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IEA Bioenergy Task 41 Project 10

**A Report from the Advanced Motor Fuels TCP and IEA Bioenergy TCP**

Technology Collaboration Programme on Advanced Motor Fuels

IEA Bioenergy Technology Collaboration Programme



# The Role of Renewable Transport Fuels in Decarbonizing Road Transport

## Summary Report

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This "Summary Report" is based on the following report parts that have been published separately:

- Key Strategies in Selected Countries
- Production Technologies and Costs
- Scenarios and Contributions in Selected Countries
- Deployment Barriers and Policy Recommendations

This "Summary Report" was written by Dina Bacovsky (BEST – Bioenergy and Sustainable Technologies GmbH), based on the other report parts which were written by the following authors:

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The IEA Bioenergy TCP is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use.
www.ieabioenergy.com

The Advanced Motor Fuels (AMF) TCP also is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. AMF´s vision is that advanced motor fuels, applicable to all modes of transport, significantly contribute to a

sustainable society around the globe. AMF brings stakeholders from different continents together for pooling and leveraging of knowledge and research capabilities in the field of advanced and sustainable transport fuels.
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## The Role of Renewable Fuels in Decarbonizing Road Transport

**Renewable fuels, in addition to all forms of electric vehicles powered by low-carbon electricity, can make an important contribution in decarbonizing the road transport sector, especially in the short and medium term and for all modes of transport.**

Bringing down the GHG emissions of the road transport sector to zero by 2050 cannot be achieved by one measure alone.

Countries that deploy a set of different measures such as reducing transport demand, improving vehicle efficiency, and adding renewable energy carriers such as biofuels, e-fuels, renewable electricity and renewable hydrogen have the best chances to meet ambitious decarbonization goals.

Our assessment shows that biofuels contribute most to decarbonization now and up to 2030, 2040, or even 2050, depending on the country. In Germany and in the USA, efficiency gains become the main contributor after 2030, and in Finland and Sweden the impact of biofuels remains largest until around 2040 when the use of electric vehicles takes over. In Brazil, biofuels remain the largest contributor until 2050.

### Background

In the light of climate change, there is an urgent need to decarbonize our societies. The road transport sector is specifically challenging, as transport demand is growing, and so are the sector´s GHG emissions. Electric mobility powered by renewable power will not be able to solve this on its own, and renewable transport fuels will be needed to bridge the gap between GHG emission reduction targets and the prospected actual emissions.

A team of experts has assessed the transport sector and its projected development up to 2030 and 2050 for a number of countries, including Germany, Sweden, Finland, USA, and Brazil. The work was initiated and carried out jointly by two Technology Collaboration Programmes of the International Energy Agency, namely the IEA Bioenergy TCP and the Advanced Motor Fuels TCP, with support of the Directorate General for Energy of the European Commission. The analysis is based on current national policies, projections of the vehicle fleet, and on the availability of renewable transport fuels.

The objective of the assessment was to quantify the role that renewable fuels play in decarbonizing the road transport sector, and to provide insights to policy makers on how individual countries differ from one another, which options for decarbonization they have, and best practice examples of successful policies.

### Research Protocol

The core of the project was the assessment of the possible evolution of the road transport sectors of five individual countries. Fleet data was provided by country experts and modelling assumptions as well as the calculation results were discussed with these experts online and in an expert workshop.

The road transport sectors of Finland, Sweden, Germany, USA and Brazil were modelled in the VTT-owned ALIISA model. This model includes 5 vehicle categories, 6 propulsion systems and 12 fuel options. Input data for each country includes assumptions on total sales in each vehicle category for future years, the distribution between the available powertrain/fuel options in sales, the evolution of energy efficiency, and the annual driven distance, which vary between categories, age classes and powertrain/fuel combinations. The model then calculates the fleet composition for each year up to 2050, the total fleet energy demand, and the resulting tank-to-wheel (TTW) $CO_2$ emissions. The model assumes zero $CO_2$ emissions from renewable shares and renewable electricity.

These calculations were performed for four different scenarios, the Current Policies Scenario, MORE EV Scenario, MAX BIO Scenario, and E-FUELS Scenario.

Other parts of the project described the key strategies of 7 countries to achieve cleaner transport sectors; renewable fuel production pathways and their technology readiness levels, GHG emissions, costs, and feedstocks availabilities; the applicability of fuels in engines; and implementation barriers, policy recommendations and best practice policy examples.

## Key Messages

### Renewable transport fuel basics

- Renewable transport fuels such as biofuels and e-fuels can, depending on the component, be used in low blends, as drop-in fuels with up to 100% substitution, and as special fuels in dedicated or adapted engines/vehicles. However, dedicated alternative fuel vehicles are not yet widely introduced globally.
- Substantial volumes of sustainable feedstocks could be made available for biofuels production, sufficient to replace up to 30% of transport fuel demand in 2060.
- When assessed in life cycle terms, biofuels offer significant GHG emission reductions over fossil fuels. The current average carbon intensity of biofuels provided to California ranges from 15 to 65 $gCO_{2e}$/MJ (versus fossil diesel and gasoline carbon intensities of 95). Future biofuel carbon intensities are expected to decrease further, and can also be net negative when obtaining credits for avoided GHG emissions from waste disposal or if combined with CCS.
- Costs of advanced biofuels depend on the production pathway and with a range from 0.35 to 1.58 EUR/l gasoline equivalent are in most cases significantly higher than the current costs of fossil fuel equivalents. Advanced biofuel technologies are currently in their early stages of development, and therefore significant potential for further cost reduction exists.

### Country assessments

- Transport sector indicators such as the number of vehicles per capita, transport work per capita and transport work per geographic area for the countries assessed (Finland, Sweden, Germany, USA and Brazil) vary highly.
- In the Current Policies scenario, biofuels already provide the largest contribution to the reduction of TTW $CO_2$ emissions now and up to 2030, 2040, or even 2050, depending on the country. Electric vehicles only catch up with biofuels by 2040.
- Even if electric vehicles are introduced at a higher rate, biofuels remain the largest contributor to decarbonization in the short to medium term.
- Depending on the fuel qualities available in a region, maximizing the use of biofuels, and in particular of drop-in biofuels, can reduce TTW $CO_2$ emissions to almost zero by 2050.
- The use of e-fuels could close the gap between emission reductions achieved by other measures and ambitious targets. The amount of e-fuels needed to fully displace fossil fuels however would require significant amounts of non-fossil electricity and captured $CO_2$ emissions, which are unlikely to be available in many countries.

**Implementation barriers**

- Competition with well-established fossil fuels-based system
- Fluctuating policy drivers, lack of long-term stable policies
- Incomplete or unbalanced set of policy measures
- Public perception of technical performance, potential and sustainability
- Requirement to build up infrastructure for alternative fuels and alternative fuel vehicles
- Successful policy examples
- Blending mandates for biofuels
- Incentives based on GHG impact
- Strict and consistent sustainability guidelines
- Advanced biofuels require specific support, such as separate obligations, RD&D support, and risk guarantees

**Policy suggestions from the expert workshop (Brussels, 18 November 2019)**

- Focus on the carbon intensity of biofuels
- Get oil majors involved and leverage their existing fuel supply chains and distribution networks to make biofuels accessible to the marketplace in a cost-efficient way
- Turn the tables and establish a requirement to phase out fossil fuels
- Allow automakers to make use of the GHG emission reductions that the use of renewable fuels offers and count these against their $CO_2$ emissions fleet targets (which could then be strengthened)

## Content

## List of Figures

## List of Tables

## The need to decarbonize the transport sector

In the light of climate change, there is an urgent need to decarbonize our societies. The transport sector, and within it in particular the road transport sector, is specifically challenging, as transport demand is growing, and so are the sector´s GHG emissions. Decarbonization includes all options to reduce GHG emissions and make road transport cleaner, including low(-fossil)-carbon energy carriers such as biofuels, e-fuels, and renewable electricity. None of these will be able to solve this grand challenge alone, and renewable transport fuels have an essential role in bridging the gap between GHG emission reduction targets and the prospected emission reductions.

A team of experts has assessed the transport sector and its projected development up to 2030 and 2050 for a number of countries, including Germany, Sweden, Finland, USA, and Brazil. The work was initiated and carried out jointly by two Technology Collaboration Programmes of the International Energy Agency, namely the IEA Bioenergy TCP and the Advanced Motor Fuels TCP, with support of the Directorate General for Energy of the European Commission. The analysis is based on the countries´ key strategies for decarbonization, their current and projected vehicle fleet, and on the availability of established and emerging renewable transport fuels.

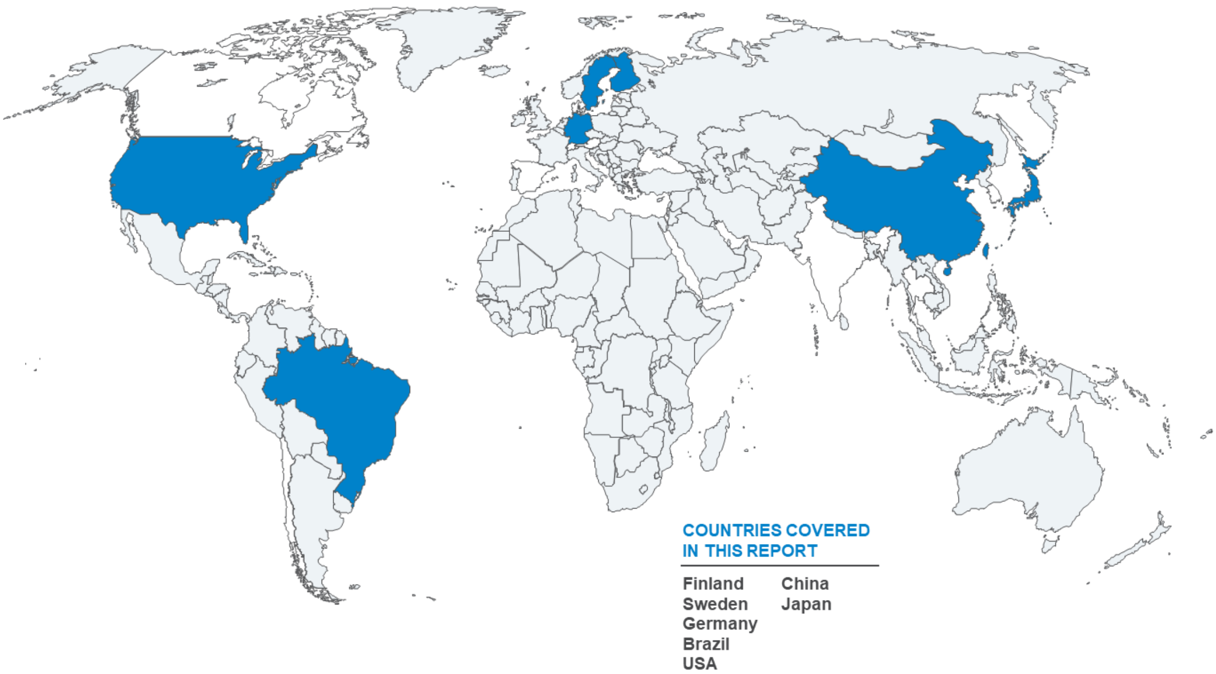


*Figure 1: Countries covered in this report*

## Country key strategies

Most countries are aware that ambitious action is needed to abate the climate crisis. GHG emissions from all sectors have to be reduced dramatically, and the transport sector is among the hardest one to decarbonize. Measures can be taken according to the avoid-shift-improve principle, i.e. avoid excessive transport, shift to less carbon-intensive transport modes, and improve the carbon intensity of all transport modes. The use of renewable energy carriers such as biofuels, e-fuels and green electricity for electric vehicles constitutes one of the main measures to improve the carbon intensity of transport.

Consequently, many countries have set up legislation that mandates or encourages the use of renewable transport fuels. The European Union has introduced the Renewable Energy Directive RED and its recast RED-II, mandating all EU member states to cover 10 % of their transport energy demand from renewable sources by 2020, and 14% by 2030. In the USA the Renewable Fuel Standard (RFS) established volume requirements for renewable fuel based on life-cycle GHG emission reduction thresholds across several fuel categories. Annual volume targets in the initial legislation culminate at 36 billion gallons (136 billion liters) of total renewable fuels per year in 2022. In Brazil, the RenovaBio system shall gradually reduce the average GHG intensity in the Brazilian transport system by around 10% in 2030, relative to 2017.

Finland, Germany and Sweden (all EU member states) have set even more ambitious targets for biofuels than mandated by the EU RED. Finland has a target of increasing the share of biofuels (by energy content) in road transport fuels to 30% by 2030. Germany has a target of reducing GHG emissions from the transport sector stepwise to 95 million tons by 2030 which is about 42% compared to 1990. One measure for achieving this is a GHG-based quota system which obligates fuel suppliers to sell a fuel mix which achieves a 6% GHG mitigation a year compared to fossil gasoline and diesel mix from 2020 onwards. Finally, Sweden has a target to reduce emissions from the road transport sector by at least 70% by 2030, compared with 2010. One measure to achieve this is a GHG reduction obligation, which entails an obligation for fuel suppliers to reduce GHG emissions from sold volumes of gasoline and diesel fuels by incorporating biofuels. In 2020 the reduction obligation is 4.2 % for gasoline and 21 % for diesel. The reduction obligation will be increased over time with an indicative target of 40% overall reduction in 2030, indicatively composed of 28 % for gasoline and 66 % for diesel.

In the USA, besides the federal RFS, California was the first state to introduce a mandate on transport fuel GHG emission reductions based on GHG intensities of fuels. The Low-Carbon Fuel Standard (LCFS) sets annually decreasing carbon intensity benchmarks for gasoline, diesel, and their replacement fuels. The LCFS has a goal of reducing the carbon intensity of its transportation fuel pool by 20% by 2030 (relative to a 2011 baseline). The State of Oregon has a program similar to the LCFS requiring reduction of carbon intensity of its transport fuels. Some Mid-West states are exploring similar clean fuel programs to reduce transport fuel GHG emissions.

Other countries are more focusing on electric vehicles in order to decarbonize the transport sector. China has committed to lower its overall carbon intensity and to peak its national carbon emissions by 2030 or earlier. In the transport sector, China is primarily focusing on the introduction of electric vehicles (so-called new energy vehicles), but also promoting the use of E10. Japan has committed to reduce GHG emissions from the transport sector from 225 million $t_{CO2eq}$ in FY 2013 to 163 by 2030, constituting a reduction of 27%. Measures include the promotion of next-generation automobiles, and transport-system level measures.

All mentioned countries have also implemented legislation to gradually increase the fuel efficiency of vehicles, directly resulting in GHG emission reductions.

More details on the key strategies of these countries can be found in Part 1 of the overall report (“Key Strategies in Selected Countries”).

## Ambitions versus trends

Comparing the actual reduction of GHG emissions from the transport sector with national ambitions or with global low-carbon scenarios tends to be depressing, as forecasts based on current trends show that the ambitions will almost never be met.

In the World Energy Outlook 2017 publication, the IEA has introduced the 2°C Scenario (2DS), which is consistent with a 50% chance of limiting future global average temperature increases to 2°C by 2100. The 2DS sees an increase of biofuels use by a factor of 10 by 2060, providing 30 EJ in the transport sector. In this scenario, biofuels provide some 30% of transport energy, complementing increases in electricity and improvements in energy efficiency in the sector as shown in Figure 2. This scenario also sees a rapid increase in the level of biofuels in the short term, with its contribution in the transport sector growing by a factor of 3 by 2030.

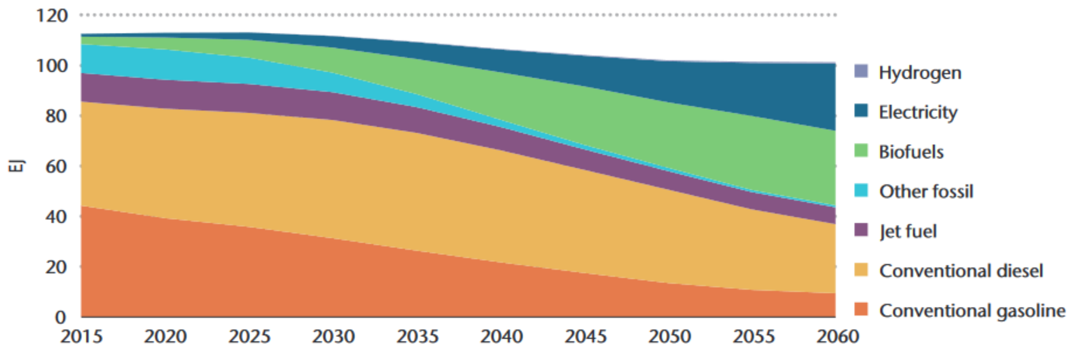


*Figure 2: Role of biofuels in transport – IEA 2DS Scenario*

However, when comparing the needed production and use of biofuels for low-carbon scenarios to current biofuel production trends, it is apparent that the figures don´t match. Figure 3 shows the anticipated trends in total global biofuels production to 2024, and compares these to the 2025 figures in the New Policies Scenario and the Sustainable Development Scenario of the IEA´s World Energy Outlook (WEO NPS and SDS)[1]. Comparison shows that current and proposed policies (as represented by the NPS scenario) are only likely to stimulate around 70% of the deployment level needed in the SDS scenario, even if proposed measures are actually put in place and effective. More ambitious targets and policy measures will be essential if biofuels are to be developed in a way that is compatible with scenarios such as the SDS.

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[1] The NPS provides an assessment of where today's policy frameworks and ambitions, together with the continued evolution of known technologies, might take the energy sector in the coming decades. The policy ambitions include those that have been announced as of August 2018 and incorporates the commitments made in the Nationally Determined Contributions under the Paris Agreement.
The SDS, introduced for the first time in the 2017 edition of the WEO starts from the assumption that selected key outcomes related to the main energy-related components of the Sustainable Development Goals, agreed by 193 countries in 2015, can be achieved and then works back to the present to see how they might be realised.

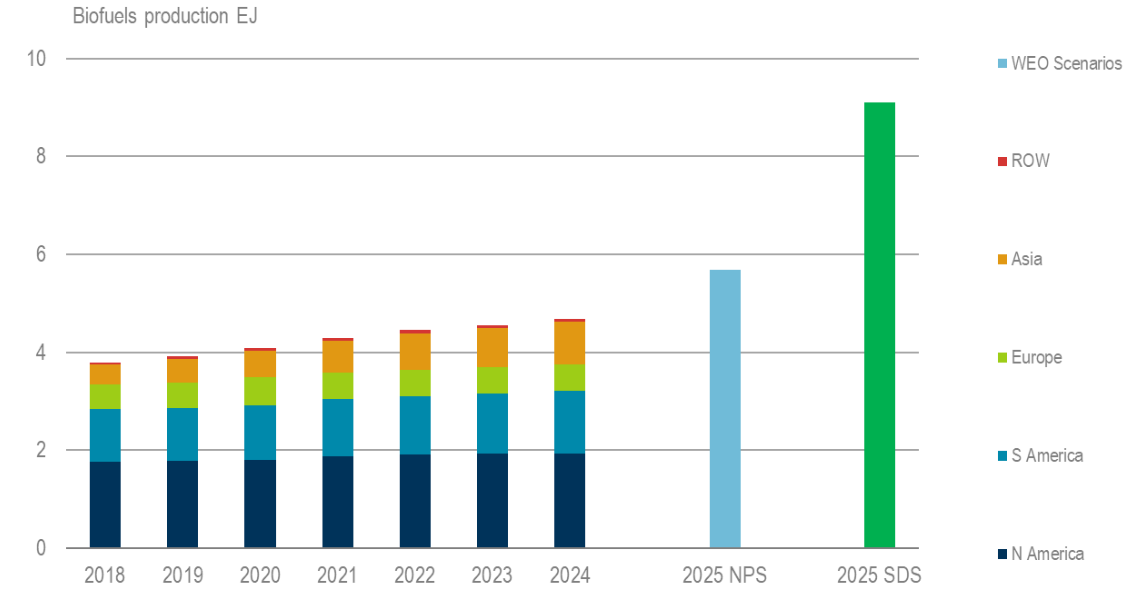



*Figure 3: Comparison of projected biofuels growth to 2025 with WEO Scenarios*
*Source: IEA Renewables 2019 and WEO 2018*

This global analysis is complemented by national analyses with essentially the same result, as can be seen in the following two figures for Finland and Sweden that compare national forecasts for GHG emissions from the transport sector with the national goals.

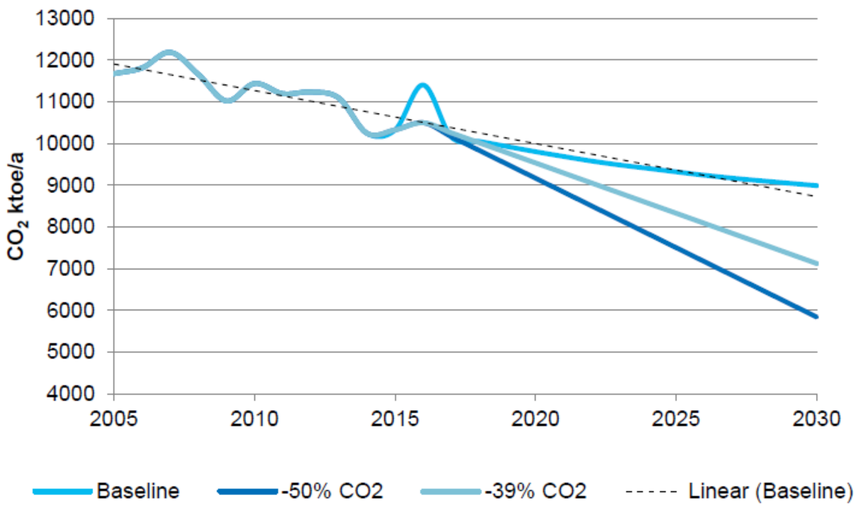



*Figure 4: Finnish road transport $CO_2$ inventory from 2005 (reference year) to 2030 (target year) and the trajectories needed to reach emission reductions of -39 or -50 % by 2030.*

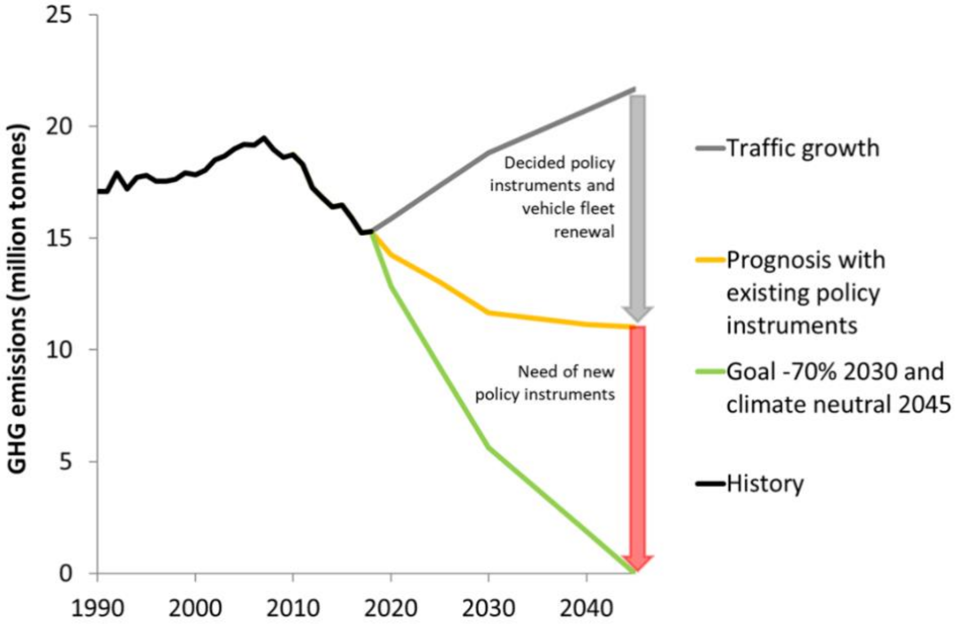



*Figure 5: The gap between BAU scenario and the goals for the Swedish transport sector. Source: Swedish Transport Administration*

It should be noted though that there are also examples of a contrary development. Japan has actually managed to decrease the energy use and thus the GHG emissions from the transport sector. Japan´s energy demand in the transport sector has already peaked in FY 2001 (see Figure 6). Gasoline provides 54.4% of transport energy, followed by diesel with 31.7%. There is a small share of electricity of 2.0%, and only 1.5% biofuels (countable number as ETBE mixed into gasoline).

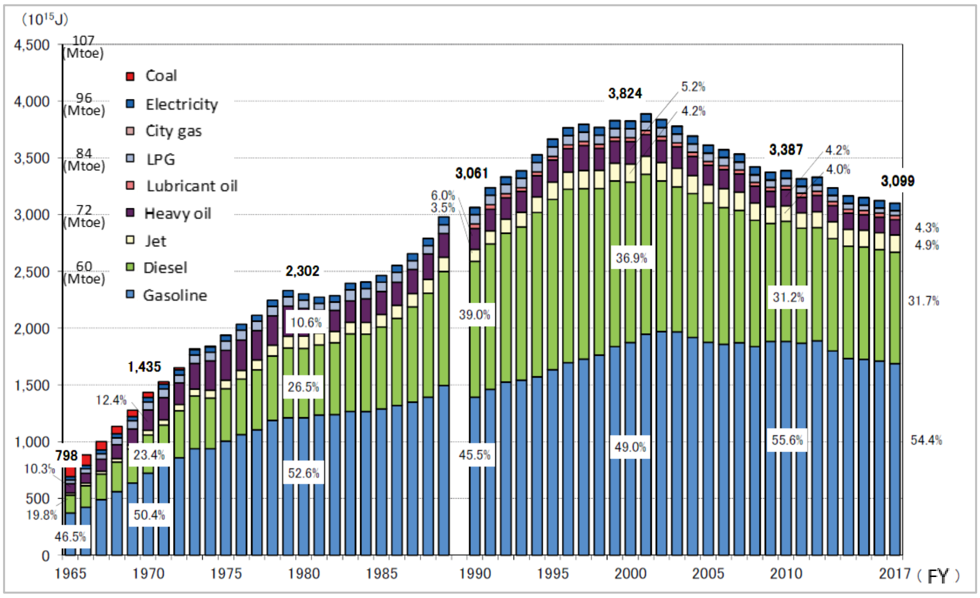



*Figure 6: Trends in energy consumption in the Japanese transport sector.*

## Assessing the development of the transport sector in selected countries

The core of this study was the assessment of the road transport sector and its development for a number of selected countries, namely Finland, Sweden, Germany, USA and Brazil. This sample of countries is quite diverse and differs largely in land area, population density, number of cars per capita, and average transport work in passenger cars and in trucks, as shown in Table 1.

*Table 1: Comparison of some transport-related indicators*

*Source: https://www.worldometers.info/world-population/population-by-country/.*

| | 2020 | | | | |
|---|---|---|---|---|---|
| | **Finland** | **Sweden** | **Germany** | **USA** | **Brazil** |
| Population size | 5,545,000 | 10,100,000 | 83,780,000 | 331,000,000 | 212,600,000 |
| Land area, $km^2$ | 303,890 | 410,340 | 348,560 | 9,147,420 | 8,358,140 |
| Pop. density | 18.2 | 24.6 | 240.4 | 36.2 | 25.4 |
| Cars/capita | 0.501 | 0.486 | 0.552 | 0.717 | 0.180 |
| Car-km/capita | 7,600 | 5,600 | 7,800 | 13,000 | 3,000 |
| Car-km/$km^2$ | 138,000 | 137,000 | 1,880,000 | 270,000 | 76,000 |
| MDT&HDT-km/capita | 633 | 502 | 496 | 1,535 | 374 |
| MDT&HDT-km/$km^2$ | 11,555 | 12,344 | 119,214 | 55,554 | 9,514 |

For this assessment, the transport sector of each of these countries was modeled in the ALIISA model. This model was developed to assess the Finnish transport sector in the ”Biofuels 2030” study; for which an English translation of the main parts of this study is available as appendix to Part 1 of the overall report.

The ALIISA model includes 5 vehicle categories, 6 propulsion systems and 12 fuel options. Input data for each country includes assumptions on total sales in each vehicle category for future years, on the distribution between the available powertrain/fuel options in sales, on the fuel consumption (or energy efficiency gain) for future years, and on the annual driven distance, variable between categories, age classes and powertrain/fuel combinations. The model then calculates the fleet composition for each year up to 2050, the total energy demand of this fleet, and the resulting tank-to-wheel (TTW) CO2 emissions. It should be noted that CO2 emissions of renewable shares and electricity are considered to be zero, although in reality both energy carriers cause upstream emissions.

These calculations were performed for four different scenarios:

- Current Policies Scenario
  This is the base case scenario, including input data from each country based on historic data and on current policies.
- MORE EV Scenario
  This scenario reflects higher than anticipated sales of electrified vehicles up to the levels still deemed conceivable by the country experts involved.
- MAX BIO Scenario
  This scenario applies biofuels to the maximum extent possible in the respective

country, starting from current deployment level up to the maximum level in 2050.

- E-FUELS Scenario
  This scenario introduces e-fuels in 2030 and increases linearly to reach full displacement of fossil fuels by 2050.

## Decarbonization based on current policies

As mentioned before, the transport sectors of the selected countries differ from each other quite a lot. For example, in Finland almost half of the energy in 2030 will be used in trucks, while in Sweden and Germany passenger cars dominate. In the USA the passenger car fleet is complemented by an equally sized fleet of vans, trucks and SUVs used for personal mobility, and Brazil features the largest contribution of buses to the energy use of the transport sector, see the following figures.

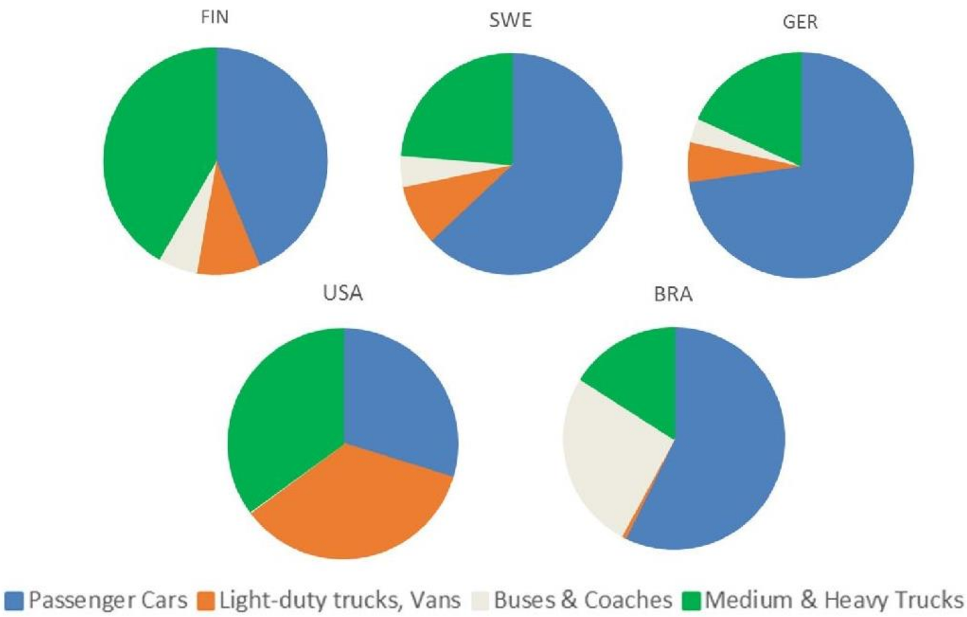



*Figure 7: Energy use per vehicle category in Current Policies scenarios – 2030.*

Taking a closer look at the fuels that will be used in the Current Policies scenarios in 2030 in each of the countries, we find different main fuels. In Germany, Sweden and Finland, diesel dominates, and Finland and Sweden will also use significant shares of renewable diesel. In Brazil the share of ethanol will be more than 30%, almost equally large as the share of diesel. In the USA, gasoline dominates over diesel, and ethanol contributes some 10%. The use of electricity is hardly visible, and also biomethane only provides a very minor share.

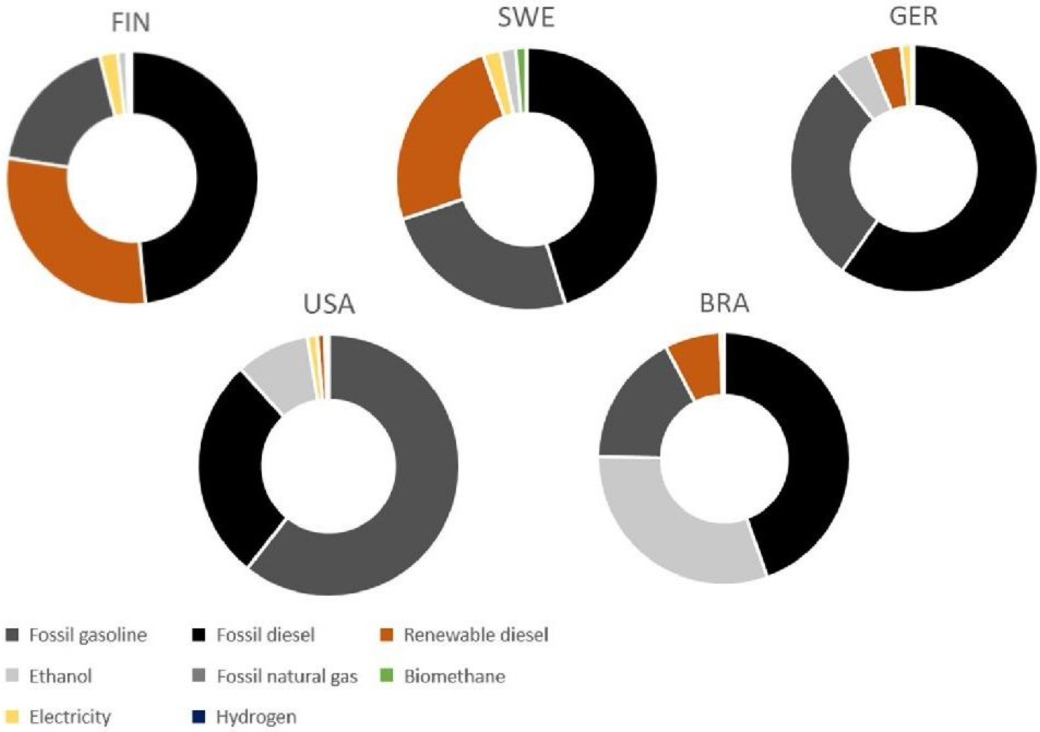
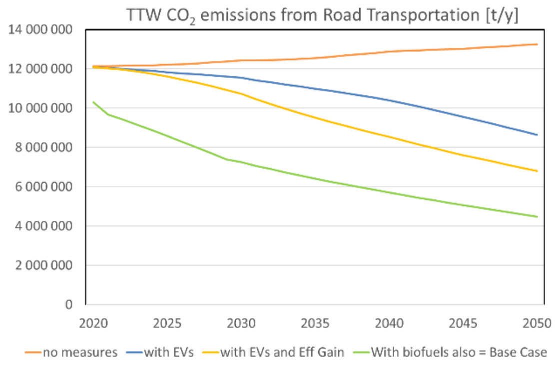


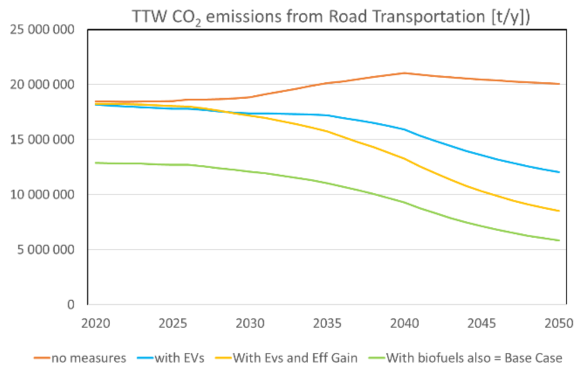

*Figure 8: Energy use per carrier in the Current Policies scenarios – 2030.*

Based on the projected energy use, the ALIISA model allowed to calculate the effects of several measures separately, namely gains in the energy efficiency of the vehicles in use, use of electric vehicles (with zero TTW $CO_2$ emissions), and the use of biofuels (also counted with zero TTW $CO_2$ emissions). In the figure below, the top-most red line is the hypothetical evolution of TTW $CO_2$ emissions from the road transport sector without any of these measures. The blue line then shows the effect of electrification alone, while the yellow one adds to this the effect of energy efficiency gains. Finally, the green line shows the combined effect of all measures including biofuels.

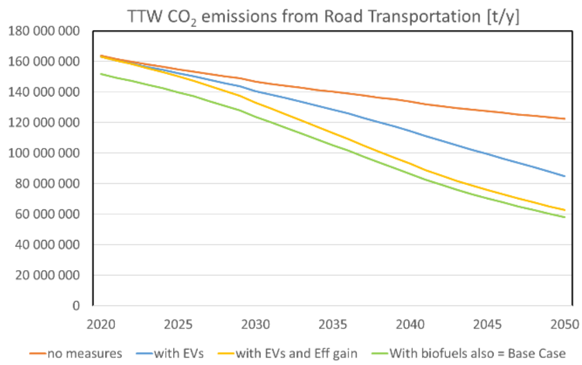
The figure below clearly shows the size of the expected contributions of efficiency gains, electric vehicles and biofuels. Biofuels contribute most to decarbonization now and up to 2030, 2040, or even 2050, depending on the country. In Germany and in the USA, efficiency gains become the main contributor after 2030, and in Finland and Sweden the impact of biofuels remains largest until around 2040 when the use of electric vehicles takes over. In Brazil, biofuels remain the largest contributor until 2050. Biofuels can be implemented in the legacy fleet, whereas electrification and fuel cell vehicles required the introduction of new vehicles and new infrastructure, requiring time to achieve significant impact. The figure also shows the difference in $CO_2$ emission trends for the selected countries, with $CO_2$ emissions decreasing in Finland, Sweden and Germany, stabilizing in the USA and still increasing in Brazil. This is due to the projected increase in GDP and the resulting increase in transport work in Brazil.



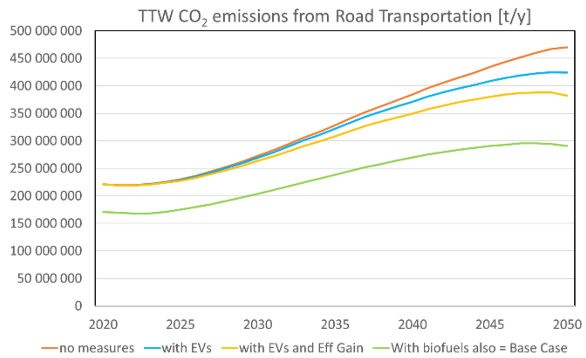

Finland



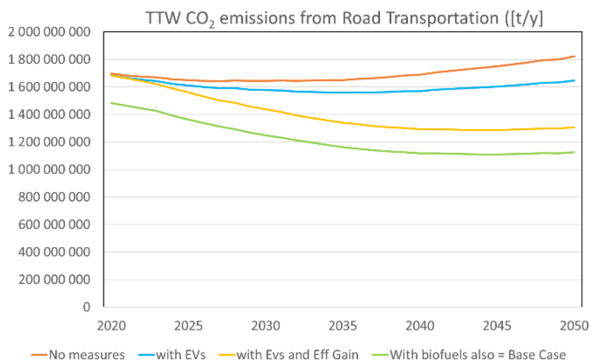

Sweden




Germany




Brazil




USA

*Figure 9: Evolution of TTW $CO_2$ emissions in road transport by different measures for Finland, Sweden, Germany, USA and Brazil in the Current Policies scenario.*

## The effect of introducing more electric vehicles

As to check the sensitivity of the results to an accelerated market introduction of electrified vehicles, the MORE EV scenarios were calculated. The assumptions for each country are based on discussions with the country experts involved in this project. For Sweden, Germany and Brazil, 100% of passenger car sales in 2050 were assumed to be various sorts of electric vehicles; only for Finland 25% of passenger car sales were still assumed to be spark ignited ICEs in 2050. The dynamics of this uptake, however, varies strongly between these four countries.

As a result, the share of EVs in the passenger car fleet reaches between 3% (Brazil) and 21% (Finland) in 2030, and between 41% (Brazil) and 77% (Sweden) by 2050 (see figure below).

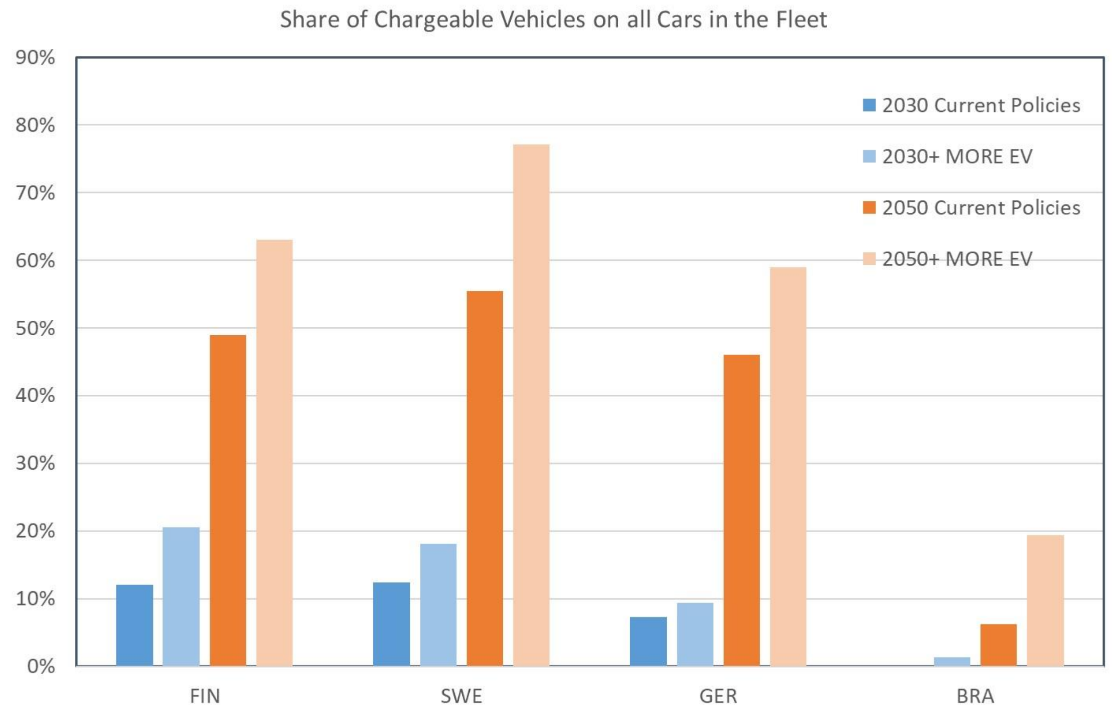



*Figure 10: Shares of chargeable vehicles in the national passenger car fleet by 2030 and 2050 for Current Policies and MORE EV (MORE EV marked with +).*

Despite these high shares of EVs in the passenger car fleets, the additional gain in $CO_2$ emission reductions is rather low, in the range of 0.5% to 4.3% for 2030 and 3.5% to 9.2% for 2050.

## Maximizing biofuels to reach better decarbonization

As the level of decarbonization is still by far not sufficient neither in the Current Policies nor in the MORE EV scenario (all transport should be carbon-neutral by 2060 under 2DS scenario, with individual national targets for carbon-neutrality by 2045 and 2050), the MAX BIO scenarios were calculated. These scenarios illustrate the potential impact that biofuels could have, if introduced to the technical maximum in the expected national fleet. This includes maximizing the use of renewable diesel in compression ignited (CI) engines, applying E25 and E30 in all spark ignited (SI) engines as well as utilizing so-called biopetrol in Sweden, and using E100 in Brazilian flex-fuel vehicles.

As a result, TTW $CO_2$ emissions can be decreased significantly by 2050, see Figure 11. Countries with options to fully substitute both fossil petrol and fossil diesel can be fully decarbonized by 2050.

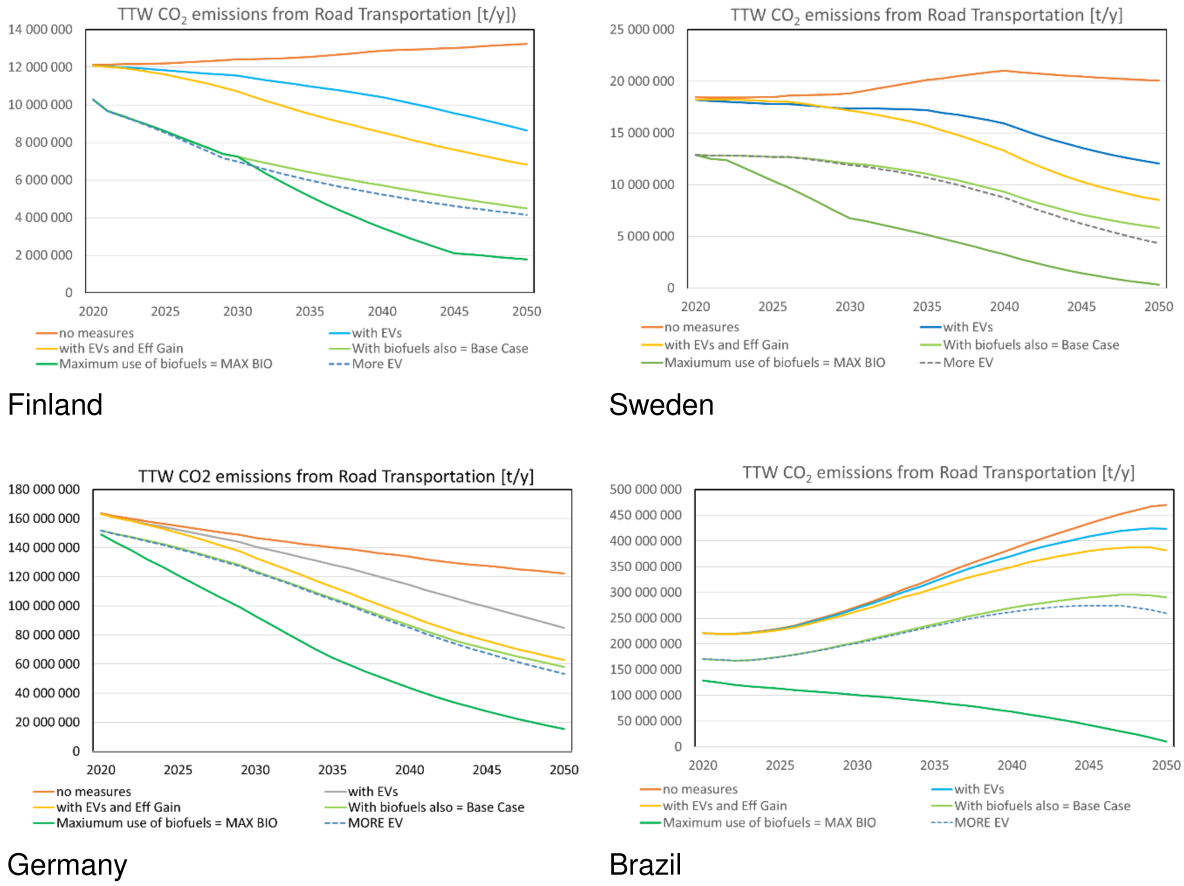



*Figure 11: Evolution of TTW $CO_2$ emissions in road transport by different measures for Finland, Sweden, Germany and Brazil in the MAX BIO scenario.*

Figure 12 shows the energy use in the MAX BIO scenario by energy carrier. Renewable diesel is the main biofuel substituting fossil fuels for Finland, Germany, and Sweden, while in Brazil also ethanol provides a large share.

The total 2050 national demands for drop-in hydrocarbons to replace diesel in the MAX BIO scenarios are illustrated for each country in the following figure. These demand estimates are contrasted with the estimate for global advanced biofuels supply from the IEA's 2DS scenario. Although current production capacities are not sufficient to cover e.g. Brazil´s 2050 demand, if global supply develops in line with the IEA 2DS estimate advanced biofuels could be a realistic option for significantly reducing transport emissions even for the largest countries.

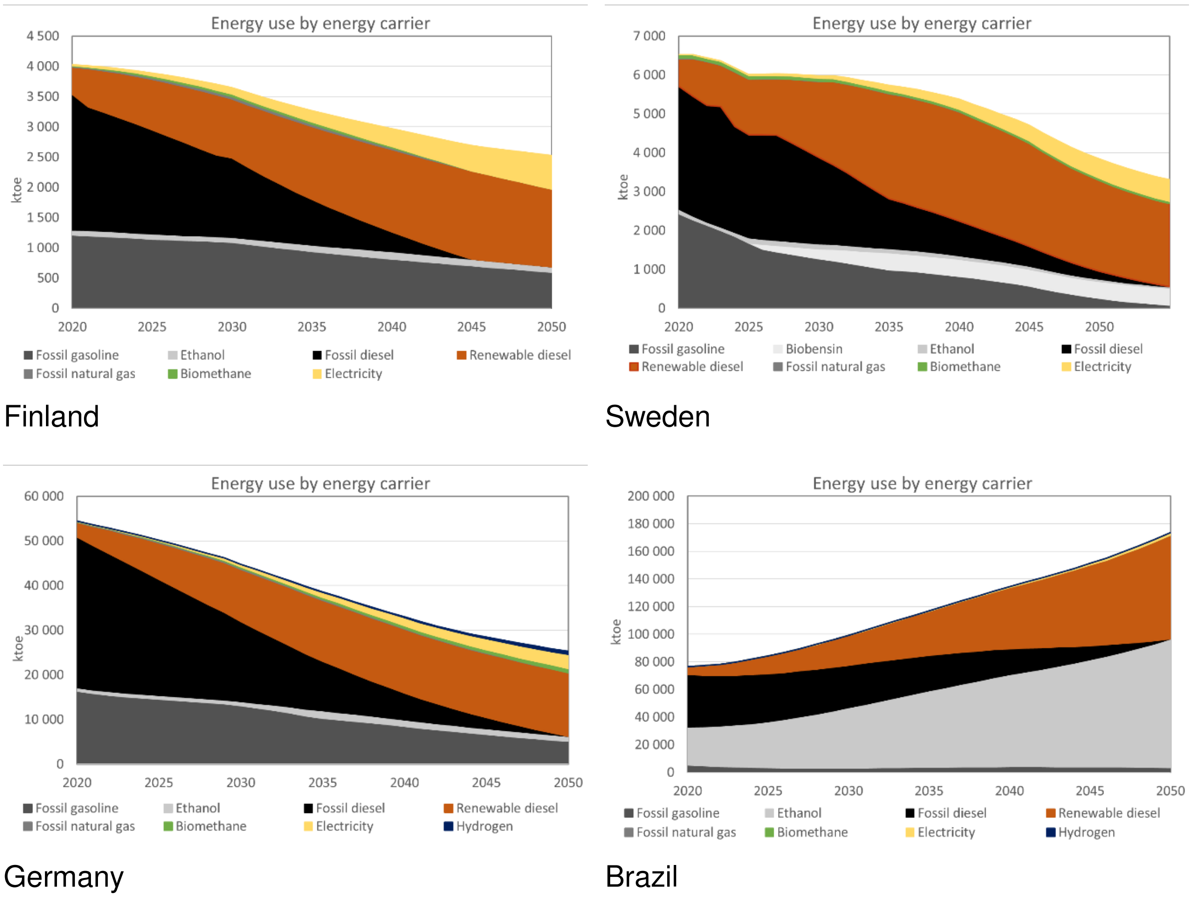



*Figure 12: Evolution of energy use in road transport by energy carrier for Finland, Sweden, Germany and Brazil in the MAX BIO scenario.*

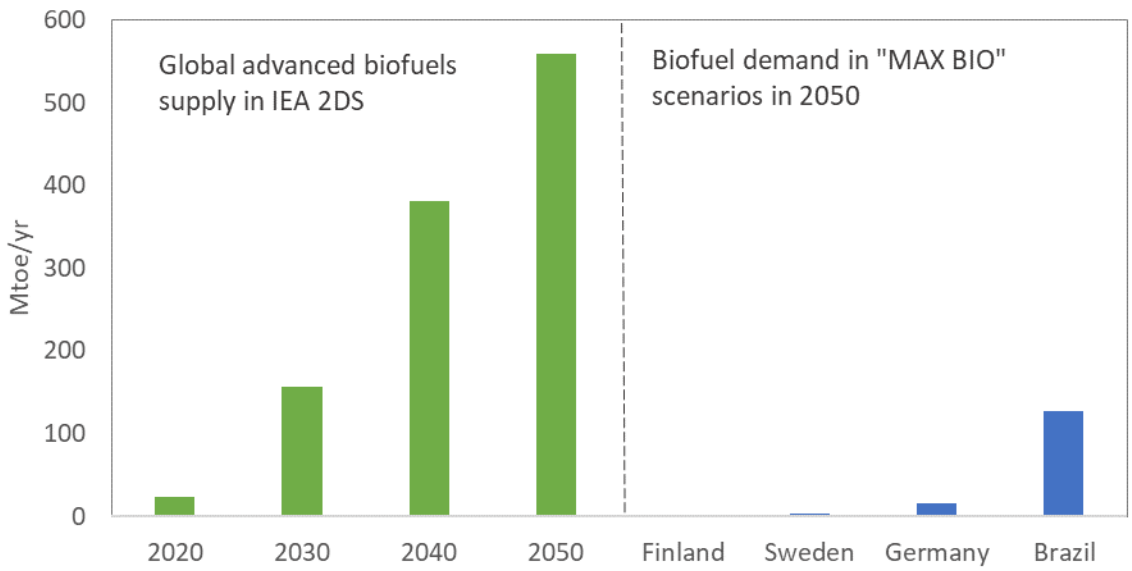
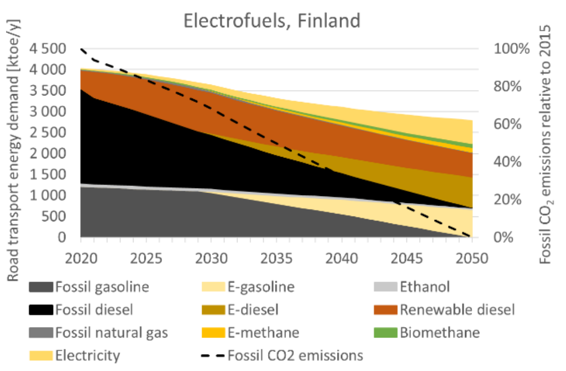



*Figure 13: Country specific demand for drop-in hydrocarbons in 2050 relative to IEA global 2DS supply scenario.*

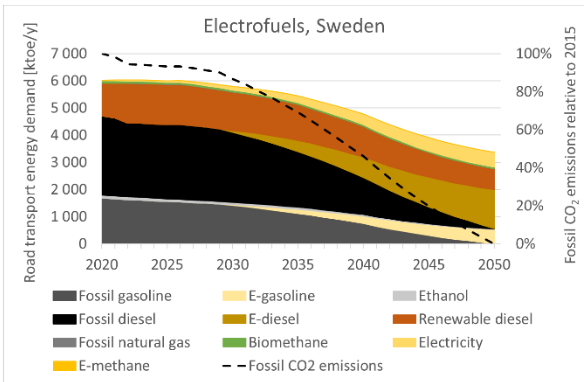
## Using e-fuels to fully decarbonize road transport sectors

Another option to fully decarbonize the road transport sectors is to use e-fuels as energy carriers. Substantial reductions in the cost of wind and solar electricity during the past decade have created interest towards the production of sustainable fuels via chemical conversion of $CO_2$ and water, using renewable energy to drive the process.

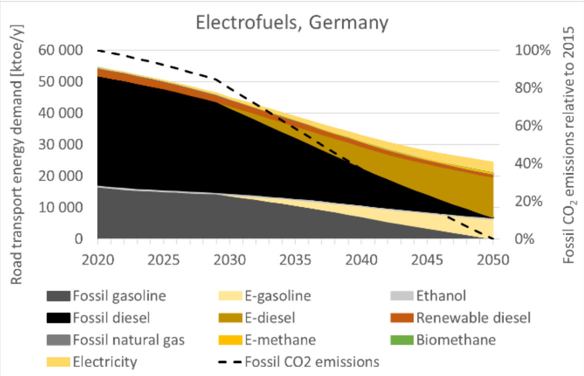
For the purpose of this analysis, synthetic replacements for natural gas, gasoline and diesel, produced from $CO_2$ and water with electrical energy were considered. In addition, for Germany fuel hydrogen was also considered. The introduction of e-gasoline, e-diesel, e-methane and e-hydrogen to the fuel pools begins in 2030 and increases linearly achieving full displacement of fossil gasoline, diesel, natural gas and hydrogen by 2050, and thus reaching zero TTW $CO_2$ emissions. The E-FUELS scenarios are based on current policies, taking the remaining fossil fuel pool as a starting point. The figure below shows the resulting energy demand for different fuels along with the resulting TTW $CO_2$ emissions.



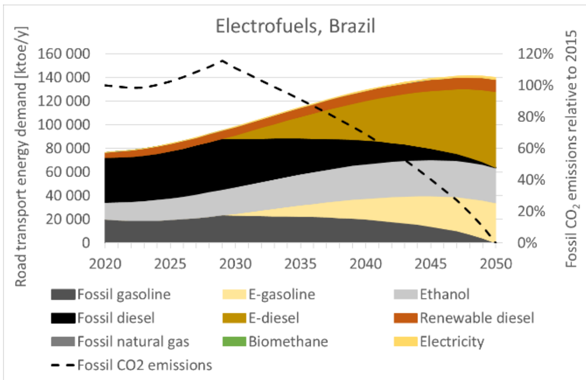

Finland




Sweden




Germany




Brazil

*Figure 14: Evolution of energy use in road transport by energy carrier for Finland, Sweden, Germany and Brazil in the E-FUELS scenario.*

Resources needed for the production of e-fuels are non-fossil electricity and $CO_2$. The demand for these resources for the production of the e-fuel volumes needed in the E-FUELS scenario is depicted in the next figure. The amount of essentially zero-carbon electricity needed for e-fuels production is comparable to the total non-fossil electricity production in Finland and Sweden today, while in Germany and Brazil the current total non-fossil electricity generation capacity would not be enough to run all the needed e-fuels plants.

However, asking for such substantial amounts of carbon-free electricity dedicated to e-fuels production seems hard to imagine on top of existing requirements for a dramatic expansion of low-carbon electricity generation to meet more traditional electricity demand. With respect to industrial $CO_2$ emissions, these seem to be sufficient for the required production of e-fuels for Finland, Sweden and Germany, but the Brazilian demand by 2050 would be almost triple the currently available amount. Maximizing the use of other decarbonization measures would therefore be important to decrease the demand for e-fuels and the associated need for non-fossil electricity.

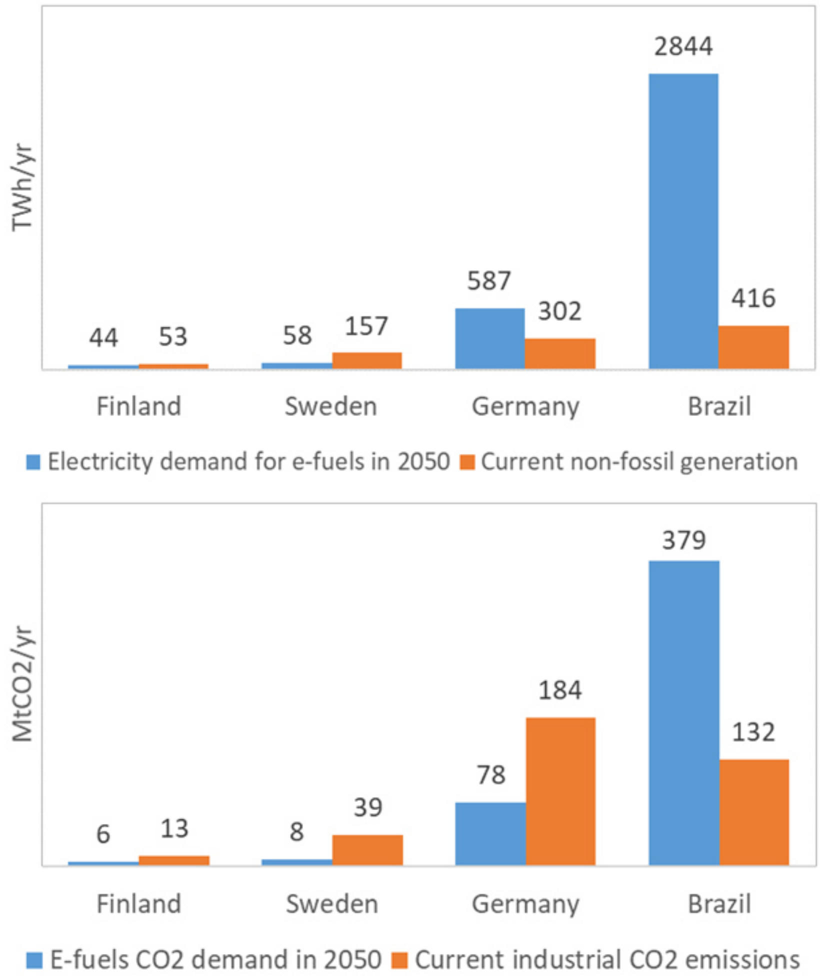



*Figure 15: Relative electricity and $CO_2$ resource requirements related to the national E-FUELS scenarios.*

However, the calculated E-FUELS scenario is an extreme scenario and based only on current policies; with increased efforts, biofuels could cover part of the required GHG emission reductions, and hereby reduce the demand for e-fuels and the associated need for non-fossil electricity.

More details on our assessment of these countries can be found in Part 3 of the overall report ("Scenarios and Contributions in Selected Countries").

## The availability of renewable transport fuels

While the assessment of the development of the road transport sector in selected countries has clearly shown that the required full decarbonization can only be reached with a combination of biofuels, electric vehicles and eventually also e-fuels, the question arises whether there will be sufficient renewable transport fuels available to support national and global needs. A large number of different renewable transport fuels exists, produced from a variety of feedstocks through a range of different production technologies. Some of these fuels are compatible with existing engines, others have to be used in low blends with fossil fuels or in dedicated engines. The multitude of options makes it difficult for policy makers to decide which fuel options to go for to decarbonize their transport sectors. Part 2 of the overall report ("Production Technologies and Costs"), provides all the required details for taking informed decisions, and is summarized below.

### Low-carbon fuel technologies and their development status

Low-carbon transport fuels can be produced from:

- biogenic feedstocks or biogenic fraction of wastes ("biofuels")
- energy and carbon contained in fossil wastes and residue streams or the fossil fraction of such materials ("e.g. recycled carbon fuels")
- energy from other renewable sources, sometimes in combination with carbon atoms from biogenic and fossil sources (CCU) ("renewable fuels")

The technology readiness levels (TRL) of the production technologies for these fuels vary, as depicted in

Figure 16.

Technologies for the production of **established biofuels** such as ethanol from sugar and starch crops, biodiesel from triglycerides and lipids, hydrogenated triglycerides and lipids, and biomethane from upgrading of anaerobic digestion biogas are at TRL9.

**Emerging biofuel pathways** include ethanol from lignocellulosic feedstocks, gasification-derived biofuels, pyrolysis-derived intermediates, hydrothermal liquefaction-derived intermediates, lignin-derived intermediates, sugars to biofuels, and biofuels derived from non-lignocellulosic biomass such as microalgae. TRLs for these technologies range from 3 to 8.

**Recycled carbon fuels** include ethanol, methanol and methane produced from industry off-gases, and fuels derived from the gasification or pyrolysis of non-biogenic wastes or fractions of wastes, with TRLs ranging from 4 to 9.

**E-fuels** include hydrogen, methanol, methane and Fischer-Tropsch liquids. While the production of hydrogen through electrolysis is at TRL9, the other pathways are at TRL 4-6.

Terminology for different low-carbon fuels is not consistent globally. In the EU fuels are classified by feedstock, in the USA by pathway, and in Brazil by the carbon intensity of the fuel. In particular, the term advanced biofuel has different meanings in different jurisdictions.

**Terminology used in this report**

In this report a distinction is being made between **established biofuel pathways** and **emerging biofuel pathways**. This is to avoid terms like first and second generation, 1G, 2G, conventional and advanced, as these terms have no homogeneous definition and are used differently in different regions and jurisdictions. Further fuel types mentioned in the report include recycled carbon fuels and e-fuels. Further descriptions of these categories are provided in **Figure 16** and the explanatory text below.

The same figure also provides the linkage between fuel production pathway, i.e. feedstock and conversion technology used, and the chemical nature of the resulting fuel. When applied in engines it is the chemical composition of the fuel that matters, not the feedstock. Thus, some fuels are grouped, e.g. **FT-liquids** and **HVO**[2] into **drop-in hydrocarbons**[3].

The linkage between these fuels and their marketed qualities is provided in **Table 2**, which also describes the applicability of these fuels in different engines.

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2 HEFA (Hydroprocessed Esters and Fatty Acids), also called HVO (Hydrotreated Vegetable Oil), is a renewable diesel fuel that can be produced from a wide array of vegetable oils and fats. The term HEFA or HVO is used collectively for these biogenic hydrocarbon-based renewable biofuels. HVO is free of aromatics and sulfur and has a high cetane number.

3 "Drop-in" biofuels are defined as liquid hydrocarbons that are oxygen-free and functionally equivalent to petroleum transportation fuel blendstocks.

| | Raw material | Technology | Fuel | Technology Readiness Level (TRL) 1–9 |
|---|---|---|---|---|
| Established biofuels | Sugar | Fermentation | Ethanol | |
| | Starch | | | |
| | Vegetable oils & lipid waste | Transesterification | FAME/Biodiesel | |
| | | Hydrotreatment | Drop-in hydrocarbons | |
| | Crops, sludges, manures etc. | AD biogas upgrading | Biomethane | |
| Emerging Biofuels | **Raw material** | **Technology** | **Fuel** | |
| | Lignocellulosic feedstocks | Enzymatic hydrolysis + fermentation | Ethanol | |
| | | | Other alcohols | |
| | Lignocellulosics, biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products | Gasification + fermentation | Ethanol | |
| | | Gasification + catalytic synthesis | Drop-in hydrocarbons, Alcohols, Biomethane | |
| | Lignocellulosics, biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products | Pyrolysis + upgrading | Drop-in hydrocarbons | |
| | | HTL + upgrading | Drop-in hydrocarbons | |
| | Lignin from lignocellulosic ethanol or forestry liquors | HTL and/or chem. treatment + upgrading | Drop-in hydrocarbons | |
| | Sugars from sugar and starch crops or lignocellulosic | Fermentation | Drop-in hydrocarbons | |
| | | | Various alcohols | |
| | | Chem. conversion | Drop-in hydrocarbons | |
| | Non-LC biomass fractions or by-products | Various | Various | |
| Recycle Carbon Fuels | **Supply of fossil waste or by-product gases** | **Technology** | **Fuel** | |
| | Steel industry & chemical industry off-gases | Fermentation | Ethanol | |
| | | Catalytic synthesis | Methanol | |
| | | | Methane | |
| | Wastes, waste plastics, non-bio fraction of RDF | Gasification + catalytic synthesis or fermentation | Drop-in hydrocarbons, Alcohols, Biomethane | |
| | Waste plastic fraction | Pyrolysis + distillation | Drop-in hydrocarbons | |
| E-fuels | **Supply of H2** | **Technology** | **Fuel** | |
| | RE electricity | Electrolysis | Hydrogen | |
| | | Electrolysis and carbon capture + catalytic synthesis | Methanol | |
| | | | Methane | |
| | | | Drop-in hydrocarbons | |

*Figure 16: Overview of technology pathways and their technology readiness level (TRL)*

## Availability and costs of sustainable bioenergy feedstocks for biofuels production

The theoretical availability and cost modelling indicate that large volumes of sustainable feedstock could be made available for biofuels production, sufficient to meet likely future demand as indicated in low carbon scenarios. Most of the material necessary could be supplied from wastes and residues, and from sustainable forestry practices. Agriculture can also be an important source of raw materials, with feedstocks produced in ways which complement traditional agricultural production through co-cropping and through use of less productive land.

Estimates of the potential available biomass and other uses vary significantly in the literature. While the theoretical potential is high, the economic availability can vary greatly, depending on numerous factors including yield and regional parameters (e.g. location and size of crop/forest lands, local infrastructure, etc.). There is a wide range of biomass availability globally, from as low as 95 Exajoule (EJ)/year to as high as 350 EJ/year.

National studies indicate that much of the raw material could be produced and delivered to users at costs of between 3 - 6 EUR/GJ. More information from real projects is needed to test the costs of procuring suitable feedstock in the real world.

The overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in biofuels are to be realized. Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock.

National and regional assessments are very helpful in providing insights into likely long-term availability and costs of feedstocks for bioenergy production, including for the production of advanced biofuels. However, in order to be useful for estimating long term global availability such assessments need to be done in a very transparent way, with clear classification of the various resources and of the assumptions made in defining how much material could in practice be available, and around the sustainability considerations applied.

A useful step in harmonizing such approaches would be the development of some best practice guidelines for such studies, including some standardization and rationalization of the classification of the various potential feedstocks, and of the sustainability constraints which are applied. Such measures could facilitate the development of more consistent resource estimates, which could be more easily compiled to give a global estimate, at least for key producer and user regions.

As shown in Figure 17, IRENA estimates the global biomass energy supply potential in 2030 to be in the range of 97 to 147 EJ/year. Feedstocks considered include energy crops, agricultural residues, processing residues, animal and food wastes, fuel wood, forest biomass and wood waste. Largest supply potentials stem from Asia, Europe and North America. Growth in biomass supply potential will be (among other factors) supported by increased plantation areas both for food/feed crops as well as for forests, higher yields of energy crops, and higher recovery of agricultural and processing residues.

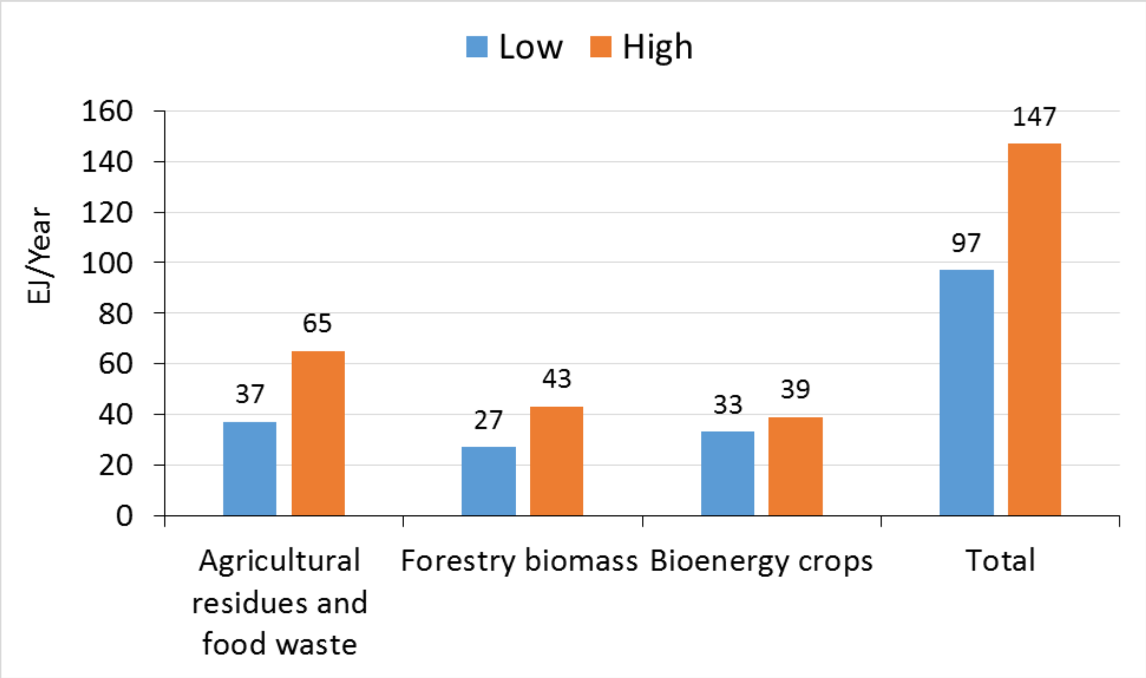


*Figure 17: Potential global biomass supply in 2030 (Adapted from IRENA, 2014[4])*

Domestic biomass resources can be classified into three supply cost groups:

- < USD 5 per GJ: processing residues and wastes
- USD 5-8 per GJ: harvesting residues
- > USD 8 per GJ: bioenergy crops and fuel wood

As depicted in Figure 18, the average global cost of biomass is about USD 8.3 per GJ, with the cost of domestic biomass ranging from as low as USD 3 per GJ in Africa (agricultural processing residues) to as high at USD 17 per GJ for bioenergy crops in more developed parts of the world. The amount of exportable biomass available in regions with surplus biomass is estimated to be about 26% of the total global supply potential. However, the costs associated with transporting this biomass to different world regions are estimated to add an average of USD 3 per GJ to domestic prices.

The overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in bioenergy and biofuels are to be realized. Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock.

[4] The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

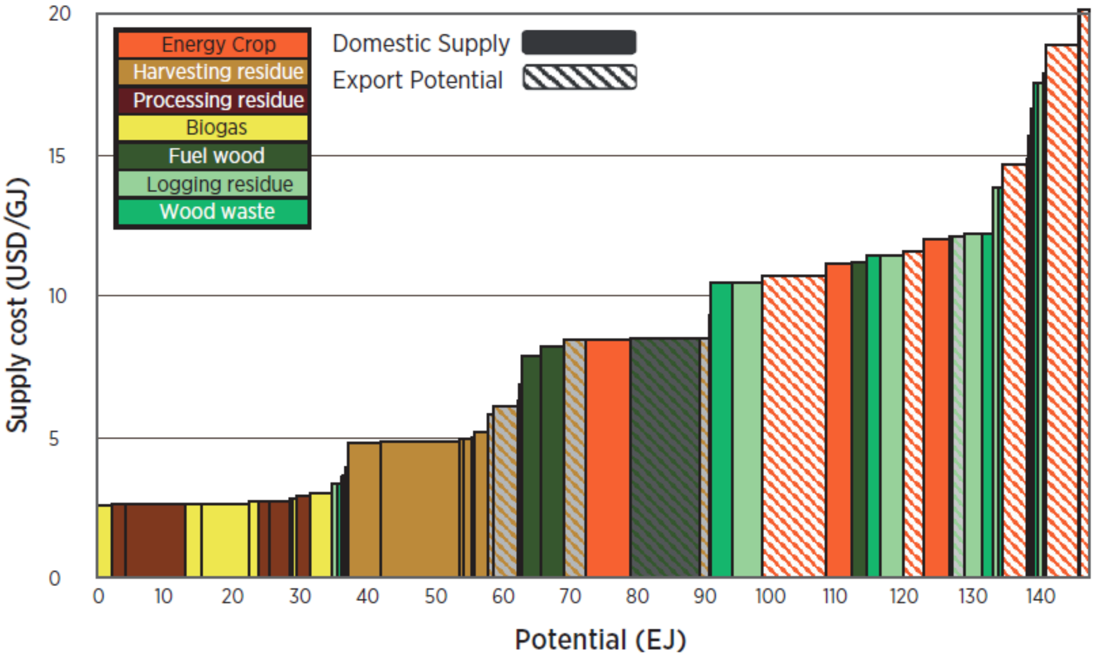


*Figure 18: Projected annual global supply for primary biomass in 2030[5]*

## GHG emissions of emerging biofuel pathways

Current legislation in the USA and the European Union require advanced biofuels to show at least 50% / 65% reduction in GHG emissions respectively, as compared to their fossil fuel equivalents. The carbon intensity of a fuel is measured in $gCO_2e/MJ$ using Life Cycle Assessment (LCA) and represents the GHG emissions emitted across the full life cycle of a product system, from feedstock acquisition to production, use, and final disposition. Carbon intensity of gasoline and diesel is about 95 $gCO_{2e}/MJ$.

Emerging biofuels, termed advanced by either USA or EU legislation, do not automatically have lower carbon intensity values than those of established biofuels. However, among the various pathways that have been certified under California Low Carbon Fuel Standard (LCFS) program, the average carbon intensity values of advanced biofuels are typically, sometimes significantly, lower than those of established biofuels, see

Figure 19 for details. The current average CI values of biofuels (both established and emerging pathways) provided to California range from 15 to 65 $gCO_{2e}/MJ$, and can also be negative when obtaining credits for avoided GHG emissions from waste disposal or if combined with CCS.

[5] The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

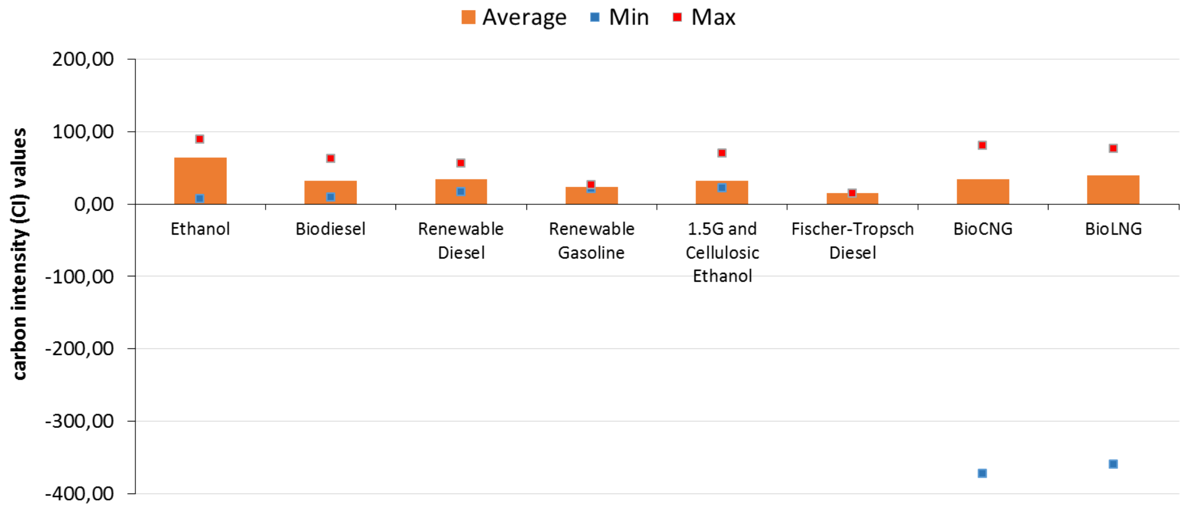


*Figure 19: Minimum, average, and maximum carbon intensity (CI) values of some of the fuel pathways certified under California LCFS program in 2019*

The location/region where the biofuel production facility is located will be a key component of the final carbon intensity of the fuel. This is due to factors such as access to low carbon intensity energy sources for heat and power, the potential to co-locate with other biofuel plants or oil refineries to develop efficient biofuel production and supply chains, the type of biofuels and co-products produced, the type of feedstock and associated logistics, land type used for crop/biomass cultivation and agronomic practices, the local regulations on the use of feedstock, and carbon accounting mechanisms for biomass.

As LCFS-type policies become more common in increasing numbers of jurisdictions, the carbon intensity of current and emerging biofuels is expected to decrease.

## The likely costs of emerging biofuels production and the scope for cost reduction

The costs of producing advanced biofuels have been assessed in a recent IEA Bioenergy study, "Advanced Biofuels –Potential for Cost Reduction"[6]. Advanced biofuels assessed include (2nd generation) cellulosic ethanol, 1.5 generation cellulosic ethanol[7], methanol and methane from biomass, methanol and methane from waste, FT-liquids from biomass, FT-liquids from wastes, co-processing of bio-oil, stand-alone upgrading of bio-oil, HVO, and anaerobic digestion followed by upgrading to biomethane. Costs of all the assessed advanced biofuels pathways are currently significantly higher than the current costs of fossil fuel equivalents, as shown in Figure 20.

---

[6] https://www.ieabioenergy.com/publications/new-publication-advanced-biofuels-potential-for-cost-reduction/

[7] 1.5 Generation most frequently refers to the production of cellulosic (such as corn fiber) ethanol integrated into a corn-based ethanol plant

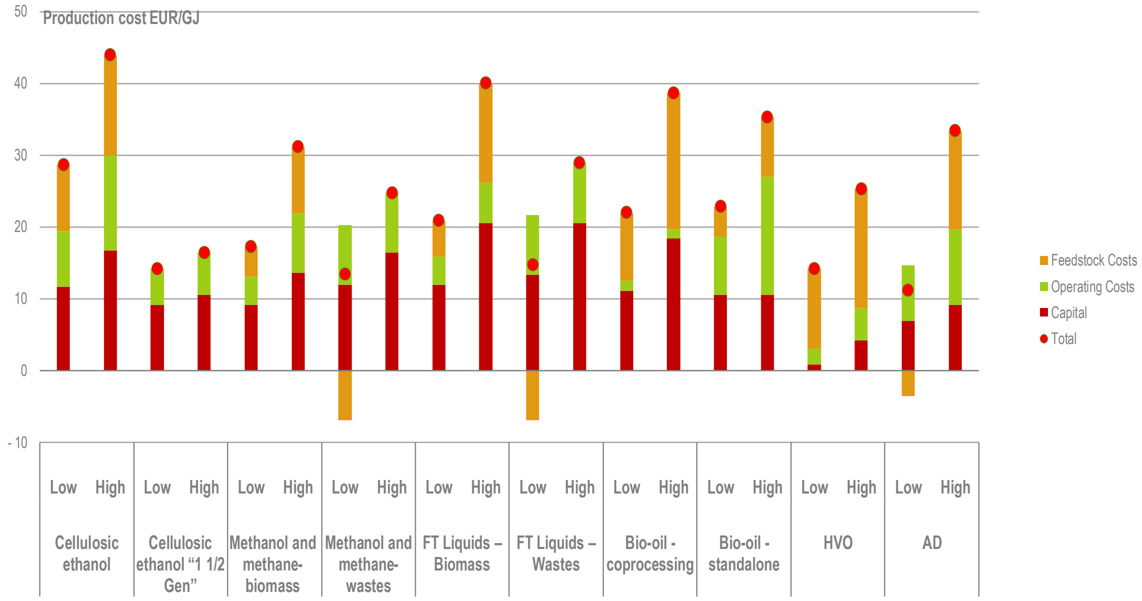


*Figure 20: Summary of current cost ranges of advanced biofuels*

There is significant potential for reducing the costs of the assessed range of emerging biofuels. In order to achieve these, projects must first demonstrate in practice that the current production objectives in terms of reliable production at high availability and efficiency can be achieved consistently. The reductions will only then be achieved if there are opportunities to build a significant number of further generations of plants which will allow experience to accumulate and provide the basis for learning, and for growing confidence in the technologies. The figure on the next page shows possible future emerging biofuel production cost ranges, after improvements in the process and after gaining access to capital at lower cost.

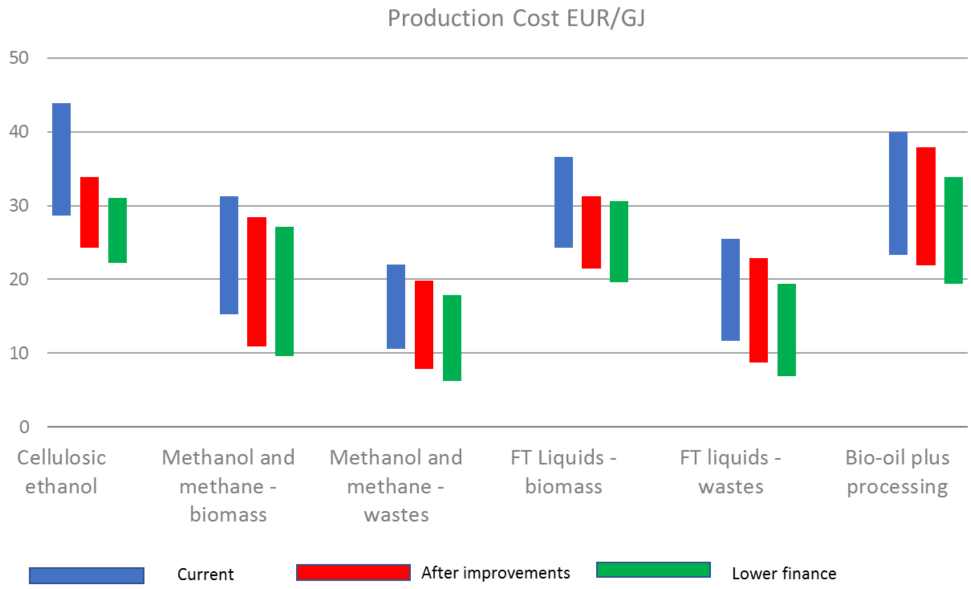


*Figure 21: Potential costs of advanced biofuels production after reductions*

Large scale deployment will depend on continuing policy support. First, industry will need support during the demonstration and risky and costly early commercialization of the technologies, so as to bridge the “valley of death”. And then, continuing strong support will be needed to offset the differences between biofuels and fossil fuel prices, and to incentivize low carbon transport fuels.

While the costs of the emerging biofuels and other fuels discussed above are an important factor, a broader range of issues also need to be considered when comparing these options and also when looking at other low-carbon options. These include the extent to which they can directly replace fossil fuels, the costs of any modifications or of distribution costs associated with fuels, the likely availability of feedstocks and the life-cycle GHG emissions associated with particular routes. The overall consideration of the future for emerging biofuels need to be seen in the context of these other factors, and based on an analysis of full system costs, feedstock availability and life-cycle GHG emissions.

## Compatibility of fuels with existing engines

The compatibility of fuels with fuel infrastructure and vehicles includes the aspects material compatibility, tolerance, vehicle compatibility and vehicle compliance, i.e. fulfilment of all regulatory requirements concerning pollutant emissions and safe vehicle use. Biofuels can be used in low blends, as drop-in fuels with up to 100% substitution, or as special fuels in dedicated or adapted engines. Table 2 provides an overview on fuels and their applicability in engines.

*Table 2: Application of transport fuels*

| Fuel | Application in road transport |
|---|---|
| **Ethanol**[8] | Gasoline blends (E5, E10, E85 in FFVs), stoichiometry and materials issues constitute blending walls in conventional vehicles<br>Additive treated ED 95 for diesel-type engines (commercial), potentially also engines with assisted ignition (spark-plug, glow-plug, dual-fuel) |
| **Methanol** | Low-level blends with gasoline<br>Heavy-duty engines as in the case of ethanol (additive treated fuel, engines with assisted ignition) |
| **Various higher alcohols** | E.g. butanol in gasoline blends |
| **Ethers** | E.g. MTBE (from methanol) and ETBE (from ethanol) in gasoline blends, preferred by the auto manufacturers over ethanol or methanol as such; blending wall stems from stoichiometry |
| **FAME/Biodiesel** | Diesel blends (B7, B10, B20, B30), neat B100<br>Neat B100 typically requires some vehicle modifications |
| **Drop-in hydrocarbons** | Gasoline-type components with limited octane for blending components |

[8] Brazil: special case for ethanol, regular gasoline contains 27 % ethanol (E27), also hydrous ethanol (E100) on the market, special flex-fuel vehicles combining gasoline with any amount of ethanol available, some ICEs adopted for methane use

| | |
|---|---|
| | Paraffinic HVO and Fischer-Tropsch diesel, drop-in, up to 100% substitution |
| **Methane** | Passenger cars (mostly bi-fuel methane/gasoline vehicles)<br>Heavy duty vehicles with either mono-fuel or dual-fuel technology<br>On-board storage either as compressed biogas (CBG) for LD vehicles or liquefied biogas (LBG) for HD vehicles |
| | **Application in shipping** |
| **Biofuels** | Various types of bioliquids, including some "biocrudes" less stringent fuel requirements than in the on-road sector |
| **Methane** | Mainly dual-fuel engines, fuel storage in liquid form, currently fossil natural gas, bio-methane could replace natural gas |
| | **Application in aviation** |
| **Liquid renewable fuels** | Current regulation allows up to 50 % renewable components, very stringent certification process, hydrotreatment (HEFA fuels), synthesis and e-fuels potential routes to aviation fuels |

The easiest way to introduce biocomponents is to operate within the framework of existing standards for gasoline and diesel fuel. Typically, standards allow blending of ethanol and FAME biodiesel corresponding up to an energy share 10 - 15 %. Some activities to introduce intermediate ethanol blends (E20, E25) are under way. However, for higher substitution and more substantial decarbonization of transport, complementary actions are needed.

Drop-in type fuels are fully fungible with conventional hydrocarbon fuels and compatible with existing vehicles and fuel infrastructure; no infrastructure or vehicle modifications are needed. Paraffinic renewable diesel fuel, whether from hydrotreatment of oils and fats (HVO) or Fischer Tropsch synthesis, can in principle completely substitute fossil diesel and for most performance criteria is superior to regular diesel.

B100 is not a real drop-in type fuel, as it requires some changes in calibration, engine hardware and maintenance schedules. Notwithstanding, some heavy-duty vehicle manufacturers allow the use of B100 fuel in present-day sophisticated vehicles.

In the case of gasoline, there are no superior renewable hydrocarbon drop-in components, as bio-gasoline hydrocarbon compounds tend to have low octane numbers. New blending components, such as pure hydrocarbons, higher alcohols or ethers, could alleviate this.

Finally, special fuels can be used as such or as high blends in dedicated or adapted engines. Such fuels are, e.g., gaseous fuels (methane, LPG), dimethyl ether (DME) and high concentration alcohol fuels (E85, ED95). These fuels have a merit in chemically simple structure, and in most cases, also inherently clean burning. However, the market introduction of such fuels has to go hand in hand with building up the refueling infrastructure and the vehicle fleet, requiring huge joint efforts.

The world population of natural gas vehicles exceeds 20 million units. Cleaned biogas, biomethane, is a drop-in substitute for natural gas. Ethanol flex-fuel vehicles (FFV) are still offered for the markets in North and South America, but have in practice vanished from the European market. FFVs are a cost-effective way of enabling the use of high concentration ethanol.

Regardless of the method to introduce biofuels, whether low-level blending, drop-in fuels or special fuels for dedicated vehicles, fuel quality, vehicle/fuel compatibility and vehicle compliance have to be maintained. Prerequisites are standards defining and securing fuel properties and vehicles adapted to and certified for the fuels they are using. The fuel is simply not a parameter that can be decoupled from the rest of the system, which comprises of engine, lubricant, exhaust after-treatment system, refueling infrastructure and regulation regarding safety and emissions.

## Role of policy on production and use of emerging biofuels

Policies have been and will continue to be essential to foster the growth of the advanced biofuels used to decarbonize transport, particularly long-distance transport. Policies used include blending mandates, excise tax reductions or exemptions, renewable or low carbon fuel standards, as well as a variety of fiscal incentives and public financing mechanisms. Countries that use a mixture of market-pull and technology-push policy instruments have been most successful at increasing biofuels production and use and also at developing and deploying less mature emerging biofuels production technologies.

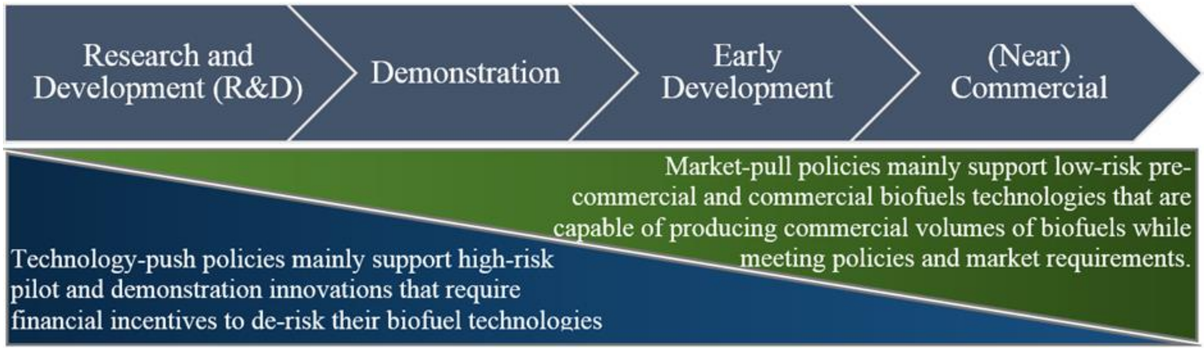


*Figure 22: Technology-push and market-pull biofuel policies*

So far, most of the policies used to promote transport decarbonization have focused on road transport. Other transport sectors, such as rail, aviation and shipping, have, until recently, received comparably less policy attention despite being large energy consumers and GHG emitters. However, transport policies and industry efforts are increasingly focused on decarbonizing long-haul transport sectors (i.e., road, rail, aviation and shipping), where electrification is much more challenging.

While the production and use of transport biofuels has more than doubled over the last decade, progress in expanding biofuels production remains well below the levels required to decarbonize transport significantly. Several factors continue to impact the effectiveness of biofuels policies such as relatively low petroleum and fossil fuel prices, uncertainty about future policy and funding programs to support conventional and advanced biofuels, the inconsistent regulation of global trade of biofuels and continuing concerns related to food security, land use change and overall sustainability.

## How to reach widespread deployment of renewable fuels

In the course of the study it has become apparent that the countries assessed are aware of the urgent need for decarbonizing their road transport systems; that the required level of decarbonization can only be reached with a set of measures, including biofuels, electric vehicles, and eventually e-fuels; and that globally there is sufficient feedstock available for the sustainable production of biofuels to be used in vehicles to cover the demand of low-carbon scenarios. But why is the production and use of biofuels not yet growing as needed?

This question was analyzed in Part 4 of the overall report ("Deployment Barriers and Policy Recommendations").

### Barriers to widespread deployment

Reflecting the assessments carried out in this project, findings from AMF Annex 59, findings from the IRENA study, the discussion at the project workshop, and also other existing literature, the following barriers seem to be most important:

- Well-established transport system to compete with
- Fluctuating policy drivers / lack of long-term stable policies
- Low public acceptance / perception of technical performance issues and sustainability concerns
- Incomplete set of policy measures
- The need to build up infrastructure for alternative fuels and alternative fuel vehicles such as FFVs, EVs, FCEVs
- Risks associated with biofuels

#### Well-established transport system to compete with

What we are looking for if we are to reach the required level of decarbonization, is the transition into a new transport system that uses multiple alternative fuels in a range of vehicles. This new, complex system has to compete with the current system, which has been established and optimized over the past 100 years and offers predictable income to the established stakeholders, while the infrastructure required for the future transport system still has to be built, with higher costs and risks associated and unclear and risky business cases. Table 3 lists features of the current and the future transport system.

*Table 3: Current and future road transport system*

| Current road transport system | Future road transport system |
|---|---|
| Well-performing fuel/engine/after-treatment combinations | Adaptation of fuel/engine/after-treatment system required |
| Established material compatibility | Ev. lack of material compatibility |
| Many vehicle models available | Few models available |
| Robust vehicle repair infrastructure | New repair knowledge required |
| Good driving range | Sometimes lower driving range |
| Well-established fuel production | Fuel production infrastructure has to be built |

| | |
|---|---|
| Limited number of fuel options provided | Large variety of alternative fuels |
| Ubiquitous refueling infrastructures | Refueling infrastructure has to be built and might not be profitable |
| Existing fleet uses existing fuels | New fleet has to be built up |

The system of stakeholders in the established transport sector (as depicted in Figure 23) includes the fossil fuel industry and fuel marketers, the automotive industry and vehicle marketers, and the consumers freight sector and private car owners. In the new system, new stakeholders come into the picture, such as biomass producers and biofuel producers, and existing stakeholders are expected to adapt their businesses to produce alternative fuels and alternative vehicles. Doing so is not economic for any of these stakeholders unless policies set regulations to offset the increased production and infrastructure costs. As a result, the biofuels market depends on political interventions. Thus, it is of major importance that policy sends strong signals and keeps up the support for renewable fuels over a long period of time. Workshop participants even called for targets for renewable fuels in 2040 and 2050 to be communicated already now.

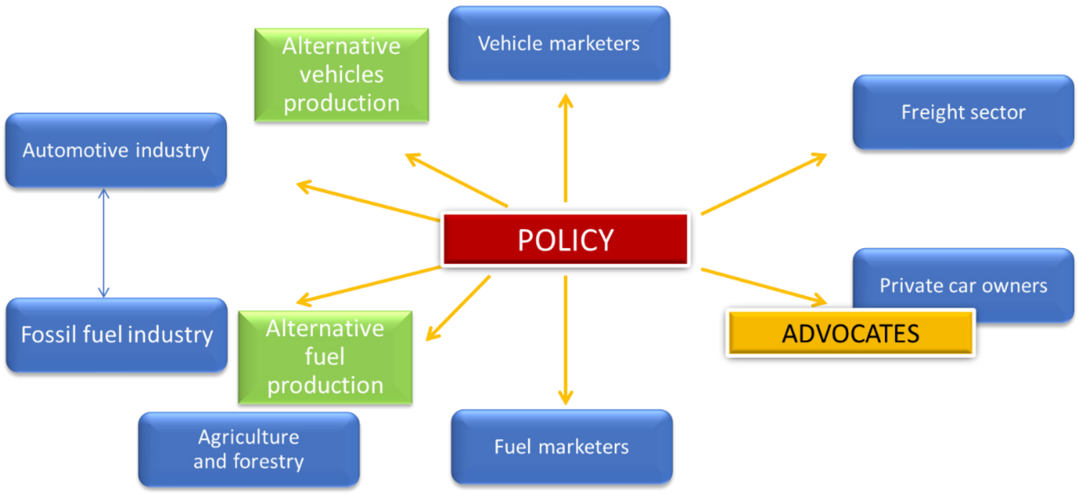


*Figure 23: Multitude of stakeholders involved in the market implementation of alternative fuels and vehicles*

## Fluctuating policy drivers

However, policy drivers are often fluctuating, as described earlier for the example of the USA. Through improvements in the existing system, the driver towards renewable fuels became weaker and ineffective, and the new fuels and vehicles, not yet fully established, vanished from the market again.

## Public perception

Another very important aspect is the public perception of new fuels. The debate around the implications that large-scale production of biofuels could have on GHG emissions through direct and indirect land use change (LUC and iLUC) has stalled the growth of established biofuels production and use in Europe. And although EU policy has been adapted and now includes measures to safeguard the sustainability of biofuels, the public image of biofuels remains severely damaged.

## Incomplete set of policy measures

For the market introduction of alternative fuels and vehicles it is also important to provide a set of carefully balanced policy measures that considers all stakeholders in the transport system and offers benefits to each of them. Also, the very details of regulations can create serious problems, as currently is the case with EU state aid rules that are in conflict with tax benefits for biofuels.

As to not forget any of the multiple stakeholders in the transport sector, Argonne National Laboratory has developed a checklist that can be used to assess whether everyone´s needs have been considered[9]. While it might be obvious to talk to the fossil fuel industry and also to the automotive industry, a group that can rather easily be forgotten is private car owners. While freight operators act based on economic considerations and this is their main business, private car owners often lack sufficient insight into the pros and cons of the multitude of vehicle and powertrain/fuel options. Their knowledge is rather based on what is reported in the media, with magazines of motorist associations often playing a major role. The influence of these advocates should not be underestimated, and they should be involved in efforts to introduce alternative fuels and vehicles.

### Infrastructure requirements

Renewable fuels can, depending on their chemical nature, be applied in engines as low blends, high blends, or neat, as drop-in fuels or with the need for adapted engines or vehicles. Also they can be produced in stand-alone biofuel production facilities, or through co-processing in refineries, or from $CO_2$ and hydrogen in e-fuels facilities. The introduction of renewable fuels to the market always requires investment in some type of new infrastructure, be it biofuel or e-fuel production facilities, adaptation of refineries, adaptation of engine and vehicle production systems, purchase of alternative fuel vehicles, or adaptation of fuel pumps. These investments will be made by different actors from within the broad range of stakeholders involved, and they will only be made if the actors can define their business case. Policy makers should be aware of these multiple options and they need to find the solution that works best for their country.

### Risks associated with the take-up of low-carbon fuels

Different fuels face different barriers which need to be recognized in designing policy portfolios to promote more widespread deployment. These relate to

- Technical risk
- Economic competitiveness
- Ease of integration of fuels
- Availability of appropriate feedstock, meeting sustainability requirements
- Perception of associated sustainability risks

[9] Risch, C. E., Santini, D. J., and Johnson, L. R. Using Checklists to Assess Your Transition to Alternative Fuels: A Technical Reference. United States: N. p., 2016. Web. doi:10.2172/1344887

Table 4 summarizes the points above, highlighting key barriers to more widespread deployment.

*Table 4: Main risks for biofuels*

| | Technology risk | Economic Competi-tiveness | Fuel integration | Sustainable Feedstock availability |
|---|---|---|---|---|
| Ethanol | Green | Yellow | Yellow | Yellow |
| Biodiesel | Green | Yellow | Yellow | Yellow |
| HVO | Green | Yellow | Green | Yellow |
| Biomethane | Green | Yellow | Yellow | Green |
| Cellulosic ethanol | Red | Red | Yellow | Green |
| Thermochemical biofuels | Red | Red | Green | Green |

**Key:**

| | |
|---|---|
| Green | No significant barrier |
| Yellow | Some barriers |
| Red | Major barriers |

## Policy requirements for increased advanced transport fuels deployment

Long term and stable policy frameworks are essential to foster growth of renewable transport fuels. An appropriate policy portfolio would include measures to “level the playing field” by removing fossil fuel subsidies and putting effective carbon pricing mechanisms in place. The portfolio also includes specific targets for low-carbon fuels, and mechanisms to ensure that the fuels are competitive in the transport market, along with a stringent, evidence-based sustainability governance regime.

Additional measures are needed to promote the development of these fuels and processes, since these will not initially be able to compete in a “technology-neutral” policy environment. These can include:

- Mandatory obligations for deployment of emerging biofuels and for specific subcategories that are at different stages of technical and market maturity.
- Appropriate and dedicated financial mechanisms and instruments to facilitate technological development and subsequent market deployment. These can include loan guarantees, and ways of bridging the initial cost differences between the novel energy sources and more established ones (fossil or other bioenergy).
- Support for RD&D focused on priorities identified in previous sections.

## Policy best practice

Policy best practice for the deployment of conventional biofuels such as ethanol, biodiesel (FAME), HVO, and biomethane already exists in a number of countries. The main elements of policy portfolios which have been successfully adopted include:

- Blending mandates which make a percentage of biofuels mandatory. These are widely in place but not always effective if there are insufficient penalties for non-compliance, and arrangements to share any additional costs amongst market players (such as a certificate scheme). The mandates also need to be consistent with fuel specifications and blending regulations.

- There is growing trend to move to systems which incentivize transport fuels based on their GHG impacts (such as the Californian LCFS, the Brazilian RenovaBio scheme and various programs in Europe). These provide a significant incentive to move to higher biofuels blend levels and to encourage the development of more GHG efficient fuels.
- Strict but consistent sustainability guidelines are needed to ensure fuels meet necessary environmental, social and economic goals.

However, the same set of measures does not sufficiently support the market introduction of emerging biofuels such as cellulosic ethanol and fuels based on thermochemical technologies such as gasification and pyrolysis. Policy measures which can support the introduction of these processes include:

- Separate obligations for new fuels with high rewards to reflect likely high cost of first successful plants (e.g. US RFS2 provision for cellulosic fuels)
- Continuing support for RD&D, recognizing especially the extended period likely to be needed in order to commission novel plants and to solve problems which inevitably arise when operation at commercial scale commences.
- Risk guarantees such as those available within the US can help reduce the financial risk associated with constructing large scale first of a kind facilities.

Finally, suggestions made by the participating industry representatives during the policy workshop on 18 November 2019 in Brussels include:

- to install some sort of carbon price
- to focus on the carbon intensity of renewable fuels
- to get the oil majors involved,
- to establish a requirement to phase out fossil fuels in the transport sector, and
- to allow the automotive industry to count the GHG emission reductions offered by the use of renewable fuels against their $CO_2$ fleet targets (which could then be strengthened).

## Final remarks

With the above tools at hand, each government has to find the right alternative fuels and vehicles to go for, and to find the right set of policy measures for the particular national situation at a given time. There are no one-size-fits-all solutions to decarbonize transport. The only constant is that bold action needs to be taken now to reach decarbonization at the required level and speed.

## Abbreviations

| | |
|---|---|
| 2DS | IEA 2 Degree Scenario, compatible with the goal of limiting global heating to 2°C by 2100 |
| ALIISA | Model used by VTT to calculate the future composition of vehicle fleets in this study |
| AMF | Advanced Motor Fuels |
| B5, B7,… | Diesel blends with x% FAME |
| BAU | Business as usual |
| CCU | Carbon capture and utilization |
| CPS | IEA Current Policies Scenario |
| E5, E10,… | Gasoline blends with x% ethanol |
| EPE | Brazilian Energy Research Office |
| ETBE | Ethyl tert-butyl ether, ethanol-containing gasoline additive |
| EUR | Euro |
| EV | Electric vehicle |
| FAME | Fatty acid methyl ester |
| FCEV | Fuel cell electric vehicle |
| FFV | Flex-fuel vehicle, capable of using either gasoline or high-blend ethanol (or pure hydrous ethanol in the case of Brazil) |
| FT | Fischer Tropsch |
| FY | Fiscal Year |
| GHG | greenhouse gases |
| HDT | Heavy duty truck |
| HEFA | Hydrotreated esters and fatty acids |
| HEV | Hybrid electric vehicle |
| HVO | Hydrotreated vegetable oils |
| ICE | Internal combustion engine |
| IEA | International Energy Agency |
| ILUC | Indirect land-use change |
| IRENA | International Renewable Energy Agency |
| LCA | Life-cycle assessment |
| LCFS | Low-carbon Fuel Standard, Californian regulation |
| LPG | Liquefied petroleum gas (auto gas) |
| LUC | Land-use change |
| MDT | Medium duty truck |

| | |
|---|---|
| MTBE | Methyl tert-butyl ether, methanol-containing gasoline additive |
| NPS | IEA New Policies Scenario |
| RED | Renewable Energy Directive, EU regulation |
| RED-II | Recast of the Renewable Energy Directive, EU regulation |
| RenovaBio | Renova Bio, Brazilian regulation |
| RFS | Renewable Fuel Standard, US regulation |
| SDS | IEA Sustainable Development Scenario |
| TCP | Technology Collaboration Programme (of the IEA) |
| TRL | Technology Readiness Level |
| TTW $CO_2$ emissions | Tank-to-wheel $CO_2$ emissions, i.e. tailpipe emissions |
| UCO | used cooking oil |
| USD | United States (of America) Dollar |