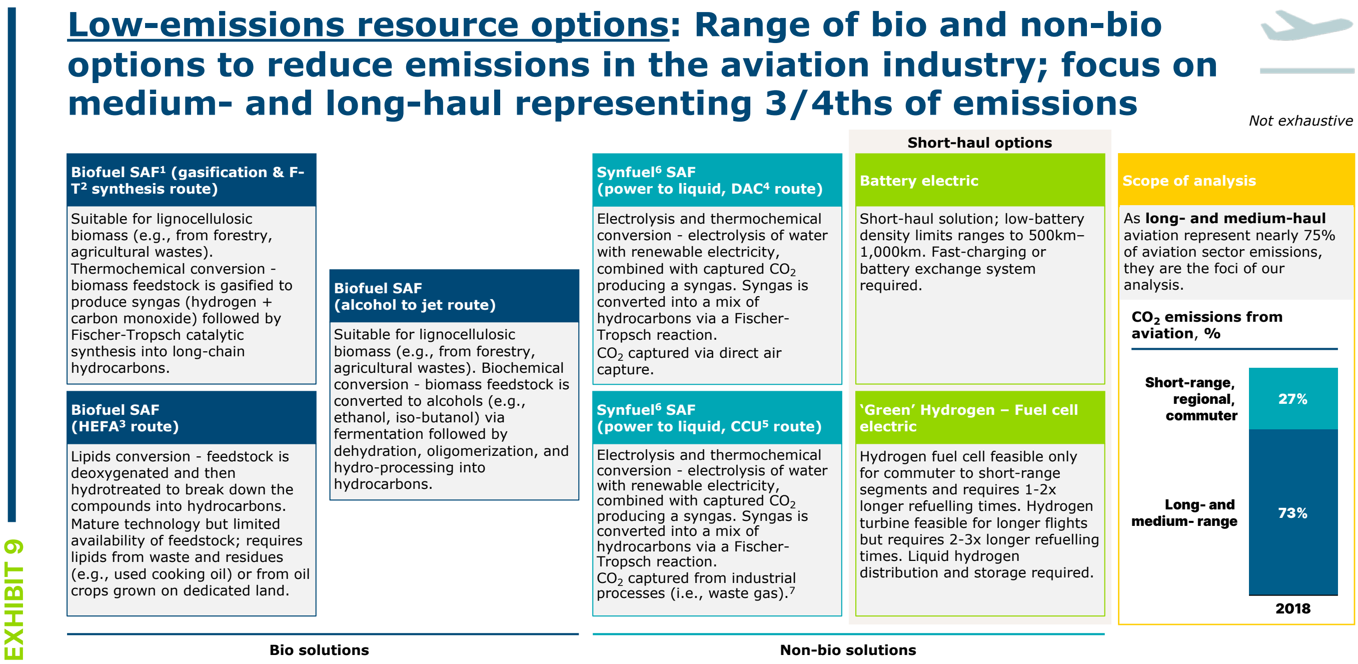
As with road transport and shipping, the major distinction for aviation end segments is the distance travelled. Air transport can be segmented into commuter/regional/short-haul and medium/long-haul segments, with the analysis focusing on the long-haul segments as they form the bulk of CO_2 emissions from aviation. For example, two-thirds of aviation fuel used for commercial passenger flights is used in flights of 2000 km or more.[23]

The energy demand for aviation presented on the value curve is based on 2050 projections for medium- and long-haul flight demand taken from IEA.[24]

Net-zero compatible mitigation options

The options considered in the analysis are summarised in Exhibit 9.

EXHIBIT 9: POTENTIAL TECHNOLOGIES FOR DECARBONIZING AVIATION



Notes: (1) Sustainable Aviation Fuel.(2) F-T : Fischer-Tropsch.(3) HEFA: hydro-processed esters and fatty acids. (4) DAC: Direct Air Capture. (5) CCU: Carbon Capture & Utilization. (6) Synthetic fuel. (7) CO_2 could also be captured in a BECCU process: bio-energy with carbon capture and use.

Sources: Clean Skies for Tomorrow (2020): Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.[25]

Three biofuels were considered as options for future large-scale use in aviation:

- Biofuel Sustainable Aviation Fuels (SAF) from gasification and Fischer-Tropsch synthesis. In this route, lignocellulosic biomass gasified to produce syngas (hydrogen + carbon monoxide) followed by Fischer-Tropsch catalytic synthesis into long-chain hydrocarbons. This technology has an advanced TRL in both production (6-7) and use in aviation (9), as it is available as a drop-in fuel.

- 'Alcohol-to-Jet' Biofuel SAF: Lignocellulosic biomass converted to alcohols (ethanol or iso-butanol) via fermentation followed by dehydration, oligomerization, and hydro-processing into hydrocarbons. Advanced TRL in both production (6-7) and use in aviation (9), as it is available as a drop-in fuel.

- Hydro-processed Esters and Fatty Acids (HEFA) Biofuel SAF: Biogenic oils from waste (e.g., used cooking oil) or from oil crops that is deoxygenated and then hydrotreated. These fuels are currently being produced at scale for road transportation (as biodiesel, TRL 9); future production volumes are very limited by available supply of sustainable feedstock.

Overall, the conclusion was that the two first routes have large-scale potential, while the latter is limited by the much smaller available supply of sustainable feedstock. The Fischer-Tropsch route was chosen as the main comparison point to non-bio-based options.

These bio-based options are contrasted with synthetic fuel production, based on 'Power-to-Liquid' Synfuels via a Direct Air Capture (DAC) route. This combines carbon dioxide from DAC with hydrogen to produce a syngas that is converted into a mix of hydrocarbons using Fischer-Tropsch synthesis. Electrolysis and DAC processes can be run on renewable electricity, so that the energy feedstocks used are renewable power, water, and air. The fuel is usable as a drop-in to current engines, in blends of up to 50%.

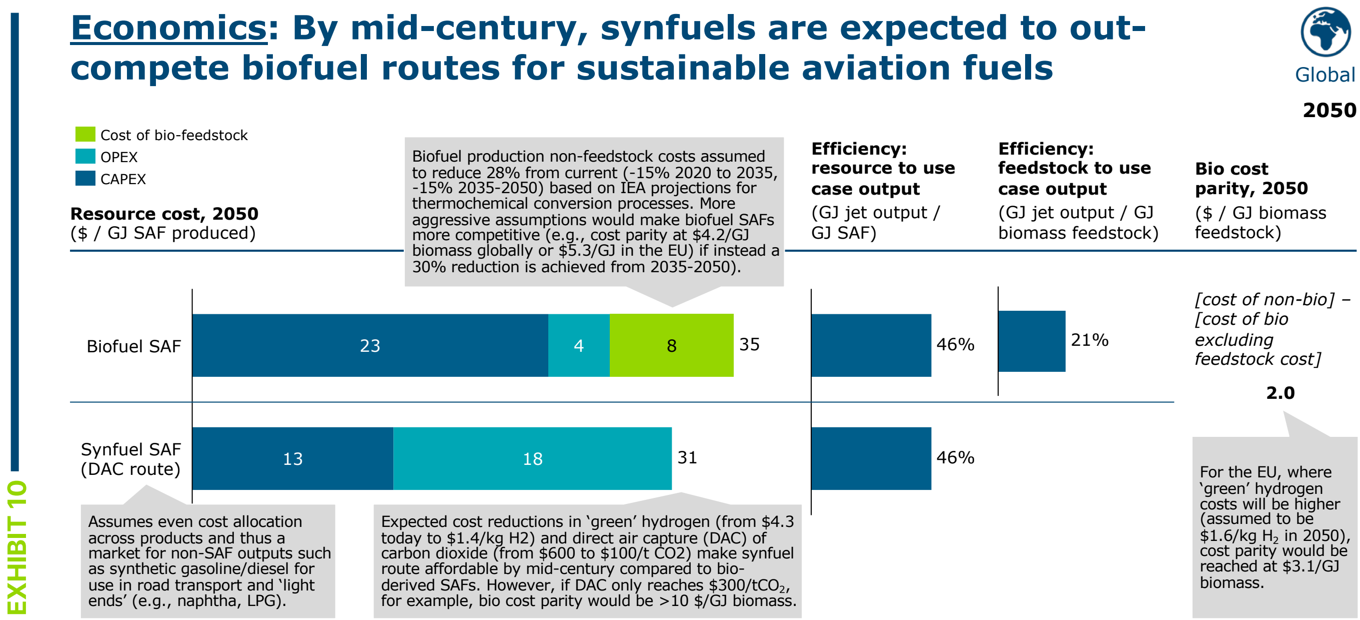
As a variation, the analysis also considered the use of CO_2 captured from industrial processes. However, the DAC route was used for the main comparison with biomass options, to elucidate the value of using biomass within aviation. This is in keeping with the focus on net-zero emissions, which require no net flow of carbon from fossil sources to the atmosphere (as would be the case if fossil CO_2 from industrial processes were used to make fuels that are then burnt).

This analysis also considered a number of electric options, including those based on batteries or hydrogen fuel cell technologies. Battery technologies are likely limited to only a small share of overall aviation energy use. However, according to a recent IEA assessment, hydrogen could be used for around half of the total energy use in commercial passenger aviation, given successful technology development. The early stage of this technology makes it difficult to include in a robust cost analysis, however, so it is not included in the evaluation of biofuels options that is the focus of this study. The main consequence is that the case for biofuels could be overstated, by omitting an additional non-bio-option from the analysis.

Cost assessment of mitigation options

The cost assessment of synfuel and biofuel routes for aviation is summarized in the below exhibit.

EXHIBIT 10: 2050 COST OUTLOOK OF SUSTAINABLE AVIATION FUEL TECHNOLOGIES



Notes: Biofuel SAF assumes a cost reduction by 2050 of 15% on non-feedstock opex/capex costs from current figures. Synfuel SAF assumes 2050 cost of hydrogen at $1.6/kg, DAC at $100/t CO_2 captured, and even cost allocation amongst products (70% SAF yield from synfuel in 2050). Jet engine assumed to start from a baseline of ~35% today with fuel efficiency improvements of ~1% annually through 2050, based on historical trends.

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[26]

The cost of biofuels was calculated using the same underlying assumptions as in the WEF report "Clean Skies for Tomorrow" (2020) and adjusted for 2050 by assuming a 28% reduction from 2020 costs (a 15% reduction in costs from 2020 to 2035 and an additional 15% decline from 2035 to 2050, based on IEA projections for thermochemical conversion processes).[27] The cost of synfuel SAF was calculated based on input costs (green hydrogen and renewable electricity), building on similarly detailed production modelling. The findings are similar to those in the WEF report "Clean Skies for Tomorrow" (2020), Shell and Deloitte's "Decarbonising Aviation" (2021) and academic literature.[28] These costs were then converted to energy terms using the relevant efficiency factors. Costs for synfuel SAFs assume an even allocation across Fischer-Tropsch synfuel products (70% SAF yield from synfuel in 2050) and thus a market for non-SAF outputs such as synthetic gasoline/diesel for use in road transport and 'light ends' (e.g., naphtha, LPG).[29]

Comparing projected SAF production costs in 2050, this results in biofuel SAFs costs of ~$35/GJ aviation fuel and synfuel SAFs (using CO_2 sourced from DAC) at $31/GJ aviation fuel. When combined with their respective energy efficiencies, this leads to a global cost parity between the two of just $2/GJ biomass feedstock in 2050. For the EU, where 'green' hydrogen costs will be higher (assumed to be $1.6/kg H2 rather than $1.4/kg in 2050), cost parity would be reached at €2.6/GJ biomass ($3.1/GJ).

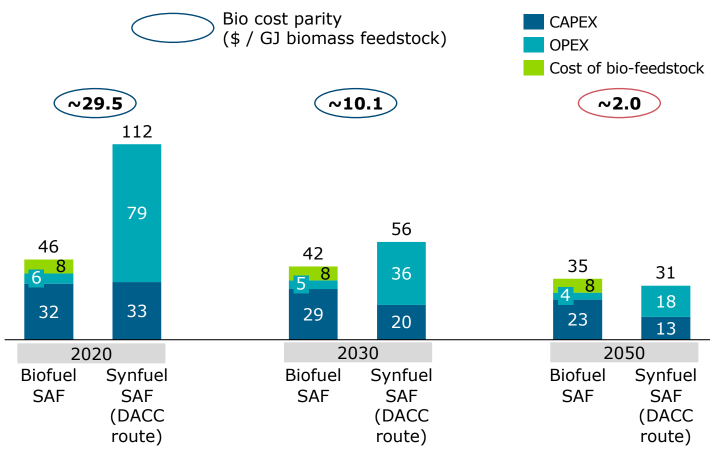
To an unusual extent, the value estimated for biomass depend on simultaneous reduction in the cost of three key technologies: solar PV and wind power renewable electricity, and synfuel cost modelling, comprising electrolysers for hydrogen production, and the cost of direct air capture of CO_2. The final cost of both bio- and non-bio SAF were therefore tested with a number of sensitivity checks (Exhibit 11).

EXHIBIT 11: SAF COST SENSITIVITY TO CHANGES IN INPUT PRICES

Synfuels using renewable electricity and direct air carbon capture (DACC) are unaffordable today but may become competitive if 'green' hydrogen and DACC take off

Global

Resource cost
$ / GJ Sustainable Aviation Fuel (SAF) produced



Sensitivity analysis – Bio cost parity, global 2050
$ / GJ biomass feedstock

Bio cost-competitiveness

Hydrogen cost / **Direct air capture cost**	$2 / kg	$1.4 / kg	$1 / kg
$300 / tCO_2	13.5	10.2	7.9
$150 / tCO_2	7.4	4.1	1.8
$100 / tCO_2	5.3	2.0 *Scenario illustrated*	-0.2
$75 / tCO_2	4.3	1.0	-1.2

The cost-competitiveness of non-bio synfuel SAFs in 2050 is dependent on the cost reductions achieved for direct air carbon capture (DACC) and 'green' H_2 production

Global

Bio cost parity in 2050
USD/GJ biomass feedstock

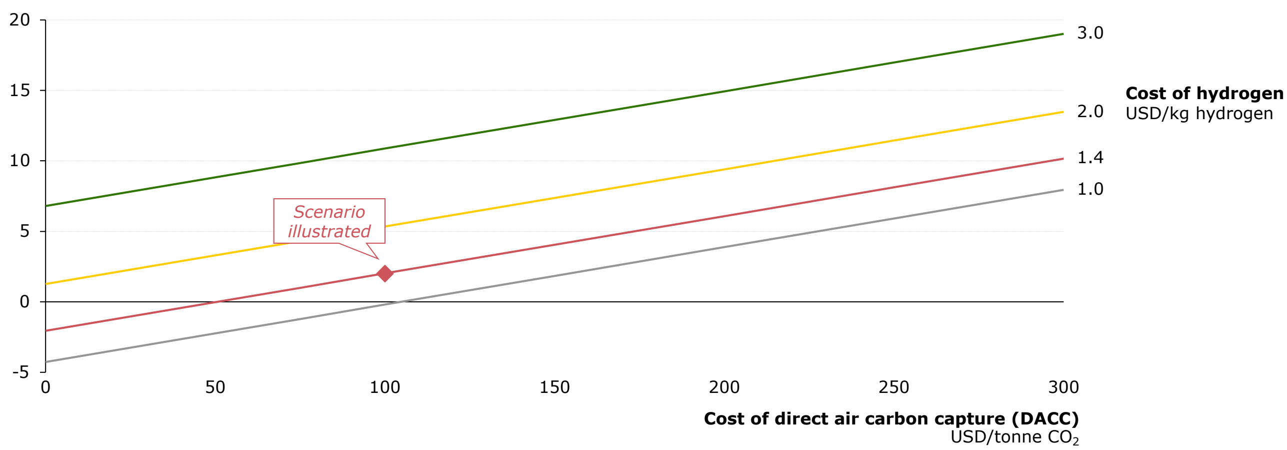


EXHIBIT 11

Notes: SAF: sustainable aviation fuel. Biofuel SAF assumes a cost reduction by 2050 of 28% on non-feedstock OPEX/CAPEX costs from current figures (-15% 2020 to 2035, -15% 2035-2050) based on IEA projections for thermochemical conversion processes. Synfuel SAF assumes 2050 cost of hydrogen at $1.4/kg H2, DACC at $100/t CO_2 captured, and even cost allocation amongst products (70% SAF yield from synfuel in 2050).

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[30]

The overall conclusion of the sensitivity analysis is that the cost of synfuels and biofuels for aviation overlap for plausible technology development trajectories. With DAC costs of 150 USD/t or more and hydrogen costs of 2 USD/kg, the break-even cost of biomass feedstock would be 7 USD/GJ, well within the range of many biomass production systems worldwide. However, with DAC at 100 USD/t CO_2 and hydrogen at 1.4 USD/kg, the breakeven cost is as low as 2 USD/GJ. Much more clarity about future cost developments therefore is needed for firm conclusions about the relative competitiveness of the two routes at any one future point in time.

Resource Efficiency

As the bio- and non-bio SAF routes compared both utilise Fischer-Tropsch synthesis, their chemical products and energy efficiencies from the energy content of the drop-in SAFs to the output of the jet engine are the same. A mid-century jet engine efficiency of 46% is assumed to start from a baseline of ~35% today with fuel efficiency improvements of ~1% annually through 2050, based on historical trends.[31]

However, biofuel SAFs have a higher overall energy efficiency from feedstock to engine output than synfuel SAFs due to different energy efficiencies in converting feedstock materials to SAFs. While 46% of the energy content in the chemical bonds of lignocellulosic biomass remains after conversion into biofuel SAF, just 27% of the energy required to produce synfuel SAF is retained in the aviation fuel.[32] This is largely due to the substantial electricity requirements to capture dilute CO_2 from the atmosphere via DAC and to produce hydrogen from electrolysis of water (steps which photosynthesis has already achieved during plant biomass growth). The resulting overall energy efficiency from feedstock to engine output is ~21% for biofuel SAF and ~12% for synfuel SAF.

EXHIBIT 12: ENERGY EFFICIENCY OF SUSTAINABLE AVIATION FUEL TECHNOLOGIES

EXHIBIT 12

Resource efficiency: Biofuel SAFs more energy efficient but significantly less land efficient

				Energy efficiency of resource production and use			Efficiency of land use	
Type of resource	Resource	Feedstock/s	Output	Feedstock to resource[4] GJ SAF / GJ feedstock	Resource to use case output[3] GJ jet output / GJ SAF	Feedstock to use case output GJ jet output / GJ feedstock	Feedstock from land GJ feedstock / ha	Land use requirement ha/GJ jet output/year
Bio	Biofuel SAF	Lignocellulosic biomass	GJ jet engine output	46%	46%	21%	35[1] <350[1]	0.14 0.01
Non-bio, low-emissions	Synfuel SAF	CO_2 from DAC (renewable electricity)	GJ jet engine output	27%	46%	12%	~2,000[2]	0.004

Notes: (1) Maximum land productivity of biomass feedstock growth presented (i.e., top of productivity range for lignocellulosic biomass crop miscanthus grown on fertile, dedicated land (~25 tonnes/ha/yr = ~350 GJ/ha/yr)). Biomass from waste and residues (e.g., primary and secondary forest residues from managed forest land) expected to be ~10-fold less. (2) Renewable electricity assumed to be generated from solar PV at 600 MWh/ha/yr. (3) Jet engine efficiency assumed to start from a baseline of ~35% today with fuel efficiency improvements of ~1% annually through 2050, based on historical trends. (4) Assumes feedstock to resource yield of total biofuel output (including aviation, road fuel, and light ends) on a mass basis to be 20% for gasification + Fischer-Tropsch from lignocellulosic biomass. Assumes improvement of (bio and non-bio) SAF output from gasification + F-T processes from 60% (today) to 70% (from 2030) of total output on a mass basis; remaining products suitable for road transportation and light ends (e.g., LPG, naptha). If total output were considered (rather than the 70% suitable for jet engines) the feedstock to resource efficiencies would be higher (46% → 66% for total biofuel output and 27% → 38% for total synfuel output). Synfuel figure includes all renewable electricity required and ~18% efficiency from CO_2 to synfuels on a mass basis.

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[33]

4. Building heating

End-segments and use case requirements

The analysis considered two subsections of building heating: district heat and local heat. District heating refers to systems of generating heat in a centralized location and then distributing it to other buildings via a system of insulated pipes. Local heating refers to technologies which generate heat on site, with a range of loads from a few MWh per year for residential heating and hot water, to much larger loads in commercial building heat,

District heating is generally more energy efficient than local heating, but it requires significant new capital expenditures to add buildings to the district heating network (or to build a new district heating network from scratch). This analysis splits 2050 energy demand for building heating as follows: all residential buildings which currently use district heating are assumed to do so in 2050, while no existing buildings are assumed to retrofitted from local to district heating and all new buildings are assumed to have local heating. Total demand for 2050 building heating demand is based on a collation of multiple different scenarios for potential future heat demand, with a common thread a substantial increase in building energy efficiency in all scenarios for future net-zero emissions.[34]

Net-zero compatible mitigation options

Within this overall categorisation, the modelling considers a range of biomass, electrification, hydrogen, and other local heat sources (Exhibit 13).

EXHIBIT 13: POTENTIAL TECHNOLOGIES FOR DECARBONIZING BUILDING HEATING

EXHIBIT 13

Feasibility: Heating technologies are technologically mature but with limited applicability for most solutions except heat pumps and electric radiators

Category	Technology/ solution	TRL	Applicability	Decentralised heating option	District heating option	Description
Biomass	Biomass boiler/CHP	9		✓	✓	Biomass often used off-grid. Volumes restricted.
	Biogas boiler/CHP	9		✓	✓	Biomethane is limited to existing gas grid infrastructure. Availability of the volume also restricted as well as higher production costs.
	Biowaste CHP	9			✓	Biogenic waste is a limited resource that is valuable to use in incineration plants connected to district heating networks.
Electrification	Electric radiators	9		✓	✓	Technically ubiquitous; though often not cost-competitive
	Air-source heat pumps	9		✓	✓	Technically ubiquitous. Contrary to common belief, air-source heat pumps are efficient and cost-competitive in cold climates.
	Ground/water-source heat pump	9		✓	✓	Needs sufficient space to be installed. More expensive and intrusive than air-source heat pumps.
Hydrogen	Hydrogen boiler	7		✓	(✓)	Limited to existing gas grid and need extensive retrofits of the infrastructure*. Hydrogen not cost-effective for district heating.
Local heat sources	Solar thermal	9		✓	✓	Available only in sunny locations (Southern Europe)
	Geothermal	9		✓	✓	Restricted to locations with suitable geology; district heat network required (Can be installed)
	Waste heat	9			✓	Buildings in sufficient proximity to waste heat source, distributed using district heating infrastructure.

Notes: *Hydrogen is a smaller molecule and thus more likely to leak than natural gas). Initial safety issues may result in consumers continuing to view hydrogen as a dangerous solution.

Sources: Material Economics analysis based on multiple sources.[35]

Biomass options. These include biomass boilers fuelled by wood or pellets, as well as biogas boilers. Biogas in turn is modelled both from anaerobic digestion and for biomass-to-biomethane gasification routes and distributed either directly via replacement of natural gas in existing gas grids or used directly in combined heat and power (CHP) plants for district heating. Additionally, the analysis considers biowaste combined heat and power (CHP). For net-zero emissions, this requires either the prior separation of fossil waste (especially plastics) from the biogenic wastes to qualify as a low-CO_2 option, or the use of CCS, which is cost-effective suitable only for large facilities.

Electric options, including heat pumps. These include electric boilers and radiative heat, which is generally a costly option for small loads, but which (given low capex) can be cost-effective for some small heat loads. However, the main option is s combination of air-source and ground-source heat pumps, in turn in different configurations for delivery of heat either via air or to hot water.

Hydrogen options. These replace fossil gas with green hydrogen at a variety of scales. This requires modifications to both existing natural gas boilers and to the natural gas grids.

Other direct heat sources. These are i) solar thermal heat, primarily used for water heat but also applicable to space heating via the use of solar heat to 'pre-heat' water used in a water radiator circuit, ii) direct geothermal heat, and iii) waste heat, captured from industry or commercial buildings (e.g., grocery cold storage) that is then transferred to residential buildings via district heating networks. These sources can all be locally significant but are also highly dependent on local availability.

Costs

The costs of each technology were analysed separately for district heading and decentralized heating. This differs slightly for some of the technologies between the global and the EU values since e.g., the cost of electricity differ. In general, the cost to produce heat is lower for large-scale district heating than decentralized heating, but with cost savings balanced by the need for extensive capital-intensive infrastructure. For this reason, the final calculation of the value curve assume that homes currently heated by district heating will still use district heating in 2050. However, the baseline assumption is that no new district heating infrastructure will be built.

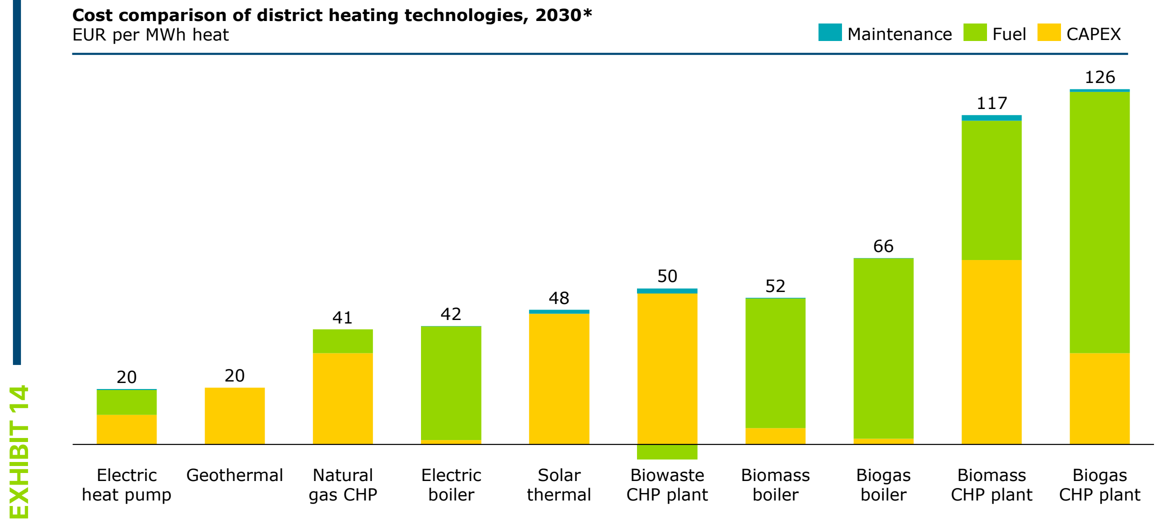
The cost of heating was calculated on a levelized basis, accounting for CAPEX, maintenance, and fuel. Levelized capital costs for each district heating technology were calculated as an average of available sources.[36] Levelized capital costs for decentralized heating were calculated separately, using estimates for initial asset cost, installation size, and load factor.[37] Fuel cost was calculated based on estimated efficiencies and a set of assumed energy prices for 2050, which were then checked for robustness via sensitivity checks. The assumed cost of fuel varies slightly between the EU and Global analysis, with expected costs of $25/MWh for electricity and $1.6/kg$H_2$ for hydrogen in 2050, and the global calculations assume prices of $20/MWh electricity and $1.4/kg$H_2$ in 2050. As in other calculations, the wholesale price of electricity for less flexible loads – and heat pumps in particular – was considerably higher (between 40-65 USD per MWh for different regions).

The estimates account for rapid change in available heat loads as well as in technology. Heat pump technologies are improving rapidly, at both small and large scales and for a growing range of temperatures. Several other factors are at play as well: energy efficiency improvements, the potential use of hydrogen in selected areas with developed clusters, and the use of excess / waste heat, including from new technologies, such as electrolysers or synthetic fuel production.[38]

Exhibit 14 summarises a set of results from a representative assessment of different heating technologies. However, we emphasise that this is a stylized representation. In common with other studies of renewable and other low-carbon heat, this analysis finds a wide range of estimates for each technology, with strong variation with numerous factors. These include the size of the heat load (capital-intensive solutions being more costly for small loads and vice versa); the extent of flexibility and storage in avoiding periods of high energy prices; the underlying building heating system and grade of heat required; local availability of resources such as waste heat; availability of pre-existing infrastructure, including gas grids and district heating networks; the co-benefits and co-revenues from other services such as waste disposal; and the constraints on feasibility created by factors such as building age, space, etc.

EXHIBIT 14: ECONOMICS OF HEATING TECHNOLOGIES

Economics: Biowaste CHP is the most cost-effective option for district heating



Nonetheless, across heat loads covering a large share of heat demand, the conclusion is that only very low-cost biomass, and only particular configurations, put biomass energy at parity with alternatives. The main driver of this is the increasing competitiveness of heat pumps for a growing range of heat loads, especially when combined with flexibility in diurnal patterns of heat use (e.g., via thermal storage or other inertia). However, the declining heat loads associated with improving energy efficiency also challenge some biomass-based heating systems. All in all, the analysis identifies a weighted-average break-even price for biomass of just 2-3 EUR / GJ across a variety of European settings, with less still for many decentralised applications. As biomass resources become more valuable for other uses in the economy – including as feedstock for materials – the break-even prices required may be increasingly difficult to attain. The modelling therefore suggests that low-temperature heat is less likely to see the use of biomass resources in a situation where all energy and materials sectors move to net-zero compatible solutions.

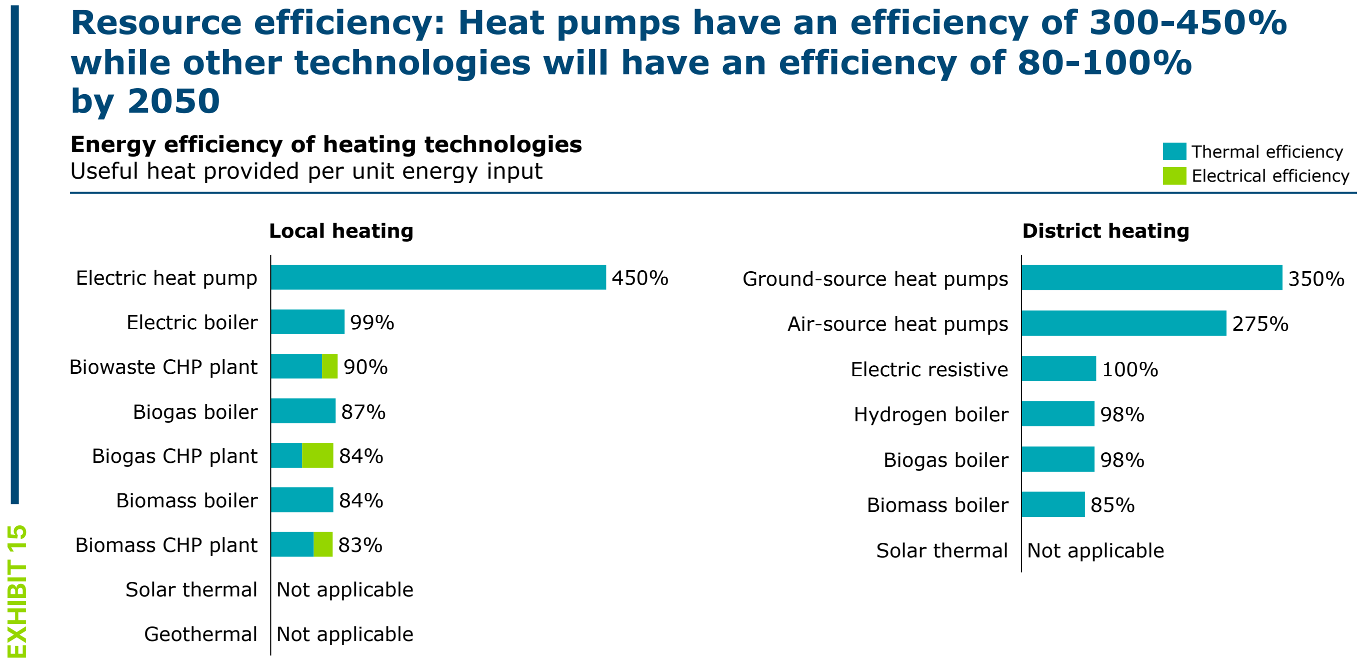
This raises important strategic questions for providers of large-scale heating solutions, often via district heating networks. Waste-based options often provide a range of services beyond just heating, notably waste management (hygiene, destruction of toxic substances, safe disposal of streams rejected for recycling, avoided environmental impact from landfill, etc.). Increasingly, value also is tilted towards the provision of local electricity grid capacity and dispatchable zero-carbon power, via combined heat and power provision. In the future, the list of co-benefits could grow to include negative emissions solutions (via CCS on incineration of biomass in waste) or provision of raw materials (via upgrading of separated CO_2 for chemicals or fuels). The modelling suggests that such integrated offerings, serving a wide variety of societal needs, are likely to be far more competitive than incineration alone.

Resource Efficiency

Each technology was assessed on its energy efficiency, the amount of useful heat provided per unit of energy input. Heat pumps are the most energy efficient option for decarbonizing building heating, as energy is used to move heat rather than create it. All other mitigation options have efficiencies between 80 – 100% (Exhibit 15). Efficiencies were assessed separately for local heating and district heating.

Biogas technologies are assumed to maintain efficiencies from natural gas. However, there is a loss of energy in converting biomass to biomethane. This analysis expects anaerobic digestion to increase to 64% efficiency (from 63%) and gasification to increase to 75% (from 65%).

EXHIBIT 15: RESOURCE EFFICIENCY OF HEATING TECHNOLOGIES



Notes: The efficiency of gas technologies is the same for both biogas and natural gas.

Sources: Material Economics analysis based on multiple sources.[39]

5. Industrial heating

End-segments and use case requirements

Energy demand for industrial heating applications can be categorized by the temperature of the heat required for the specific industry application. In this analysis, demand has been characterized as either low temperature heat (<100 °C), medium temperature heat (100-400 °C), or high temperature heat (>400 °C).

2050 industrial heating demand has been calculated on an industry-by-industry basis. End-product demand is expected to be partially offset both by significant energy efficiency potential in several sectors, and by increases in economy-wide materials efficiency that affects overall demand.[40]

Low and medium temperature heat technologies are generally generic and can be applied across sectors. The largest single category is for steam production, with large loads in chemicals, paper, and food – but also a list of applications in many other sectors. Other important loads include space heating, cooling, and drying. Other direct thermal loads up to 400 °C also are found in smaller volumes across a wide range of sectors, from machinery to ceramics, glass, and paper production. Overall, low and medium temperature heat represents ~40% of the total energy use for industrial heating.

There is an important separate segment for very high-temperature process heat (more than c. 1000 °C). These are found primarily in steam cracking in petrochemicals production; kilns and furnaces in cement, lime, glass and ceramics production; and a range of metals processing (ore sintering, steel reheating furnaces, foundries, aluminium remelting, etc.). In many cases, these heating processes are highly specialised, such as the joint high temperatures and reduction processes in steel blast furnaces.

Pulp and paper production are a special case for the evaluation of bioenergy use in industry. In integrated pulp and paper production, raw materials processing results in large volumes of biomass resources suitable for energy use but not for pulp production. Additionally, the chemical pulping process combines thermal energy generation with recovery of process chemicals. Few experts interviewed for this work foresaw a major change to the fundamental pulping process. Paper production differed substantially, as a major user of biomass today for often relatively low-temperature processes. Electrification of these therefore provides one way to reallocate biomass resources, provided the fundamental economics and logistics can be solved.

Net-zero compatible mitigation options

LOW- AND MEDIUM-TEMPERATURE HEAT

The analysis included cost modelling for the following sets of technologies (Exhibit 16):

Biomass boilers – biomass, in this case pellets sourced from lignocellulosic biomass via densification used as a substitute for coal in existing solid-fired boilers, serving as a drop-in option for medium temperature heat.

Biogas boilers – biogas sourced from lignocellulosic biomass via thermal gasification used as a substitute for natural gas in existing gas-fired boilers, with ability to reach temperatures up to 620° C and have a maximum heat capacity of >300,000 kW.

Electric heat pumps for industrial purposes use waste heat from other processes to provide low temperature heat, with some potential to reach temperatures of up to 165° C in smaller capacity. Contrary to common belief, heat pumps are efficient even in colder climates. These heat pumps are in use today.

Electric resistance heating, where boilers applications use electric current to generate hot water and steam can generate temperatures up to 600° C. These are in use today. In addition to these, there is a range of variations, including infrared, microwave, and radiofrequency heaters that are already in use. Their costs are approximated by the electric resistance heating.

- Hydrogen boilers use green hydrogen as a fuel in modified gas boilers. These boilers are not yet in use due to the dearth of low-cost green hydrogen. A number of conventional industrial boilers are being sold as "H_2-ready", with the ability to be converted to hydrogen when prices are more competitive.

EXHIBIT 16: POTENTIAL TECHNOLOGIES FOR DECARBONIZING INDUSTRIAL HEATING

EXHIBIT 16

Feasibility: Boilers and heat pumps are mature technologies (Except hydrogen boilers) and can be used across industrial sectors

Category	Technology/ solution	TRL	Applicability (Low-temp.)	Applicability (Medium-temp.)	Description
Biomass	Biomass boiler	9	◑	◑	Volumes of available biomass restricted.
	Biogas boiler	9	◕	◕	Natural gas is today widely used for industrial heating which biogas can replace, though often not cost-competitive.
Electrification	Electric boiler	9	◕	●	Technically ubiquitous; though often not cost-competitive for low-temperature heat compared to heat-pumps.
	Electric heat pumps	9	●	○	Technically ubiquitous. Can be used for heating below ~120°C (165°C in smaller capacities). Contrary to common belief, heat pumps are efficient and cost-competitive in colder climates.
Hydrogen	Hydrogen boiler	8-9	◔	◔	Hydrogen boilers are currently not in use due to high prices. Manufacturers are starting to create 'Hydrogen-ready' boilers that can switch to hydrogen from natural gas at later stage.

HIGH-TEMPERATURE HEAT

For high-temperature heat, equipment is often highly specialised. An emerging research literature shows a wide range of heating technologies.[41] For this analysis, the evaluation included:

- **Hydrogen burners for oxyfuels** (the joint combustion of fuel with oxygen), which are widely used or applicable as an energy efficiency measure across high-temperature direct heat (metals remelting, glass production, etc.). The analysis suggests that hydrogen produced via electrolysis can be economically attractive already today on an opex basis, and for the total levelized cost of heat with cheaper hydrogen production.

- **Increased use of electric arc heating**. Electric arc heating is used already as the mainstay of steel remelting, but is also used in the glass industry, stone wool production, and several other high-temperature options.

- **Resistance heating** for a range of high-temperature furnaces, e.g., in ceramics and glass production.

In addition, the chemicals, cement and primary steelmaking sectors are key considerations. They combine very large heat loads with lower technical maturity for electrification options. However, a range of options are under development that would enable the use of electricity and hydrogen-based heating also in these sectors:[42]

- **Electrification of steam crackers**. This is an ongoing research and development areas. Few stakeholders foresaw the use of biogas to power steam crackers.

- **Electrification of cement kilns**, where plasma burners provide one option, alongside development of hydrogen and direct electrification solutions.

- **Electrification of primary steelmaking**, where hydrogen-based direct reduction enables the use of electric arc furnaces.

HYBRID SOLUTIONS

A major feature of industrial heating systems is the potential to use hybrid systems, combining

- Pre-heating systems, using heat pumps for the first step of heating

- Joint biomass and electric heating systems. For example, some papermaking already has electric boilers that are used in periods of low prices, switching to the use of biomass fuels when prices are higher. Similar systems are possible for a range of other electric heating options, not least where the capex is low (such as for electric resistance heating).

- Joint hydrogen and bio / fossil gas heating. The same burners can often use either hydrogen or either propane, natural gas, or upgraded biogas. As electrolysers often are highly flexible, this provides another hybrid solution, with potential to use electrolysis-derived hydrogen when electricity prices are low, and other gaseous fuels in periods of higher prices.

The latter two options therefore also provide important potential sources of flexibility in electricity loads.

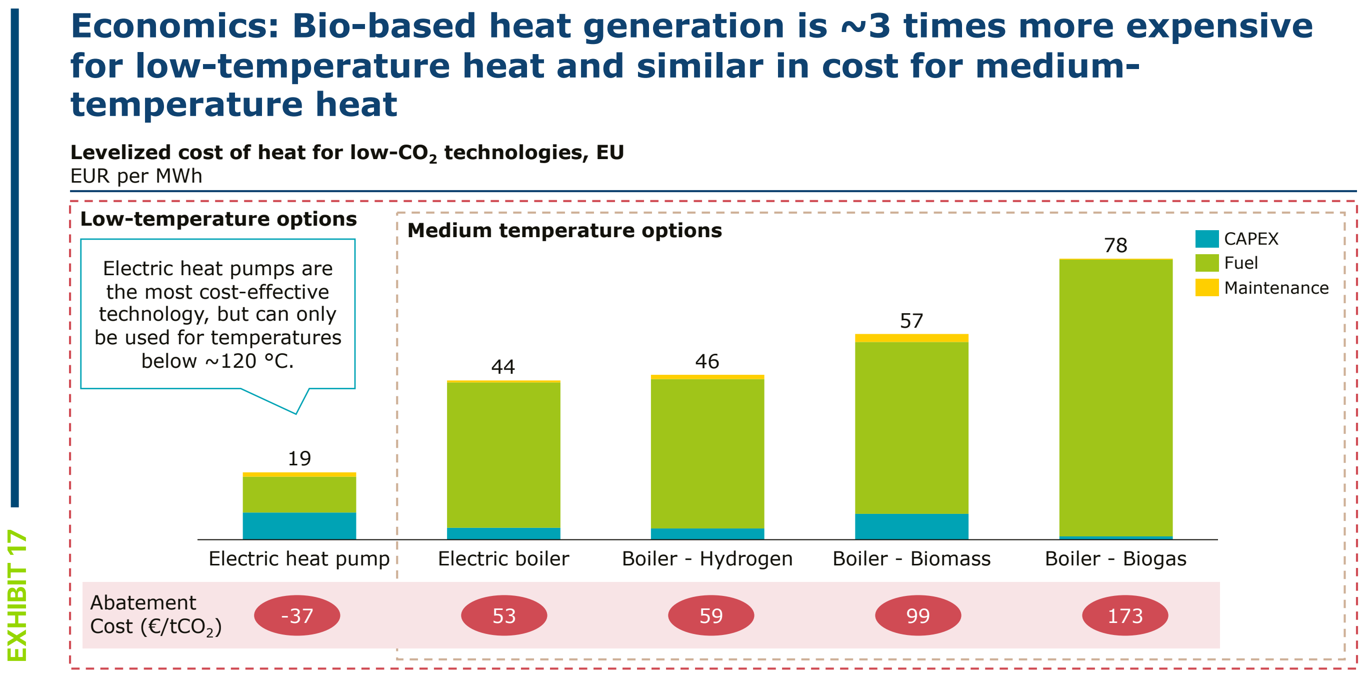
Costs

The cost of heating was calculated on a levelized basis, accounting for CAPEX, maintenance, and fuel. Levelised capital costs for each district heating technology were calculated as an average of available sources.[43] Levelized capital costs for decentralized heating were calculated separately, using estimates for initial asset cost, installation size, and load factor.[44] Electricity-based options can have additional benefits, including lower costs of air pollution control and higher energy and process efficiency. Except for energy efficiency, these benefits are not accounted for in this assessment. Calculations were made on the basis of the relevant technology, and then applied to each industrial segment. For the purpose of the value curve, the relative bio-option is a biomass boiler using pellets. The non-bio low temperature heat demand is assumed to be heat pumps, and all medium temperature heat uses an average of the costs of all other technology options.

Cost is heavily dependent on the price of fuel and electricity, which accounts for 62-98% of levelized costs, depending on technology. The cost of electricity was evaluated at 40 and 60 EUR per MWh in the EU analysis. For hydrogen, lower electricity costs are used, with expected costs of \$25/MWh for electricity and \$1.6/kgH_2 for hydrogen in 2050, and the global calculations assume prices of \$20/MWh electricity and \$1.4/kgH_2 in 2050.

Exhibit 17 illustrates the type of output resulting from the cost modelling, showing a boiler application for low- and medium-temperature heat. The cost difference arises chiefly because of differences in fuel costs, which in this case are at a generic EU levels of marginal biomass supply at scale from energy crops, at 6-8 EUR per GJ (depending on transport distance and processing costs). However, the assessment clearly looks very different for stranded biomass resources that are locally available, e.g., in regions with significant local forestry industries. Likewise, the assessment is highly sensitive to future electricity costs. Given that many industrial heat loads have a 'baseload' profile with supply required up to 8000h per year, costs could escalate in regions where seasonal flexibility resources are high.

EXHIBIT 17: LEVELISED COSTS OF SELECTED INDUSTRIAL HEATING TECHNOLOGIES



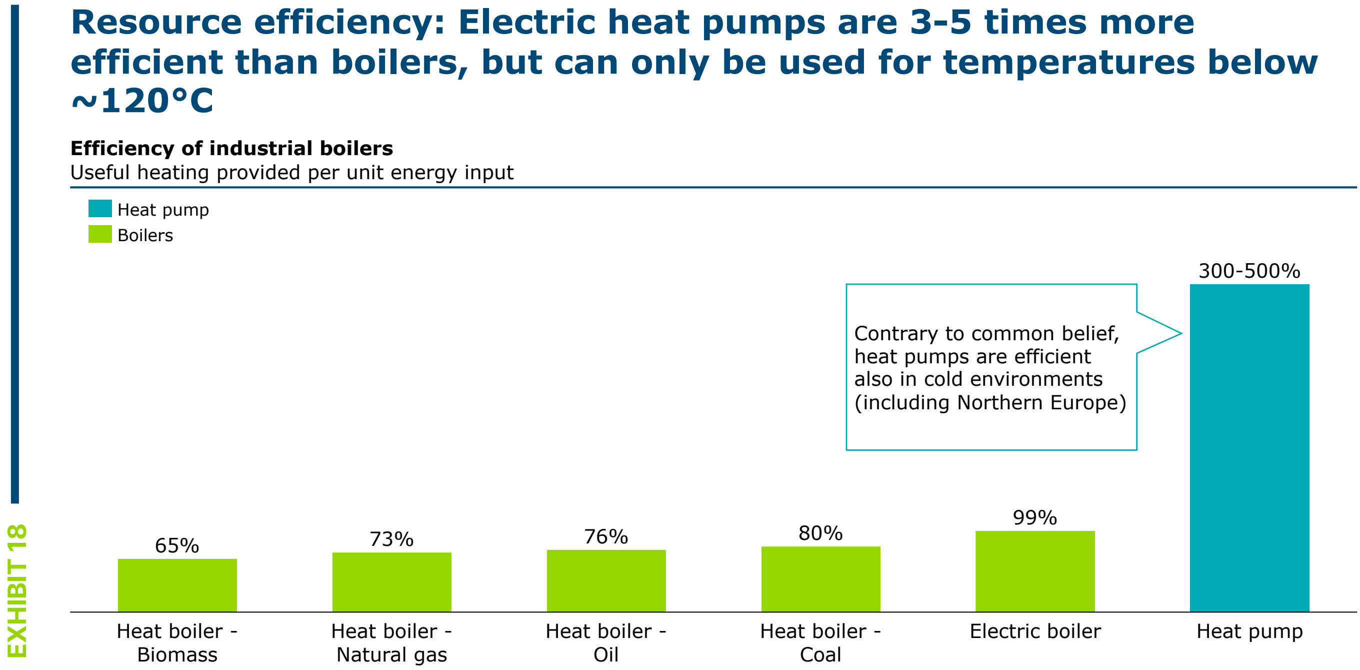
Overall, the cost assessment therefore points to several conclusions: Electrification-based options are feasible for most heat loads. However, the near-constant load requirements of many industrial heat applications can also render them expensive in some future electricity systems. Overall, therefore, industrial heat is among the loads that can support the cost of incremental biomass of around 6-8 EUR / GJ in the EU. However, these economics mostly play out favourably in selected niches: where the technical limitations to electrification are particularly difficult, and in hybrid systems where sufficient electricity price variability means that the additional capex of retaining biomass (often biogas) based systems can be offset by substantial electricity savings.

Resource Efficiency

Energy efficiency for industrial heating depends entirely on the base technology. Fuel-based boilers using, biomass, natural gas, or oil have an efficiency of 65-80%, while electric boilers have an efficiency of 95-100%. Heat pumps, by contrast, make available more heat than consumed with an overall efficiency of 300-500%, and somewhat lower values for seasonal performance factors.

Efficiency values are not forecast to change significantly by 2050 and depend largely on the utilization rate of the boiler. The value curve is calculated using an estimate of 81% energy efficiency for biomass boilers.[45]

EXHIBIT 18: ENERGY EFFICIENCY OF SELECTED INDUSTRIAL HEATING TECHNOLOGIES



6. Power

End-segments and use case requirements

Power demand can be categorized as belonging to either bulk power generation (meeting overall demand) or balancing (providing immediate response to keep the power system balanced).

Electricity cannot be easily stored and thus production and consumption must be balanced at all times. As variable renewable energy sources such as solar or wind increase in deployment, this balance is significantly more difficult to maintain as they do not produce energy consistently. As the share of variable generation increases, so too does the need for power which can be used responsively to balance the short- and longer-term variations in renewable energy.

Furthermore, there is increasing confidence that rising shares of solar and wind power can be effectively integrated into power systems around the world, up to very high penetrations and with limited or no impact on total system cost.[46] The ETC estimates that 75-90% of global electricity demand could be produced through wind and solar.[47]

- Meeting the variability in wind and solar supply can be met by a combination of solutions, including existing thermal (transitional role), as well as an increased deployment of zero-carbon sources, including batteries, hydro, interconnectors, CCS, and hydrogen. Zero-carbon solutions for daily balancing – in particular lithium-ion batteries – are increasingly cost-competitive with fossil-based sources of dispatchable generation.[i]

- While transmission and distribution systems will need to be expanded and upgraded, additional costs per unit of electricity delivered can be offset by better grid management capabilities on the distribution side, and digitalisation upgrades to reduce redundancy in network capacity required.

This report considers two categories of balancing needs: daily balancing and seasonal balancing. Daily balancing includes power that can be supplied due to rapid change in demand/supply due to predictable events (e.g., sunset). Seasonal balancing involves shifting energy to ensure balance across the year (e.g., providing energy during the winter in areas with high solar power penetration).

Total power needs for 2050 are calculated based on an average of BNEF's NCS and ETS scenario projections.[48]

Net-zero compatible mitigation options

BIOBASED MITIGATION OPTIONS:

Wood pellets, sourced from lignocellulosic biomass via densification, fired in retrofitted combined cycle power plants. These plants can provide power continuously or on a schedule, allowing them to serve both bulk and balancing power generation. This is a proven and deployed technology.

Biogas, sourced from lignocellulosic biomass via thermal gasification, fired in retrofitted combined cycle power plants. These plants can provide power continuously or on a schedule, allowing them to serve both bulk and balancing power generation. This is a proven and deployed technology.

NON-BIOBASED MITIGATION OPTIONS:

Photovoltaic solar power is a clean, renewable source of energy that uses solar radiation to produce electricity, capturing it via a semiconductor device called photovoltaic cell. The electricity provided is variable as it depends on the strength of solar radiation available. Solar power is already a large provider of bulk power generation today but is unable to provide balancing power.

Onshore and offshore wind power is the clean and renewable energy obtained by using wind turbines to capture the force of the wind on so-called wind farms. Onshore wind farms are located on terrestrial locations with high incidence of winds while offshore wind farms capture the force of the wind that is produced on the high seas, where it reaches a higher and more constant speed than on land due to the absence of barriers. Both onshore and offshore wind farms are deployed today to provide bulk power. The variable nature of the resource leaves them unable to provide balancing power.

i Technical grid management challenges (e.g. system inertia and frequency response) in high variable renewable power systems can be met by a combination of better forecasting tools and equipment (e.g. synchronous condensers).

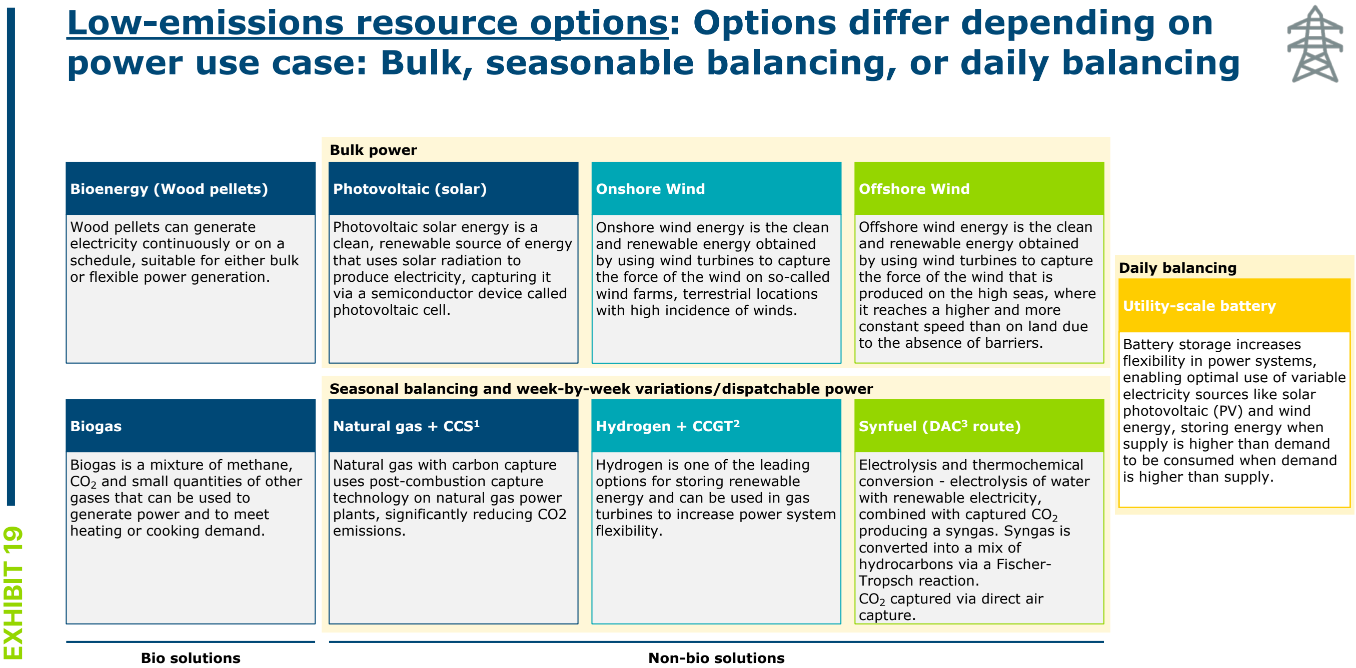
Natural gas with CCS uses post-combustion carbon capture technology on existing natural gas power plants, significantly reducing CO_2 emissions. These plants are able provide extremely flexible power, capable of providing both bulk and daily/weekly/seasonal balancing. However, the decarbonisation potential of this option is limited by the carbon capture efficiency of CCS technology.

Hydrogen with a combined cycled gas turbine uses green hydrogen fired in gas turbines at combined cycle power plants to provide flexible power capable of providing balancing electricity.

Synfuels are synthetic fuels created via electrolysis and thermochemical conversion. The electrolysis of water is powered with renewable electricity, combined with captured CO_2 producing a syngas. Syngas is converted into a mix of hydrocarbons via a Fischer-Tropsch reaction, and the CO_2 is captured with direct air capture (DAC). This fuel can be used to provide balancing electricity.

Utility scale battery storage involves using batteries to store excess power generated by variable sources such as wind or solar. This power can then be used when variable sources of power are not available (e.g., the sun is not shining or wind is not blowing). Utility scale battery storage is still a relatively immature technology, and the ability of batteries to provide balancing at the weekly or seasonal level is still unclear. However, batteries are being used for daily balancing in markets with high shares of variable electricity already today. Utility scale battery storage is used as the relevant comparison point for daily balancing on the value curve.

EXHIBIT 19: POTENTIAL TECHNOLOGIES FOR DECARBONIZING POWER



Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[49]

Notes: (1) CCS = Carbon Capture and Storage. (2) CCGT = Combined Cycle Gas Turbine. (3) DAC = Direct Air Capture.

Decarbonising power

Decarbonising power involves two major challenges:

- **Phasing out carbon-intensive bulk power generation** (usually from coal, oil or natural gas) and replace these technologies and infrastructure by low- or zero-carbon power generation such as Variable Renewable Electricity (solar, onshore and offshore wind), nuclear or power from bio-sources combustion.

- **Balancing a power system with an increasing percentage of variable electricity and hence a decreased control of the power supply**, using balancing technologies such as flexible thermal generation, hydro resources exploitation, storage of power through batteries or hydrogen, or demand management.

Feasible decarbonisation technologies vary depending on the use-case considered. Both key bioenergy power generation solutions (wood pellet combustion and biogas combustion) can provide power for bulk generation as well as daily, weekly or seasonal balancing, as power supply from bioenergy plants is flexible and easy to control. Their feasibility and competitiveness hence depend on the alternative decarbonisation options for each use case.

For **bulk generation**, bio resources are feasible, but renewable electricity is more scalable:

- **Variable Renewable Electricity (VRE)** from photovoltaic, onshore or offshore wind technologies outcompete all other technologies in terms of feasibility and applicability, as they use unlimited natural resources and are already deployed at a large scale. However, these technologies are inherently dependent on natural resources (wind and sun). That said, extensive research suggests the majority of future bulk power generation can be derived from VRE.[50]

- **Sustainable biomass combustion** is a proven and deployed technology, relatively easy to retrofit from existing CCGT plants, but facing a constraint of access to a limited sustainable feedstock.

- **Nuclear energy** is a proven and deployed technology delivering high supply capacity but faces major constraints including waste management concerns and costs, as well as local opposition.

- **Natural gas plants using Carbon Capture and Storage** present the advantage to be flexible and easy to retrofit using the existing thermal plants infrastructure. However, the capture efficiency of CCS processes is limited to a certain cap, and the political and social acceptability of this technology is low.

For **daily balancing**, VRE would need to be paired with storage to provide round-the-clock flexibility and generation. Progress in reducing battery costs and improving efficiency suggests that a combination of VRE + batteries is likely to be lower cost than bio decarbonisation options for this role.[51]

However, VRE are not flexible enough to solve the challenge of **week-to-week and seasonal balancing** (or interday balancing), which determines a need for either energy storage technologies or thermal capacity, combined with other technologies (hydro resources, interconnectivity, demand management). Bioenergy combustion could play a role in providing long-term flexibility to VRE-dominated power systems over a transition to 2050. Its ultimate role will depend on how fast and efficiently the alternative options (hydrogen production from VRE and storage, CCS applied to CCGTs) reach cost-competitive readiness levels and are able to deploy. If bioenergy combustion were to play a role in week-to-week and seasonal balancing, then it would likely to become more competitive in daily balancing markets as well.

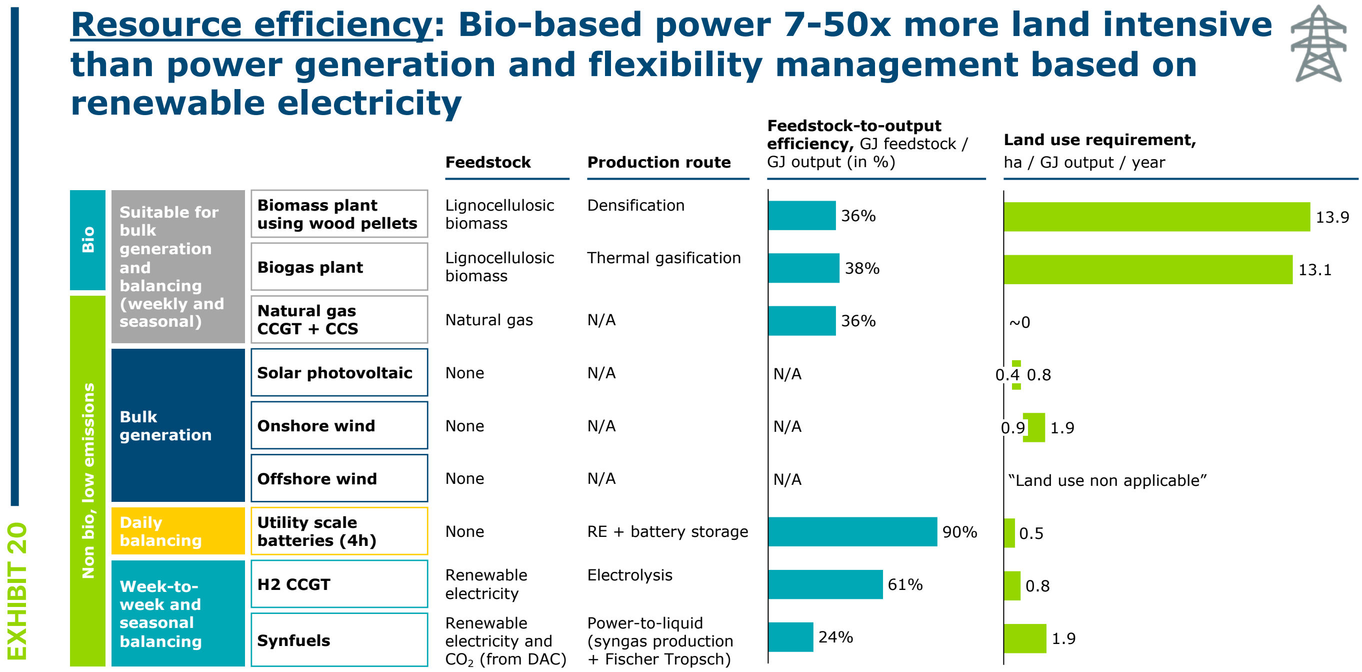
Resource Efficiency

ENERGY EFFICIENCY

Bio power generation solutions have equivalent energy efficiency levels as existing fossil power plants as they rely on similar thermal processes, 36-38% efficiency. Non-bio bulk generation technologies have no efficiency losses as they convert renewable resources directly to power.

Renewable balancing technologies require an efficiency loss as that renewable electricity must be stored in some form. Batteries are the most efficiency storage mechanism, at 90% efficient, but their use is limited to daily balancing in this analysis. Both hydrogen and synfuels entail efficiency losses in the creation of the fuel and then additional losses when the stored fuel is converted to energy.

EXHIBIT 20: ENERGY EFFICIENCY IN DECARBONIZING POWER



Sources: SYSTEMIQ analysis for the Energy Transitions Commission (2021) based on Kraan et al. (2019) An Energy Transition That Relies Only on Technology Leads to a Bet on Solar Fuels; PlanEnergi (2018) Solar cell and solar heating systems on arable land; Strengers B. et al. (2018) Negatieve Emissies.

Notes: Land productivity of biomass feedstock production depends on whether biomass is sourced from dedicated land (e.g., from lignocellulosic energy crops) or from waste and residues (e.g., from managed forest land). The range of productivity between the two varies substantially (e.g., from 2.5 to as much as 25t of lignocellulosic biomass per hectare per year, or approximately ~35-350 GJ biomass/ha/yr). In the figures presented, ~200 GJ/ha/yr is used.

Costs

A recent report by the Energy Transitions Commission assessed the cost, feasibility and scale up challenges associated with clean electrification.[52] In particular, it noted that costs of power sector decarbonisation technologies are likely to vary according to the role they play in the system:

- Costs for bulk generation are likely to be lowest, as this is driven by low-cost variable renewables.

- Costs will increase for daily balancing, due to the addition of battery storage. However, the high utilisation rate of the battery means overall costs remain low.

- Costs for week-to-week and seasonal balancing are likely to be highest due to a combination of low utilisation factors and the need to invest in high volumes of storage.

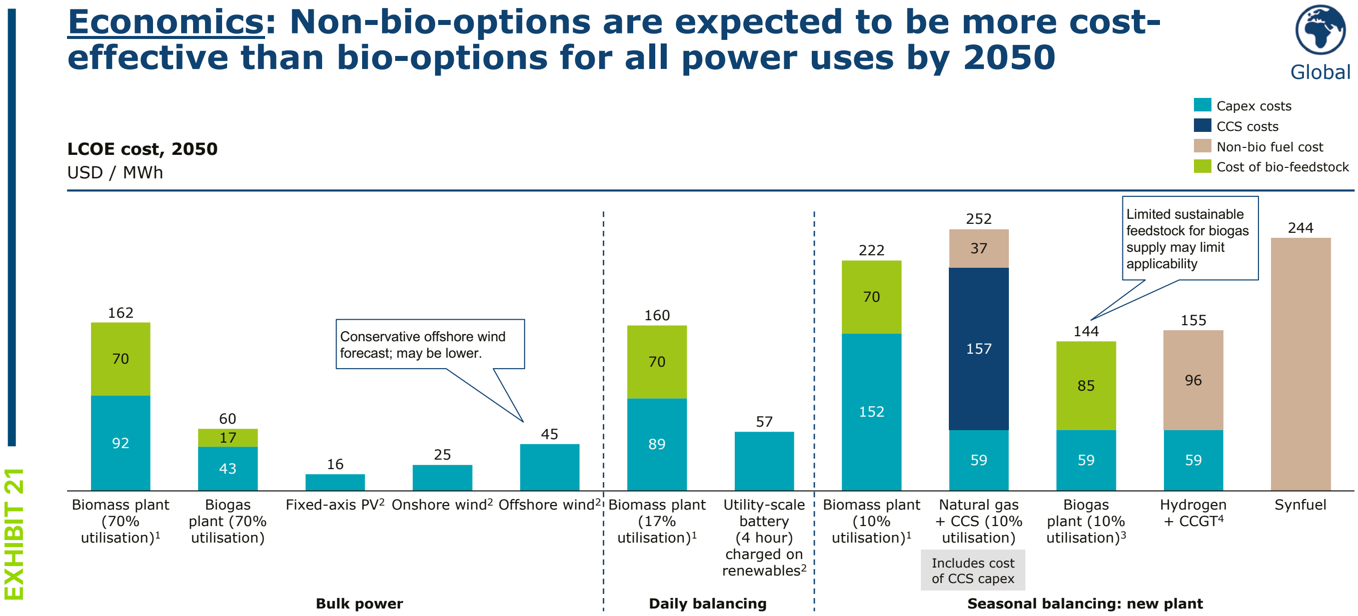
The cost of power for all three segments is calculated on a levelized basis and estimated for the year 2050 (Exhibit 21). The cost calculations for bio-based power generation assume a 70% utilization for bulk power, 17% utilization for daily balancing power, and 10% utilization for seasonal balancing power.

Levelized costs of solar, wind, and utility battery power were based on mid-point estimates of Bloomberg New Energy Finance (BNEF). The EU analysis uses the midpoint for Germany while the Global analysis uses the midpoint for the US.[53] Synfuel and H2 CCGT costs are modelled using input costs for green electricity, hydrogen, and DAC CO_2. Natural gas calculations include the costs of CCS technology but assume a 30% reduction the estimated cost of adding CCS to a natural gas CCGT plant today.

Biomass plants expect a 15% reduction in 2050 non-feedstock costs from today's levels, as calculated by IRENA.[54]

As Exhibit 21 shows, bio-based decarbonisation options in the power sector are either outcompeted on cost compared to other options, or potentially limited by availability of sustainable bio supply. In the case of biogas, costs are competitive with hydrogen. In a transition to 2050, bio-based options may present advantages in scale, flexibility and use of existing assets.

EXHIBIT 21: LEVELISED COSTS OF SELECTED POWER TECHNOLOGIES



Notes: (1) Considers a 15% reduction on non-feedstock costs. Considers 44% energy conversion to electricity from wood pellets based on Strengers B., et al. (2018). Capex represents 45% of non-feedstock costs when utilization is at 70%. (2) Considers the mid estimates of LCOE for US, BNEF. (3) Capex represents 34% of total costs. (4) Considers 50% efficiency of conversion, $1.3/kg hydrogen production cost, $0.1/kg transport and storage costs. In reality, capital costs (including costs for CCS) may be spread over > 10% utilisation.

Sources: Bloomberg New Energy Finance; Power Generation Costs – IRENA (2018); Biomass for power generation – IRENA (2012); Lazard's levelized cost of energy analysis (2018); Strengers B., et al. (2018), Negatieve emissies; Technisch potentieel, realistisch potentieel en kosten voor Nederland, Den Haag: PBL; Gas decarbonization pathways 2020-2050, Guidehouse (2020)

7. Plastics

Decarbonizing plastics is a more complex process than decarbonizing energy. Today's plastics emit CO_2 both in their production and in their end-of-life, when the carbon built into the material is released. Decarbonizing plastics requires decarbonizing both the production of plastic (feedstock production, refining, cracking, and polymerization) and the outcomes of end-of-life treatment (incineration, recycling, or landfill). This means the strategies considered below are not simply technologies that can be considered and compared in isolation, but components of a shift in how plastic is created and used. A combination of these strategies is necessary for fully decarbonizing plastics.

This analysis considered two potential scenarios for how much biomass can be demanded by plastic in 2050. Both use expected 2050 plastic demand as a starting point. European demand is taken from Material Economics' publication "Industrial Transformation 2050" and Global demand is taken from Material Economics' "The Circular Economy – A Powerful Force for Climate Mitigation". The first scenario considers how much biomass would be necessary if all plastic demand were to be met by production from bio-based feedstock. The second considers how much plastic demand would need to be met by bio-based feedstock, given how much demand could be satisfied by other low carbon technologies.[55] The latter scenario is what is displayed on the value curve in the main reports.

Net-zero compatible mitigation options

BIOBASED MITIGATION OPTIONS:

Plastic production from bio-based feedstock: Biomass feedstock is used to create bioethanol, bio-methanol, biogas, or bio-naphtha which can then be used as feedstocks to create conventional plastics. The end-of-life incineration of the biogenic carbon in these plastics does not lead to net emissions as they are offset by the carbon sequestered in the growth of the biomass. This analysis focuses on two production pathways of bio-methanol from lignocellulosic biomass: anaerobic digestion and gasification. Both pathways require significant amounts of electricity, and anaerobic digestion also requires green hydrogen as an input.

Substitution to low-CO_2 materials: Demand which is currently being met by plastics can in some cases be directly replaced by biobased materials such as paper and cardboard. This analysis assumes that up to 25% of plastics currently used in packaging can be substituted for these materials without compromising on the unique properties of plastics such as barrier quality, formability, or transparency.[56]

NON-BIOBASED MITIGATION OPTIONS:

Mechanical recycling: The collection, sorting, grinding, washing, and reprocessing of end-of-life plastics into granules that can be used to manufacture new plastics products. Only some types of plastic (e.g., monomaterials) are capable of being mechanically recycled. Mechanical recycling is a mature industry, though with some minor exceptions (e.g., PET bottles) it is not a "closed loop", and the end product from mechanical recycling is generally lower quality than virgin plastics and involves some yield losses. However, this material can still be used to replace some virgin plastic demand.

Chemical recycling: Chemical recycling is a means of producing high quality recycled plastics by chemically breaking down end of life plastics to its constituents. As with mechanical recycling, there are yield losses throughout the recycling process. Chemical recycling in its current form still emits CO_2, though this report assumes that a combination of electrification and mass balance increases will allow for lower emissions in 2050. This report considers two chemical recycling technologies, pyrolysis with electric steam cracking and gasification to methanol-to-olefins.

Steam cracking + CCS: Carbon capture and storage (CCS) on steam cracker furnaces, refinery processes, and on waste-to-energy plants. Universal coverage of CCS would be difficult to achieve since three separate emissions sources would have to be addressed (petroleum refining, steam cracking, and waste incineration). Waste incineration is also typically small-scale and thus also less efficient for CCS.

Electric steam cracking + CCS: Electrification of steam crackers and other processes as well as carbon capture and storage (CCS) on end-of-life incineration. While electrification will require technology development, this is assumed to be in place by 2050, based on a literature review. The challenge is one of commercial viability: it will require significant investment and requires competitive electricity prices.

Carbon capture and utilisation (CCU): 'Synthetic chemistry' to produce new chemicals from CO_2 ('power to X'), using non-fossil sources of carbon. This pathway is limited by energy requirements, with as much as 27 MWh of zero carbon electricity required to produce one tonne of high value chemicals.

EXHIBIT 22: POTENTIAL TECHNOLOGIES FOR DECARBONIZING PLASTICS

EXHIBIT 22

Decarbonisation options: Bio-resources can be used to decarbonise chemicals feedstock and as substitution materials (e.g., fibres)

Circular economy
New and improved processes
Carbon capture

Bio-based feedstock	Mechanical recycling	Chemical recycling	Carbon capture and utilisation (CCU)
Plastics production from biomass feedstock with methanol as a new platform chemical provides an option for a fossil-free plastics system.	Mechanical recycling by sorting, grinding, washing and reprocessing end of life plastics into granules that can be used to manufacture new plastics products.	Chemical recycling is a means of producing high quality recycled plastics by chemically breaking down end of life plastics to its constituents.	'Synthetic chemistry' to produce new chemicals from CO_2 ('Power to X'), using non-fossil sources of carbon
Substitution	**Steam cracking + CCS**	**Electric steam cracking + CCS**	**Material efficiency and circular business models**
Switch to low-CO_2 materials such as sustainably sourced fibre alternatives where they can provide equivalent functionality	Carbon capture and storage (CCS) on steam cracker furnaces, refinery processes, and on waste-to-energy plants. Alternatively long-term storage of plastic.	Electrification of steam crackers and other processes as well as carbon capture and storage (CCS) on end-of-life incineration	Reducing the amount of material used for a given product or structure, or increasing the lifetime and utilisation through new business models
Bio solutions	Non-bio solutions		

Sources: Material Economics, 'Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry'.

Resource Efficiency

The potential technologies for decarbonizing plastics were assessed on how much feedstock (in tonnes) was required to produce one tonne of low carbon plastics, and how much electricity is required for this process.

Biomass has a lower mass balance (more input is required for each tonne of output) than fossil feedstock because the biomass contains oxygen that is not needed in the chemistry of the plastic. The resource efficiency analysis of bio-based feedstocks considered both first- and second-generation gasification production pathways for bioethanol as well as second generation production pathways of anaerobic digestion and gasification for biomethanol. There is significant variation in feedstock needs depending on which bio-based production pathway is used.[57] As there is still significant uncertainty in which pathway will prove dominant in 2050, an average of the resource needs of the second-generation gasification and anaerobic digestion pathways to biomethanol were used for calculating biomass needs for bio-based feedstock.

The resource demands of the other pathways were taken from Chapter 3 of Material Economics' publication "Industrial Transformation 2050".

Costs

The costs of each production pathway for low carbon plastics are based on modelling from Material Economics' publication "Industrial Transformation 2050". The calculations have been updated to match input prices for hydrogen, electricity, and CCS costs with the other sectors analysed in this report. The EU calculations assumes prices of $25/MWh electricity and $1.6/kgH$_2$ in 2050, and the global calculations assume prices of $20/MWh electricity and $1.4/kgH$_2$ in 2050.

EXHIBIT 23: PRODUCTION COSTS OF SELECTED LOW CARBON PLASTICS PATHWAYS

EXHIBIT 23

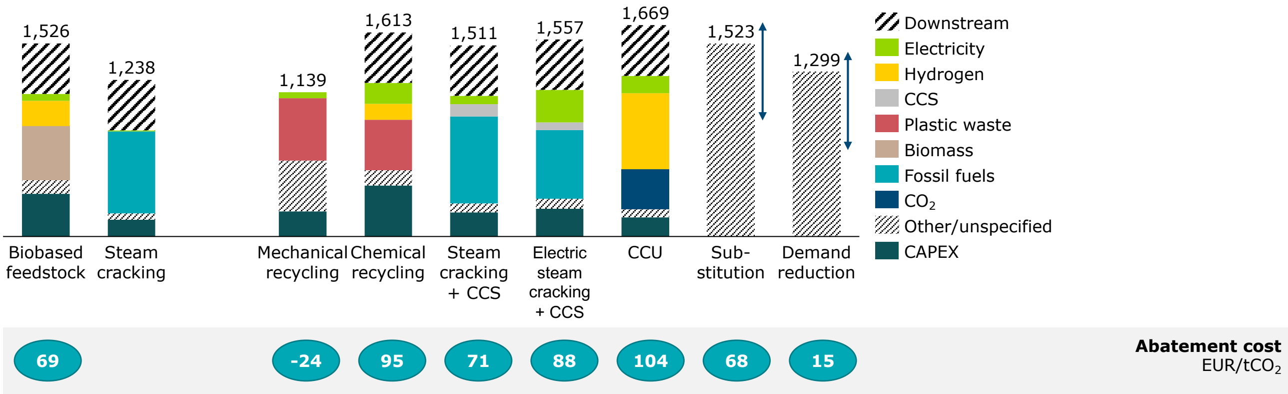
European Union

Economics: The production cost of the bio-based feedstock route is higher than other solutions except the CCU route

EU

EXCLUDING CO_2 PRICES

Cost breakdown of technologies in the EU
EUR per tonne plastics, 2050 (Indicative)

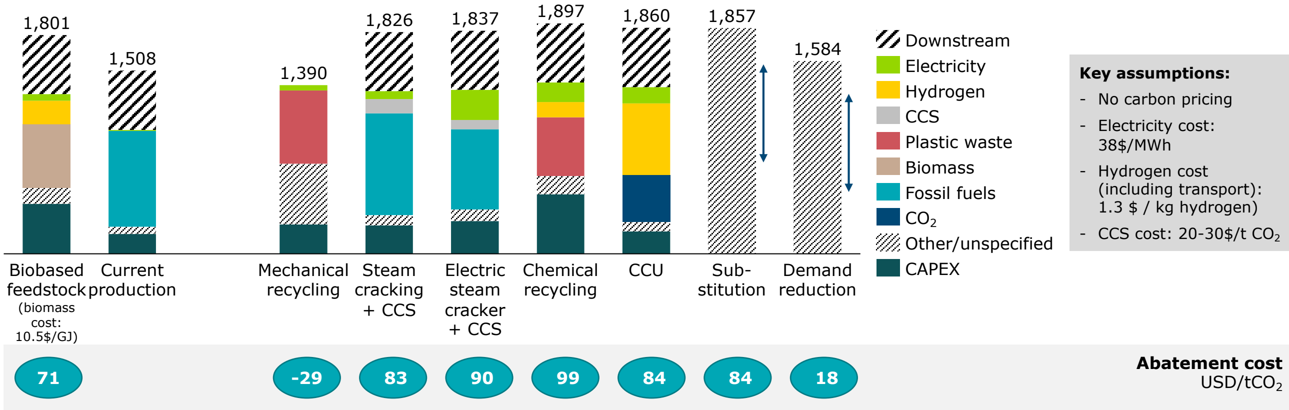


Global

Economics: The production cost of the bio-based feedstock route is higher than other solutions except the CCU route

Global

Cost breakdown of technologies, global prices
USD per tonne plastics, 2050 (Indicative)



Notes: Abatement cost calculated assuming zero-carbon electricity. Costs for new low-CO_2 technologies are very similar and based on this alone, it is not possible to determine how much of the plastic production should be bio-based.

Sources: Material Economics modelling.[58]

8. Pulp, paper, and solid wood products

In contrast to the previous sectors, the analysis of the pulp & paper and solid wood product categories did not compare a biobased decarbonisation option with a non-biobased decarbonisation option. Instead, this analysis assumes that these sectors will continue to demand biomass in the future and provides an estimate of how much biomass these sectors could demand, and at what price.

The values presented on the European and Global value curves amount to estimated biomass feedstock demand for these segments in 2050. Demand estimates have been taken from previously published reports, and costs (for the purposes of the value curve) are taken to be the estimated 2050 prices of the relevant feedstocks.

Pulp & paper

The demand for European pulp & paper estimates is based on a midpoint of projections from a variety of reports.[59] The estimate of the global pulp and paper market for 2050 is taken from the SIFE Global Foresight 2050 report.[60] Pulp demand is calculated in tons, and converted to EJ using a factor of 0.019 EJ/Mt.

The relevant price for the value curve was taken to be the price of the requisite feedstock for pulp and paper, pulpwood. 2050 global pulpwood prices are taken from Tian et al (2016).[61] 2050 European pulpwood prices are estimated by applying a growth rate to current pulpwood prices. Current European pulpwood prices are taken to by Q4 2020 prices from the Swedish Forest Agency and expected to grow at the rate provided in Tian et al.[62]

Solid wood products

The demand for solid wood products for Europe is taken from the "European Forest Industry and Forest Bioenergy Outlook up to 2050" baseline case.[63] Global sawn-wood demand is taken from Biogiorno et al, scenario A1, linearly interpolating between the estimates for 2030 and 2060 to provide an estimate for 2050.[64] Sawn-wood demand is calculated in Mm3 and converted to EJ using a factor of 8.72 PJ/Mm^3.[65]

The relevant price for the value curve was taken to be the price of the requisite feedstock for pulp and paper, sawtimber. 2050 global sawtimber prices are taken from Tian et al (2016).[66] 2050 European pulpwood prices are estimated by applying a growth rate to current sawtimber prices. Current European sawtimber prices are taken to by Q4 2020 prices from the Swedish Forest Agency and expected to grow at the rate gathered from expert interviews.[67]

9. Calculations of land efficiency

In addition to the energy efficiency comparisons made in the individual sectoral analyses above, each individual technology was also compared on a land efficiency basis, i.e., how much land is required to generate each unit of output.

Land efficiency was calculated separately for bio and non-biomass mitigation options. The land requirements for biomass options were based on the land necessary to grow the requisite biomass. A range of land productivity estimates were used. The top end of this range was defined as the top productivity (~25 tonnes/ha/year) for lignocellulosic biomass crops, miscanthus grown on fertile, dedicated land. The low end assumes biomass from waste and residues (e.g., primary and secondary forest residues from managed forest land) and is expected to be ~10-fold less, 2.5 tonnes/ha/year.[68]

The land requirements for non-bio-options consider the land necessary to generate the requisite amount of renewable electricity, assuming that renewable electricity is generated from solar PV with an efficiency of 600 MWh/ha/year.[69]

10. Cross-cutting assumptions and technology development

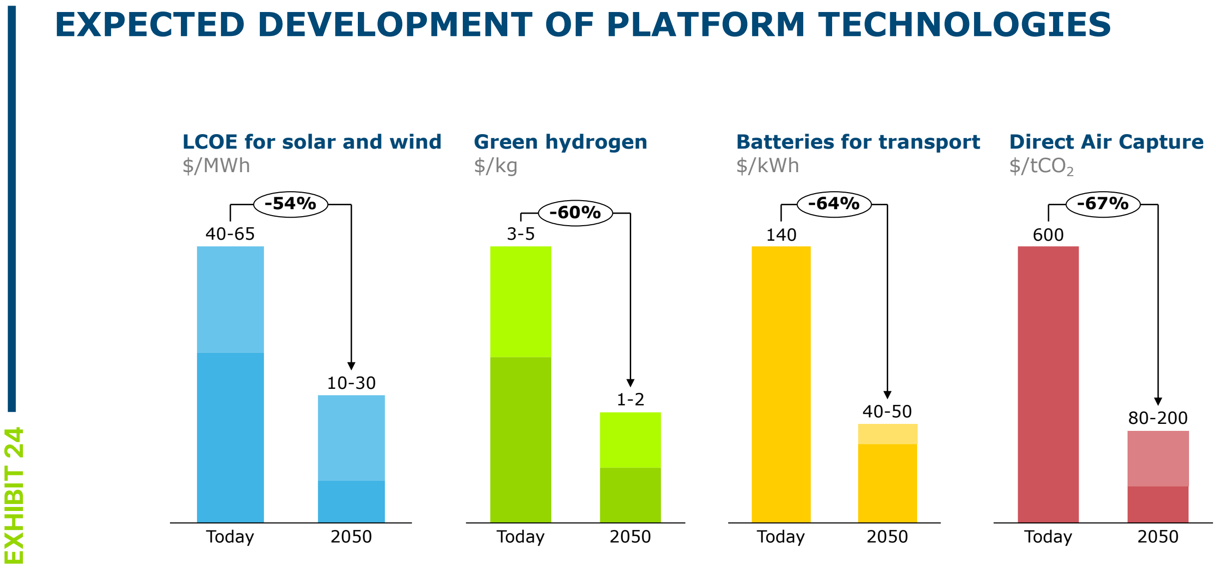
The methodology used in this study contrasts bioenergy and bio-materials with other potential net-zero compatible solutions. With a few notable exceptions, it relies on no major technology breakthrough. However, the results depend strongly on how a small number of future platform energy technologies develop, and especially on renewable energy technologies, hydrogen production, and batteries. This section presents the assumptions underlying the analysis.

FUTURE TECHNOLOGY COST, PERFORMANCE, AND SENSITIVITY ANALYSIS

Forecasting future technology costs is notoriously tricky territory, and there is a risk that conclusions are driven strongly by assumptions far into the future. To ensure transparency, this study takes a 'platform technology' approach, where cost developments over time are driven principally by a small number of key inputs: 1) solar and wind power generation, 2) water electrolyser performance and cost, 3) vehicle battery density and cost, and 4) carbon capture technology. The approach arguably is conservative, as it leaves out potential cost reductions proposed in research (digitisation, autonomous vehicles, novel chemistry, etc.). The assumptions used for the development of these platforms are shown in Exhibit 24.

EXHIBIT 24: EXPECTED DEVELOPMENT OF PLATFORM TECHNOLOGIES

Global:



Notes: Ranges for global cost numbers show that costs are likely to vary by location with lower bound being most favourable locations, and upper bounds representing a global average. Importing hydrogen to the EU will likely have lower costs than local production due to cheaper renewable electricity from solar power.

Sources: Material Economics and Energy Transitions Commission analysis based on multiple sources.[70,71]

RENEWABLE ELECTRICITY

The assumptions for power technology costs follow continued downward trajectories, in common with most future outlooks (e.g., those from the International Energy Agency, International Renewable Energy Agency, or Bloomberg New Energy Finance). Cost declines are driven by economies of scale, learning effects, efficiency gains in the technology, as well as improvements in operational efficiency delivered by digital solutions.

The translation of power generation technology developments to the actual cost of delivered power is complex and depends on multiple factors – and especially on the flexibility resources available in different power systems, and on the load profile of different applications. In this study, the analysis of costs of different applications builds on the insights from previous Energy Transitions Commission studies on power systems, which in turn survey a large literature on the topic.[72] We refer to these studies for much more extensive documentation of the reasoning behind the assumptions used.

This analysis also addresses the question of availability. There are scarcity considerations similar to those of bioenergy that are relevant for power applications. These are unlikely to apply in the aggregate: renewable electricity production requires just 1.5% of global land, and mineral and other material resources are sufficient.[73] However, for some geographies, meeting growing electricity demand with wind and solar power will be a challenge (e.g., due to high population density and or constraints on available land area). Solutions to these challenges include long distance energy transport as well as increasing other zero-carbon generation options with lower land footprint, including nuclear generation, CCS, and the deployment of a suite of increasingly efficient wind and solar technologies. Scaling-up wind and solar generation at speed and low cost will also require increasing the mobilisation rates of project and capital deployment speed. Streamlined planning and permitting regimes for both generation and networks, as well as appropriate power market design to provide long-term revenue certainty for renewable projects, will be required.

CLEAN HYDROGEN

The assumptions used for clean hydrogen build on the analysis in the ETC report "Making the Hydrogen Economy Possible".[74] Zero- or low-carbon hydrogen can currently be produced via one of two main technologies: electrolysis using zero-carbon power or SMR/ATR combined with CCS/U. Bioenergy transformation and CCS/U can also be used to produce hydrogen, and costs might also be reduced significantly if those technologies were developed at large scale. However, the analysis suggests that, with last cost declines in electrolysis, this is unlikely to be a large-scale option except where (e.g., stranded) bio-feedstock is available at very low costs.

For this reason, the analysis uses hydrogen produced via water electrolysis as the reference technology in evaluating different end-use technology options. The conclusions are similar to those of some recent studies, which also see low-carbon hydrogen as an important decarbonisation vector across heavy industry, heavy transportation and the power sector.[75]

BATTERIES

The assumptions used for batteries build on the analysis underlying the ETC's "Making Mission Possible" and "Clean Electrification" reports. This work noted that lithium-ion battery prices have decreased annually by 18% in the last decade and are expected to reach $100/kWh by 2023. These cost reductions enable batteries to be used cost-effectively in the road transport sector (particularly in light duty vehicles) and in balancing the power system.

DIRECT AIR CAPTURE OF CO_2

Direct air capture of CO_2 is still a nascent technology, although the underlying technology and engineering principles in most cases are well-known. Today's capture costs are high, but some techno-economic assessments suggest very significant potential for cost reductions.

At the lower end, some recent estimates have suggested that DACCS could fall to costs as low as 50 USD/t by 2040.[76] Other assessments suggest less aggressive but nonetheless very significantly lower costs than today, at 100–200 USD/t CO_2.[77]

These cost ranges put DAC in similar ranges as cost estimates for CCS on some bioenergy sources. The potential for DACCS to be as cost-effective as BECCS provides a major shift in perspective. Most climate scenarios analysing future biomass use have not included this possibility.[78] The use of DACCS has other potential benefits: Notably, the land footprint is 10-50 times smaller than that of BECCS per tonne of CO_2 captured.[79] Given the risk that land-use changes cut into a large share of the benefits of BECCS, the cost gap may be smaller still than pure engineering-based estimates have suggested. Direct air capture of CO_2 therefore deserves to be taken very seriously. Nonetheless, major questions remain about how viable and cost-effective this early-stage technology will prove.

In this study, we explore various scenarios of DAC costs between 80-200 USD /t, following the above literature. However, given the very large technology uncertainty, we provide no single cost-estimate, but include variability in the overall bio-resource value curve.

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